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[T2.1 Test Requirements]

Test recommendations and gap analysis report

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Executive summary

Marine renewable energy is still an emerging technology. As such, there is still a lack of mature standards and guidance for the development and testing of these devices. This report aims to summarise relevant published guidance and standards, and highlight any gaps or areas for further development: covering wave, tidal and offshore energy technologies for the full range of technology readiness levels.

Recommendations are given on which documents addresses particular aspects of testing. This has been split into two parts:

1. By device type: wave energy converters; tidal energy converters; offshore wind turbines; and cross-cutting technologies.
2. By facility type: test tanks (flumes, towing-tanks, & basins); wind tunnels; field test sites (sheltered & exposed sites); and component test facilities.

Due to the scope of the report, this document covers a wide range of topics, ranging from health & safety and documentation, to scaling laws and instrumentation. A gap analysis has been undertaken to identify areas not well covered by existing documents. This is based on the review of published documents, from responses to a questionnaire sent out to each test facility involved in the MaRINET2 programme, and the experience of project partners contributing to this report. Key areas highlighted include:

- Modelling the PTO subsystem, including scaling, simulation at model scale, and performance prediction/ assessment.
- Moorings and cable systems.
- Working towards a coherent set of guidelines/standards used by all test facilities.
- Testing in combined wave-current conditions.
- An understanding of failure mechanisms resulting from corrosion, and of the effect of wear, corrosion and fatigue combinations.

Importantly, despite the reviewed documents covering a variety of technical aspects it is noted that there is a lack of guidance on how to transition between stages, and deal with scaling from a controlled laboratory setting to the uncontrolled, hostile, ocean environment.

In highlighting this, and other key areas for improvement, this document lays the foundation for the MaRINET2 programme and other future projects to make significant progress in closing these gaps in understanding.

1. Introduction

1.1 Scope of report

This report is a review of published standards and guidelines for testing of marine renewable energy devices. Recommendations are given on which documents address particular aspects of testing. Additionally, a gap analysis has been undertaken to identify areas not well covered by existing documents. This is based on the review of published documents, from responses to a questionnaire sent out to each test facility involved in the MaRINET2 programme, and the experience of project partners contributing to this report.

Marine renewable energy is a very diverse topic, with a wide range of technology types and configurations, including wave energy converters (WECs), tidal energy converters (TECs), and floating offshore wind turbines (FOWTs). These devices also span the full range of technology development, from early concept to commercial deployment. The commonality between these is that all are designed to extract renewable energy from the marine environment, and are therefore subject to the harsh conditions this entails.

One of the challenges in producing guidance for marine renewable energy testing is the shear diversity of device concepts. A three level device classification template was developed for wave and tidal energy converters as part of the EquiMar protocols [1]. This categorises devices based on the general form, the power take-off subsystem, plus the reaction and control subsystems. For each level, there are a number of standardised descriptors, giving many thousands of possible device concept permutations. Technology reviews, such as [2], [3], identify more than 100 wave and tidal energy concepts in various stages of development.

Marine renewable energy is still an emerging technology. As such, there is still a lack of mature standards and guidance for the development and testing of these devices. This report aims to summarise relevant published guidance and standards, and highlight any gaps or areas for further development.

1.2 Outline of report

The remainder of this report is structured as follows. Section 2 provides a summary of standards and guidance used by these facilities.

Sections 3–10 cover the test recommendations, which are split as follows, as testing of marine renewable energy devices is a complex multi-faceted problem.

- Section 3 covers general considerations applicable to all device types and facilities.
- Sections 4–7 are split by device type covering wave, tidal, wind, and cross-cutting technologies, subdivided by stage of development as appropriate. These sections cover recommendations that are focused more towards developers of these specific device/technology types.

- Sections 8–10 cover general considerations for test facilities, and recommendations for different types of test facilities: namely hydrodynamic test tanks, wind tunnels, offshore test sites, and component test facilities.

The gap analysis is presented in section 11, followed by general conclusions in section 12.

Appendix A contains information regarding the questionnaire and results, and Appendix B provides a tabular summary of key topics covered in relevant standards and guidance documents. It is envisioned that this tabular summary will be a useful resource for those involved in testing marine renewable energy devices, serving as a useful tool to identify quickly relevant standards and guidance.

1.3 Structured device development plans

It is typical for devices, including marine renewable energy converters, to be developed in an incremental staged approach from concept to commercialisation. Similar multi-stage development plans are outlined in published guidance for offshore renewable energy devices. These typically relate to the widely used technology readiness level (TRL) concept, developed initially by NASA [4], suggesting increasingly complex testing as the device technology matures. At each stage, the developer is aiming to maximise understanding of the device performance with the minimum of risk and outlay. The stages can broadly be defined as per Table 1.1, although there is likely to be overlap between stages in reality. The developer may also choose to skip particular stages if appropriate. Development might also be an iterative process, particularly for subsequent revisions to the device concept, for example, going back to tank test improvements to the design following open water deployment.

Larger models and facilities are typically more expensive, but give results that are more accurate, and unwanted scale effects can be minimised. More instrumentation can also be installed in larger models, increasing the understanding that can be gained from a particular test programme.

Stage gates are outlined in guidance, such as OES IA guidelines for WEC development [5]. These are also adopted in forthcoming IEC guidelines for early stage development of WECs [6]. These development stages specify particular outcomes that should be attained, or tasks that should be completed, before the device developer proceeds to the next stage of testing.

> “It should be stated that following a staged, systematic development plan is not a guarantee for success, but not following one is probably a pathway to disappointment, lost time and wasted resources.” — B. Holmes and K. Nielsen [5]

Table 1.1 Five stages of development, for marine renewable energy devices [5], [7]–[9]

Stage	TRL	Nominal test scale*	Typical infrastructure
1. Concept Validation	1-3	Small scale (c. 1:100-1:25)	University laboratory
2. Design Validation	3-5	Larger scale (c. 1:25-1:10)	Industrial scale laboratory
3. Systems Validation	5-6	Sub-prototype size (c. 1:4)	Benign test site
4. Device Validation	7-8	Approaching full size (c. 1:1)	Exposed test site
5. Economics Validation	9	Full size, small arrays	Commercial site

* Scales refer to WEC & TEC models, for OWT smaller scales are typically used at each stage given the larger size of the full-sale prototype

1.4 Benefits of laboratory/field testing

Prototype testing is an integral part of the development process for many technologies. This includes scale model testing in laboratories and field test sites, as well as testing of components and sub-assemblies. Table 1.2 gives a brief rationale for scale testing of marine renewable energy devices. Although this specifically considers tidal energy devices, it is generally applicable to all types. At each stage, the aim is to learn as much as possible about the device or component, while keeping the risk and financial outlay as low as practicable.

Table 1.2 Rationale for scale testing of marine renewable energy devices, from [10]

Why test at small scale (Tank)?	Testing at Small scale can be quick and inexpensive. The controlled environment helps as experiments can be easily repeated for a range of parameters. An additional advantage of testing at small scales is that each individual subsystem can be independently tested.
Why test at medium scale (Tank)?	Testing at medium scale is an important step as it can reproduce some of the full-scale physics, and this can eliminate some of the scaling issues while still maintaining the ability to be precise, accurate and repeatable in a controlled environment.
Why test at medium scale (Channel / Sea trial)?	Testing at an outdoor medium scale facility can be used to characterise the power take-off under realistic circumstances. This is the opportunity to validate the technology and the device design. At this scale, it is possible to test new designs and make improvements without excessive additional cost. There is also the chance to perform some endurance testing before going to full scale.
Why test at large scale (Sea trial)?	Sea trials are the last stage of testing and perform a vital role in terms of verification and the attraction of development funding. Lessons learnt thru deployments and recovery are vital for cost reductions in O&M, reliability and survivability performance.

1.5 Terminology

Cross-references within this document are specified as “section 1”, whereas references to specific parts of guidance documents use the section mark, i.e. “§1”.

There are many different abbreviations, acronyms, and symbols used in the field of marine renewables, a summary of these is provided below. Crossover with other industries means that different abbreviations may be used for similar terms (e.g. MRE & ORE). Additionally, the same symbol may be used to represent different concepts in different sectors. Whilst care has been taken to define abbreviations and symbols used throughout this document, the reader is directed to the original source(s) in the case of discrepancies.

Abbreviations and acronyms

ADCP	Acoustic Doppler Current Profilers
ADV	Acoustic Doppler Velocimeter
CORES	Components for Ocean Renewable Energy Systems
DAQ	Data acquisition
DMEC	Dutch Marine Energy Centre
DTU	Danmarks Tekniske Universitet (Technical University of Denmark)
ECN	École Centrale de Nantes
EMEC	European Marine Energy Centre
FRT	Fault ride through
IEC	International Electro-technical Commission
IEEE	Institute of Electrical and Electronics Engineers
IFREMER	Institut français de recherche pour l'exploitation de la mer (French Research Institute for Exploitation of the Sea)
IP/IPR	Intellectual Property/ Intellectual Property Rights
ISO	International Standards Organisation
ITTC	International Towing Tank Conference
MBL	Minimum Break Load
MEC	Marine energy converter
MERiFIC	Marine Energy in Far Peripheral and Island Communities
MRE	Marine renewable energy
NREL	National Renewable Energy Laboratory
OES	Ocean Energy Systems
ORE	Offshore renewable energy
OWC	Oscillating water column
OWT/FOWT	Offshore wind turbine/floating offshore wind turbine
PTO	Power take-off
pu	Per unit
RES	Renewable energy resources
TEC	Tidal energy convertor
TKE	Turbulence kinetic energy
TNA/TA	Trans-national access

TRL	Technology readiness level
TSO	Transmission system operator
TSR	Tip speed ratio
WEC	Wave energy convertor
WES	Wave Energy Scotland
WP	Work package
WPP	Wind power plant

2. Summary of standards and guidance used

This section provides a summary of the key sources of standards and guidance available and used by MaRINET2 project partners. “Standards and guidance” are quite general terms and may apply to a range of topics including technical specifications, guidance protocols, best practice, or recommendations from industry. The documents used include both general and technical standards, guidance produced by various bodies and projects, and a few key published papers. A tabular summary of the topics covered in each of the relevant standards and guidance documents is provided as Appendix B.

The questionnaire sent out to facilities, Appendix A, asked which standards and guidance documents were used by each facility. The percentage of respondents using these is reported in Tables 3.1–3.3. Other potentially relevant standards and guidance that were not included in the questionnaire have been included at the bottom of these tables.

Although the proportion of questionnaire respondents using these documents appear low, it is noted that not all documents are applicable to every test facility and/or the facility may be using similar practices without explicitly referring to these documents. It is also noted that some of these documents are aimed towards device developers, who were not included in the survey of MaRINET2 facilities, and thus these documents may be used more widely than might be assumed from the questionnaire responses alone.

As part of MaRINET1, a summary of standards and guidance for testing the power-take-off (PTO) subsystem was collated in deliverable 2.25 “Definition of standardised PTO Test Procedures” [11]. This was then included as §3 of D4.02 “Report on dynamic test procedures” [12]. For the wind, wave, and tidal sectors, it covers standards creation bodies, key standards for the sector, plus informative documents and the associated committees writing them.

2.1 General standards

There is a range of standards covering non-technology-specific aspects (such as quality management) that are used by MaRINET2 test facilities. Those included in the questionnaire are summarised in Table 2.1 together with the percentage of respondents using them. These general standards are used equally by all facility types (test tanks, field test sites, component testing, and other facilities). Other general standards may cover aspects relating to marine renewable energy testing, the list included in the questionnaire is not considered exhaustive.

Table 2.1 General standards used, with percentage of questionnaire respondents using them

Standard Nr.	Title	Respondents using
ISO 9001	Quality management	38%
ISO/IEC 17025	General requirements for the competence of testing and calibration laboratories	28%
BS OHSAS 18001	Occupational Health and Safety Management	15%
ISO/IEC 17020	Conformity assessment — Requirements for the operation of various types of bodies performing inspection	11%
ISO 14001	Environmental management systems	2%
ISO/IEC 11179	Information Technology	0%

2.2 Technical standards

Technical standards, including those used by MaRINET2 test facilities, are listed in Table 2.2. These cover technology-specific aspects that typically also apply to other more established sectors, such as electrical grid codes, wind turbines, and fibre ropes. From the questionnaire results (see Appendix A) these standards appear to be predominantly used by component test facilities.

The International Electro-technical Commission (IEC) is in the process of publishing technical standards for wind turbines and for marine energy devices. Technical Committee (TC) 88 is developing Technical Standard 61400 on wind turbines, whilst TC 114 is in the process of publishing 62600 on wave, tidal and other water current converters. The various parts of these are listed in Table 2.3 and Table 2.4 respectively. The published parts have the status of Technical Specification (TS) and not yet International Standard (IS). Other parts have the status Committee Draft (CD) or Draft Technical Specification (DTS). Although the guidance for tank testing is still under development, it is used by a significant number of the test tanks and field test sites in MaRINET2.

IEC TS 62600-2 includes the following caveat regarding the suitability and/or relevance of non-marine-renewable-energy specific standards, and recommends a formal assessment of risks before these are used.

> “The use of a standard from other mature industries where nothing explicitly written for MECs [marine energy converters] is available carries a risk that important considerations for the marine energy application are given insufficient emphasis or ignored completely. This applies to standards written for offshore wind, oil and gas, and shipping.”

EquiMar deliverable 1.2 “Recommendations from other sectors” [13] lists a number of additional standards that may be applicable to some areas of marine renewable energy.

Table 2.2 Technical standards used, with percentage of questionnaire respondents using them

Standard Nr.	Title	Respondents using
ASTM G52	Standard Practice for Exposing and Evaluating Metals and Alloys in Surface Seawater	2%
DNVGL-SE-0163	Certification of tidal turbines and arrays	2%
DNVGL-ST-0164	Tidal turbines	– *
DNVGL-RP-0416	Corrosion protection for wind turbines	– *
DNVGL-OS-B101	Metallic materials	– *
DNVGL-RP-B401	Cathodic protection design	– *
DNVGL-RP-C203	Fatigue design of offshore steel structures	– *
DNV-RP-C205	Environmental Conditions and Environmental Loads	– *
DNV-OS-C501	Composites Components	– *
DNV-OS-C502	Offshore Concrete Structures	– *
DNV-OS-E301	Position Mooring	2%
DNV-OS-J101	Design of Offshore Wind Turbine Structures	– *
DNV-DS-J102	Design and Manufacture of Wind Turbine Blades, Offshore and Onshore Wind Turbines	2%
DNV-OS-J103	Design of Floating Wind Turbine Structures	– *
IEC 60076	Transformers	2%
IEC 60137	Insulated bushings for alternating voltages above 1000V	2%
IEC 60502	Cables and accessories	2%
IEC 60840	Cables above 30kV	2%
IEC 61400	Wind turbines (see Table 2.3 for details)	9%
IEC 62008	Performance characteristics and calibration methods for digital data acquisition systems and relevant software	– *
IEC TS62600/ TC114	Wave, tidal and other water current converters (see Table 2.4)	23%
IEEE 1043	Recommended Practice for Voltage-Endurance Testing of Form-Wound Bars and Coils	2%
IEEE 1310	Recommended Practice for Thermal Cycle Testing of Form-Wound Stator Bars and Coils for Large Rotating Machines	2%
ISO 2307	Fibre ropes – Determination of certain physical and mechanical properties	2%
ISO 5168	Measurement of fluid flow – Procedures for the evaluation of uncertainties	– *
ISO 7500	Metallic materials — Verification of static uniaxial testing machines	– *
ISO 8044:2015	Corrosion of metals and alloys – Basic terms and definitions	
ISO 12944	Paints and varnishes- Corrosion protection of steel structures by protective paints	– *
ISO 18692	Fibre ropes for offshore station keeping – Polyester	2%
ISO 19901-1	Requirements for offshore structures. Recommendations on use of oceanographic data	– *
ISO TS 19336	Fibre ropes for offshore station keeping – Polyarylate	2%
ISO 21650	Determination of wave and current actions on coastal structures	– *

Standard Nr.	Title	Respondents using
NORSOK M-501	Surface preparation and protective coating	– *

** not included in questionnaire to MaRINET2 facilities*

Table 2.3 Parts of IEC 61400 Wind turbines (TC88 Wind energy generation system) [1]

Part	Title	Published
61400-1	Design requirements	Apr-2014
61400-2	Small wind turbines	Dec-2013
61400-3	Design requirements for offshore wind turbines	Feb-2009
61400-3-2	Design requirements for floating offshore wind turbines	Draft
61400-4	Design requirements for wind turbine gearboxes	Dec-2012
61400-5	Wind turbine rotor blades	Draft
61400-6	Tower and foundation design requirements	Draft
61400-7	Safety of wind turbines power converters	Draft
61400-8	Design of wind turbine structural components	Draft
61400-11	Acoustic noise measurement techniques	Nov-2012
61400-12-1	Power performance measurements of electricity producing wind turbines	Mar-2017
61400-12-2	Power performance of electricity-producing wind turbines based on nacelle anemometry	Sep-2016
61400-13	Measurement of mechanical loads	Dec-2012
61400-14	Declaration of apparent sound power level and tonality values	Mar-2005
61400-15	Assessment of site specific wind conditions for wind power stations	Draft
61400-21	Measurement and assessment of power quality characteristics of grid connected wind turbines	Aug-2008
61400-21-1	Measurement and assessment of electrical characteristics - Wind turbines	Draft
61400-21-2	Measurement and assessment of electrical characteristics - Wind power plants	Draft
61400-22	Conformity testing and certification	May-2010
61400-23	Full-scale structural testing of rotor blades	Apr-2014
61400-24	Lightning protection	Jun-2010
61400-25-1	Communications for monitoring and control of wind power plants – Overall description of principles and models	Jul-2017
61400-25-2	Communications for monitoring and control of wind power plants – Information models	Jun-2015
61400-25-3	Communications for monitoring and control of wind power plants – Information exchange models	Jun-2015
61400-25-4	Communications for monitoring and control of wind power plants – Mapping to communication profile	Nov-2016
61400-25-5	Communications for monitoring and control of wind power plants – Compliance testing	Sep-2017

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[1] http://www.iec.ch/dyn/www/f?p=103:23:2488977271676::::FSP_ORG_ID,FSP_LANG_ID:1282,25/

Part	Title	Published
61400-25-6	Communications for monitoring and control of wind power plants – Logical node classes and data classes for condition monitoring	Dec-2016
61400-25-7	Communications for monitoring and control of wind power plants – Configuration description language for communication in wind automation systems related to IEDs	Draft
61400-25-41	Communications for monitoring and control of wind power plants – Mapping to communication profile based on IEC 62541 (OPC UA)	Draft
61400-26-1	Time-based availability for wind turbine generating systems	Nov-2011
61400-26-2	Production-based availability for wind turbines	Jun-2014
61400-26-3	Availability for wind power stations	Aug-2016
61400-26-4	Reliability for wind energy generating systems	Draft
61400-27-1	Electrical simulation models - Wind turbines	Feb-2015
61400-27-2	Electrical simulation models - Model validation	Draft
61400-30	Safety of Wind Turbine Generator Systems (WTGs) – General principles for design	Draft
61400-40	Electromagnetic Compatibility (EMC) – Requirements and test methods	Draft
61400-50-3	Use of nacelle mounted lidars for wind measurements	Draft
61400-101	General requirements for wind turbine plants	Draft

Table 2.4 Parts of IEC TS 62600 Marine energy – Wave, tidal and other water current converters (TC114)[2]

Part	Title	Published
62600-1	Terminology	Dec-2011
62600-2	Design requirements for marine energy systems	Aug-2016
62600-3	Measurement of mechanical loads	Draft
62600-10	Assessment of mooring system for marine energy converters (MECs)	Mar-2015
62600-20	General guidance for design and analysis of an Ocean Thermal Energy Conversion (OTEC) plant	Draft
62600-30	Electrical power quality requirements for wave, tidal and other water current energy converters	Draft
62600-40	Acoustic characterization of marine energy converters	Draft
62600-100	Electricity producing wave energy converters – Power performance assessment	Aug-2012
62600-101	Wave energy resource assessment and characterization	Jun-2015
62600-102	Wave energy converter power performance assessment at a second location using measured assessment data	Aug-2016
62600-103	Guidelines for the early stage development of wave energy converters –Best practices and recommended procedures for the testing of pre-prototype scale devices	Draft
62600-200	Electricity producing tidal energy converters – Power performance assessment	May-2013

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[2] http://www.iec.ch/dyn/www/f?p=103:22:25054285320428::::FSP_ORG_ID,FSP_LANG_ID:1316,25/

Part	Title	Published
62600-201	Tidal energy resource assessment and characterization	Apr-2015
62600-202	Scale testing of tidal stream energy systems	
62600-300	Electricity producing river energy converters – Power performance assessment	Draft
62600-301	River energy resource assessment	Draft

2.3 Guidance documents

In addition to formal standards, there are a number of other key sources of guidance for the testing of marine renewable energy devices, as shown in Table 2.5. These are also used by a significant number of the test tanks, field test sites, and other facilities in MaRINET2. None of the component test sites reported using these guidance documents however.

The main guidance documents can be summarised as follows:

- **Protocols for the Equitable Assessment of Marine Energy Converters (EquiMar)**, an FP7 EU project (2008 to 2011) to provide guidance for the sector. In addition to the main protocols [14], a series of supporting work package deliverables were produced. These are summarised in Appendix B, and cover a wider range of topics than just testing, including resource assessment and economic evaluation. These EquiMar Deliverables are referred to as *ED0.0* in this document.
- The first **MaRINET** project (2011 to 2015) also produced a range of guidance in the project deliverables. These are available online[3], with the key topics of each report summarised in Appendix B. The MaRINET1 deliverables are referred to as *MD0.0* in this document.
- Building on this, **MaRINET2** will produce additional guidance for marine renewables infrastructure and testing, including this document. These will be published over the next three years, see Table 2.6 for a list of public deliverables.
- The **International Towing Tank Conference (ITTC)** is one of the key organisations involved in tank testing of ships and offshore structures. It produces recommended procedures and guidelines on how to conduct various tests for all types of test tanks. These are published every three years, most recently in 2017. A full list of reports is given in ITTC 0.0 Register, with the following highlighted as particularly relevant.
    - 7.5-02-01-01 Guide to the Expression of Uncertainty in Experimental Hydrodynamics[15]
    - 7.5-02-07-01.1 Laboratory Modelling of Multidirectional Irregular Wave Spectra [16]
    - 7.5-02-07-01.2 Laboratory Modelling of Waves: regular, irregular and extreme events [17]
    - 7.5-02-07-03.7 Wave Energy Converter, Model Test Experiments [18]
    - 7.5-02-07-03.8 Model Tests for Offshore Wind Turbines [19]
    - 7.5-02-07-03.9 Model Tests for Current Turbines [20]

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[3] http://www.marinet2.eu/archive-reports-2/research-reports/

- The **European Marine Energy Centre (EMEC)** published 12 draft standards and guides in 2009, for wave and tidal energy. Six of these have been submitted as a suggested work programme for IEC TC 114, marked *.
    1. Assessment of Performance of Wave Energy Conversion Systems*
    2. Assessment of Performance of Tidal Energy Conversion Systems*
    3. Assessment of Wave Energy Resource*
    4. Assessment of Tidal Energy Resource*
    5. Guidelines for Health & Safety in the Marine Energy Industry
    6. Guidelines for Marine Energy Certification Schemes*
    7. Guidelines for Design Basis of Marine Energy Conversion Systems*
    8. Guidelines for Reliability, Maintainability and Survivability of Marine Energy Conversion Systems
    9. Guidelines for Grid Connection of Marine Energy Conversion Systems
    10. Tank Testing of Wave Energy Conversion Systems
    11. Guidelines for Project Development in the Marine Energy Industry
    12. Guidelines for Manufacturing, Assembly and Testing of Marine Energy Conversion Systems
- EMEC created a series of guidance documents based on lessons learnt with local supply chain as funded by Wave Energy Scotland. The documents covered topics on compliance such as consents, H&S; installations, operations and maintenance including handling. These documents are located on the WES online library.
- **Ocean Energy Systems**, a framework created by the International Energy Agency, published guidance for development of tidal and wave energy devices.
    - OES IA (2008): Tidal-current Energy Device Development and Evaluation Protocol
    - OES IA (2010): Guidelines for the development & testing of wave energy systems
- Additionally, a number of laboratories have published guidance and best practice documents specifically on tank testing of renewable energy devices, including the University of Edinburgh and IFREMER.

Another useful information source is the knowledge capture project set up by Wave Energy Scotland (WES) following the demise of two key players in the wave energy industry: Pelamis Wave Power and Aquamarine Power. A selection of reports from these companies and others including those involved in the ongoing WES funding calls can be found on the WES website[4].

Table 2.5 Other key guidance documents, with percentage of questionnaire respondents using them

Organisation	Guidance title	Respondents using
MaRINET 1	Supporting work package documentation	30%
EquiMar	Protocols and supporting work package documentation	23%
ITTC	Recommended procedures and guidelines	21%
UEDIN (2009)	Best Practice Guidelines for Tank Testing of Wave Energy Converters	13%
EMEC (2009)	Tank Testing of Wave Energy Conversion Systems	8%

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[4] https://library.waveenergyscotland.co.uk/knowledge-capture/

IFREMER (2008)	Marine current energy converter tank testing practices	8%
OES IA (2010)	Guidelines for the development & testing of wave energy systems	8%
OES IA (2008)	Tidal-current Energy Device Development and Evaluation Protocol	0%

Table 2.6 Public deliverables planned for the MaRINET2 project [5]

Ref	Title	Deliverable Due
D1.2	Project website (http://www.marinet2.eu/)	Ongoing
D2.1	Test recommendations and gap analysis report (this document)	Apr-2018
D2.4	Test verification process	Dec-2019
D2.5	Round Robin findings and recommendations	Aug-2020
D2.6	Final guidelines for test applicants	Aug-2020
D2.7	Final guidelines for test facilities	Aug-2020
D2.8	Ocean energy technology guidance report	Dec-2020
D4.1	Common MaRINET 2 standard testing and benchmarking plan	Dec-2018
D4.2	Report on remote access assessment and development	Dec-2019
D4.3	MaRINET 2 Standard Testing Procedures manual	Jun-2020
D4.4	Present and future grid connection testing	Jun-2020
D4.5	Delivery of high fidelity, high resolution empirical data sets	Feb-2021
D5.5	Industry and academic liaison Consultation Activity Reports	Apr-2020
D5.6	Report on MaRINET2 Users groups Workshops	Aug-2020
D5.9	Final report on Academic dissemination	Mar-2021
D5.11	Final report on Promotion of the TNA Calls, Training and e-Infrastructure activities	Apr-2021
D5.12	Project success/impact brochure	May-2021
D5.13	Plan for the use of project results	Jun-2021
D6.3	E-infrastructure use cases and guidelines	Dec-2020
D7.4	Draft plan for higher education on ORE	Dec-2020

2.4 Other sources

The review of standards and guidance in the following sections has predominantly been limited to the above-mentioned sources. A limited number of other published papers, etc. have been referenced where appropriate, but a comprehensive literature review has not been undertaken for this project.

Test facilities may have internal guidance documents detailing methods and practices for testing. Unless these are publicly available, they have not been discussed or referenced.

The standards and guidance included in this review are predominantly European based, owing to the location of the facilities involved in the MaRINET2 programme. A number of key international standards have been referenced where these are most appropriate however.

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[5] Internal/management deliverables for MaRINET2 project partners only are not listed here

3. General considerations for testing

This section deals with guidance and recommendations on common themes between all forms of testing of all device types. There may be specific guidance providing more details regarding a particular facility, type of test, or device.

3.1 Test planning and management

3.1.1 Experimental design and test plans

A well thought out test-campaign is essential for getting the most out of the test programme. To facilitate this, a test matrix should be developed in conjunction with the test facility. This should set out the test objectives, the groups of tests to be run, and provided details of individual test such as environmental conditions required, test duration, etc.

It is noted that the testing process is often subject to delays, and may proceed slower than anticipated. The priority of tests should be decided in advance so that lower priority tests can be dropped if required. It is also good to have a list of additional tests to fill additional time. This could arise either: if things go well, or if a particular set of tests cannot be run.

General considerations for a staged development programme are covered in section 1.3 above. This is also covered to varying degrees in guidance documents that deal specifically with particular device types. The experimental design will then relate to the requirements of that stage and upcoming stage-gate.

EquiMar protocols II.A and II.B cover tank testing and sea trials respectively. These focus primarily on procedural aspects of testing, including experimental best practice, project planning, and experimental design. Further considerations for the design of experiments, such as test randomisation, are given in §3 of ED3.4 Best practice for tank testing of small marine energy devices [21].

Risk analysis is fundamental to safe field testing. Creation of risk matrix from prototype manufacturing to sea deployment, testing, recovery and decommissioning stages will inform and improve successes during field testing.

3.1.2 Reporting and documentation

A sample reporting structure is presented in §9 of ED3.4 Best practice for tank testing of small marine energy devices [21], although it is recognised the report structure will vary depending on the test purpose, who is producing it, and the intended audience.

ITTC procedures for wave, wind, and tidal turbines [18]–[20] outline generic test reports, giving a list of topics that should be considered. They also recommend all results of model tests be presented as (full-scale) prototype values, with model values scaled to full scale by applying the proper similitude laws.

3.1.3 Intellectual property and publicity

If the model to be tested is IP sensitive, provisions to protect the IP should be discussed with the infrastructure manager. If the model is not IP sensitive or is IP protected, the developer and/or the local facility may wish to use the testing as a news story or for their own marketing purposes. This can be a good opportunity to gain some publicity for the design. In general, it is recommended that some IP protection be in place prior to testing, if it is felt necessary by the user. The European IPR Helpdesk[6] is a useful reference for any questions or issues relating to IP on EU funded research projects.

3.1.4 Risk assessment

Risk assessment can and should be used in a number of areas, including project and finance, technology, as well as the risks associated with installation and operation.

There is a wide range of available guidance on risk assessment, which is outside of the scope of this document. Risk assessment is by no means specific to marine renewables and is used in all areas. Of particular relevance would be lessons from similar but more mature sectors such as onshore wind, offshore oil and gas exploitation, and more general marine operations. Project and financial risks from other small/medium enterprises could also be transferred.

3.1.5 Health and safety

It is important that all testing be undertaken in a safe manner. Consideration should be given to this early in the planning stage, as changing the test plan may involve significant reworking and additional costs. Sufficient time shall be allowed in the test plan to undertake all tasks in a safe manner. Accidents are most likely to happen when people are rushing around following poor planning.

In addition to relevant legislation, each test facility will have specific health and safety procedures that should be followed. When testing marine renewable energy devices, there are a number of specific considerations to be aware of:

- Working adjacent to and over water, particularly where water currents are generated in the lab or in open water at field test sites.
- Electrical systems require proper design and implementation, particularly where mains/high voltage or powerful capacitors/batteries are involved.
- Safe handling and lifting of equipment, models, and instrument rigs needs to be addressed.

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[6] https://www.iprhelpdesk.eu/

3.2 Acquiring and processing test data

The specifics of the measurement made and instrumentation used will vary considerably depending on both the device or component being tested and the facility where the tests are conducted. The analysis required also depends on the test requirements. Some general considerations are however given below.

3.2.1 Data acquisition and storage

Technical specifics for DAQ are covered in IEC 62008 “Performance characteristics and calibration methods for digital data acquisition systems and relevant software” [22]. This document does not provide guidance on typical use cases such as a laboratory environment.

More practical considerations for acquisition of data are given in ED3.3 “Assessment of current practice for tank testing of small marine energy devices” §7 [23].

There is a short section on archival and storage of data in ED3.4 “Best practice for tank testing of small marine energy devices” [21].

3.2.2 Uncertainty and errors

Uncertainty analysis and data quality assurance procedures are addressed in §4 of ED3.4 Best practice for tank testing of small marine energy devices [21].

A number of the ITTC recommended procedures and guidelines cover uncertainty analysis:

- 7.5-02-01-01 Guide to the Expression of Uncertainty in Experimental Hydrodynamics [15],
- 7.5-02-01-06 Determination of a type A uncertainty estimate of a mean value from a single time series measurement [24],
- 7.5-02-01-07 Guideline to Practical Implementation of Uncertainty Analysis [25],
- 7.5-02-02-02 Uncertainty Analysis, Guidelines for Resistance Tests [26],
- 7.5-01-03-01 Uncertainty Analysis, Instrument Calibration [27],
- 7.5-01-03-02 Uncertainty Analysis, Laser Doppler Velocimetry Calibration [28],
- 7.5-01-03-03 Guideline on the Uncertainty Analysis Particle Image Velocimetry [29].

There are also three example uncertainty analyses for different types of tests:

- 7.5-02-03-02.2 Uncertainty Analysis Example for Open Water Test [30]
- 7.5-02-07-03.12 Uncertainty Analysis for a Wave Energy Converter [31]
- 7.5-02-07-03.15 Uncertainty Analysis - Example for Horizontal Axis Turbines [32]

3.2.3 Performance assessment

When undertaking a power performance assessment, it is essential to define the input power available (e.g. wave power per unit crest length) as a benchmark to what is generated by the PTO [9]. The IEC Technical Specifications 62600-100 and 62600-200 cover the power performance assessment for wave and tidal energy converters respectively, with further guidance on performance assessment discussed in relevant subsections of this document.

3.3 Tie-in to numerical modelling

Although numerical modelling is not specifically part of this report, many experimental programmes are used to validate computer models. Numerical modelling is also utilised for resource assessment, which may be used to give baseline environmental conditions to define testing undertaken. It is therefore important to understand how the physical testing links in with the numerical modelling.

Ideally, all conditions that will be examined during tank testing should be simulated numerically prior to physical testing. This information is very useful when planning the test campaign as it will allow for selection of appropriate sized sensors and the provision of sufficient motion capture volume. Generally, the best tank testing campaigns are those which are used to validate numerical models rather than to examine model performance for the first time.

Guidance for numerical modelling in wave and tidal energy [33] was produced as part of SuperGen Marine, and covers the design and implementation of numerical models.

(Part I) Recommendations by device type

The following four sections summarise guidance and offer recommendations particularly relevant to different types of marine energy: wave energy converters (4), tidal energy converters (5), offshore wind turbines (6), and cross-cutting technologies (7).

4. Wave energy converters

4.1 Introduction

The quest to capture energy from the waves has seen a wide variety of wave energy convertor (WEC) concepts proposed and developed to varying stages. Many of these have been tested at small scale, and some completed larger scale testing and/or filed trials. The diversity of device concepts, including oscillating water columns (OWCs), point-absorbers, attenuators, overtopping devices, etc. makes this a challenging topic to produce standards and guidance for testing.

4.1.1 Development progression

As with other technologies, development of WECs is typically undertaken with small-scale models in the controlled environment of laboratories (test tanks) before progressing to field test sites exposed to real sea conditions. These structured development plan stages and accompanying TRLs are discussed in section 1.3 above. The requirements for stage-1 and stage-2 tank testing are similar, with guidance and recommendations discussed in section 4.2. Field testing at stages 3 and 4 is then covered in section 4.3.

More detail on how this applies to WECs is given in “OES IA Guidelines for the development & testing of wave energy systems” [5]. There is a progression of facilities used, typically using smaller flumes and tanks initially, then larger and more capable basins, before open water deployment in sheltered waters, and finally exposed sites.

For wave energy devices, there is also a relatively clear progression of environmental conditions for tank testing [5], [9], [34]. This can be broadly summarised as regular waves initially followed by long-crested parametric spectra, before introducing directional spreading in order to test within short-crested parametric sea states. It is advantageous, particularly at stage-2, to test within site-specific conditions if actual site data is available, which may include the use of non-parametric spectra. Other metocean conditions such as wind plus tidal range and currents should also be included if appropriate, i.e. where they might have a significant impact on device performance, or are significant at the deployment location.

The practices adopted by a selection of WEC developers during stage-1 development is covered in ED3.1 “Identification of limitations of the current practices adopted for early stage tidal and wave device assessment” [35]. This study includes the responses received from 14 of the 36 developers contacted.

4.2 Lab scale testing (TRL1–5, Stage1–2)

4.2.1 Model and scaling considerations

There are many, potentially conflicting, drivers for the section of model scale. Guidance on some key drivers are discussed below. There are also constraints imposed by the facility used for testing, including the environmental conditions that can be generated and physical size of the tank used, see section 4.2.3.

4.2.1.1 Selecting appropriate scale(s) for testing

The University of Edinburgh "Best Practice Guidelines for Tank Testing of Wave Energy Converters" [36] summarises many of the issues regarding scaling and tabulates the commonly used Froude scaling law for key quantities such as stiffness and power. Froude scaling is typically used for WECs and other tests involving surface gravity waves to maintain the relationship between inertial and gravitational forces. ITTC guidance recommends testing at large scales to minimise scale effects [18], subject to other constraints.

There are several important parameters that do not follow Froude scaling, highlighted in ITTC guidance [18]. This includes compressibility of air in pneumatic systems, which is addressed by Weber [37]. Mechanical friction and viscous damping also do not follow Froude scaling, and may be overestimated for small models in particular. For devices that use deformable materials, alternative scaling may also be required [38].

The size, and thus scale, of the model may also be determined by availability and size of components used to construct and/or instrument the device.

Survivability testing is typically conducted at stage-2, where larger waves are required to simulate more extreme conditions. To reduce expense, it may be possible to reuse a smaller stage-1 model in the larger facility capable of producing the scaled extreme wave heights [21].

4.2.1.2 Representing the power take-off

Representing a power take-off (PTO) designed to extract energy from the waves is highlighted by the ITTC as a key challenge of tank testing WECs [39]. Accurately simulating a PTO and quantifying the power production is difficult, particularly at small scale. Both may require bigger models at larger scales. Following the Froude scaling law, power scales as $\lambda^{3.5}$ where λ is the scale factor, therefore testing a 1:25 scale model of a 1.0 MW device would result in a maximum power output of just 12.8 W, requiring measurements in the mW range [36].

Seven methods for representing and instrumenting the PTO are discussed in §3 of MD2.05 "Report of Instrumentation Best Practice" [40], namely: friction based; weight lifting by rotating axle; eddy current brakes; pressure difference; overtopping flow; passive linear actuators; and advanced PTO systems. PTO options are also covered in §4.4 of MD2.28 "Protocol for Model Construction" [38].

Quantifying energy capture performance is covered in §2.8 of ITTC 7.5-02-07-03.7 "Wave Energy Converter Model Test Experiments" [18]. This is generally expressed as a capture width.

Considerations for testing the PTO system as a separate component are given in MD2.11 "Best Practice Manual for PTO Testing" [41], and MD4.02 "Report on dynamic test procedures" [12] for electrical simulation of the PTO. These are discussed in more detail in section 10.3 below.

4.2.1.3 Constructing and instrumenting model

It is important that key parameters of the model match the full-scale prototype as far as practicable, including the geometry, mass distribution, etc.

A number of guidance documents were produced as part the first MaRINET project covering construction and instrumentation of model WECs. MD2.13 "Collation of Model Construction Methods" [42] and MD2.28 "Protocol for Model Construction" [38] include discussion on scaling considerations, materials selection, and types of instrumentation to measure key parameters of interest. Further discussion on instrumentation for tank testing is given in MD2.05 "Report of Instrumentation Best Practice" [40] and MD4.01 "Tank test related instrumentation and best practice" [43].

ITTC 7.5-02-07-03.7 "Wave Energy Converter Model Test Experiments" [18] covers in §3 the model and installation, plus instrumentation and representing the PTO.

A subsystem approach to model design is suggested in §6 of ED3.3 "Assessment of current practice for tank testing of small marine energy devices" [23].

For floating bodies, it is also important to consider the weight of instrumentation and cables, and the impact these may have on model motions.

4.2.2 Environmental conditions

4.2.2.1 Specifying wave conditions

It is important to specify waves in a clear and consistent manner when considering the environmental conditions for testing WECs. Key wave parameters, and how to use these to describe the wave climate at a measurement location, are summarised in §2 and §3 of MD2.1 "Wave Instrumentation Database" [44]. This covers wave specification in both the time and frequency domain, plus the inclusion of directional spreading (i.e. 2D spectra). Similar information is also presented in MD2.14 "Wave data presentation and storage review" [45], together with example methods to represent wave data from both laboratory and field, such as time histories, single and bi-variate distributions, binning, and spectral plots.

Further relevant information is presented in MD2.8 "Best Practice Manual for Wave Simulation", and MD2.9 "Standards for Wave Data Analysis, Archival and Presentation" [46]. The former outlines important characteristics of ocean gravity waves that must be considered for the completion of a systematic and structured technical development programme of a WEC. The latter includes a brief review of the standardization efforts carried out to date. It addresses types of wave data commonly considered for wave energy purposes and typical data processing outputs, common and suggested practices in wave measurement and data analysis, as well as data archival and presentation approaches to be followed.

Regular wave tests can be short duration, allowing a wide range of conditions to be tested in a relatively limited time. A minimum run length of ten cycles is given in ITTC guidelines "Laboratory modelling of Waves: regular, irregular and extreme events" [17], however some longer tests may be considered. It may also be appropriate to allow conditions to reach a steady state, which will depend on the the facility used and the dynamics of the model.

When testing irregular sea states, the test duration should be long enough to give a statistically representative sample. ITTC guidelines and procedures recommend a minimum length of 20–30 minutes (at full scale), or approximately 500–1000 waves, a well-established benchmark in tank testing [23]. For survivability conditions, a three-hour (full-scale) storm duration should be simulated.

EquiMar work package 2 "Physical Environment Specification" deals with the assessment of wave (and tidal) resource across five reports [47]–[51]. Of particular relevance when testing is ED2.6 "Extremes and Long Term Extrapolation" [50], which covers methods to calculate extreme wave conditions from observations. Other more general textbooks on extremes may also contain relevant information.

4.2.2.2 Selection of wave conditions for testing (test matrix)

It is common to define waves as a matrix of height and period, to tie up with industry standard power matrices [9]. Particular care is required with the specification of period, as there are several similar definitions, e.g. $T_p, T_E, T_z, \bar{T}$ (peak, energy, zero-crossing, and mean).

ITTC 7.5-02-07-03.7 "Wave Energy Converter Model Test Experiments" [18] covers typical test case parameters in §2.7, for a range of development stages and use cases, including proof of concept, energy capture performance, and survivability.

Methods of defining environmental conditions for different load cases are covered in §3 of MD2.19 "Generation of a set of typical dynamic load regimes for common conversion devices" [52], these are optimal operating conditions, no-load and extreme-load conditions, plus extreme safety conditions.

4.2.2.3 Other environmental conditions to consider (current/wind/etc.)

Other environmental conditions such as tidal currents or wind should be included where appropriate. It is important to understand that currents may have a non-trivial impact on wave shape and power available.

ITTC guidance 7.5-02-07-03.1 on "Floating Offshore Platform Experiments" [53] recommends that where a current is included, the wave spectrum be calibrated in the presence of that current.

4.2.3 Facility selection/considerations

The choice of facility used for testing is intrinsically linked to the environmental conditions required for the testing, and the capability of the selected facility to generate the required conditions (e.g. spread seas) at an appropriate scale. There are also client-specific considerations such as cost and location that cannot be covered by guidance.

Facility specific considerations for each stage of testing are given in OES IA Guidelines for the development & testing of wave energy systems [5]. Smaller tanks are typically used for stage 1 testing, with larger and more capable facilities used at stage 2.

Limitations of different facility types (towing tanks, flumes, and basins) for testing WECs are discussed in §4 of ED3.3 “Assessment of current practice for tank testing of small marine energy devices” [23]. Different wave-maker types and arrangements are discussed in §2 of MD2.12 “Collation of Wave Simulation Methods” [54]. Details are also provided on methods of wave simulation and accurate generation of a sea state across the tank, covered in section 8.2 below.

It is important for device developers to be aware of these potential limitations of facilities before testing, as these may influence the choice of facility used and/or the scope of testing undertaken.

4.2.4 Data requirements and analysis

A discussion of measurements that should be made at each stage of testing is given in OES IA “Guidelines for the development & testing of wave energy systems” [5]. As a minimum these are: water surface elevation (waves); vessel motion (translator, rotational, or both); mooring forces; and PTO factors (wave induced operating forces and pressures, plus overtopping rates if applicable). The physical parameters of most interest will depend on the research questions for each particular developer, the specifics of their device, and the stage of development. Similar measurement parameters are specified in ITTC 7.5-02-07-03.7 “Wave Energy Converter Model Test Experiments” [18].

The data that can be recorded will link in to the facility selection process and the capabilities of the facility used for testing. The developer may also choose to log data from on-board measurements via their own DAQ.

Tie in to numerical modelling may also influence the data requirements from testing, as discussed in section 3.3 above.

Data analysis, including uncertainty, is covered in §3 of ITTC 7.5-02-07-03.7 “Wave Energy Converter Model Test Experiments” [18], linking to other ITTC guidelines where appropriate. It is recommended that all test results be presented as full-scale values. Equimar D3.3 "Assessment of current practice for tank testing of small marine energy devices" [23] and Equimar D3.4 "Best practice for tank testing of small marine energy devices" [21], also include sections of uncertainty analysis and data acquisition.

4.3 Field testing at sheltered/exposed sites (TRL5–7, Stage 3–4)

Field tests for WECs include tests on sheltered/scale sites for early TRL 5–6 and exposed full-size test sites for TRL 7–9. Testing at sheltered sites requires fully operational PTO and it is at these sheltered locations where the operations and maintenance are done for the first time, with the relevant procedures being reviewed. In exposed sites, the full-scale machines are tested in real conditions in grid connected configuration. The full size WEC testing could start at the sheltered site, gradually moving to the exposed location for deployment and testing.

Future test plans for survivability, reliability, and power performance can be informed during sheltered site testing. Operations are fully informed with risk assessments further detailed in preparation for exposed site testing.

4.3.1 Prototype design considerations

The requirements for design and testing of WEC components are provided in several standard documents, including EMEC guidelines [55] and [56]. Description of the tests conducted during various stages of field testing and the corresponding requirements for different WEC components are detailed in MD4.1 "Sea Trials Manual" [57].

The IEC TS 62600-100 Technical Specification [58], provides a guideline for performance test of WEC at exposed test sites. Performance assessment of the WEC deployed at second location different from the primary test site is addressed in IEC TS 62600-102 [59].

The Bureau Veritas NI 631 Note [60] provides certification guidelines for marine energy converters in general and lists several useful standards that relate to materials, mooring components and operations. One of the important points to note before transition from lab testing to field testing is the increased complexity of the operations, i.e. equipment towage, deployment and recovery should be considered.

It is a common practice to have the Third-Party Verification of the device design carried out by a certification body to ensure the integrity of the WEC under extreme environmental conditions specific for the site.

4.3.2 Facility Selection

There are many open water test sites in Europe allowing the testing of wave energy converters, namely:

- European Marine Energy Centre (EMEC) in Scotland, UK
- ECN–SEMREV in France
- SmartBay – MARETS, and Galway Bay test site, both in Ireland
- University of Exeter – FaBTest and Wavehub in Cornwall, UK
- Biscay Marine Energy Platform (BiMEP) in Spain
- Islandsberg marine research site in Uppsala, Sweden
- PLOCAN Marine Test Site, Gran Canaria Island, Spain
- Wavec in Portugal

Most of the sites mentioned are part of the MaRINET consortium.

Outside of Europe, other countries are developing wave test sites: PMEC in the US, CMEC in China, MAREC in Chili [61].

4.3.2.1 Wave resource

The testing strategy will guide the selection of the test site. Some sites will offer a very energetic resource, suitable for higher TRL WECs and survivability testing. Other sites have more sheltered location with milder environmental conditions that would be more suitable for scale prototypes.

4.3.2.2 Grid connection

The requirement for a grid connection and the available resource are usually the first criteria to be considered. Sheltered sites are rarely grid connected, however lower TRL scale prototypes are usually used to demonstrate the concept and rarely need a grid connection. Some test facilities, however, offer the possibility to connect the device to instruments, dump loads or even use microgrids. These are usually placed on test support buoys near the device, carrying auxiliary electrical equipment and are attached to the prototype by an umbilical. Grid simulations provide valuable electrical data for informing the potential electrical profile of a full scale WEC, critical for grid compliance.

For full-scale prototypes, proving the ability of the device to produce grid compatible electricity is usually a requirement of the test programme and the choice of a facility with the ability to provide a grid connection is an important factor.

4.3.2.3 Other factors to consider

For higher TRL, it might be important to be able to prove the performances of the device, assessed not only by the amount of electrical energy it can generate but also by other metrics such as survivability, installability, and reliability. Some tests sites have the accreditation to provide services like performance assessments and verification.

The presence or proximity of a supply chain for assembly, marine operation and services, such as survey, the ability to provide a good data network / infrastructure are important to consider. The local experience of the supply chain is very critical to the success of prototype deployment, as the marine energy industry sector is niche and does not have the budget of other offshore industries. The health and safety management of the test site is also very important to avoid accidents that can impact the project.

4.3.3 Environmental Conditions (TRL 5-7)

The environmental conditions on wave test sites are generally described and investigated on early resource assessment and site characterisation stages and the information is made available to the interested parties. A guideline for resource assessment of wave test sites is provided in IEC Technical Specification 62600-101 [62]. Due to the stochastic nature of the wave conditions and relatively short in-situ observational datasets, primarily hindcast numerical modelling is used for characterisation of wave conditions at the site. Existing documents provide guidelines for model configuration, level of model resolution for various stages of resource assessment and verification and calibration procedures [47], [48], [62].

The metocean data is used to estimate the available energy, plan operations, and to calculate extreme environmental loads on the device, mooring lines, and foundation/anchor points. The resource assessment itself could be done in stages, with the uncertainty of the results decreasing towards later stages. The model validation against in-situ observational data is an essential part of the model uncertainty estimation and reduction, which is addressed [47], [48], [62]. The relatively long hindcast dataset is used to derive the operational ('normal') conditions at the site, which could also be used for fatigue and extreme value analysis [50]. Besides, other environmental parameters are important for design and operational considerations. Such parameters include typical and extreme currents (tidal, wind induced, due to density gradient), meteorological conditions including wind, seabed conditions, and bathymetry, etc. The required additional data is listed in IEC TS 62600-101 [62].

Once a WEC is deployed on site, its performance and survivability are assessed, based on observed environmental conditions. The IEC 62600-100 Technical Specifications [58] provides guidance for WEC device performance testing and associated observations. The document requires at least six months of the WEC operating on site with simultaneous in-situ observations. The requirements for the equipment and sampling strategy utilised are also described in the guideline. In some cases, a wave observational equipment and/or ocean current measuring instruments might be deployed prior to the WEC arriving on-site (mainly in case the site is not well characterised).

The MD2.1 "Wave Instrumentation Database" [44] provides description of typical wave observational systems, with their advantages and limitations. This includes surface following buoys, X-band and HF radars, and subsea-deployed equipment such as Acoustic Doppler Profilers or pressure gauges, etc.

Collected data should be processed, analysed, presented, and stored in an appropriate way. Several guidelines and best practice documents and standards had been developed available for data processing, analysis, and storage [46], [63].

5. Tidal energy converters (STRATH)

5.1 Introduction

The development of tidal stream energy devices from model to large-scale prototype involves a sequence of testing activities with specific aims. The goals of testing can range from concept assessment to performance verification, device survival experiments, interactions between more than two devices or environmental impact assessments. The dimensions and complexity of tested models increase as the concept technology readiness level (TRL) increases. In parallel to this, operating conditions established during experiments should be designed to be more representative of real operating conditions for the full-size device deployed in open waters.

In order to conduct experimental studies of increasing complexity and relevance to real operating conditions, a range of model testing facilities with different characteristics are typically involved. MaRINET1 gathered best practice guidelines to evaluate environmental conditions around tidal stream turbines that comprised different device concepts including, but not limited to, horizontal axis turbines, vertical axis turbines, oscillating foils and their variations, e.g. ducted, cross flow turbines.

This section aims to bring up to date the best practice guidelines for the testing of tidal stream turbines, from small scale experiments performed in laboratories to full scale measurements used for site and resource assessment based on previous best practice manuals and new research material.

5.1.1 Development progression

Development progression guidelines were established in 2008 for tidal energy converters as part of Implementing Agreement for a Co-operative Program on Ocean Energy Systems ANNEX II, “Tidal-current Energy Device Development and Evaluation Protocol” [7]. The guidelines for wave energy converters (section 4.1.1 above) may also be applicable for the development and testing of tidal converters.

Progression through tank testing phases is normally accompanied by an increase in test complexity and realism. The choice when to consider parameters such as turbulence and wave-interactions will largely depend on the specifics of the TEC and deployment conditions expected.

5.2 Lab scale testing (TRL1–5, Stage 1–2)

Laboratory experiments are desired for various reasons. Tests on small scale models which can be considered to be in the order of 1:10–1:30 with respect to full scale are usually conducted for proof of concept studies, to make a preliminary validation of a numerical model, to investigate the device features that affect the performance of the device, to optimise the device power capture and so on. These tests are undertaken in a controlled environment such as in a flume or tow tank, to achieve repeatable tests at relatively low cost.

5.2.1 Model and scaling considerations

5.2.1.1 Selecting appropriate scaling for testing

Equimar D3.3 "Assessment of current practice for tank testing of small marine energy devices" [23], MD2.7 "Tidal Measurement Best Practice Manual" [64] and ITTC 7.5-02-07-03.9 "Model Tests for Current Turbines" [20] recommends the use of common scaling laws such as Reynolds and Froude depending on the objective of the model to be tested. The use of Reynolds number is advised if the test aims to quantify the hydrodynamic performance of the scaled prototype [64]. Depending on the geometry of the blade profiles, to quantify Reynolds number (Re), it is recommended to use $Re = Uc_{0.75}/\upsilon$, where c is the chord length at the non-dimensional length of the rotor (r/R), U the flow velocity and, υ the kinematic viscosity, as recommended by ITTC 7.5-02-03-01.1 "Propulsion/Bollard pull Test" [65]. If the tests to be performed involve the investigation of cavitation, it is preferable to scale according to $c_{0.8}$ or $c_{0.9}$ as cavitation usually affects the tip of the blades (ITTC 7.5-02 03-03.6 "Testing and Extrapolation Methods Propulsion, Cavitation Podded Propulsor Model – Scale Cavitation Test" [66]).

Scaling using Froude number (Fn) is recommended if the device interacts with the free-surface. Instances of this may arise when investigating supporting platform sea-stationing, moorings, device survivability (i.e. wave-current interactions). It is difficult to achieve a correct similarity with respect to both parameters (i.e. Fn relates inertial forces whilst Reynolds relates viscosity; thus, these parameters cannot be matched in the same model). Therefore, a compromise must usually be made by selecting the most appropriate of the two parameters to scale correctly between model and prototype.

The aforementioned parameters are mostly used for 'conventional' horizontal and vertical axis turbines. However, when dealing with oscillating foils, the Strouhal number (St) should also be considered when scaling the performance of the model to a full-size device.

All of the above can be complemented with the use of the non-dimensional parameter Tip Speed Ratio (TSR). TSR can be used to define the ratio between blade tip tangential speed and the flow velocity.

These non-dimensional parameters are defined as below:

- Reynolds number, $Re = UL/\upsilon$
  Ratio between inertia and friction forces acting on a fluid mass. Where L is the chord

of the tidal turbine blade at $0.75\ r/R$ or the characteristic length, U is the flow velocity and υ is the kinematic viscosity.

- Froude number, $Fn = U/\sqrt{gL}$
  Ratio between inertia and gravity forces acting on a fluid mass in the presence of a free surface. Where U is the flow velocity, L is a characteristic length and g is gravity.
- Strouhal number, $St = fL/U$
  Ratio between a characteristic time associated with an oscillatory/periodic phenomenon and time associated with flow velocity. Where f is the oscillatory/ periodic phenomenon frequency, L the characteristic length and U the flow velocity.
- Tip-speed ratio, $\mathrm{TSR} = \Omega R/U$
  Where Ω is the turbine rotational speed, R the radius of the turbine rotor and U the flow velocity.

Choosing an appropriate scaling ratio will depend of the specifics of the facility, the expected forces on the prototype and the blockage ratio of the facility, which is described in section 5.2.2 below.

Achieving complete similitude between the prototype and the full-scale device can become increasingly difficult. MD2.2 “Collation of Tidal Test Options” [10] describes some of the limitations of using Reynolds scaling laws. However, it has been shown numerically by Mason Jones *et al* [67] that it may be possible to achieve Reynolds independence in horizontal axis turbines after $Re = 5{\times}10^5$ where the length scale is based on the turbine diameter rather than using the blade chord length at $r/R = 0.75$ as suggested here. Similarly, Bachant and Wosnik [68] performed an experimental evaluation with a vertical axis tidal stream turbine demonstrating that Reynolds independency is reached at Re=$0.8{\times}10^6$ based on turbine diameter and $Re = 2.1{\times}10^5$ which corresponds to an approximate average blade chord. A complete explanation of scaling consideration in laboratory testing can be found in [69]. Even though this book is more focused on techniques related to coastal engineering, it covers in full depth the topics of dimensional analysis and principles of similitude.

5.2.1.2 Model construction and instrumentation.

MD2.7 “Tidal Measurement Best Practice Manual” [64] and ED3.3 "Assessment of current practice for tank testing of small marine energy devices" [23] provide some guidance on model manufacturing and installation. The latter can be complemented with MD2.13 “Collation of Model Construction Methods” [42] which refers to a compilation of construction methods for wave energy converters. Even if the focus of the document is not completely related to tidal energy conversion, it is recommended it be considered for guidance on small-scale prototypes as it includes topics related to materials, components, waterproofing, and instrumentation.

In ITTC 7.5-02-07-03.9 “Model Tests for Current Turbines” [20] document there is a detailed section related to power take off modelling including recommendations of the use of resistance loadings to represent PTO in small devices, to the use of electric generators.

Control mechanism strategies can also be found in MD2.7 “Tidal Measurement Best Practice Manual” [64].

For instrumentation recommendations, along with MD2.13 “Collation of Model Construction Methods” [42], §6 of ED3.4 "Best practice for tank testing of small marine energy devices" [21] provides information of the instruments that can be used in small scale models. The limitations of various types of devices are included. Moreover, §5 of ED3.4 provides guidance of how to calibrate sensors. The latter can be complemented with the ITTC 7.6-01-01, “Sample Work Instructions Measuring Equipment Control of Inspection, Measuring and Test Equipment” [70].

5.2.2 Facility selection

Test conditions in laboratories can be set according to the facility selected and the aim of the experimental campaign. Testing campaigns can be related, but not limited to, proof of concept evaluation, energy capture evaluation, survivability and device layout settings. Depending on the testing objectives, the environmental conditions must be selected appropriately.

When undertaking energy capture, proof of concept, and device layout (e.g. pitch settings or yawed devices) studies, the tests may be undertaken in towing tanks, current flumes or basins, ensuring that the model has been appropriately scaled and the blockage ratio is within appropriate margins (described later in this section). When using tow tanks, carriage velocities are usually within high precision margins. In contrast, the precision of the onset flow in flumes may be limited to the measurement system utilised.

Tests aimed at investigating aspects related to the survivability of the device (e.g. fatigue, unsteady loading, extreme events, etc.) may be limited to certain facilities. It may be possible to differentiate the survivability cases into two main areas: turbulence and non-homogeneity, and wave-current interactions.

The investigation of survivability cases due to turbulence and non-homogeneity considers the effects of turbulence parameters (e.g. turbulence intensity, length scales, energy spectra and turbulence dissipation rate). Setting the required turbulence parameters can be easily achieved to some extent in a flume tank, an example of this can be seen in Blackmore *et al* [71]. However, performing turbulence loading investigations in a tow tank may be difficult. Options to generate turbulence in tow tanks may include the use of grids, which are required to be installed close to the device, as the turbulence dissipates rapidly.

Wave and current interaction studies can be conducted in both flume and tow tanks. The main limitations of the wave characteristics are mainly due to the wave maker capabilities. Regular waves can be set by setting the wave height and amplitude of the incident wave. Irregular waves can be set by producing a spectrum with characteristics related to wave shape, width and peak frequencies. According to the facility selected, it may be possible to set a time series to enable repeatability of the test pattern. If wave-current interactions are performed in a tow tank, the user should be aware that the wave frequency will be the apparent or encountered frequency, as the tidal turbine moves in relation to the wave, either in the same direction or opposite to it.

ED3.3 "Assessment of current practice for tank testing of small marine energy devices" [23] describes some of the limitations associated when testing tidal energy converters in flume and tow tanks. MD2.2 “Collation of Tidal Test Options” [10] presents a collation of some of the tidal test options available in Europe. Comparisons between tow and flume tanks are presented in MD2.7 “Tidal Measurement Best Practice Manual” [64] which can be referred to for more detailed information.

There are only a few studies dedicated to comparing the results of identical devices in different facilities, [72]–[75] are some examples. Perhaps the most representative and complete comparative tests was the one presented by Gaurier *et al* [75], who compared the performance of a 0.7m diameter horizontal axis turbine installed in two different flumes and two tow tanks. The turbulence intensity obtained in the flumes was minimal, to be able to compare to the tow tanks. It was found that the average power and thrust were similar between facilities, even with turbulence intensities of 3% and blockage ratios ranging from 1.2% to 4.8%. They concluded that the fluctuating loads were mainly driven by the flow turbulence [75].

Blockage is one of the other aspects that can critically affect the results of the testing objectives. Blockage ratio is defined as the rotor swept area of the device compared to the cross-sectional area of the tank. The effects of blockage have not been studied extensively. Blockage correction method comparisons can be found in [76] (Figure 5.1). These figures were obtained based on work by Barnsley and Wellicome in [77]–[79]. It can be observed in Figure 5.1 the disparity between the methods.

MD2.7 “Tidal Measurement Best Practice Manual” [64] recommends the use of a blockage ratio less than 10% to mitigate the influence on the tests when experimenting with tidal energy components and also avoid the use of correction methods. However, the experiments done by Gaurier *et al* [75] show that blockage may have some effects even at very low ratios such as 5%. The correction method utilised was the one proposed by Bahaj *et al* [80].

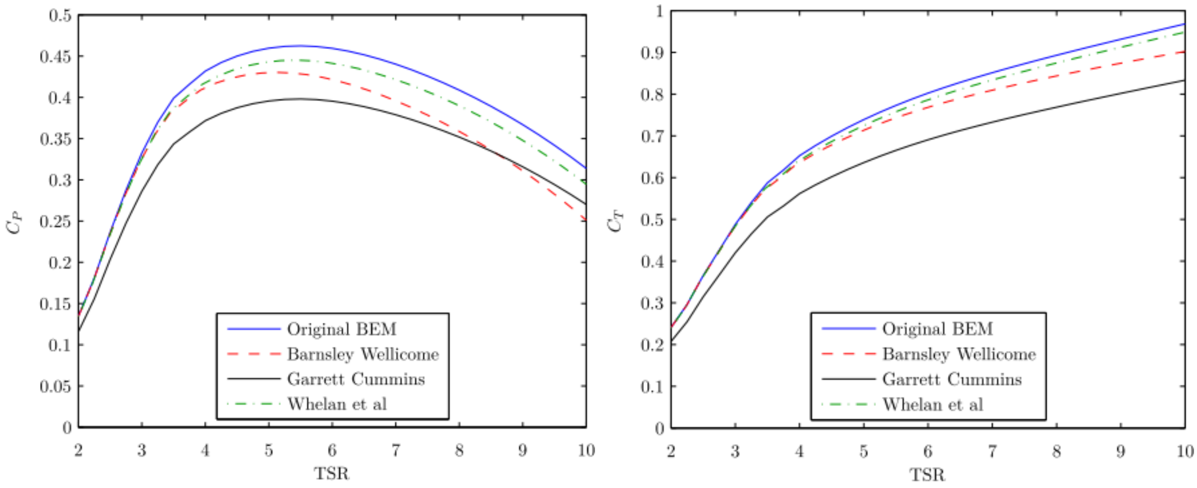


Figure 5.1 Examples of the use of blockage correction methods in experimental data (taken from [76]*).*

5.2.3 Environmental conditions

The environmental conditions set at the laboratories will depend on the aims of the test campaign. To set the appropriate flow conditions, adequate instrumentation must be used when possible.

The carriage velocity in most towing tanks can be set with high precision. However, contrary to towing tanks, the flow characteristics must be well investigated when working in a flume tank. These should be identified across the test section to characterise appropriately the turbine performance and if the wake characteristics are of interest, these should be measured along the working section.

The flow field can be captured with various instruments. A description of some of these devices can be found in ED3.3 "Assessment of current practice for tank testing of small marine energy devices" [23] and new information can be found in MD4.11 "Report new instrumentation and field measuring technology for tidal currents" [81]. To date, little information on the performance of different instruments to quantify the performance of a turbine is available. A recent study undertaken by Frost *et al* [74] compared the performance of a turbine at a real site and in a towing tank using a 1.5m turbine rotor diameter and 2 ADCP Aquadopps. It was found that the non-uniformity of the flow field at the real site affected the performance of the device by about 13% of power drop. Another repercussion to this power drop may be related to the Doppler noise bias collected at the real test site.

5.2.3.1 Turbulence

Turbulence is complex to measure and accurate replication of a real test site in a laboratory is challenging. Recently, Blackmore *et al* [71] designed an experiment consisting of integrating a grid with a regular mesh of rods placed transversally with respect to the flow. This study found that the larger grid produced larger integral length scales that increased to

0.41 m, while the smaller grid produced integral length scales that grew to 0.22 m. The turbulence intensities behind the grids were found to vary from 6.8% to 25.2%. With this investigation, it was observed that by increasing the integral length scale, the power and thrust coefficients increase by over 10% but the fluctuations on the loading also increase which will impact the lifespan of the rotor itself and eventually the drivetrain.

To represent full scale conditions, it is required to quantify the eddy size L, and intensity of velocity fluctuations scaled to preserve non-dimensional parameters (e.g. L/R and TSR) as explained in MD2.7 “Tidal Measurement Best Practice Manual”. To obtain these measurements high sampling rates are required such as those obtained with ADVs or LDVs, however ultimately, it depends on the aim of the testing campaign. A summary of flow measurement techniques describing its spatial, temporal and a brief explanation of their working principle is available in Table 5.1 in section 5.3 below.

5.2.3.2 Wave-current interactions

Small scale experiments may also be focused on wave-current interactions to investigate the survivability, reliability and fatigue of devices and components, amongst others. Wave conditions can be scaled using Froude number. Wave gauges are required to quantify wave heights and periods that can give an insight into any wave reflections occurring in the facility. A summary of the main types of wave gauges can be found in [82]. Other methods can be employed to measure surface elevation, see §5 of ED3.3 "Assessment of current practice for tank testing of small marine energy devices" [23].

5.2.4 Data requirements

As described in §2 of MD2.18 “Tidal Data Analysis Best Practice”, a basic performance analysis of a tidal energy converter must provide information of at least torque, thrust, velocity of the rotor and inflow velocity. These parameters are required to provide power and thrust metrics in the form of power and thrust coefficients in relation to tip speed ratio. Additional parameters should be measured according to the research questions for each particular developer, e.g. thrust and torque of each of the turbine blades, mooring line forces, etc.

The data that can be recorded will link in to the facility selection process and the capabilities of the facility used for testing. The developer may also choose to log data from on-board measurements via their own DAQ.

Uncertainty analysis is covered in the ITTC 7.5-02-07-03.15 “Uncertainty Analysis – Example for Horizontal Axis Turbines” [32], and as its name suggests, there is an example procedure at the end of the document for a small scale tidal turbine. ED3.3 "Assessment of current practice for tank testing of small marine energy devices" [23] and ED3.4 "Best practice for tank testing of small marine energy devices" [21], also include sections of uncertainty analysis and data acquisition.

5.3 Field testing at sheltered/exposed sites (TRL3–7, Stage 2–4)

Field testing may be related to small scale prototypes in TRLs between 3–5 and full-scale devices in TRL stages between 5–7. When referring to small scale devices, these could be towed in still water or can be installed in tidal streams at very low depths or with currents lower than those used for full scale devices. If it is intended to use a small-scale device in real test sites, it is advised to follow the recommendations given in sections 5.2 and 4.3.3.

5.3.1 Model construction considerations (TRL 1-7)

The European Marine Energy Centre (EMEC) developed a set of guidelines related to full-scale tidal energy converters. These guidelines include recommendations related to manufacturing, assembly, project development, grid connection, performance assessment, amongst others. Special attention should be taken to the following documents: “Assessment of Performance of Tidal Energy Conversion Systems” [83], “Guidelines for Design Basis of Marine Energy Conversion Systems” [84], and “Guidelines for Manufacturing, Assembly and Testing of Marine Energy Conversion Systems” [85].

Similarly, IEC TS-62600-200 “Power Performance Assessment of Electricity Producing Tidal Energy Converters” provides recommendations for power performance assessments. This covers topics related to test equipment, measurement procedures, and so on, that complement the information provided by EMEC.

Bureau Veritas also released a “Certification Scheme for Marine Renewable Technologies” Guidance Note NI 631 DT R00 E [60] which intends to help with identifying the necessary certificates that developers must consider when conducting their full scale tidal device tests. The document summarises the information from a series of documents that provide information related to diverse issues; for example, NR480 provides information on manufacturing processes for metallic materials. However, it must be noted that this certification scheme is also directed to other marine energy conversion technologies such as floating offshore wind turbines, ocean thermal energy converters, and wave energy converters. The only documents clearly identified for tidal energy converters are the IEC TS 62600 and NI 603 developed by EMEC, plus DNVGL-ST-0164 “Tidal Turbines” [86].

5.3.2 Facility selection

Compared to small scale testing, the facilities available to test tidal devices in real test sites are quite limited. In Europe there are only a few testing sites to deploy tidal energy converters at TRLs > 5; e.g. EMEC in Scotland, a demonstration site in Northern Ireland at Queens University Belfast, the Dutch Marine Energy Centre (DMEC), and the Söderfors marine currents research site in Sweden. The first three sites mentioned are part of the MaRINET consortium.

Other countries are on the route of developing new open water testing sites, or already have established tidal tests centres, for example, the Fundy Ocean Research Centre for Energy (FORCE). Ocean Energy Systems released a progress report of the open sea test facilities around the globe [61].

The selection of each real testing site will depend on the requirements of the testing campaign. It must be noted that not all the sites are grid connected, and some offer limited water depths or are limited in infrastructure; therefore, the developer must ensure that the site complies with the necessary requirements.

5.3.3 Environmental conditions (TRL 5-7)

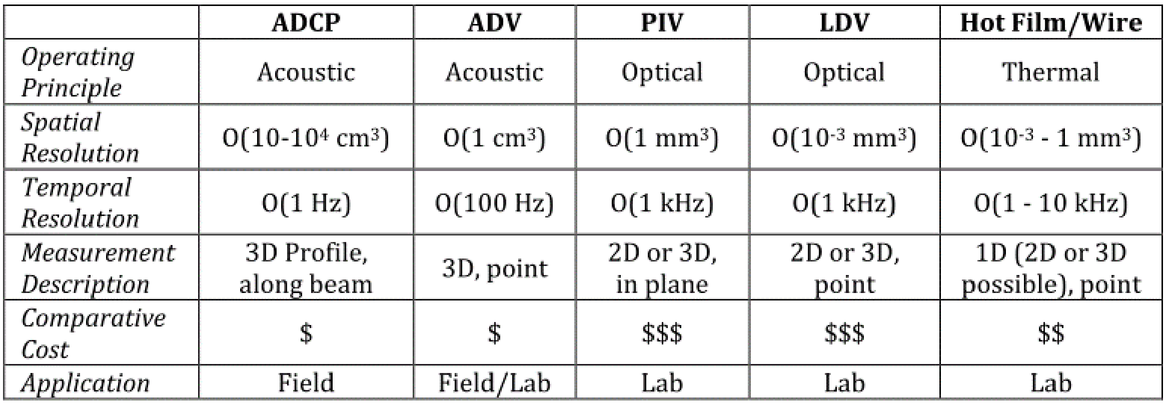
At full scale, the characteristics of the flow field are critical for the selection of installation sites. MD2.7 "Tidal Measurement Best Practice Manual" [64] recommends methods to estimate the current speeds based on the measurements taken at site and to predict the power performance, while MD4.11 "Report new instrumentation and field measuring technology for tidal currents" [81] provides exhaustive information of new instrumentation and field measuring technology for tidal stream sites. It is thus recommended that those reports be used as guidelines for measuring and quantifying the tidal resource in a real tidal site.

As mentioned previously, one of the most complex things to quantify and replicate from a tidal site is the existence of turbulence, its intensity and the broad range of length scales that exist. As mentioned in MD4.11 "Report new instrumentation and field measuring technology for tidal currents" [81], Acoustic Doppler Current Profilers (ADCPs) are useful technologies to measure bins along the water column. By using ADCPs it is possible to identify mean flow velocities and direction of the flow stream. However, detection of turbulence and length scales may be limited depending on the type of ADCP that it is being deployed. In theory, ADCPs should only require three beams to record the three flow velocity components; however, ADCPs work on the assumption that the velocity field is horizontally homogeneous within the measurement area. Therefore, an additional beam was incorporated to the instrument to get a second estimate of the vertical velocity components and since then this technology has been used widely in the field of marine energy (e.g. [87]).

Since 2014, advancements to this technology have been made by incorporating a fifth beam which allows for a true measurement of the vertical velocity component and therefore, it is possible to evaluate five Reynolds stresses [88]. The capabilities of an RDI Sentinel V five-beam ADCP compared to a 4 beam one are examined in [89]. This study showed that using the additional 5th vertical beam in an ADCP does not substantially improve the ability to estimate turbulence kinetic energy (TKE) density in low wave climate regions, and users may prefer to use the vertical beam data to record surface elevation. Similarly, Guerra *et al* [88] used a Nortek Signature1000 AD2CP and a Teledyne RDI Sentinel V50 to compare the suitability of using those instruments to measure turbulence parameters. They found that the Nortek instruments allow for the observation of the turbulent inertial subrange in both the frequency spectra and the turbulence structure function perhaps due to its capabilities to measure high sampling frequencies. In that study, they validated the turbulence data with an Acoustic Doppler Velocimeter (ADV). It was observed that even if it was not possible to quantify the inertial subrange with the RDI Sentinel V50, the lower-frequency portion of the spectra was resolved and in agreement with the estimates from the Nortek Signature and the ADV. It was concluded that the low Doppler noise of the Nortek Signature was in a similar range to ADV noise levels, therefore, it is suitable to be used in lower turbulence environments. A previous study [90], attempts to characterise the spatial and temporal resolution of an ADV and a RDI Sentinel-V ADCP. It was found that even if the ADCP data is corrected, it may be impossible to blade-scale turbulent fluctuations. A comparative table showing some of the flow measurement techniques available for laboratory and field measurements is presented in [90] and is included here for reference (Table 5.1).

A comparison using a four beam ADCP and a shear probe to quantify turbulence parameters in an open test site was undertaken in [91]. They found that speed-bin averaged dissipation rates estimated at mid-depth from the ADCP measurements agree to within a factor of two with direct estimates obtained using shear probes. They concluded that possible sources of bias and error are due to the cross-channel separation between the instruments and the high degree of spatial variability in the flow.

Table 5.1. Common flow measurement techniques used in the field of tidal energy, taken from [90].



	ADCP	**ADV**	**PIV**	**LDV**	**Hot Film/Wire**
Operating Principle	Acoustic	Acoustic	Optical	Optical	Thermal
Spatial Resolution	O(10-10^4 cm^3)	O(1 cm^3)	O(1 mm^3)	O(10^{-3} mm^3)	O(10^{-3} - 1 mm^3)
Temporal Resolution	O(1 Hz)	O(100 Hz)	O(1 kHz)	O(1 kHz)	O(1 - 10 kHz)
Measurement Description	3D Profile, along beam	3D, point	2D or 3D, in plane	2D or 3D, point	1D (2D or 3D possible), point
Comparative Cost	$	$	$$$	$$$	$$
Application	Field	Field/Lab	Lab	Lab	Lab

6. Offshore wind turbines

6.1 Introduction

Bottom-fixed offshore wind turbines (OWTs) are well established commercially, and innovation in the sector is now focused on floating concepts in order to develop sites further offshore. The world's first floating offshore wind farm, Hywind Scotland, began production in October 2017. New concepts in floating platforms for offshore wind turbines continue to be developed and therefore, the focus of this section of the report is to outline the main guidance available in the public domain in relation to the development of floating offshore wind turbines (FOWTs).

6.1.1 Development progression

The development progression for an offshore wind turbine is similar to that of other MRE devices. Validation of the OWT concept (TRL 1–3) uses small-scale models in shallow water wave basins to investigate the physical properties and performance of the OWT. The concept development stage (TRL 4–6) involves the development of control strategies to improve performance and the verification of mooring systems. Such testing tends to involve larger scale models in deep ocean basins (TRL 5) or scaled model tests at sea (TRL 6). At TRL 4–5, increasingly sophisticated methods of simulating aerodynamic loading are required, and the response of the model to the combined effects of wind and waves is quantified. The prototype demonstration stage (TRL 7–8) is carried out at sea using full scale or near-full scale models. TRL 9 represents demonstration of a full-scale commercial prototype at sea.

6.1.2 International standards

There are similarities between offshore wind turbines and the mature industry of constructing and installing wind turbines onshore. Details of the parts comprising IEC-61400 are given in Table 2.3. Of particular note are 61400-3 "Design requirements for offshore wind turbines" and the draft Technical Specification 61400-3-2 "Design requirements for floating offshore wind turbines" due to be published later in 2018.

6.2 Lab scale testing (TRL1–5, Stage1–2)

6.2.1 Model and scaling considerations

6.2.1.1 Model scaling

Scaling FOWT systems can be very challenging, as two different scaling laws are applicable where a system interacts with water and air. Froude scaling is used when modelling floating structures for hydrodynamic similarity. Reynolds scaling is applied when modelling aerodynamics. Both are applicable when performing scaled testing of a FOWT; however, the two methods are not fully compatible in a typical tank-testing scenario. Therefore, compromises must be made which can have an effect on the scaled model performance.

A detailed summary of the Froude and Reynolds scaling methods is given in §3 of MD2.4 "Collation of offshore wind-wave dynamics" [92]. This document also derives a recommended scaling method for a FOWT. An overview of model scaling for FOWT systems and the challenges presented is also given in MaRINET D2.20 "Report on Physical Modelling Methods of Floating Wind Turbines" [93] and INNWIND D4.22 "Methods for performing scale-tests for method and model validation of floating wind turbines" [94]. presents a schematic of the different forces and dimensionless numbers that must be considered when testing a scaled FOWT. In general, it should be recognised that due to the complexity of implementing the scaling laws, the dynamic behaviour of a FOWT system can only be approximated in a tank-testing environment.

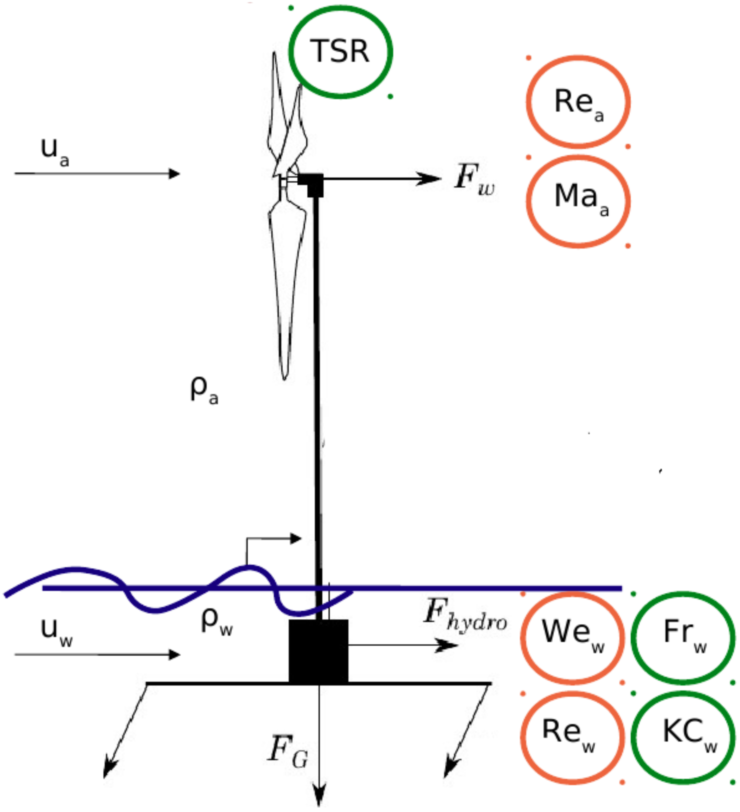


Figure 6.1 Forces and dimensionless numbers (circles) that characterise the environment and motion of a FOWT (Taken from [92])

6.2.1.2 Moorings

Guidance published by ITTC in relation to floating offshore platforms can be applied to the scaled testing of FOWTs. These publications include ITTC Recommended Procedures 7.2-02-07-3.4 [95] and 7.2-02-07-3.5 [96] which deal with active and passive testing respectively, of floating offshore structures with mooring lines.

When published, MaRINET2 D2.6 "Final guidelines for test applicants", will contain guidelines for installing and testing a variety of mooring systems. In addition, §6 of INNWIND D4.22 [94] describes and evaluates the different types of mooring systems applicable to FOWT systems. It also provides a comprehensive list of the standards and guidelines dealing with mooring systems and their application to FOWT.

6.2.1.3 *Model construction*

Many of the same considerations for constructing a model of a wave or tidal energy converter apply to the construction of a FOWT. MD 2.13 “Collation of Model Construction Methods” [42] and MD2.28 “Model Construction Methods” [38] is aimed at the construction of WECs, but many of the principles apply to FOWT model construction, e.g. in relation to materials, water tightness, instrumentation etc.

INNWIND D4.22 [94] outlines details of the construction of the OC4-DeepCWind semi-submersible scaled model.

6.2.2 Environmental conditions

6.2.2.1 *Wave and current loading*

Wave and current loading on FOWT platforms is similar to that of WECs and other floating bodies. MaRINET deliverables MD2.8 [34] and MD2.2 [10] provide guidance on creating the appropriate wave and current conditions respectively in the laboratory.

Uncoupled hydrodynamic tests of a FOWT without the rotor are appropriate in the early stages of device development, e.g. to assess the response of different platforms to waves or to validate numerical models. However, in order to evaluate the global response of the FOWT, there must be at least a simplified representation of the rotor and associated thrust and gyroscopic forces.

6.2.2.2 *Aerodynamic loading*

MaRINET D2.20 “Report on physical modelling methods for floating wind turbines” [93] provides an overview of the aerodynamic forces applicable to offshore wind turbines. These include thrust forces, gyroscopic forces, aerodynamic damping and wind spatio-temporal variance. Turbine control strategies are also discussed.

There are a number of ways of simulating aerodynamic forces on a wind turbine in a laboratory. These range from a simple hanging weight to a full-scaled rotor with individual blade pitch control and full dynamic control system. These methods are described in detail in MD2.20 [93] and ITTC guideline 7.5-02-07-03.8 [19]. The former report also provides examples of different experimental set-ups applied in a variety of facilities. §3 of INNWIND D4.22 [94] describes how several of these methods were applied at École Centrale de Nantes (ECN) to a 1:40 scale model of a semi-submersible platform with a catenary mooring system for a 6MW turbine.

6.2.3 Facility selection/considerations

As for testing of wave and tidal energy devices, facility selection for the testing of FOWTs depends largely on the scale of the model, and the ability of the facility to reproduce the desired environmental conditions. The facility choice will also depend on the stage of the design process: shallow wave basins are typically used for early stage testing, while deeper ocean basins with more advanced wind generation capabilities are required to achieve TRL 4–5. As discussed in the previous section, there is a wide range of ways of simulating the effect of wind thrust and measuring the response of the device. The required level of accuracy in these methods will have a large bearing on the facility selection.

6.2.4 Data requirements and analysis

The following is a non-exhaustive list of the typical measurements and tests carried out during a FOWT test campaign.

- Free decay testing for each of the six DOFs
- Regular waves
- Irregular waves
- Hub height accelerations
- Mooring line loads
- Ballasting
- Towing tests

Guidance in relation to conducting tests on floating platforms is given in ITTC guidance document 7.5-02-07-03.1 [53].

7. Cross-cutting technologies

There are a number of cross-cutting technologies which are applicable to the different types of marine renewable energy convertors. These include PTO and control systems, grid and electrical systems, materials, and the moorings/support structure. Guidance and test recommendations for these are summarised in the following sections.

7.1 PTO/Control systems

For offshore renewables, the power take-off (PTO) is a device that transforms hydrodynamic or wind energy into a mechanical or electrical energy. There are different PTO systems for marine energy technologies and the design is usually defined per device because the operating conditions are different. In the case of wind energy, the power take-off consists typically in a three-blade turbine coupled throughout a rotor bearing to a generator that is connected to a power electronic that injects electric energy to the grid. In the case of tidal current energy, the PTO is often similar to wind energy because the objective is to extract energy from a fluid movement in one direction; the difference is the fluid density, speed ranges, and the environment that affects the design of the different components. On the other hand, in wave energy there are many different type of power take-off depending on the capture principle. Some of these PTO types are depicted in Figure 7.1.

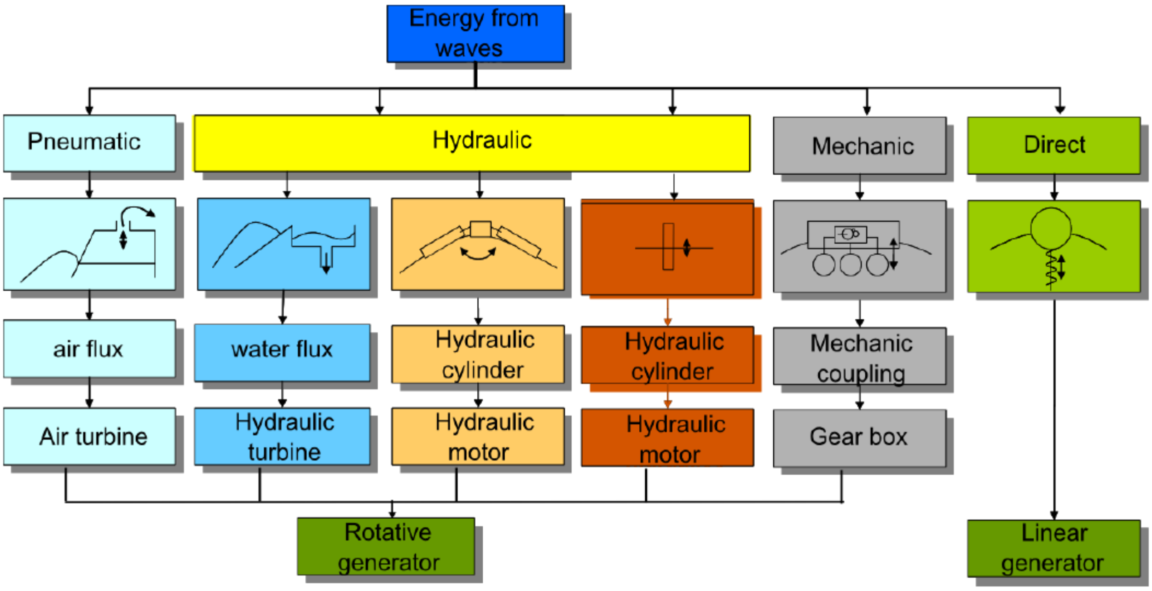


Figure 7.1 Power Take-Off typologies for wave energy conversion

Despite the different PTO design depending on the working principle of the device, the main objectives of the control of these devices are the same: capturing wind/wave/current energy and converting it into useful electricity. Moreover, marine must be designed in order to minimize the cost of energy produced. This minimization process of cost of energy involves partial objectives:

- Energy captured: Maximization of energy captured taking into account safety restrictions such as those related to power rating. The generation capacity of marine energy devices specifies how much power can be extracted from the device.
- Mechanical loads: Preventing the device from excessive dynamic mechanical loads. These loads may cause fatigue and thereby reduce the useful life of the system thus increasing the cost of energy produced.
- Power quality: Requirements to prevent negative impacts on the grid and assure correct working of the grid. The production of poor quality energy will require investments in transmission lines

To fulfil this multi-objective problem there should be different control levels. Figure 7.2 shows a global control system framework:

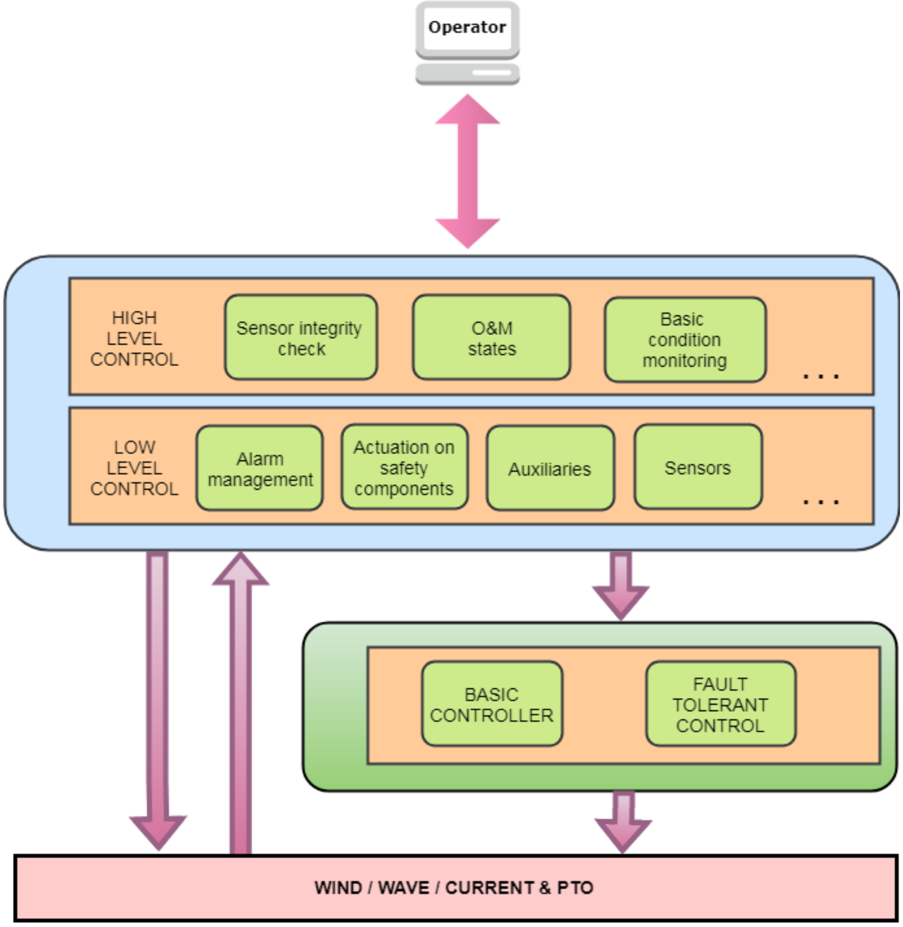


Figure 7.2 Global control system framework

To provide guidance on PTO control systems testing, a set of deliverables were developed within the MARINET Project[7]. These have demonstrated the methodology of integrating a MEC into an electrical test infrastructure, and adapting the MEC to fit to the physical limitations of the testing infrastructure. These are summarised below:

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[7] available at http://www.marinet2.eu/archive-reports-2/research-reports/

MD2.03 “Review of Relevant PTO Systems” [97]: Describes different types of active interface between the systems considered and the fluid they extract energy, and presents the corresponding dynamics. Moreover, the typical components used in the energy conversion chain are presented:

MD2.11 “Best practice manual for PTO testing” [41]: Describes electrical infrastructures that emulate the dynamics of the energy converters. Moreover, a model implementation guidance is a methodology to make tests in a test bench the electrical side of a PTO.

MD2.25 “Definition of standardised PTO Test Procedures” [11]. This deliverable intended to provide an overview of the important issues to consider when planning and executing tests for renewables PTOs. For this issue, typical test purposes, different standards for offshore renewables, common practices and some case studies are described.

MD4.15 “Report on Numerical Methods for PTO Systems” [98]: It is a cost-effective approach to evaluating the PTO capabilities of the ocean energy converter, under a range of different resource and operating conditions. An overview of various PTO numerical modelling approaches; from hydrodynamic models, pneumatic, hydraulic, hydro, and tidal PTOs, to generators. The emphasis is on describing the typical software used, background theory and equations that characterise these PTO devices.

7.2 Grid/Electrical

Marine energy converters connected to the grid must meet the existing grid connection normative. The main applicable rules have been focused on wind energy. Due to the widespread geographical availability of the marine resources, the requirements for the grid connection are normally influenced by local regulations, which can partly differ from country to country. One of the major problems regarding grid connection of intermittent renewables in general, is their impact on the power quality of the external grid and this requires *ad hoc* regulation by national and international grid-codes. This implies a need to match a specific configuration to meet the demands of local grid code requirements [99], and, to make a review of the existing power quality requirements regarding marine energy converters as demanded by European Transmission System Operator (TSO) Countries.

International groups are in process of adapting rules for applicability to the marine sector. The main reference for power quality measurements is the Technical Standard IEC TS 62600-30 “Electrical power quality requirements for wave, tidal and other water current energy devices” [100] that is being prepared by IEC technical committee 114: Marine energy - wave, tidal and other water current converters. This document is based on the IEC 61400-21 “Wind turbines - Part 21: Measurement and assessment of power quality characteristics of grid connected wind turbines” [101]. This standard will have the form of recommendations for international use and will focus on:

- Power quality issues and parameters (non-device specific and non-prescriptive) for single/three-phase, grid-connected/off-grid (including micro-mini grid) marine wave, tidal and other water current converter-based power systems.
- Establishing the measurement methods, application techniques and result-interpretation guidelines.

Therefore, the technical specification only evaluates the power quality of the marine installation. It does not give indications about the compliance of the installation regarding power quality criteria but only general rules. For that purpose, the user should refer to the Grid Codes.

The IEC technical committee 88: wind energy generation systems, is working on the standardization of the latter and is focused on giving a general basis for design, quality assurance and technical aspects for certification. This guide of recommendations is focused on:

- Addressing site-specific conditions.
- All systems and subsystems of wind turbines and wind power plants, such as mechanical and electrical systems, support structures, control and protection.
- Communication systems for monitoring, centralized and distributed control and evaluation, implementation of grid connection requirements for wind power plants, and environmental aspects of wind power development.

Regarding electrical testing, different aspects must be addressed:

- Steady state or normal operations conditions
- Voltage and frequency deviations
- Active and reactive power control
- Voltage control
- Power factor control
- Power quality
- Fault ride through requirement during grid disturbance, and active and reactive power support during grid faults.

Previous work in MD2.26 "Collation of European grid codes" [102] and further updated in [103] highlight the most demanding aspects of grid interconnection of marine energy installations. These documents also provide an updated overview and comparative analysis of the connection requirements of eight European Grid Codes. This covers the Network Code on Requirements for Grid Connection applicable to all Generators (NC RfG) developed by the European Network for Transmission System Operators for Electricity (ENTSO-E) [104].

Some issues pertaining to marine energy systems and related to their grid impact are expected to be due to resource intermittency and variability:

a) **Limited dispatchability:** variable sources, such as wind, tidal or wave, are difficult to adjust for the system operators when there is not sufficient prior knowledge.
b) **Stress on the electrical grid:** Many RES (Renewable Energy Resources) have direct dependence on variations of the environmental conditions. Therefore, a sudden increase in the output power or a drop from one or more of the surrounding generations may cause the neighbouring grid to reach its upper or lower threshold of continuous operation.
c) **High penetration effects:** a low level of renewable generation integration into a huge power system has nearly no effect even when variations arise. However, with higher levels of RES integration the system has lower inertia, and occasional difference between generation and demand levels may cause disequilibrium condition in the system.

7.2.1 Grid code requirements for integration of renewable generation

This section shows a summary of the main requirements in the Grid Codes studied in MD2.26 "Collation of European grid codes" [102].

7.2.1.1 Active and Reactive power control in normal operations

7.2.1.1.1 Frequency and active power

The nominal frequency for all the reviewed grid codes is 50Hz. In general, in all countries continuous operation is required below or above this value within some limited range. Furthermore, a time limited operation is required beyond the continuous operation range. Disconnection is allowed at frequency values outside the time-limited operation ranges or if the frequency does not return to the continuous range after the limited time is over. Figure 7.3 shows the different frequency operation ranges for all the studied grid codes.

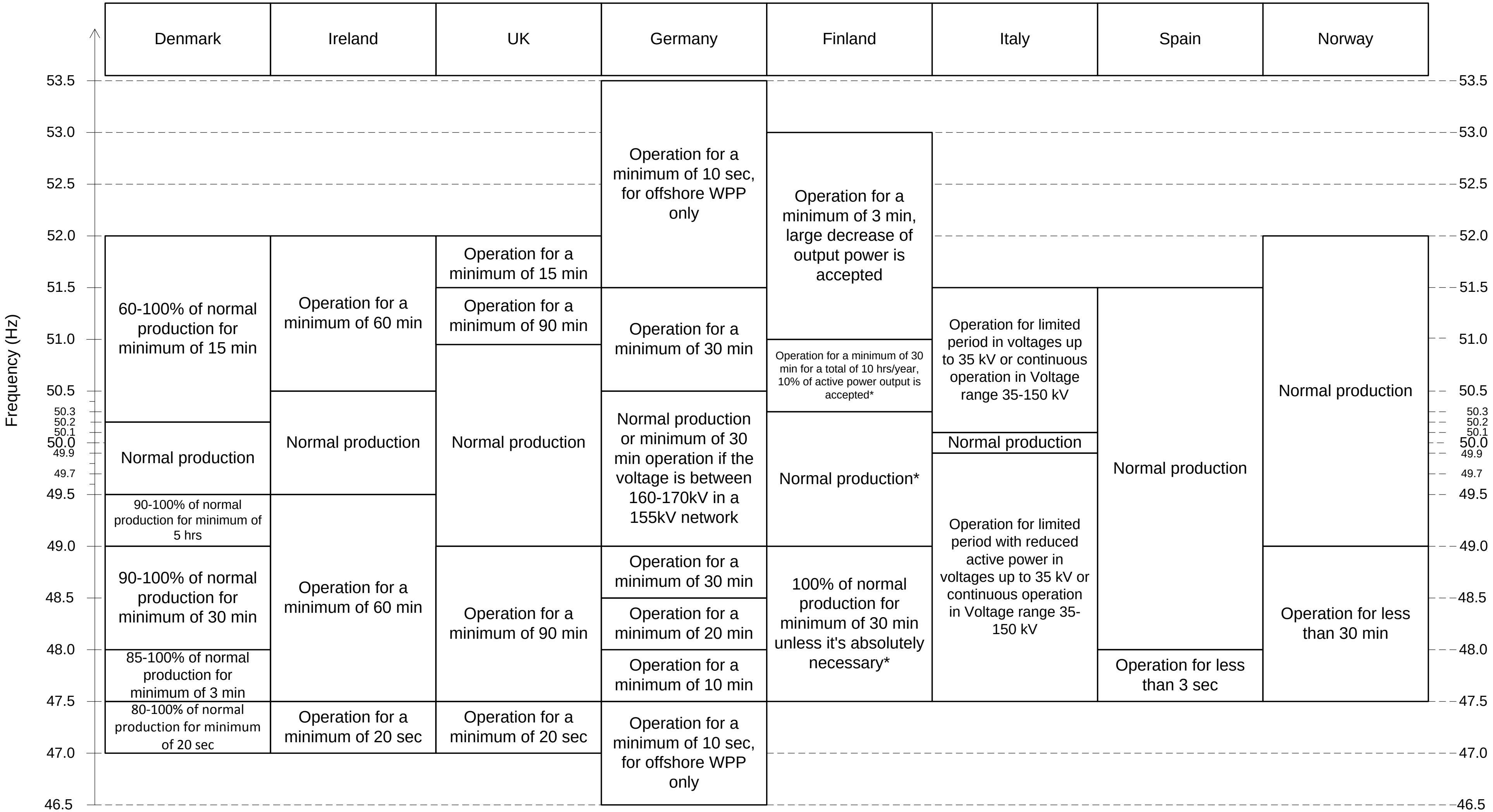


Figure 7.3: Frequency Operation ranges for different countries (From [102])

7.2.1.1.2 Voltage and reactive power

The voltage ranges under normal operation differ from country to country and transmission voltage level. In general, continuous operation is expected within the ±10% of rated voltage at connection point. Unless abnormal conditions prevail, the voltage at connection points for different network voltages for the different studied countries shall be within the values shown in Table 7.1. These voltage variation ranges are frequency dependent and the ranges shown are for normal frequency ranges. The term pu refers to per-unit voltage.

The reactive power regulations requirements are defined based on active power (installed capacity or production level), connection point voltage or both. These regulations are used to achieve voltage, reactive power or power factor control at the connection point. Summary of reactive power requirements from the studied grid codes is presented in Table 7.2.

Table 7.1: Voltage variation ranges for different countries under normal operating conditions (From [102]).

Denmark		Ireland		UK		Germany	
	Nominal voltage		Nominal voltage		Nominal voltage		Nominal voltage
0.9 - 1.1 pu	400 kV	0.875 - 1.05 pu	400 kV	0.95 - 1.05 pu	400 kV	0.92 - 1.105 pu	380 kV
	150 kV	0.91 - 1.12 pu	220 kV	0.9 - 1.10 pu	275 kV	0.877 - 1.113 pu	220 KV
	132 kV	0.90 - 1.12 pu	110 kV	0.90 - 1.10 pu	132 kV	0.903 - 1.097 pu	155 kV
						0.873 - 1.118 pu	110 kV

Finland		Italy		Spain		Norway	
	Nominal voltage		Nominal voltage		Nominal voltage		Nominal voltage
0.90 pu - 1.05 pu	400 kV	0.85 - 1.10 pu	15 and 20 kV	0.90 - 1.115 pu	400 kV	0.93 - 1 pu	420 kV
	220 kV		150-132-120 kV		220 kV		300 KV
	110 kV		220 and 380 kV		150 kV		
					132 kV		
					110 kV		

Table 7.2: Reactive power regulation requirements in different countries (From [102]*)*

Country	Requirement
Denmark	- 11 kW - 25 kW: 0.95 < PF < 1 at 20% of rated power or more - 25 kW - 1.5 MW: Between 0.995 leading and lagging but dependant on P production - >1.5 MW: 0.975 leading and 0.975 lagging for 20 – 100% of rated power, and the range decreases for lower production levels
Ireland	- Between 0.95 leading and 0.95 lagging at rated power - Reactive power is kept constant at 50 - 100% of rated power - Between 0.84 leading and 0.84 lagging at 0 – 50% of rated power
UK	- Between 0.95 leading and 0.95 lagging at 50 - 100% of rated power - Reactive power consumption (leading PF) requirement decreases linearly for power outputs between 20 - 50% of rated power while 0.95 lagging limit remains constant
Germany	- Between 0.95 leading and 0.925 lagging at rated power - Constant reactive power at 20 – 100% of rated power - Between 0.55 leading and 0.45 lagging at 0 – 20% of rated power
Finland	- 0.5 - 10 MVA: Between 0.995 leading and 0.995 lagging at active power above Pmin - >10 MVA: 0.95 leading and 0.95 lagging at active power above Pmin
Italy	- Between 0.95 leading and 0.95 lagging from 50% - 100% of rated power - Constant power factor from 20 – 50% of rated power - Reactive power regulation as a function of voltage is required outside of voltage control dead-band
Spain	- Minimum of 0.99 leading and lagging for all active power productions and nominal voltages - For connections to 220 kV and 400 kV networks: Minimum of 0.95 leading and lagging at maximum power production
Norway	- Between 0.95 leading and 0.95 lagging at rated power

7.2.1.2 Behaviour under grid disturbances

Fault ride through requirements are different based on generation capacity, connection point voltage or dip duration. Denmark has Fault Ride Through (FRT) requirements only for Wind Power Plants (WPPs) greater than 1.5 MW while Finland has two FRT curves; one for 0.5 – 10 MVA and another for WPPs greater than 10 MVA. Italy and Norway have different FRT curves for different connection voltage levels, while UK FRT curves depend on dip duration.

The strictest low voltage fault ride through requirements for all the studied countries are shown in Figure 15 on the same graph. Table 7.3 shows the maximum residual voltage and duration values in a table format to make it easier to understand and compare for the reader. Germany, Finland, Italy and Norway require riding through complete short circuit at the connection point. Finland requires the longest duration for zero voltage ride through of 250 ms. Ireland, UK and Spain require 15% voltage ride through with Ireland having the longest duration of 625 ms. German and Spanish grid codes require WPPs to give voltage support during voltage dips by injecting reactive current.

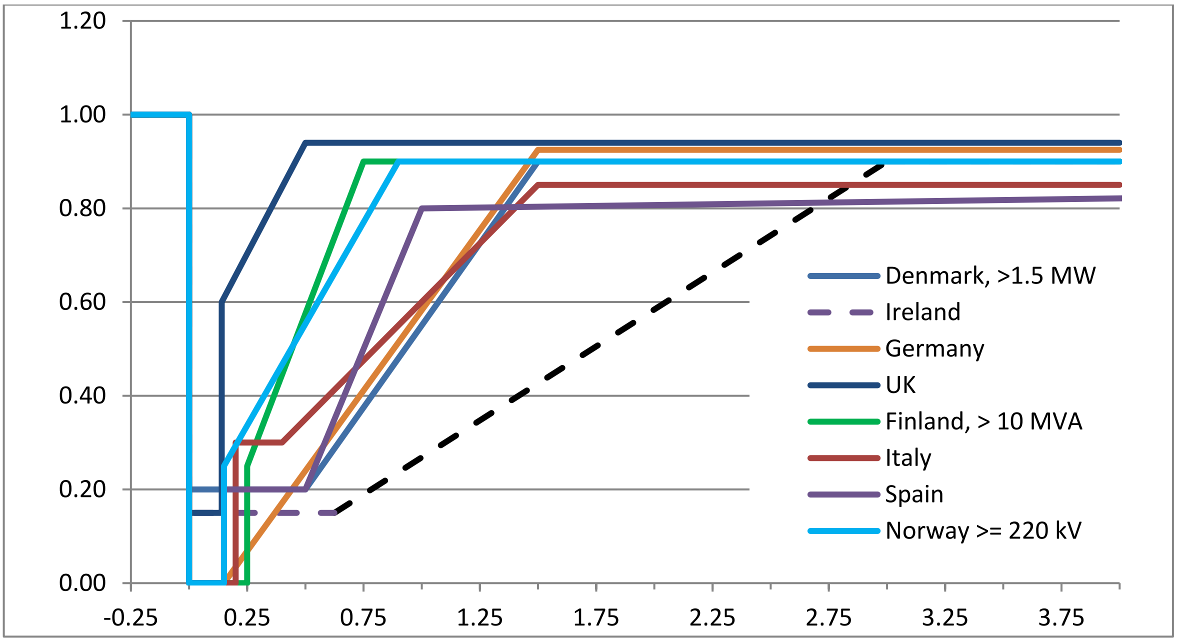


Figure 7.4: Low voltage ride through curves for different countries

Table 7.3: maximum residual voltage and duration values of the FRT curves

Country	Residual voltage (%)	Duration (ms)
Denmark	20	500
Ireland	15	625
Germany	0	150
UK	15	140
Finland	0	250
Italy	0	200
Spain	15	200
Norway	0	150

7.3 Materials

From design to testing and fabrication, materials need to be considered as important drivers of cost and performance for the MECs. Clear similarities are observed between the usage of materials in MECs and other industries like offshore wind and the offshore Oil and Gas industry. Therefore, some standards can be extended to apply to MECs because they have been developed for similar marine environments and materials used in marine energy converters.

7.3.1 Materials selection

There is a wide range of materials that may be used for the main structure, sub-structures and components of a MEC. There are relevant factors for material selection like durability, life cycle cost, materials compatibility, strength, maintenance and inspection which are explained in §8.2 of IEC TS 62600-2 “Design requirements for marine energy systems” [105]. In the case of tidal energy converters (TECs) §7 of DNVGL-ST-0164 “Tidal turbines” [86] explains that verification is needed for several components to determine if they are capable to resist a variety of environmental loads and conditions. These criteria can be extrapolated to wave energy converters (WECs). Material selection requirements for TECs are collected in §7 of DNVGL-ST-0164 and in §1.4 of BV Rule Note NI 603 DT R00 E “Current and Tidal Turbines” [106]. A summary of requirements for MECs are written in the following points:

- **Metallic materials**: Structural steel, stainless steel and aluminium

  The requirements for rolled steel, for tubes and pipes, and for forgings and castings can be defined according to §6 of Offshore Standard DNV-OS-J101 “Design of Offshore Wind Turbine Structures” [107]. The same steel grades hold for WECs according to §11.1 of DNV and Carbon Trust “Guidelines on design and operation of wave energy converters” [108]. Both standards also reference to Offshore Standard DNVGL-OS-B101 “Metallic materials” [109], where yield and ultimate minimum strength requirements are described for each grade.

  Stainless steel shall have a maximum of 0.05% of carbon (C) content and in passivated condition according to DNVGL-ST-0164 [86]. Further recommendations for stainless steels as avoiding low oxygenated waters are included in §8.4 of IEC TS 62600-2.

  Aluminium shall be resistant to sea water as specified in DNVGL-ST-0164 [86].

- **Concrete materials**: reference is made to section §6 of DNV-OS-J101 [107] for TECs. In the case of WECs, 40-50 mm of minimum cover for reinforced bars is recommended by DNV and Carbon Trust “Guidelines on design and operation of wave energy converters” [108], and requirements for corrosion protection of concrete can be read in §6 of DNV-OS-C502 “Offshore Concrete Structures” [110]. Grout used in joints and connections have specific requirements summarized in §6 of DNV-OS-J101 [107].

- **Composite materials**: long term effects should be carefully evaluated, as well as compatibility in case of carbon fibre composites with metals, as discussed in DNV and Carbon Trust “Guidelines on design and operation of wave energy converters” [108]. A reference is made to DNV-OS-C501 “Composites Components” [111] for composite material. Further requirements are specifically described for blade materials, where coating is required according to DNVGL-ST-0164 [86].
- **Solid ballast**: the materials used as permanent ballast for stability purpose shall be evaluated respect to long-term effects. Avoid materials susceptible of liquefaction or washout, as contractant sands, DNVGL-ST-0164 [86].
- **Materials for mooring lines**: requirements for the selection of materials for mooring systems, like mooring chains, fibre ropes or wire ropes, are given in DNV-OS-J103 “Design of Floating Wind Turbine Structures” [112].

As mentioned above, compatibility between different combinations of materials can be a critical issue during selection as indicated by IEC TS 62600-2 and by DNVGL-ST-0164.

7.3.2 Degradation mechanisms

Degradation due to environmental conditions can induce total failure of a component, or render it in an out-of-service condition. These environmental effects can act alone or in combination with mechanical stresses, resulting in the initiation or growth of cracks.

7.3.2.1 Corrosion

Corrosion is defined in ISO 8044 “Corrosion of metals and alloys” [113] as “*the physicochemical interaction between a metal and its environment that results in changes in the properties of the metal, and which may lead to significant impairment of the function of the metal, the environment, or the technical system, of which these form a part*”. In carbon steel, a direct consequence is rust formation and thinning of structural sections if there is no protective system. It is essential an environment characterization for adequate protection, marine environment is commonly classified in atmospheric, splash, and submerged zones, DNVGL-RP-0416 “Corrosion protection for wind turbines” [114]. Internal confined spaces also need to be protected from corrosion as indicated by DNVGL-ST-0164 [86]. In MECs, different types of corrosion may occur:

- Uniform Corrosion: Corrosion allowance is considered for corroded steel in §4.5 of DNVGL-RP-0416 [114]. For mooring chains, corrosion allowances are also defined in DNVGL-ST-0164 [86].
- Marine Corrosion
- Pitting Corrosion
- Galvanic Corrosion: due to electrical contact of dissimilar conductive materials.
- Stress Corrosion Cracking
- Hydrogen Embrittlement
- Corrosion Fatigue: For the fatigue analysis, corrosion effect is considered in §8.3 of DNVGL-ST-0164 where reference is made for S-N curves for different protection conditions described in DNVGL-RP-C203 “Fatigue design of offshore steel structures”

[115]. In Appendix A of DNV and Carbon Trust "Guidelines on design and operation of wave energy converters" [108], there is a guide for the fatigue analysis of WECs, including corrosion effects. Preloaded bolt fatigue is also studied in MD 2.6 "Report on Offshore Wind System Monitoring Practice and Normalisation Procedures" [116].

- Cavitation Corrosion
- Erosion Corrosion

A description of failure mechanisms related to the different corrosion types is not found in current standards and guidance for MECs.

7.3.2.2 Composite Ageing

Polymer matrix and fibres are known to degrade in the marine environment by means of photochemical reactions and UV radiation, among others as indicated by "Ageing of composites" [117]. This effect usually implies a reduction in mechanical properties and it also affects organic coats. In TECs, ageing of fibre reinforced plastics (FRPs) is considered as part of the failure mechanism of the blades according to §11.2 of DNVGL-ST-0164 [86]. The combination of composite ageing and fatigue is not considered in current standards and guidance for MECs.

7.3.2.3 Fouling

Marine growth is known to affect structures in the sea environment. Fouling increases weight and reduces performance of the converter. Values of thickness increase due to marine growth are indicated in §4.6 of DNVGL-ST-0164 [86]. Marine growth is considered in mooring lines and blades in DNVGL-ST-0164.

7.3.2.4 Wear

Wear is defined as loss of material from a solid surface because of a pressure from other body (liquid or solid) according to §11.2 of DNVGL-ST-0164 [86]. Wear also includes erosion and cavitation. In DNVGL-ST-0164, erosion is described to occur in tidal blades and mooring lines, including abrasion between different mooring parts. Cavitation is also studied in this standard only for the main blade, which involves several types of cavitation like tip vortex cavitation, sheet cavitation or bubble cavitation. For further guidance about cavitation, reference is made to GL rules III.1.2 "Propulsion Plants" [118].

The combination effect of wear with corrosion or fatigue is not considered in current standards and guidance for MECs.

7.3.3 Mitigation and protection systems

Standards have focused on the mitigation and protection of the systems of MECs to accomplish full service-life.

7.3.3.1 Protective Coatings

Protective coatings include coatings that protect metals or FRPs from different degradation mechanisms such as corrosion, marine fouling and composite ageing DNVGL-ST-0164 [86]. Coatings also are beneficial to extend fatigue life. Coating systems for steel with proven performance in marine environment are defined in ISO 12944-5 "Protective paint systems"

[119] and NORSOK M501 “Surface preparation and protective coating” [120], which are selected considering the environmental zones. In the case of anti-fouling paints is relevant to consider environmental friendly agents as explained by DNV and Carbon Trust “Guidelines on design and operation of wave energy converters” [108].

Coatings for blade materials should be durable for the entire design-life, which means long term resistance to seawater, along with the ability to withstand erosion associated with sand particles and water (as stated in §7.8.8 of DNVGL-ST-0146).

For Corrosion protective coatings, detailed guidance is found in GL VI.10.2 “Guidelines for Corrosion Protection and Coating Systems” [121] and in ABS Guidance Notes [122].

7.3.3.2 Environment resistant materials

The selection of corrosion resistant alloys for critical applications such as bolting can ensure a safe service life of the joint or component. In the case of FRPs, polyester composites are known to have better marine durability as indicated by DNVGL-ST-0164 [86].

7.3.3.3 Cathodic Protection

Cathodic protection (CP) is a well-known technique for the corrosion protection of offshore structures. There are two types of CP: galvanic anode cathodic protection (GACP) and impressed current cathodic protection (ICCP). GACP is preferred since ICCP is more vulnerable to environmental damage and third-party damage, as stated by DNVGL-RP-0416 [114]. For steel structures, the galvanic anodes allowed to utilize are Zn and Al, DNVGL-RP-0416.

For the design of GACP reference is made to DNVGL-RP-B401 “Cathodic protection design” [123]. CP system in waters with high currents should be increased, see DNVGL-RP-0416 [114].

7.3.3.4 Corrosion Allowance

Minimum corrosion allowance for mooring chains is given in §15.6.3 of DNV-ST-0164 [86], which recommends chains to be increased in diameter. Corrosion allowance of steel parts for different environments is calculated with equations given in §4.5 of DNVGL-RP-0416 [114] depending on corrosion rate, useful life of the coating, and design life of the structure or component.

7.4 Moorings/support

Mooring solutions in the marine renewable energy (MRE) sector have been informed by commonly applied approaches adopted from the oil and natural gas industries. In contrast to the early stages of the MRE industrial development, significant information is now available across a range of resources to inform mooring material and design decisions. This includes improved scientific knowledge, lab and field test facilities, as well as offshore deployment experience. While components of existing research are confidential due to the competitive nature of the industry, EU funded projects like MaRINET 1, EquiMar protocols, CORES (Components for Ocean Renewable Energy Systems), and MERiFIC (Marine Energy in Far Peripheral and Island Communities) provide publicly available design and test procedures.

The MERiFIC D3.5.1 "Testing of synthetic fibre ropes" [124] provides a comprehensive list of applicable test standards that are commonly used in the MRE mooring design approaches. However, a large proportion of these standards are tailored for the conventional offshore oil and gas industries and are used in the MRE sector with appropriate adjustments.

7.4.1 Introduction

Mooring systems provide a significant engineering and monetary challenge in MEC development; therefore, novel mooring configurations are being proposed for compliant structures in the MRE sector. This need for economical mooring solutions has driven the MRE industry away from conventional chain and wire rope mooring systems towards synthetic fibre mooring lines.

In addition to economic drivers, MEC deployment requires a different balance of design analysis relative to the conventional moored offshore platforms due to the device-mooring size ratio and the highly dynamic behaviour due to the device response characteristics. Additional discernible differences and similarities between existing application of offshore mooring systems and potential MEC application are outlined in Table 1 of MERiFIC D3.5.2 "Guidance on the use of synthetic fibre ropes for marine energy devices" [124]. Therefore, as MRE devices advance to TRL 6–7, the surrogate guidance documents listed in [124] need to be adapted to meet industry-specific requirements to ensure safe and economical station-keeping of devices.

Wave forcing, tidal fluctuations, and wind loads lead to heave, sway, and surge of the typically small and highly responsive floating MECs. Therefore, it is imperative to utilise realistic loading regimes for prediction of operational reliability and durability of moorings for testing at a system as well as component level.

For detailed guidance on types of mooring systems and respective configurations, please refer to §6 and §7 of IEC TS 62600-10 "The assessment of mooring system for marine energy converters (MECs)" [125].

A combination of dynamic finite element methods, analytical models and physical models may be used for determining the structural reliability characteristics of mooring systems

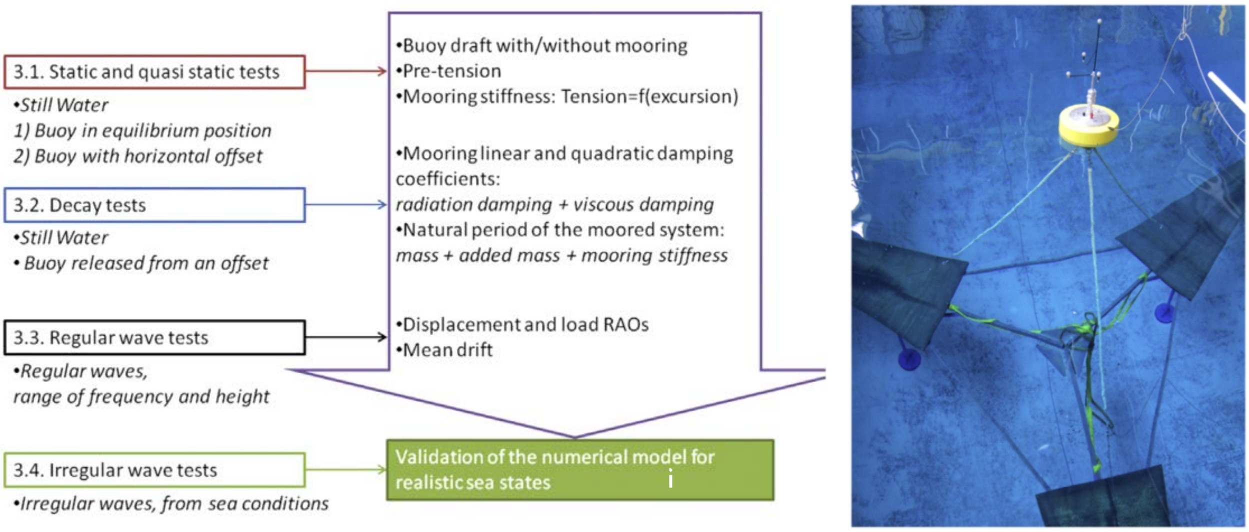
[126]. Using data collected at the South West Mooring Test Facility, the aforementioned publication provides a published record of detailed mooring load measurements for a MEC with an estimate of consequent fatigue life and safety factors.

This section of the report deals with physical model testing at laboratory and field level. To this purpose, it provides an overview of test practices and methodologies for synthetic rope testing at small scale in a controlled environment as well as at the large-scale field test site to identify gaps in knowledge.

When detailed information regarding the derivation of performance metrics from the experimental set ups is required, the reader is referred to additional sources to compliment the information provided in this section.

7.4.2 Lab scale testing

Lab scale testing allows for the validation of numerical design tools as well as contributing to proof of design concept of the mooring configuration in an accessible and controlled environment at a fraction of the cost of sea trials. A standardised approach of mooring system testing has not been formalised for MEC devices internationally partly due to the lack of convergence to a design solution and insufficient field deployment experience. However, Harnois et al [127] identify a series of tests required to finely calibrate a numerical model and correct inaccuracies with experimental data, whereby each test provides different information about the buoy and mooring hydrodynamics as seen in Figure 8.5(i).



(i) *(ii)*

Figure 8.5. (i) Range of experimental investigations required to validate numerical data.
(ii) Experimental set-up for a scaled device in a deep water wave basin at IFREMER. [127]

7.4.2.1 Types of tests

For most early stage tank tests of wave energy converters, the core aim is to validate concept design and improve the power take-off, therefore, the mooring system is often represented in a simplified way so that it does not influence the PTO. Tank depth also limits the accurate scaling of mooring systems; however, it is crucial for tank testing to incorporate influences of mooring systems on PTO at more advanced stages to optimise WEC performance. Analysis of structural motion, mooring line characteristics and mooring load results allow for the identification and optimisation of a cost-effective mooring solution with extreme and fatigue load mitigation.

Laboratory tests are performed with the ultimate objective to obtain reliable results that may be scaled up and compared to analytical designs. Figure 8.5(ii) displays the experimental set-up to conduct lab tests for a scaled, moored buoy at the deep-water wave basin at IFREMER with a false floor to imitate depth.

As recommended by MD2.21 “Technical note: Mooring Testing” [128], a set of six tests must be conducted for a MEC in a controlled tank environment to support mooring system analysis. This includes the free decay, stiffness, and umbilical tests as well as limit state tests for the ultimate, accidental, and extreme conditions.

IEC 62600-10 advises the user to additionally determine the serviceability and fatigue limit states for a robust mooring design [125].

The ISO Technical specification documents 19336 “Fibre ropes for offshore station keeping – Polyarylate” [129] and ISO 18692 “Fibre ropes for offshore station keeping – Polyester” [130] provide material-specific guidelines regarding the characterisation and test methodology to be employed for synthetic rope testing. This includes material break strength, cyclic loading endurance, quasi-static and dynamic stiffness as well as axial compression fatigue testing.

While first order wave frequency loading influences the stiffness and damping at different pre-tensions, the second order wave forcing (in conjunction with tidal and wind forcings) leads to the overall displacement of the device. This causes change in stiffness, mooring line tension and damping characteristics.

Relevant drag and mooring line coefficients must be used from available standards and guidances, whereas, axial stiffness of mooring lines can be determined by tension-tension testing of multiple samples from the material used to construct the mooring system subjected to scaled loads. Additionally, quasi-static tests allow for the estimation of horizontal stiffness characteristics of the mooring system by determining the horizontal MEC position relative to the mooring line tension [127]. These horizontal stiffness characteristics can be used as an indicator of the natural period of the moored system.

To simulate the drag, the floating MEC structure must be moored in the tank and appropriate environmental loading must be applied. Therefore, the overall structural response of a floating MEC depends on the following characteristics of the dynamic behaviour of mooring lines:

- Mooring line pretension
- Mooring line stiffness and pretension damping
- Load at the fairlead by the mooring line

Physical investigation of damping characteristics may be performed by the free decay or forced oscillation methods. A range of decay tests allows for the identification of the dominant periods of oscillation and the natural frequencies of the structure and the mooring lines.

Additionally, the relationship between the top-end frequency of the floating MEC system and the natural frequency of the mooring line must be investigated since variation in this relationship influences damping properties [128].

Comparison between various possible mooring line configurations may be conducted by calculating the Response Amplitude Operators. Once a decision has been made on the mooring configuration, a comparison between maximum mooring forces on individual mooring lines, in conjunction with the device motion envelope, is critical for informing further design improvements and cost optimisation.

7.4.2.2 Scaling and uncertainty

Well-designed scaled physical modelling of a novel mooring system is highly beneficial for concept verification; however, slight distortion of the system introduces a higher degree of uncertainty than that in a full-scale device.

The foremost consideration for model testing is to investigate modelling laws governing the planned test. Of particular significance are scaling laws, which influence the construction of a scaled test sample/device.

Existing research by Harnois et al [127] outlines methodologies to determine scale properties and axial mooring stiffness characteristics of the mooring system. The tank model may yield inaccurate results if the model is too small or the mooring system is large relative to the tank size. To eliminate these inaccuracies, truncated mooring lines may be used with a larger tank model. Numerical investigation allows for the identification of the length of mooring line constantly at rest on the seabed for a range of surge, sway and heave motions (in the same order of magnitude as the sea trials) of the buoy. This length of the mooring line does not impact the hydrodynamic behaviour of the system; therefore, it may be removed from the tank testing process. The truncated mooring lines may then be scaled based on the Froude model keeping in mind the dimensions of the tank.

A degree of similitude between full-scale device and test model may be achieved by satisfying the geometric, hydrodynamic and structural (Cauchy) similitude requirements.

To achieve hydrodynamic similitude, Froude, Strouhal and/or Reynolds may be used, however, there exist limitations in the application of each law, as discussed in section 5.2.1 above. Owing to these limitations, a degree of distortion in the scaling parameters of all principal parameters is inevitable and acceptable for industrial application.

Similar to wave and tidal energy converters, of the hydrodynamic similitude laws, the Froude similitude law is considered the most appropriate to derive scaling factors for moored floating structures. A table of relevant scaling factors can be found in MD2.21 “Technical note: Mooring Testing” [128].

Uncertainty in the Froude number is introduced by the effect of the significantly reduced Reynolds number in a small-scale model and this necessitates appropriate adjustment of the model tests and scaling of collected data.

For a robust analysis, sufficient data must be collected by the investigator. Therefore, the model must be equipped with the required instrumentation to collect and collate data for calculation of the above parameters [128].

The measurement accuracy at small scale may be compromised by the introduction of superfluous physical phenomena in test tanks that do not exist in the field. When correlating and scaling data, this measurement error must be accounted for to an appropriate degree.

7.4.2.3 Test facility selection

There exist numerous facilities dedicated to failure investigation and material testing for mooring systems. In order to determine the robustness of a mooring system, tests must be conducted at system level as well as component level.

For system level testing, test tanks of various sizes, flumes and basins are available. As stated in sections 4.2.3 and 5.2.2 above, various characteristics may influence the developer’s choice of facility. However, the ultimate deciding factor for lab test facility selection is based on the facilities’ capability to generate required sea states for device testing. The capabilities and limitations of the wave maker, current, and wind system (if available), should be assessed and included in test schedule design accordingly.

For component level testing, numerous intrinsic rope parameters must be determined at available rope test facilities. Available facilities include those at rope makers’, in test-houses, research and academic institutes. It has been observed that there is a broad variation between the type, size and capabilities of rope test machines.

The developers can choose between tensile, tension-torsion and bend over sheave test machines, which may be load and/or displacement controlled.

Typical rope testing facilities at rope-makers can apply loads of between 50-100 tons. At research and academic institutions while some test rigs are purpose built, others were developed for load testing in other industries. This may introduce limitations regarding the control mechanism of the rig. As an example, rigs developed for testing suspension bridge cables under high cyclic loads may have displacement limitations, which limits possible outputs for rope testing.

Rope samples can be tested dry, however, to simulate offshore conditions samples should be tested with sprayed water or fully submerged in water, based on the test rig capability.

7.4.2.4 Environmental loads

The mooring-induced damping of the MEC may be exposed to a spectrum of combined loading regimes which can be determined by appropriate analytical or empirical methods, as noted in IEC/TS 62600-10 [125]:

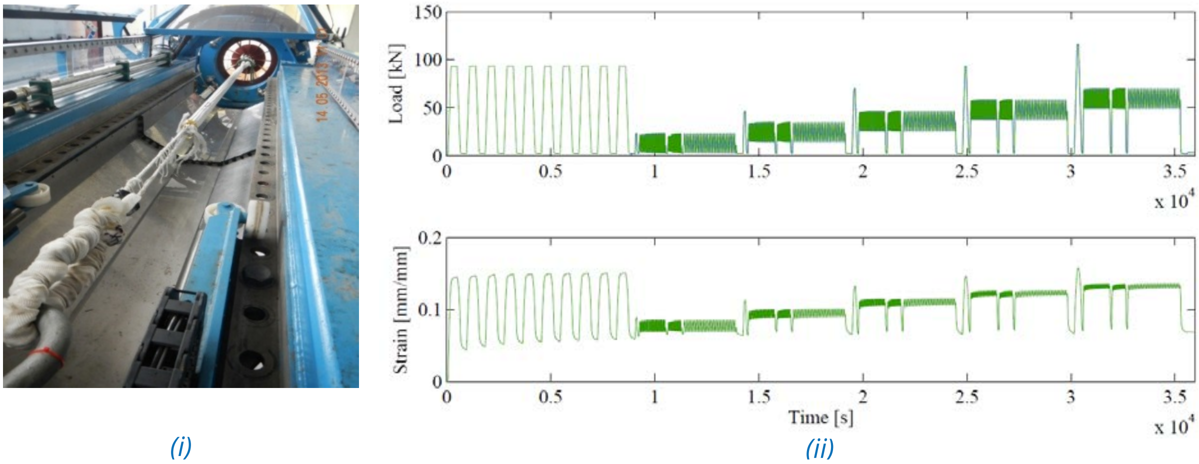
- Low frequency wind, slow wave drift and current loads - The wind and current loads can be estimated with a drag force approximation, whereas, the mean wave drift load is the rate of ocean wave reflection from the hull of the floating MEC.
- Wave frequency loads – An approximation using the Morison equation is sufficient for structures that are smaller in size relative to the predominant ocean wavelengths. For larger structures, the wave radiation and diffraction effects must be appropriately captured.
- High frequency vortex-induced vibration, PTO, and loads due to seismic activity, ice, and ship impact – Influence of vortex induced vibration on the drag coefficient, dynamic operational loading by the PTO and possible near shore impacts like ship collision must be quantified.

Simplified numerical modelling requires only the second order mean drift forces for the estimation of second-order motion of the floating MEC using Newman’s approximation. These may be evaluated for a broad range of wave period and steepness by regular wave tests.

The facility of choice should establish capability to simulate the loads at the deployment location sufficiently for robust design analysis. Introduction of wave machines that can actively absorb reflected waves from the device model allows for accurate reproduction of real sea conditions in a wave tank when applying mean drift forces.

When selecting the component test facility type, the developer must bear in mind that the tensile loading capacity of the test machine must be greater than the specified MBL for a successful breaking test. Figure 7.6(i) shows the results of a rope test to failure at a dynamic component test rig.

For rope testing, Annex F of ISO/TS 19336:2015(E) [129] provides diagrammatic representation of loading regimes for bedding in, quasi-static stiffness, dynamic stiffness, linear density, cyclic endurance and breaking test sequences. Figure 7.6(ii) shows a sample applied load and measured strain time series for a sample rope. It must be noted that this load and response profile changes depending on the type of investigation and material characteristics.



(i) *(ii)*

Figure 7.6. (i) Fibre rope failure result for a test in dry conditions. (ii) Applied load and measured strain profile for a sample nylon rope (from [128]*).*

7.4.3 Field testing

Selection of appropriate deployment sites for Stage 3–4 testing forms an important part of Stage 2 of the structured development plan. This is because the latter stages aim to validate the outcomes of the laboratory testing to establish the reliability and survivability of the device. After development and testing through numerical methods and in small-scale tanks, the prototype must be optimised and deployed for sea trials. This facilitates the integration and validation of the numerical simulations and test tank data with collected field data to improve incrementally the system model.

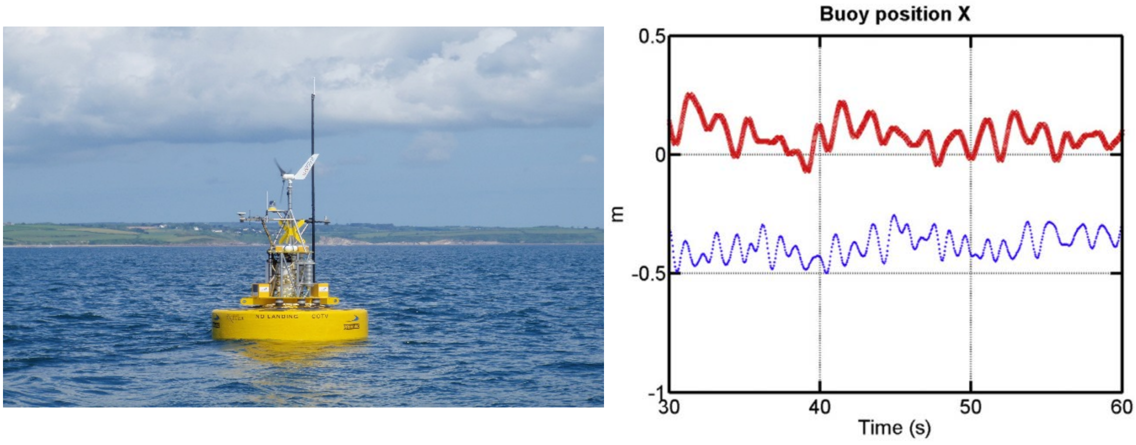
7.4.3.1 Types of tests

For sea trials of a large or full-scale device, special consideration must be given to the device instrumentation to collect extensive data regarding the environmental loads and structural response. MD2.21 “Technical note: Mooring Testing” [128] provides examples of instruments that may be used along with associated resolution and range.

Of particular importance are the axial and inline load cells at the interface of the mooring and main structure, which provide data with multiple degrees of freedom for extreme and fatigue load analysis. Additionally, associated environmental parameters must be collected to identify critical conditions and quantify risk to the integrity of the mooring systems. The principal hardware to collect wave action, tidal current forcing, and wind-blown surface currents data can be fitted on to the device or installed locally at the seabed. In case of the latter (as in the case of when wave rider buoys and acoustic Doppler current profilers are deployed at a close by location), appropriate correction factors must be applied to adjust the metocean data for use in the device response profile analysis.

Reliable autonomous operation of the data acquisition system in a harsh marine environment must be ensured due to reduced accessibility based on local weather windows. The comprehensive range and number of sensors will sample data at a high frequency, generally in the order of kilohertz, generating data in excess of the capacity of most data loggers. Therefore, it is imperative that an environmental threshold is set for data storage, and not all uncompressed data is recorded at low environmental conditions. For real-time data transmission, it must be ensured that the controller is capable of compressing the data and transmitting it over radio link to the shore station without any loss.

As discussed for the South West Mooring Test Facility in [127], and shown in Figure 7.7, poor correlation between numerical simulations and field tests of mooring load and buoy displacement results is seen if the assessment of the final embedment anchor position is not accurate. This is particularly true for devices deployed in shallow water, which is usually the case for MEC test sites. Underwater surveying techniques and circumference techniques described by [131] can be used to determine final anchor position for improved accuracy of field test results of mooring load and MEC displacement.



(i) *(ii)*

Figure 7.7. (i) South West Mooring Test Facility buoy deployed at the Falmouth Bay Test site. (ii) Offset in buoy position in field testing (dotted blue line) from tank test results (thick red line) due to incorrect position of the embedment anchor (from [127]).

7.4.3.2 Test facility selection

As with the lab test facility, a critical aspect for field test facility selection is associated to the environmental characterisation. Device developers can choose between profiles of nursery and main test sites based on preference of exposing their prototype to benign or more dynamic sea states, respectively.

Additionally, the choice of test facility for sea-based trials is based on numerous facility characteristics including geographical location, access charges, consent process, financial and research services provided in conjunction with deployment. While some facilities can provide support for both standardised and tailored qualification of large-scale mooring systems, others might be restricted in the types of tests they can conduct.

Also, for each individual site, procedures governing the use, including site characteristics, legislative and consenting requirements, are highly likely to incorporate elements specific to the country where the facility is situated. Therefore, geographical location is a highly significant deciding factor.

7.4.3.3 Environmental loads

The definition of environment for testing of the mooring system of a MEC includes seabed characterisation as well as a combination of metocean parameters of wind, wave and tidal current as outlined in DNV-RP-C205 "Environmental Conditions and Environmental Loads" [132].

Field test site selection for determining mooring loads must take into account the prevalent loading conditions in the eventual deployment location. Common industry practice for TRL 5–7 involves initial deployment at a benign nursery test site, followed by deployment at a more dynamic test field. Further information regarding experimental investigations of mooring systems can be found in the CORES (Component for Ocean Renewable Energy Systems) deliverables [133]. Component-level results from sea trials of an Oscillating Water Column were collected in the project and these can be used to provide guidance to developers for lab and field deployment.

An estimate of mooring system and component reliability requires the definition of the operating period and prevalent operational and environmental conditions. Using available field load measurements under the aforementioned conditions, the expected load regime for the lifetime of the system/component can be approximated using the methodology defined in §5 of MD2.21 "Technical note: Mooring testing" [128].

(Part II) Recommendations by facility type

The following four sections summarise guidance and offer recommendations particularly relevant to different types of test facility: test tanks (including flumes, towing tanks, and basins) (8), wind tunnels (1), field test sites (9), and component test facilities (10).

8. Test tanks (flumes, towing tanks, basins)

8.1 Test support

Support is typically offered to clients through the test programme

- Pre-test engineering: including experimental design/set-up, test programme development, integration with the facility, and possibly model or component manufacture.
- Conducting the test campaign, including dealing with issues that may arise during this.
- Post-test analysis, reporting, and data transfer.

The scope and detail of test support offered by test tanks will vary depending on the specific facility, the type and experience of client testing there, and the contract requirements. This is shown in the responses to the MaRINET2 facilities questionnaire, section 0 below.

There is no specific guidance on test support, although a number of these topics are covered to some degree by other guidance documents. General considerations on topics including data acquisition and analysis, health and safety, and reporting are covered in section 3 above.

8.2 Physical/environmental conditions

ITTC recommended procedures and guidance are available to assist test tanks with conducting model tests in waves. This is not specifically targeted at marine renewable energy devices; it includes considerations for ship testing etc. that may be less relevant. It is important that waves are modelled and documented according to proper and well-defined methods. ITTC 7.5-02-07-01.2 “Laboratory Modelling of Waves: regular, irregular and extreme events and Laboratory” [17] focus on some rather basic questions like linear and nonlinear waves, regular and irregular wave conditions, as well as some more challenging problems like the generation of extreme waves in a tank. Additional detail on more complex spread sea conditions is given in 7.5-02-07-01.1 “Modelling of Multidirectional Irregular Wave Spectra” [16].

8.2.1 Specifying conditions

While test facilities will have a good understanding of how to specify the conditions to be generated in their tank, prospective clients may not have such detailed understanding.

Guidance is given on selecting and specifying environmental conditions in sections 4.2.2, 5.2.3, and 6.2.2 above.

There is uncertainty of both the real-world flow field dynamics in energetic tidal channels where TECs will be deployed, as well as how to reproduce these in test facilities once the flow is characterised. The local bathymetry of tidal channels can be complex and lead to localised conditions that may not be captured effectively [20].

The flow conditions that can be generated is specific to the type of facility, e.g. towing tank, cavitation tunnel, offshore basin, etc. ITTC 7.5-02-07-03.9 "Model Tests for Current Turbines" [20] advises these conditions should be documented, including:

- Flow speed and direction;
- Spatial uniformity, including blockage effects and vertical flow profile;
- Steadiness and turbulence characteristics.

Turbulence is commonly described by a single 'turbulence intensity' parameter, but length scales are also important to characterise small and large-scale fluctuations within the flow. Many facilities are only able to change the mean flow velocity, but cannot easily adjust turbulence or change the vertical flow profile. Generation of small-scale turbulence may be possible in some facilities by introducing a grid or other structure upstream of the turbine [20].

Similarly, care is required on how combined wave-current conditions are specified. ITTC guidance 7.5-02-07-3.1 for "Floating Offshore Platform Experiments" [53] recommends that where a current is included, the wave spectrum be calibrated in the presence of that current, i.e. specifying the combined wave-current field.

8.2.2 Generating the required conditions in the tank

The conditions that can be produced in each facility will depend on the particular constraints thereof. The requirements for environmental conditions will also depend on the device being tested, as covered in previous sections.

The ability of facilities to produce desired environmental conditions in an accurate and repeatable manner as required is a key benefit of tank testing. It is therefore important to understand how well the conditions are produced in the tank.

ITTC guidance 7.5-02-07-01.2 on "Laboratory Modelling of Waves: regular, irregular and extreme events" [17] ideally requires for regular wave testing a unidirectional periodic wave field with amplitude, period and direction constant throughout time and space. In practice, deviations from the ideal situation are observed, for various reasons, which are associated with wave maker, basin and wave absorbing devices. Model testing procedures must take these effects into account, in one or several of the following ways: a) avoiding them, b) reducing them, c) documenting them and interpreting their effect on device responses.

Calibration of the test environmental conditions is covered in §2.5 of ITTC 7.5-02-07-3.1 "Floating Offshore Platform Experiments" [54]. The environment needs to be calibrated prior to the test to ensure the correct environment is going to be tested. The environment is a combination of waves, current, and wind, depending on facility capability and test requirements. Additionally, external forces may be required to simulate specific loads acting on the model, which also need to be calibrated and documented if used.

In addition to the ITTC guidance, MD2.12 "Collation of Wave Simulation Methods" [54] provides details on methods of wave simulation used in test tanks (§4) and the accurate generation of a sea state across the tank (§5)

8.3 Instrumentation, data requirements, and model installation

The following six sections give a summary of test recommendations, with relevant guidance tabulated in section 8.3.7 below.

8.3.1 Types of instrumentation

Typical instrumentation for tank testing includes:

- Wave gauges (incident waves and run up)
- Current meters
- Wind sensors
- Force sensors (including multi-component gauges)
- Pressure sensors (in air and water)
- Motion sensors
- Accelerometers
- Fluid velocity flow
- Classical electrical measurements (voltage, current)

Once the choice of the scale has been made according to the characteristics of the basin and of the full-scale device, it is advisable to select the appropriate measurement instruments. Nevertheless, some expensive sensors can influence the scaling factor. For example, the use of a six-component gauge of limited capacity may result in a reduced model size.

A complex subsystem such as a servo-controlled rotor for a floating wind turbine may have been calibrated for a power level suitable for a particular model scale; the installation on board a floater can then impose its own scale ratio.

It should be noted that motion measurements are now possible by optical method using video and image processing. These video tracking systems can be used to follow the translations of groups of points on flexible structures (like underwater mooring lines) or on rigid bodies to calculate the parameters of their six degrees of freedom. Increased accuracy of Inertial Measurement Units (IMU) makes them suitable for particular motions measurements as far as no electromagnetic perturbation arises and absolute yaw angle is not required.

8.3.2 Instrumentation calibration and checks

Sensors which deliver a single measurement should be calibrated prior to each test campaign, and checked at the end. This is the case for wave gauges and of a one component strain gauge. Sensors which deliver multiple channel information, such as a six-component gauge, are usually supplied with a calibration certificate by their manufacturer. A control of the sensors calibration at the beginning and at the end of the tests campaign can be enough to validate the measured data. Calibration of linear sensors should follow the recommended procedure in ITTC 7.5-01-03-01, "Recommended Procedures and Guidelines: Uncertainty Analysis, Instrument Calibration" [27].

Almost all non-linear sensors such as optical motions tracking system need an initial calibration at the beginning of the tests and regular re-calibration as often as necessary when the measurement accuracy is degraded. The accuracy level is usually given by an extra channel value, which is inferred through combinations of the other channels. The calibration procedures for motion video tracking systems are established by the manufacturers and must be carefully followed.

Some kinds of calibration need a special bench that can be disconnected from the model and the tank. Some calibrations must be made in the tank area (optical motion tracking) and other ones must be made with the sensor installed onboard the reduced scale model itself and in the tank (run up gauge, pressure sensor, etc.).

8.3.3 Data acquisition

The sensors generally deliver micro-electrical quantities which values need to be increased by amplification to reach a level of several Volts. The continuous analogical values are then transposed into discrete digital values.

Some sensors whose measurements are based on optical tracking of motions directly deliver digital values (numbers of pixels in images).

Different sources of data can be available, for example:

- "ground" data: incident waves measurements
- onboard data: six component gauge located between the mast of a floating wind turbine and the rotor itself
- 6 degrees of freedom motions

These three data sources must be synchronized in order to have consistent data records. This assumes identical time steps and a common reference time which can be achieved by using a trigger to declare the start of each acquisition and by a common sampling rate. A trigger is a voltage step on a special channel available in each data acquisition system and initiated by a common event (press button type). 100 Hz is a quite common sampling frequency but could be lower. The sampling frequency must be adapted to the fastest phenomenon that should be recorded.

Practically, the fast events can be:

- sloshing in tanks or between columns of a semi-submersible platform (several tenths of seconds)
- turbine rotation: about 60 rpm at model scale with interaction of three blades with the mast
- shorter phenomenon like wave impacts
- structural vibrations (several Hz)

At the end of each test, a group of values is collected in a single file. This can be an ASCII file to facilitate sharing between users, or a proprietary file type. The file contains the time domain evolution of each variable in different tests configuration, e.g.:

- static or decay test
- regular waves test
- irregular waves test

8.3.4 Data processing, analysis, interpretation

Depending on the type of test, various signal processing can be applied: Fourier series, Discrete Fourier Transform, transfer functions, wave-by-wave analysis, Power Spectrum Densities, etc.

An important step is the comparison of experimental results with numerical ones and extrapolation to full-scale values. Particular attention must be paid to the power evaluation which, as stated in section 4.2.1.2 above, can be very small at model scale. Friction effects can strongly modify the value recorded, so care is required.

8.3.5 Model moorings

Three main types of moorings are considered: catenary, tension legs, and semi-taut moorings. The type of mooring used will depend on the type of device being tested, and some models may be directly mounted to the tank to represent a fixed foundation.

8.3.5.1 Catenary mooring

The word catenary comes from the natural form taken by a line of constant linear mass, inextensible, and without flexion stiffness (case of a chain). In practice, a catenary line may consist of a succession of homogeneous lines of different characteristics: chain, wire rope, textile rope. A textile line has generally a viso-elastic axial behaviour.

These lines are connected at one end to a floater under or above the waterline and at the other end are laid on the sea bottom up to an anchor or dead weight. Depending on the type of floater, the number of lines N is usually taken between 3 to 6, or even 9 with a third order of symmetry. For fourth order symmetry the number of lines N is usually taken between 4 to 8, up to 12. The lines extend horizontally on a relatively large radius centred on the middle of the floater.

At model scale, the lines sizes should be reduced according to the scale ratio and the tank must be wide enough to welcome an equivalent radius, accordingly the water depth must be equivalent to the full-scale water depth reduced by the scale ratio.

Some simplifications can be made:

- Reduce the number of lines to the minimum (3 when N is a multiple of 3, 4 when N is a multiple of 4) and consider the global stiffness of the mooring.
- Reduce the radius of the mooring to fit into the tank when a sufficient length is laying on the bottom.
- Install “false bottom” in the tank when the water depth is too large. If “false bottoms” are only locally installed under the laying part of the mooring lines, the wave kinematics still depends on the principal water depth.
- Horizontal lines made with very stiff ropes combined to linear springs can be used to fit the horizontal stiffness of the catenary mooring system, these lines can be above water or under water.

Most of the time, a catenary mooring has a global stiffness matrix such that the horizontal motions are low frequency natural modes and the vertical motions frequencies depend on the hydrostatic stiffness. Pre-tensions in the mooring lines must be adjusted to avoid zero tension in any spring when the model drifts.

8.3.5.2 Tension legs

Usually used in the oil and gas industry, the tension legs are vertically connected between the seabed and the bottom of the floater, increasing its immersed volume. They allow horizontal motions with low frequency natural modes, similar to pendulum motions. The vertical motions are constrained with high natural frequencies associated to the axial stiffness of the legs, and are above waves frequencies. The number of tension lines is usually 3 or 4.

At model scale, the length of the tension legs must be reduced according to the scale ratio and the water depth of the tank must be large enough. Some tanks are fitted with pits locally extending the water depth. The wave kinematics depends on the principal water depth.

8.3.5.3 Semi taut mooring

The lines are similar to tension legs, but are inclined to the vertical inducing high natural frequencies of the floater’s dynamics. The stiffness matrix is strongly related to the axial stiffness of the legs.

8.3.5.4 Consideration on mooring dimensions and materials

The mooring lines may be made with various materials: chains, metallic cables, textile ropes. When designing the model scale mooring, a due consideration must be given to the weights and the diameters of its components. The diameters condition the terms of added inertia and drag, so the Keulegan-Carpenter (KC) and Reynolds (Re) numbers must be considered.

An optimum must be found satisfying distributed weight and buoyancy, added inertia, drag equivalent diameter and stiffness. The axial stiffness is generally related to the Young's modulus and section area of the material. When using the same full-scale materials to build the model, the model-scale diameter of the material must either be reduced by the scale ratio to the power 1.5, or the section reduced by the cubic power of the scale ratio.

8.3.5.5 Global mooring stiffness

The mooring lines must be installed in the tank with a centimetre accuracy. Tests must be done to evaluate the global mooring stiffness at model scale. It can be difficult to obtain a stiffness matrix exactly equivalent to the full-scale one. In any case, the model scale stiffness should be precisely known as an input to the numerical models that will be used to compare experimental and numerical results. When possible, force sensors should be installed in the mooring lines both at full-scale and at model-scale.

8.3.6 Model installation

The model installation in the tank is a decisive step for the rest of the trials (see sections 4.2.1, 5.2.1, and 6.2.1 above). Some key considerations include:

- The equilibrium, location, and attitude of the model depend on the design and accuracy of the mooring system.
- The waves sequences depend on the distance to the wave maker which must be precisely known (centimetre).
- Transfer functions that will be computed from the tests records, and especially their phases, depend on the location of the reference waves sensors
- The distance of the wind generator to the model must be adjusted according to the initial calibration of the wind flow and to the expected horizontal drift motion of the model due to wind and waves
- The model's inertia and hydrostatics should have been previously checked (mass, location of the centre of gravity, radii of inertia, buoyancy, GMs). Particular tests should be run to check the hydrostatics with and without mooring.

In some circumstances, the model has to be kept fixed in the waves or current with prescribed position and angles or moved with prescribed motions. The use of a hexapod is then an option to fulfil these requirements. A balance can be interfaced between the hexapod and the model to measure the forces and moments associated to the motions and identify the added inertias, linear damping and drag effects. Careful measurement of the dead weight effects of the model is necessary.

8.3.7 Guidance available

Table 8.1. List of relevant references for instrumentation, data requirements, and model installation

Report / Sections	Instrumentation Sensors	Instrumentation, calibration and checks	Uncertainties	Mounting, mooring solutions	PTO representation	Data processing, analysis, interpretation
MaRINET D2.01 "Wave Instrumentation Database" [44]	§5					
MD2.05 "Report on Instrumentation Best Practice" [40]	§2				§3	
MD2.08 "Best Practice Manual for Wave Simulation" [34]						§4,5
MD2.10 "Best Practice Protocol for Offshore Wind System Fluid-Structure Interaction Testing" [134]	§5			§5		§5
MD2.13 "Collation of Model Construction Methods" [42]	§5				§6	
MD2.20 "Report on Physical Modelling Methods for Floating Wind Turbines" [93]					§4	
MD2.23 "Review of Tow Tank Limitations" [135]						§3
MD2.25 "Review Best Practice Standard for Electrical PTO Systems/Definition of standardised PTO Test Procedures" [11]					All	
MD2.28 "Protocol for Model Construction / Model Construction Methods" [38]	§4 §5			§5	§4,5	
MD4.01 "Tank test related instrumentation best practice" [43]	§2	§4,8				
MD4.04 "Report on low frequency response and moorings" [136]				§4		All
MD4.05 "Report on non intrusive wave field measurement" [137]	§3					
MD4.09 "Report on remote underwater motion measurement" [138]	All					
HYDRALAB IV D2.3 "Foresight study on laboratory modelling of wave and ice loads on coastal and marine structures". [139]	§4			§2,4		All
EquiMar D3.3 "Assessment of current practice for tank testing of small marine energy devices" [23]	§5	§7	§7			

Report / Sections	Instrumentation Sensors	Instrumentation, calibration and checks	Uncertainties	Mounting, mooring solutions	PTO representation	Data processing, analysis, interpretation
ITTC 7.5-02-01-01, "Recommended Procedures and Guidelines: Guide to the Expression of Uncertainty in Experimental Hydrodynamics" [15]			All			
ITTC 7.5-02-07-03.7, "Recommended Procedures and Guidelines: Wave Energy Converter Model Test Experiments" [18]		§3	§3		§2	§3
ITTC 7.5-02-07-03.8, "Recommended Procedures and Guidelines: Model Tests for Offshore Wind Turbines" [19]			§3	§3	§2	§3
ITTC 7.5-02-07-03.9 "Recommended Procedures and Guidelines: Model Tests for Current Turbines" [20]			§3		§3	§3
ITTC 7.5-01-03-01 "Recommended Procedures and Guidelines: Uncertainty Analysis, Instrument Calibration" [27]		All	All			
ITTC 7.5-02-07-03.12 "Recommended Procedures and Guidelines: Uncertainty Analysis for a Wave Energy Converter" [31]			All			
ITTC 7.5-02-07-03.15 "Recommended Procedures and Guidelines: Uncertainty Analysis - Example for Horizontal Axis Turbines" [32]			All			

9. Field testing (sheltered/exposed sites)

9.1 Introduction

The device development process is divided into 5 stages according to TRL groupings. The general guidance on stages and the level of readiness of the device to move from tank testing to field testing (sheltered or exposed) are detailed in [3,5]. Field tests should be carried out at stages 3 (TRL 5-6), stage 4 (TRL 7-8) and stage 5 (TRL 9). At stage 3, a sub-prototype that can be deployed at sea at a scaled (sheltered) site and produce electricity. The subsystem at this stage should include a fully operational PTO. It is also at this stage that the deployment, O&M and recovery operations are carried out at sea on a smaller scale device and first licenses and consents are obtained. As the development moves to stage 4, a full-scale device should be tested at sea and by the end of the stage the device should be grid connected. The tests at this stage could start in the sheltered site and gradually as the tests progress, move to the full-scale exposed site. The outcome of stage 4 of the development is an established, tested technology and product. Stage 5 includes array testing with several full-scale devices.

More detailed requirements and guidance for field testing of various components of marine energy devices is provided in ED4.1 “Sea Trials Manual” [57] The guidance includes requirements for the data and covers the preferred measurements and sensors to collect data from various components of the MEC under test. Other standards provide information regarding the design and manufacturing process itself, including design basis and grid connection (EMEC “Guidelines for Reliability, Maintainability and Survivability of Marine Energy Conversion Systems” [55] and “Guidelines for Grid Connection of Marine Energy Conversion Systems” [56]; IEC 62600-2; IEC TS 62600-3 – currently under development; plus DNV-GL and ISO Technical standards discussed in section 2.2 of this document).

To proceed with conducting tests at sea, a number of consents and licenses are required. “Guidelines for Project Development in the Marine Energy Industry” [140] provides an overview of the consenting procedures for MEC projects in general, with some guidelines also provided in Equimar WP6. The consenting and licensing requirements could significantly vary depending on the country where the offshore tests are conducted.

The field performance testing requirements for TECs and WECs are described in IEC 62600-100 [58] and 62600-200 [141]. These technical specifications include requirements for the environmental and power output measurements; analysis methodology and the deliverables resulting from the test execution. Guidance on planning the test program in the most efficient way to reduce the uncertainty of performance assessment could also be found in EquiMar D4.2 “Data Analysis & Presentation To Quantify Uncertainty” [142]. The test program is normally developed in agreement with the above-mentioned IEC specifications where possible, with any deviations from the requirements clearly stated.

As the testing moves from laboratories to sea-trails and field tests, Health & Safety requirements change as well. The operations should be conducted in-line with specific offshore operations Health & Safety requirements (heavy lifting; diving operations; marine transfer; etc). The MEC specific guidance and relevant marine Health & Safety standards are provided in EMEC's "Guidelines for Health and Safety in the Marine Energy Industry" [143]. An overall recommended Health and Safety Management System model is provided in the BS OHSAS 18001 standard [144]. The ISO are also developing a standard to cover this, ISO 45001 "Occupational health and safety management systems".

9.2 Physical/environmental conditions

General information regarding the physical and environmental conditions is primarily collected during the resource assessment/site characterisation stage. This data is used to estimate the available energy, plan operations and calculate extreme environmental loads on the device, mooring lines and foundation/anchor points. The resource assessment is addressed in detail in a number of standards and guidance documents including the IEC 62600 series and EquiMar WP2 documents.

The site characterisation and resource assessment studies for WEC sites are primarily based on hindcast wave modelling results, as normally in-situ observational data does not cover long enough period to allow robust statistical analysis (IEC 62600). The main goal of the existing standards is to ensure that the suitable models, verified against in-situ observations, are utilised in such manner that the results could be used to derive the necessary parameters (see IEC 62600-101 [62] and EquiMar WP2). The models utilised at various stages of resource assessment could have different resolution gradually increasing as the stage of the resource assessment moves from Class 1 to Class 3, thus decreasing the uncertainty associated with the results. It is essential, however, to validate the modelling results against in-situ observations using appropriate measurement equipment and techniques, as outlined in MaRINET D2.1 "Wave Instrumentation Database" [44]. Resource assessment and site characterisation studies should result in a good understanding of the typical sea-states and expected available resource. The relatively long timeseries of wave parameters, derived at resource assessment stage, should further be used in extreme value analysis to derive wave parameters of low probability and associated environmental loads, as described in EquiMar D2.6 "Extremes and Long Term Extrapolation" [50], ISO 19901-1 "Metocean design and operating considerations" [145], and DNV RP-C205 "Environmental Conditions and Environmental Loads" [132].

The tidal site characterisation and resource assessment similarly to wave resource assessment could be carried out using in-situ observations and/or modelling. Considering the deterministic nature of the tidal currents, the observations of sufficient length could be used on their own to carry out initial resource assessment through harmonic analysis. The models would provide a better understanding of the spatial distribution of the tidal flow. The tidal resource assessment is described in IEC 62600-201 "Tidal energy resource assessment and characterization" [146]; Equimar WP 2 documents] standards, with tidal flow measurements best practices are summarised in Marinet D2.7 "Tidal Measurement Best Practice Manual" [64].

The reports resulting from wave and tidal resource assessment are instrumental for field test planning and execution.

During the testing, environmental observations are crucial for understanding the device survivability and performance under various physical conditions. The observational strategy for performance testing is detailed in IEC 62600-100 [58] and IEC 62600-200 [141] standards for wave and tidal respectively. They provide requirements for the duration, placement of the equipment, minimum observational equipment characteristics and sampling approach. It is important to note, that the majority of the wave observations are done in the time domain, while generally required parameters are derived from wave spectra, i.e. are reported in frequency domain. As such, the sampling strategy has a significant impact on the accuracy/resolution of the derived parameters. These IEC documents were issued as Technical Specifications and will be reviewed as more information is available.

9.3 Instrumentation and data requirements

During field test execution, information about the physical conditions becomes crucial for understanding the performance of the converter and its survivability. Several documents addressing the device performance testing are described in section 9.2 of this document.

A more detailed description of the equipment used for wave observations is provided in MD2.1 “Wave Instrumentation Database” [44]. Several methods for wave observations are listed, including: surface following buoys; X-band and HF radars; subsea deployed equipment such as Acoustic Doppler Profilers or pressure gauges, etc. Advantages and disadvantages of each of the methods are provided.

TEC testing requires accurate measurements of the current profile, with relatively high vertical resolution. The measurement requirements are detailed in IEC 62600-200 [141]. The tidal current measurements are carried out and reported in the time-domain. The best practices for tidal flow measurements are provided in MD2.7 “Tidal Measurement Best Practice Manual” [64].

It is recommended that the measurements of associated resources, should be accompanied by measurements of the secondary environmental and physical parameters, e.g. during WEC testing current, wind, acoustics data should be collected, at the same time as wave measurements are performed.

Collected data should be processed, analysed, presented and stored in an appropriate way. Several guidelines and best practice documents and standards had been developed available for data processing, analysis and storage [46], [63].

9.4 Device installation/ integration and operations

The device assembling, preparation and installation involves series of high potential risk operations (heavy lifting; hot works; manual handling etc) that should be carefully addressed from the Health and Safety perspective. The related Health and Safety documents are mentioned in section 9.1.

Prior to device deployment all the sub-components should be tested to address the survivability and reliability of the system. The tests should gradually move from dry-testing to wet testing at harbour, if possible to sheltered site and then to full-scale test site. The tests should include not only the device components, but also possibility of the operations and maintenance at sea [57].

It is required in the UK as part of the consenting process and generally good practice to have a certification body do a third-party verification on the mooring and structural integrity of the device under the environmental conditions (usually 50 years return conditions), at the test site.

The risks caused by a device, mooring, or component failure are significant either from collision with marine life, other structures in the sea (fix or mobile) and/or pollution issues. At the field testing stage, these risks can be monitored with instrumentation on the structure (load cells, bragg network), regular inspection by drop camera, ROV, divers or towing back to harbour (monitoring of structural integrity, marine growth and corrosion). Having an integrated monitoring of the key components of the device allows better maintenance planning. For grid-connected devices, it is possible to get instrument signals back via the subsea cable optical fibre. For non-connected devices, radio links are used to bring the signals back to shore.

Regular monitoring allows also the testing and validation of assumptions done during the design phase. Sensors and regular inspections allow the following to be checked;

- Loads from the environment and the behaviour of the device,
- components fatigue,
- anti-corrosion methods (coatings, cathodic),
- anti-fouling methods (coatings, mechanical or material selection),
- cable fault,
- electrical component fault.

Met-ocean monitoring is important to plan marine operations for installation, recovery or maintenance. It is recommended in Equimar D4.1 “Sea-trial manual” [57] to determine weather windows that take into account met-ocean information like wave height, wave period and tidal cycles to try to operate at slack time for exposed tidal test sites and wind speed.

In case of the grid connected test deployment, the guidance on grid connection is provided in EMEC’s “Grid Connection of Marine Energy Conversion Systems” [56] and in MaRINET D4.2 report on grid integration and power quality test [12].

10. Component test facilities

10.1 Materials

All the principal materials used in the fabrication of MECs and their components have been defined in section 7.3 above. Specific standards for each material define their chemical composition and their mechanical properties. For example, UNE-EN 10025-2:2006 “Hot rolled products of structural steels “ [147] indicates the chemical composition and the mechanical properties to be fulfilled by a carbon steel. In order to assess how the degradation mechanisms explained in section 7.3.2 affect the material tested, and how the mitigation and protection systems indicated in section 7.3.3 could avoid these degradation mechanisms, specific rules for each material should be considered. For example, NORSOK M501 [120] will be considered to verify a coating will have the designed life time in certain marine conditions.

In order to run tests for obtaining the values of the mechanical properties of the materials, specific standards exist depending on the material. For example, if it is a metallic material, ASTM E8 “Standard Test Methods for Tension Testing of Metallic Materials” [148] will be used. Otherwise, if the material is plastic, ASTM D638-14 “Standard Test Method for Tensile Properties of Plastics “ [149] will be followed.

Welding, a critical point to consider in the fabrication of MECs, are assessed attending to §7 of DNV-OS-C401 [150] which details the testing and verification of welds.

The test sites to be used for testing the behaviour of metals in seawater, the racks used to hold the samples or components in the test site, the size and shape of the specimens to be tested and their preparation and evaluation are defined in ASTM G52-00 “Exposing Metals in surface seawater” [151].

Table 10.1: Selection of materials tests with purpose and field of use

Materials Test	**Purpose**	**Field of Use**
Karl Fischer Moisture Analysis	Determination of moisture levels in solids and oils.	Cable Insulation Analysis, Insulating oils used in electrical systems with the grid (or any other electrical system that contains an insulating or lubricating oil)
Thermogravemetric Analysis	Determination of material strength	Testing of cable insulation, blade ,materials, weatherproof coating, polymers in rotating machines such as turbines.
Differential Scanning Calorimetry	Determination of polymer properties such as cure temperature, and glass transition.	Testing of cable insulation, blade ,materials, weatherproof coating, polymers in rotating machines such as turbines.
Infrared Spectoscopy	Determination of material structure	All fields
Hot Set Test	Determine Material Strength of Polymers	Cable Insulation
Particle Counting	Determine purity of oil	Electrical Systems
Electrical Breakdown / Withstand	Determine the maximum electrical strength a material can withstand before it breakdowns	Materials directly used in systems with voltage requirements, such as cable insulation, turbines, stator cars and rotating systems.
Electrical Ageing	Determine how a material performs after long term exposure to electrical energisation.	Cable Insulation, materials directly involved in electrical systems.
Environmental Ageing	To determine how materials age after exposure to changes in temperature, UV exposure and humidity.	All materials
Impedance Spectroscopy	Corrosion studies of materials	Biofouling of blade technologies, wave turbines
Adhesion Testing	Determine the strength of adhesion between two materials.	Cable Insulation, Coating Materials used in all systems.
Contact Angle	Determine the surface property of materials.	Coating materials.
3D Laser Microscopy	Determine the material surface and roughness properties.	Coating materials.

Materials Test	Purpose	Field of Use
Optical Microscopy	Forensic examination of materials following breakdown to look at potential failure mechanisms	All materials.
Film Thickness	Determine Film Thickness	All materials.
Scanning Electron Microscopy – Elemental Analysis	Determine elemental composition of samples and to obtain fine details on materials structure.	All materials and all fields.
Tensile Strength	Determination of tensile strength and Elastic Modulus.	All structural materials
Compression Strength	Determination of compression strength and Elastic Modulus	All structural materials
Shear Strength	Determination of shear strength and Shear Modulus	All structural materials
Flexural Strength	Determination of flexural strength and Flexural Modulus	All structural materials
Fatigue	Determination of fatigue strength in tension, compression or combined modes	All structural materials
Lap Shear	Determination of the shear strength of adhesives	Adhesives
Peel Strength	Determination of the peel strength of adhesives	Adhesives
Flexibility	Determination of the flexibility of coatings	Coatings
Rain Erosion	Determination of the erosion resistance of coatings	Coatings
Sand Erosion	Determination of the erosion resistance of coatings	Coatings
Abrasion	Determination of the abrasion resistance	All materials
Flammability	Determination of the resistance to fire	For fire retardant materials
Moisture Absorption	Determination of the resistance of the uptake of water	All materials

10.1.1 Mooring test facilities

When designing a floating MEC structure, the mooring system must be sufficiently investigated since it is responsible for the station keeping and survivability of the device. Failure in the system could have high economic consequences since it may lead to the loss of the device.

As described in section 7.4 above, current testing practices for component testing for mooring systems are adopted from the oil and gas industry. In addition to the generic standard ISO 2307 “Fibre ropes – Determination of certain physical and mechanical properties” [152], further relevant testing regimes are selected based on the rope construction material.

Separate standards for Polyarylate [129] and Polyester [130] exist, however, the basics of rope testing for both materials are distinctly similar. The high strength, modulus and low creep of polyarylate fibres makes them ideal for use in offshore station-keeping applications, however, when subjected to tension-tension cycles in low load range (1% to 20% MBL), they display susceptibility to axial compression fatigue. Therefore, Annex C is a significant addition to ISO/TS 19336:2015(E) [129], since axial compression is a common failure mode for polyarylate and not for polyester ropes.

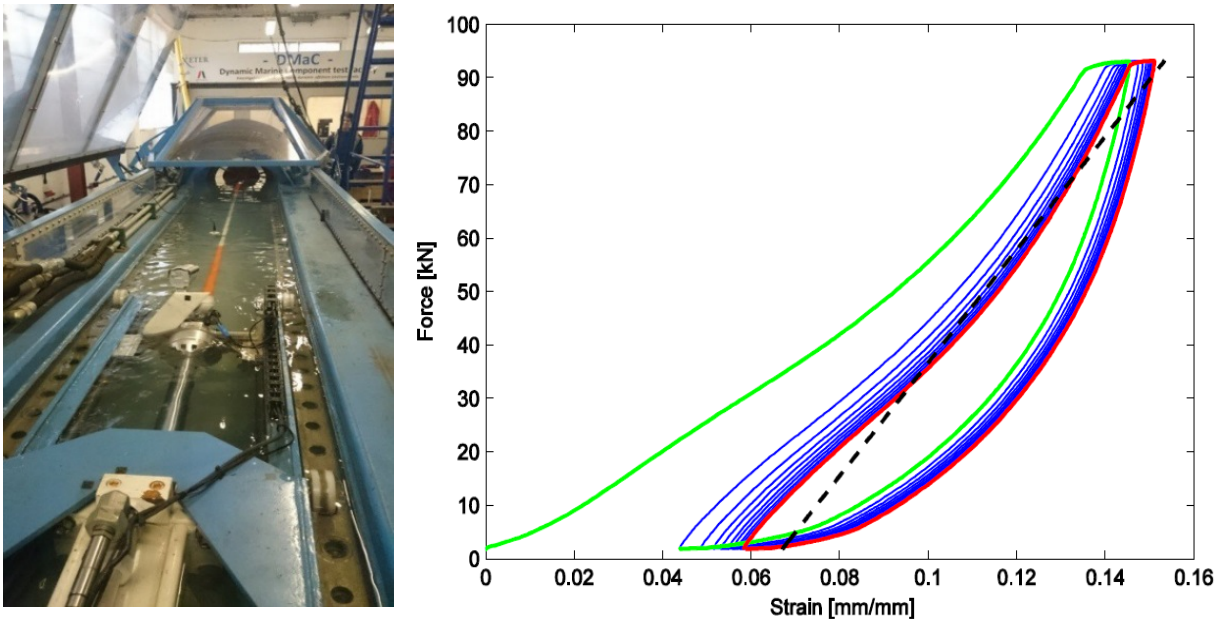
Part 1: “Tension/compression testing machines – Verification and calibration of the force-measuring system” of ISO 7500-1 “Metallic materials – Verification of static uniaxial testing machines” [153] provides recommendations for inspecting test rigs and calibrating the force-measuring equipment for tension/compression testing. Machine verification must be performed when the test machine is in good working order, therefore, a general inspection must be carried out before implementing the methods outlined in the standard by following the procedure outlined in Annex A of ISO 7500-1:2004(E).

In case the test rig employs multiple force-measuring systems, each system should be calibrated separately. The resolution and variation of the scales should be conducted by using force-proving instruments and constant indicated forces at ambient temperatures between 10°C and 35°C. Following the process outlined in §6.4 of ISO 7500-1:2004(E), the relative accuracy and repeatability errors can be calculated.

Tensile testing to ascertain Minimum Break Load (MBL) and stiffness properties of mooring lines can be conducted at various test facilities across the UK. A high degree of variation is found in the limitations, capabilities and instrumentation available at these facilities, therefore, it is important to have an increased understanding of these factors.

After selection of an appropriate number of samples with adequate length, the sample must be mounted on the test machine based on the type of grip. The grips may be one of the following prevalent designs:

- Cors de chasse
- Bollards for rope eye splices
- Wedge grips



(i)

(ii)

Figure 11.1. (i) Fibre rope test set-up in submerged water at DMaC (ii) Bedding in of nylon rope sample showing visco-elastic and visco-plastic effects for colour-coded load cycles (first cycle: green, last cycle: red). Dashed line shows linear trend used to determine quasi-static stiffness for the last cycle (from [161]).

After mounting the specimen appropriately, §9 and §10 of ISO 2307:2010 (E) may be followed to determine force-elongation and MBL.

For ropes tested under ISO 2307:2010 (E), the samples must be tested dry, however, the offshore station-keeping standards [129], [130] require that the samples must be soaked in water 24 hours prior to the time the test commences. During testing, offshore conditions can be simulated by spraying or submerging the rope in fresh water. This is dependent on the capability of the test rig being used; Figure 11.1(i) shows a submerged rope test set-up at a test rig.

Polyarylate ropes must follow the process outlined in §7 of ISO/TS 19336:2015(E). This restricts rope testing to test machines of class 2 and above, whereby, load and/or displacement control must be maintained at all times during testing. However, it allows the use of a test machine with a fixed cross-head speed for use in breaking tests if the time to failure is in excess of two minutes.

Loads applied during rope testing are expressed as a percentage of the established MBL. For details regarding the loading sequence, rate of load application and frequency of cycles of polyaralytes and polyesters, please refer to Test procedures outlined in B3.1 of ISO/TS 19336:015(E) and ISO 18692:2007(E), respectively. Steps 5–7 allow for bedding in the rope to eliminate the construction stretch, Step 8 can be used to test dynamic stiffness, Step 9 can be used to determine dynamic and quasi-static stiffness whereas Step 10 allows for the determination of MBL.

Bedding in a fibre rope is critical since mooring system designs are based on the characteristics of a rope that has been bedded-in. Figure 11.1(ii) shows the visco-elastic and visco-plastic behaviour of a nylon fibre rope for the ten bedding in cycles. After bedding in, the quasi-static stiffness can be tested by exposing the test specimen to a ramp cycle from 10% to 30% of MBL held for 30 minutes and subsequently unloading the rope back to 10% MBL. Dynamic stiffness of a test specimen can be determined by following the procedure outlined in B3.5.3 of [129] on three different specimens with each specimen exposed to an increased amount of load and increased number of cycles.

Alternatively, the quasi-static, dynamic and cyclic loading may be applied to the same sample if the number of cycles at each stage is limited to 100. It must be noted, however, with increased loading on the same sample, the stiffness characteristics undergo a significant increase.

For each sample, dynamic stiffness at the end of bedding in as well as dynamic stiffness after cyclic loading endurance testing are empirically calculated as specified in B3.6 of ISO/TS 19336:015(E) using the recorded variation of load, MBL and strain.

Quasi-static stiffness of rope specimens can be calculated from load-elongation measurements of the last ramp cycle or by averaging the result over the last two cycles.

The MBL of the tested ropes should meet the requirement of the specified MBL. In the situation where the breaking load of a tested rope is lower than MBL, an additional two ropes must be tested and must satisfy the requirement of the MBL for the batch of ropes to be considered compliant with the available technical specifications.

In case of failure, the test sample must be visually scrutinised to identify the degree of abrasion, location of failure as well as the number of sub-ropes that failed. Support by instrumentation like video image processing can provide additional support for a detailed investigation.

The test facility manager should take the daily testing period into account when determining the frequency of load application.

10.2 Blades

Blade testing aims to prove that the rotor blades of the turbine can withstand the extreme and fatigue loads that the turbine will experience in service - the design loads.

In the wind turbine industry, design loads are calculated by specialist software that can simulate the overall behaviour of the wind turbine. Examples of these software packages are HAWC 2 (DTU), Bladed (DNV-GL) and FAST (NREL). These packages will typically comprise of a structural dynamics module, with models for calculating the loading on the structure imparted by the wind, waves, and tides. They will also contain a drivetrain model and a controller to vary the generator torque, pitch the blades and perform any other control functions. Time stepping simulations are performed of load cases which are specified in design standards, and the results are compiled in a report that specifies what the highest loads experienced at each point along the blade length are in each direction.

For wind turbines with a swept area above 200m² (corresponding to a rotor diameter of around 16m), the relevant design standard is IEC 61400-1. This standard mentions blade testing as a means of reducing safety factors, but does not go into detail.

Another widely used document for wind turbine design is the DNV-GL Guidelines for the Certification of Wind Turbines [154] (this document is used by companies who are having their turbine certified by DNV-GL). This document does specify that static and natural frequency tests are required for the blade, but states that fatigue tests are only necessary under some special circumstances, which are detailed in the guideline (which is available for free online).

It is common practice in the industry to perform blade testing according to the IEC standard 61400-23 “wind turbine – rotor blade testing”. Testing of rotor blades will also be covered in IEC TS62600-3 “mechanical load measurements”. IEC 61400-23 assumes that the extreme and fatigue loads have been calculated a priori using the methods described above, and describes how these loads should be applied. A typical certification test involves cantilevering the blade from a fixed concrete hub so that it is horizontal. The following tests are then performed:

- Natural frequency and centre of gravity tests
- Static tests (to verify resistance to extreme design loads)
    - Max flapwise moment at each section
    - Min flapwise moment at each section
    - Max edgewise moment at each section
    - Min edgewise moment at each section
- Fatigue tests
    - Flapwise fatigue test (1 million to 10 million cycles)
    - Edgewise fatigue test (1 million to 10 million cycles)
- Post fatigue static tests
    - As above, to verify resistance to extreme loads after the service life

Static test loads are applied about the two main axes by loading the blade at several points along its length with winches attached to wooden profiles which fit snugly around the blade (see Figure 10.2).

Fatigue test loads are applied either by quasi-static loading (forcing the blade back and forth with a hydraulic actuator linked to the ground or a frame at a frequency well below resonance) or, more commonly, by resonating the blade. Applying test loads by resonance has several advantages: energy demand is much lower, the bending moment profile along the blade length can be tuned by adding mass, and much larger blades can be tested. A resonant blade fatigue test is shown in Figure 10.3.

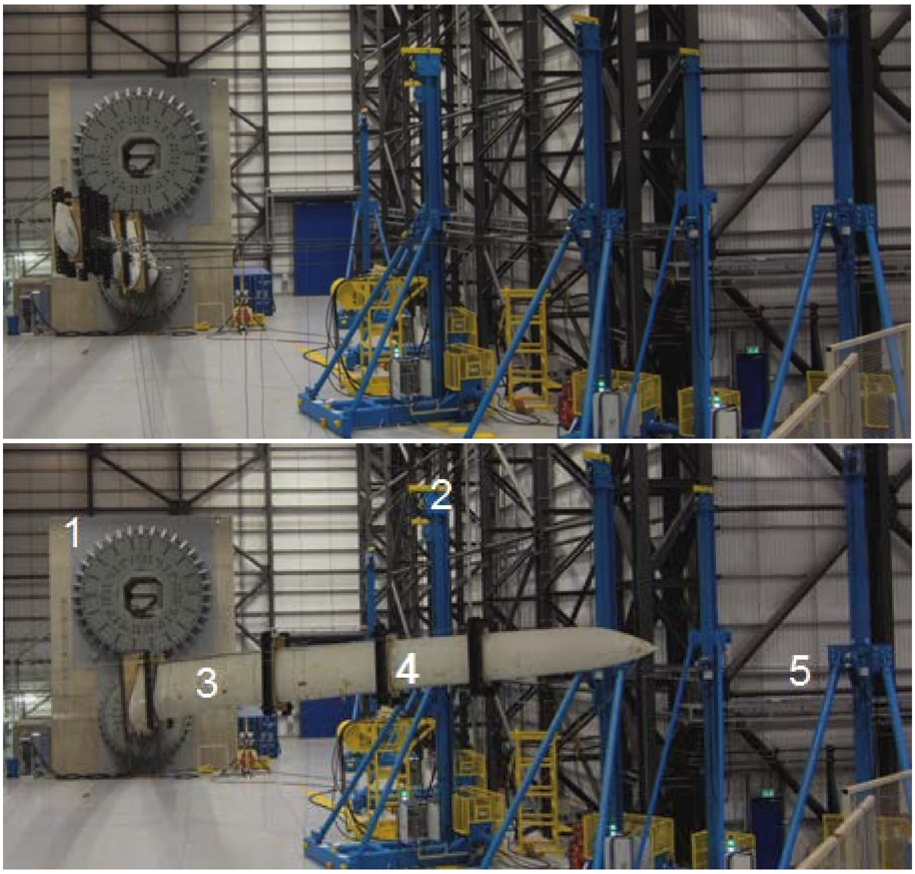


Figure 10.2. Wind turbine blade during static test (unloaded, top and with maximum flapwise load applied, bottom, with numbered items numbered items as follows: 1 – Test hub, 2 – Winches, 3 – Blade, 4 – Wooden profiles, 5 – Winch cables)

Figure 10.3 - Resonant blade fatigue testing

A broadly similar approach to blade testing would be expected for tidal turbines. International standards do not exist yet for tidal turbines, but technical specifications for turbine design are available (IEC 62600-2 Marine energy - Wave, tidal and other water current converters - Part 2: Design requirements for marine energy systems, DNVGL-ST-0164 Tidal turbines). These can be used to define design load cases, which can then be simulated to obtain design loads.

For the calculation of design loads, fewer options are available than for wind turbines. Commercial, non-industry specific OrcaFlex can be used for the calculations, or for bottom fixed devices there is Tidal Bladed (DNV-GL). Other options created by developers in-house also exist.

Once loads are available, blade testing would probably be performed in a similar manner to wind turbines. However, some differences arising from the fact that blade design drivers for tidal turbines are substantially different (the blades are much shorter and stiffer, because water is so much denser than air). This means that natural frequencies for the blades will be much higher – perhaps 10Hz for the first frequency, compared to 1Hz for a wind turbine with a comparable power rating. This means that quasi-static loading will be the preferred option for fatigue testing, and the low displacements mean that loading by hydraulic actuator would be viable for static testing.

10.3 PTO/Drivetrain

Common causes for downtime of wind turbines are unexpected bearing failures, gear damages and breakdowns of control and power electronics. Based on the failure modes and effects analysis (FMEA), analysis and design data for the PTO optimization, PTO test program designed to evaluate the design and manufacturing. These test programs generally follow industrial standard (example: IEC 61400-4, 11, and 12) and customer requirements. The main objectives are to:

- experimentally verify the electrical and thermal models
- experimentally verify the efficiency of the PTO including the generator, cables, inverter and/or possible losses in the AC filter
- experimentally verify control strategies as well as control algorithms
- evaluate the control system dynamic behaviour under different normal and extreme operational- and limiting conditions
- evaluate built-in electrical- and mechanical safety mechanisms associated with control and extreme operational behaviour
- analyse and assess the robustness and reliability of the PTO electrical components
- analyse and assess the safety and functionality system actions
- evaluate the performance of the electrical protective elements (circuit breakers, fuses)
- verify the overloading capability of the PTO electrical components
- find weak points which cannot be checked during design stage
- evaluate the reliability of PTO (if required)

To achieve these objectives, the tidal turbine drive train test needs to include test items below:

- **Functionality/commissioning test**: With rated torque and speed, the functionality of the PTO system needs to be evaluated.
- **Extreme load test:** To find out weak points of early stage failure, predefined extreme load conditions need to be applied
- **Power curve and Efficiency evaluation**: With submerged tank, the efficiency and cooling capacity of the PTO needs to be evaluated to define an accurate power curve

These tests can be conducted with the conditions below:

- No load test cold generator
- No load test warm generator
- Generator static short-circuited test
- Drive train steady state efficiency validation
- Drive train steady state performance weak grid
- Temporary grid loss at rated rpm
- Permanent grid loss at rated rpm
- Permanent grid loss at high rpm with field weakening
- Heat runs
- Low tip speed ratio transition from rated rpm
- System performance during sinusoidal speed variations
- Evaluate system performance during sinusoidal speed variations.

10.4 Grid/electrical

There is no exclusive standard of test methodologies for grid connected marine energy converters. In the more established wind industry, there is an international standard of power quality assessment for grid connected wind turbines, IEC 61400-21 [101]. A Technical Specification on power quality for MECs will be published later this year IEC TS62600-30.

Although the caveat highlighted in section 2.2 above still exists, the risk of importing standards from wind turbines into marine energy converters shall be quite limited due to a couple of reasons. Firstly, there is a wide range of PTOs among the marine energy converters, but their output voltages and currents must be conditioned to the required values before connecting to the electrical grid. Secondly, the electrical grid is well developed and there is very little change in the requirement for connection of generating units.

After years of practice and evolution, recommendations and standards are well harmonised into the IEC 61400-21, which is widely accepted by the wind industry in terms of test setup for measuring the power quality of grid-connected turbine's. For example, measurement procedure from MEASNET Europe [155], and measurement standard from China [156] are based on, and refer to, IEC 61400-21.

There are two key sections in IEC 61400-21 [101]: §6 explains characteristic parameters related to wind turbine power quality, and §7 describes test procedures of each parameter. In this document, the test methodologies will be summarised after combining the two sections. The description of the parameter and the test procedure will be directly referred to the IEC 61400-21. Only the key figures and recommendations are summarised. The parameters covered are listed as below.

- Voltage fluctuations
- Current harmonics
- Response to voltage drops
- Active power
- Reactive power

Although there are another two more parameters from the IEC 61400-21 standard [101], grid protection and reconnection time, they are usually not included site test reports since they can be tested separately from the turbine power train. As a result, these two parts are not provided in this document.

Before summarising the methodologies, measurement layout, test instrument, accuracy range and turbine specification are stated at the beginning. It is worth noting that the standard, IEC 61400-21, only provides the minimum requirement of test and measurement. The subsequent assessment of the measured results is subject to the different requirements of the grid code that the turbine is connected to.

10.4.1 Test equipment

The measurement system layout is displayed in Figure 10.4. The anemometer, voltage transducers and current transducers are the required sensors of the measurement system.

The analogue to digital conversion (A/D) shall be of at least 12-bit resolution. The required accuracy is listed in Table 10.2. The sample rate of at least 2 kHz per channel of the voltage and current signals are required for power measurement. The minimum sample rate shall be at least 20 kHz per channel for harmonic measurement.

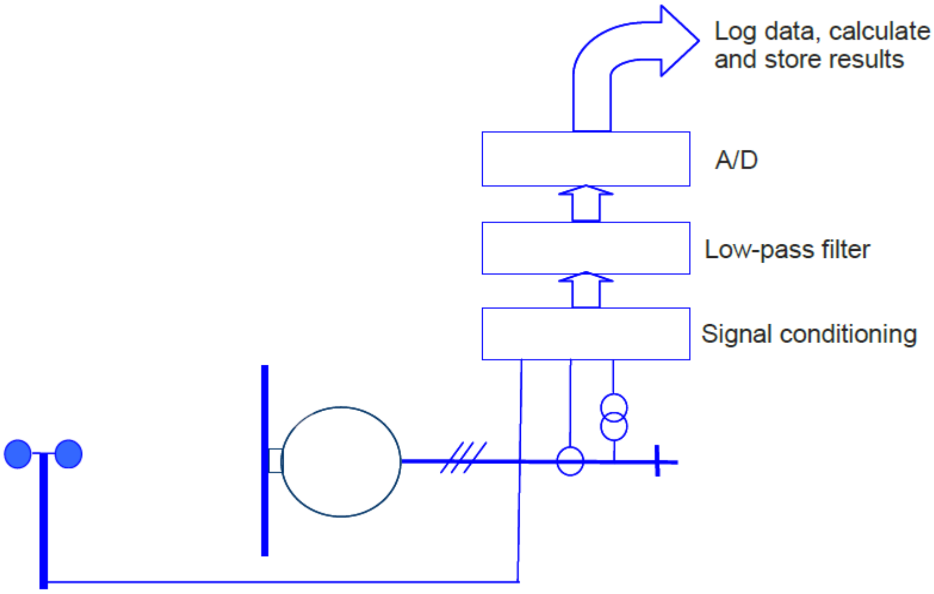


Figure 10.4 Measurement system layout (Figure 3 from [101]*)*

Table 10.2 Measurement equipment accuracy (Table 2 from [101]*)*

Equipment	**Required accuracy**
Voltage transducers	Class 1,0
Current transducers	Class 1,0
Anemometer	±0.5 m/s
Filter + A/D converter + data acquisition system	1 % of full scale

10.4.2 Wind turbine specification

The rated data of the wind turbine converter shall be specified referred to the connecting terminals, including rated power, apparent power, voltage, and current.

10.4.3 Voltage fluctuations

10.4.3.1 Continuous operation

The wind turbine flicker coefficient, $c(\psi_k, v_a)$, is used to describe the voltage fluctuation during continuous operation, which is stated in §6.3.2 of IEC61400-21 [101]. During the test process, the reactive power shall be set to zero. The minimum sampling frequency shall be at least 800 Hz.

The flow chart of the assessment procedure is shown in Figure 10.5. The procedure of measurement, simulation and calculation is specified in Annex B.1 of IEC61400-21 [101].

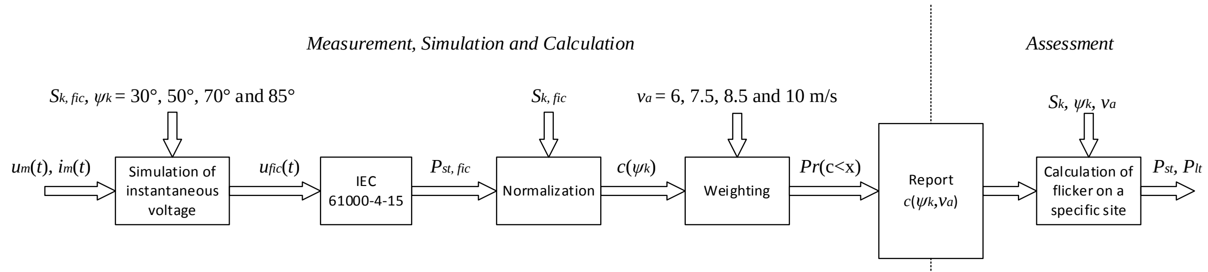


Figure 10.5 Assessment procedure for flicker during continuous operation (Figure B.1 from [101]*)*

10.4.3.2 Switching operations

The values of the parameters during the turbine switching operations are stated in §6.6.3 of IEC61400-21 [101]. During the test process, the reactive power shall be set to zero. The minimum sampling frequency shall be at least 3 kHz.

The flow chart of the assessment procedure is shown in Figure 10.6. The procedure of measurement, simulation and calculation is specified in Annex B.2 of IEC61400-21 [101].

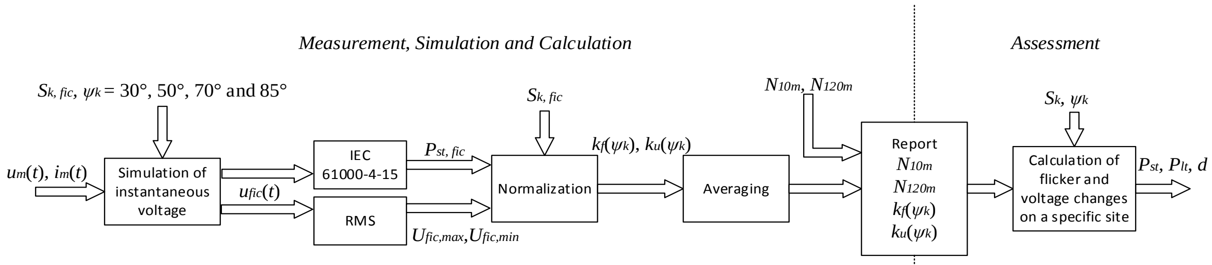


Figure 10.6 Assessment procedure for voltage changes and flicker during switching operations (Figure B.12 from [101]*)*

10.4.4 Current harmonics

The emission of current harmonics, interharmonics and higher frequency components during continuous operation shall be described. The values of the individual current components (harmonics, interharmonics and higher frequency components) and the total harmonic current distortion shall be listed in percentage of I_n and for operation of the wind turbine within the active power bins 0, 10, 20 ... 100% of P_n. 0, 10, 20 ... 100% are the bin midpoints.

At least nine 10 min time-series of instantaneous current measurements (three tests and three phases) shall be connected for each 10% power bin. The accuracy class I shall be applied. The 200ms window length is recommended for both 50Hz system (10 fundamental cycles) and 60 Hz system (12 fundamental cycles). The DFT (Discrete Fourier Transform) is applied to 200ms window of measured currents with rectangular weighting. No special weighting function, such as Hanning, Hamming, etc. shall be applied.

The individual integer harmonics current components shall be specified for frequencies up to 50 times the fundamental grid frequency (2.5 kHz for 50Hz system), and the total harmonic current distortion (THC) shall be derived from these according to Eq. 10.1.

Eq. 10.1

$$THC = \frac{\sqrt{\sum_{h=2}^{50} I_h^2}}{I_n} \times 100\%$$

where I_h is the RMS current harmonic of integer harmonic order h; I_n is the rated current of the wind turbine.

The interharmonic current components shall be specified as sub-grouped values for frequencies up to 2 kHz according to Eq. 10.2.

Eq. 10.2

$$I_{ig,n}^2 = \sum_{i=2}^{8} I_{k+i}^2$$

where $I_{ig,n}$ is the interharmonic group of harmonic order n. For example, the group between n=5 (250Hz) and n=6 (300Hz) is designated as $I_{ig,5}$. There are 9 non-integer harmonics (5.1th 255Hz, 5.2th 260Hz … 5.9th 295Hz) in between 5th (250Hz) and 6th (300Hz) since 10-cycle window introduces 5Hz resolution in frequency analysis results, which are designated as I_{k+i}.

The higher frequency current components shall be specified as sub-grouped values for frequencies from 2 kHz to 9 kHz according to Eq. 10.3.

Eq. 10.3

$$I_{band} = \sqrt{\sum_{f=b-90}^{b+100} I_f^2}$$

where I_{band} is the subgrouped current emission with the bandwidth fixed at 200Hz. The central frequency of the first possible group is 2100 Hz, followed by 2300 Hz, 2500 Hz until the last central frequency at 8900 Hz.

During the measurement of the harmonic current, the reactive power of the wind turbine shall be se to zero. Any harmonic currents less than 0.1% of the rated current need not be reported for any of the harmonic orders.

10.4.5 Response to temporary voltage drops

The temporary voltage drops are specified in Table 10.3, which are defined for the wind turbine not connected. The shape of the voltage drop shall be within the tolerance shown in Figure 10.7 before the wind turbine is connected.

The response of the wind turbine to these drops shall be stated for the turbine operating at two power levels, a) between 0.1–0.3 of rated power P_n, b) above 0.9 P_n. The response shall also be stated resulted from two consecutive tests of each case (VD1-VD6) at each power level. The time-series of active power, reactive power, active current, reactive current and voltage shall be stated at the wind turbine terminals for the time shortly prior to the voltage drop and until the effect of the voltage drop has abated. The wind turbine operational mode and the 10 min average wind speed shall be also included.

Table 10.3 Specification of temporary voltage drops occurring when the wind turbine under test is not connected (Table 1 from [101]*)*

Case	Magnitude of voltage phase to phase (fraction of voltage immediately before the drop occurs)	Magnitude of positive sequence voltage (fraction of voltage immediately before the drop occurs)	Duration (s)	Shape
VD1 – symmetrical three-phase voltage drop	0,90 ± 0,05	0,90 ± 0,05	0,5 ± 0,02	‾‾└─┘‾‾
VD2 – symmetrical three-phase voltage drop	0,50 ± 0,05	0,50 ± 0,05	0,5 ± 0,02	‾‾└─┘‾‾
VD3 – symmetrical three-phase voltage drop	0,20 ± 0,05	0,20 ± 0,05	0,2 ± 0,02	‾‾└─┘‾‾
VD4 – two-phase voltage drop	0,90 ± 0,05	0,95 ± 0,05	0,5 ± 0,02	‾‾└─┘‾‾
VD5 – two-phase voltage drop	0,50 ± 0,05	0,75 ± 0,05	0,5 ± 0,02	‾‾└─┘‾‾
VD6 – two-phase voltage drop	0,20 ± 0,05	0,60 ± 0,05	0,2 ± 0,02	‾‾└─┘‾‾

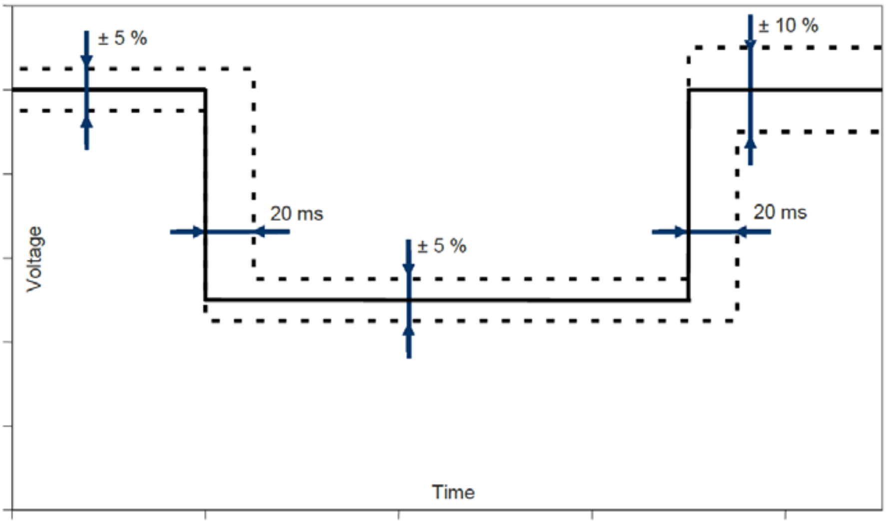


Figure 10.7 Tolerance of the voltage drop (Figure 6 from [101]*)*

10.4.6 Active power

10.4.6.1 Maximum measured power

The maximum measured power shall be measured so that it can be specified as a 600 s average value, a 60 s average value, and as a 0.2 s average value, applying the procedure specified in §7.6.1 of IEC IEC61400-21 [101].

10.4.6.2 Ramp rate limitation

The ability of the wind turbine to operate in ramp rate limitation control mode shall be characterised by test results presented in a graph, which shall show active power at a ramp rate value of 10% of the rated power per minute for a test period of 10 min. The procedure is specified in §7.6.2 of IEC IEC61400-21 [101].

10.4.6.3 Set point control

The ability of the wind turbine to operate in active power set-point control mode shall be characterised by test results presented in Figure 10.8. The detailed procedure is specified in §7.6.3 of IEC IEC61400-21 [101].

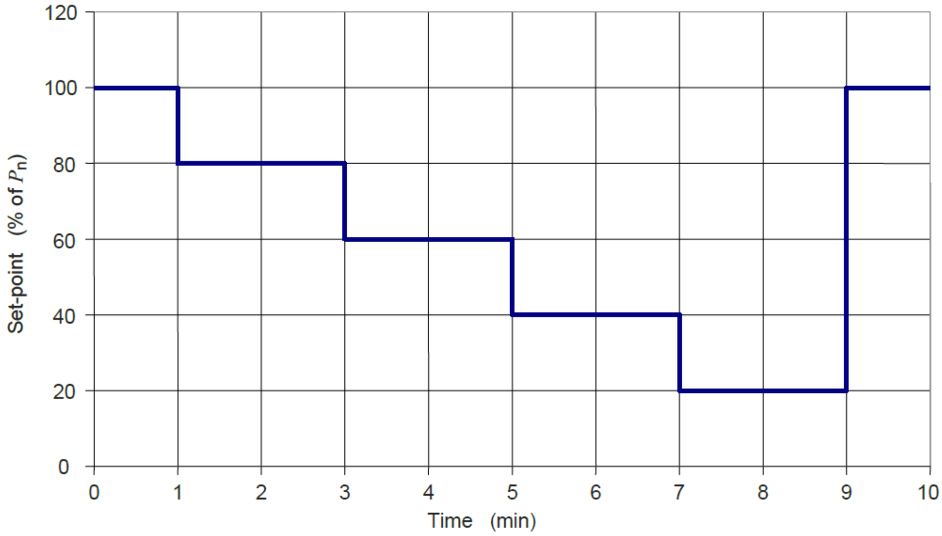


Figure 10.8 Adjustment of active power set points (Figure 1 from [125]).

10.4.7 Reactive power

10.4.7.1 Reactive power capability

The capability of the wind turbine concerning the maximum inductive and capacitive reactive power of the wind turbine shall be measured according to requirement in §6.7.1 of IEC IEC61400-21 [101] following procedure specified in §7.7.1.

10.4.7.2 Set point control

The reactive power control by set point values shall be stated according to requirement in §6.7.2 of IEC IEC61400-21 [101]. The measurement shall follow the procedure specified in §7.7.2, and the set point of the reactive power shall be varied according to Figure 10.9.

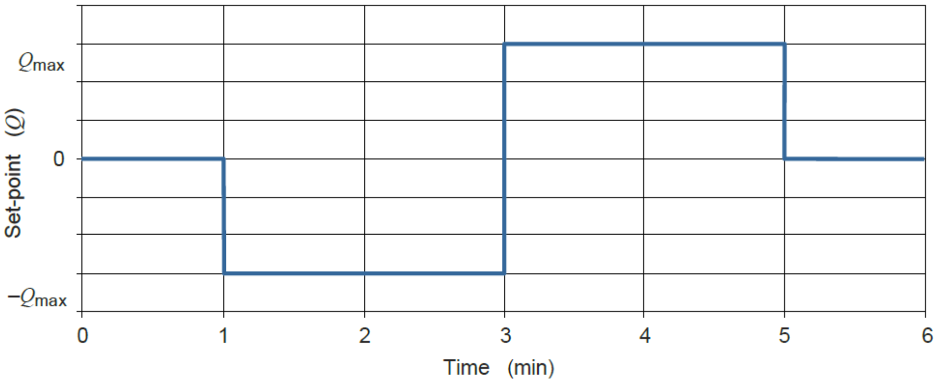


Figure 10.9 Adjustment of reactive power set points (Figure 2 from [101])

11. Gaps identified

11.1 Responses to MaRINET2 test facilities questionnaire

The questionnaire sent out to all MaRINET2 test facilities included an open-ended question asking, “Please detail areas where you feel more standardisation would be beneficial”. The following areas were highlighted as requiring further standards and guidance.

There were a couple of responses suggesting that rather than additional standards, what is required is to work towards a coherent set of guidelines/standards covering all stages of test requirements. There should also be a push towards making these more accessible and understandable. This would facilitate their incorporation into scope of work and contracts.

The most prevalent theme for additional standards related to the power take-off (PTO) subsystem. This included scaling, simulation at model scale, and performance prediction/ assessment. This was highlighted as a concern for both tidal turbines and wave energy convertors, although some existing guidance has already been published on this; see sections 4.2.1.2 and 5.2.1.2 above.

Another common area was standards for moorings and cable systems, for all floating marine energy applications (wind, wave, or tidal), section 7.4 covers the guidance that has been published on moorings.

Other areas highlighted were:

- Comparison between accelerated and real testing of components.
- Full-scale structural testing of rotor blades for tidal turbines, analogous to IEC 61400-23 for wind turbine blade.
- Aero-hydro interaction and scaling for floating wind models.
- Open water testing.
- Standardisation of marine environmental conditions, i.e. resource (wind, waves) and environmental impacts (marine life, marine growth, water quality) and in-situ monitoring
- Data management standards in general and associated tools to verify their correct implementation

11.2 Other gap identification studies

The ORE Catapult and EMEC held a workshop in March 2014 to review standards/guidelines for marine renewables (wave & tidal) and identify gaps [157]. Four topic areas were identified in advance of the workshop: Offshore Installation; Operation and Maintenance (O&M); Subsea Cable Lifecycle; and Environmental Monitoring. An additional four topics were highlighted at the workshop: Data sensing and communication; Mechanical design in shallow water environments; Vessels and equipment used in marine renewable energy developments; and Subsea connectors.

The US National Renewable Energy Laboratory (NREL) published findings from their 2017 Marine Hydrokinetic Instrumentation Workshop [158], which aimed to understand the current state of measurement technologies, identify gaps, and define pathways to resolve these. Four overall themes emerged from this work.

1. **Limited knowledge transfer**. It needs to be easier to find the wealth of experience, tools, and knowhow that have been developed by the sector, in order for the industry to avoid repeating mistakes, minimize duplicate efforts, and leverage the experience of others to accelerate development.
2. **High cost of measurement**. This can lead to a trade-off between the breadth and duration of a test, and the number and quality of measurements.
3. **Better measurement capabilities at low TRLs**. To facilitate scale model testing at 1:10 or smaller. Measurement capabilities are often inadequate and sensors either do not exist, are too expensive, or adversely impact device response.
4. **Open-source tools for unified data processing and analysis**. Currently data processing and analysis is conducted on a project-by-project basis using custom code. Sharing of vetted data reduction, processing, QA, and visualizations code, and adopting standard methods would allow the industry to accelerate the analysis, and would increase credibility of test results.

11.3 Gaps identified

In addition to those identified through the questionnaire, and from other gap identification studies, a number of additional gaps in guidance and standards were highlighted in the process of creating this document. This includes those specifically highlighted by contributors, but also those resulting from the review process and surrounding discussions. General testing gaps are provided before device specific gaps are detailed.

11.3.1 General

Pertinent to all device types is the issue of creating suitable moorings and mounting solutions (see Table 8.1). Although this has been detailed in the document, it has been highlighted that further guidance on this issue would be beneficial to the sector, particularly for the scaling of such systems for scaled tank tests.

Another gap not particularly well addressed is dealing with the issue that many test facilities will follow very different procedures, utilise differing methodologies, and have varied characteristics. Some of these facility specific effects have been explored in MaRINET1, with this work continued in WP4 of MaRINET2 using ‘round robin’ testing to isolate some of the most important discrepancies.

It has been highlighted, particularly for full-scale testing, that health and safety and risk management is not always at the forefront of developer’s considerations. This may be that due to the novelty of the application little guidance exists, or may be in part due to the gap in knowledge (rather than guidance) of individuals whose specialisms and focus are on technical delivery rather than the associated risks.

Lastly, it has been noted throughout creating this guidance overview document that, although there is an abundance of specifics on the technical aspects of testing, there remains little on how to progress from low TRL to high TRL, i.e. how we scale up test from controlled to uncontrolled environments. Stage gates are well described, but what is required to progress between these stages, whilst ensuring comparability and the correct level of focus, remains largely undocumented. This is discussed further in Section 11.4.

Duplication of guidance for floating devices between technologies

Whilst not specifically a gap, a related issue is that there is duplication of similar guidance between different technologies. This is particularly the case for testing floating devices with a PTO, which is dealt with separately for WECs, FOWTs, and floating TECs. It may be more effective to produce dedicated guidance for testing floating devices in waves, currents, and wind loading.

11.3.2 WEC testing

Respondents to the questionnaire of MaRINET2 facilities highlighted the need for additional standards on a number of topics. Directly relevant to WECs (as well as other device types) is the PTO subsystem (including scaling, simulation at model scale, and performance prediction/assessment), plus standards for moorings and cable systems.

Combined wave-current conditions, including interaction of waves and currents

There is limited guidance on combined waves and currents, both specifying conditions at sites, and relating to tank testing WECs. This lack of guidance on combined conditions was highlighted as an issue in [8]. The impact of even a moderate tidal current on wave shape and power available is explored further in [159]. This is not addressed in any guidance to date, but will be of critical importance for floating devices, and WECs in particular.

Specification of complex waves

It has been noted that the specification, creation and validation of complex wave conditions is not well covered in guidance. This includes the use of site-specific non-parametric spectra (as detailed in [160]), directional spreading, and the use of multi-modal sea states for testing.

11.3.3 TEC testing

Development progression – applicability from wave energy converter methods

The development progression for TEC testing is not as well defined as for WECs, as mentioned in section 5.1.1. For floating devices, the conditions described in OES IA Guidelines for the development & testing of wave energy systems [5] could be applied, but certain aspects may not be applicable. Further guidance on what should be tested at each stage of development, and facilities for doing so, would be useful.

Power take off effects

The effects of employing different types of power take off systems for tidal energy scaled prototypes has not been studied so far. The influence of PTOs may not be as critical as for wave energy conversion; however, attention should be paid when simulating a PTO with certain damping systems. For example, using mechanical dampers may be highly affected by thermal variations on the system.

Blockage effects

The round robin testing undertaken during MaRINET1 and reported in Gaurier *et al* [75], showed that testing small scale tidal turbine prototypes in a facility producing blockage ratios as low as 5% may still influence the performance of them. In addition, specific blockage correction technique(s) have not been established to date.

Standardised procedures

The previous MaRINET round robin testing campaign aimed to identify if the use of specific facilities would have effects on the performance of a scaled tidal turbine device. A secondary aim was to put in practice best practices established previously, e.g. Equimar D3.4 "Best practice for tank testing of small marine energy devices" [23]. The round robin testing programme was limited to experiments under steady flow conditions.

Building up on the success of this programme, MaRINET2 aims to replicate a round robin testing where a scaled tidal turbine prototype will operate under wave-current interactions at different facilities but also in the uncontrolled environment. Thus, the second stage of round robin testing aims to identify if more complex environmental conditions affect the performance of the testing specimen.

11.3.4 OWT testing

At present, there are no standardised procedures for testing FOWTs, and no quantification of uncertainty and how it varies between facilities. Addressing this gap will be a key outcome of the round robin testing that is part of MaRINET2. MaRINET2 D2.6 “Final guidelines for test applicants” will provide comprehensive guidelines on the tank and field testing process for FOWTs and other MRE devices when published in 2021.

11.3.5 Cross-cutting technologies

PTO/Control systems

Guidance exists for PTO and control systems, as detailed in Sections 4.2.1.2 and 5.2.1.2. However, one of the most prevalent themes for additional standards was related to the power take-off (PTO) subsystem, and was consistently raised in relation to both wave and tidal energy converters. It was highlighted that there is a desire for guidance surrounding the effective scaling and simulation of PTO at model scale, along with methods for performance assessment.

Additionally, it has been noted that there is a gap in terms of physical infrastructure available to test the wide range of PTO types for each technology. Test benches that do exist have their own physical properties and constraints, and it is difficult to get analogous testing between PTO types.

Materials

A number of gaps have been highlighted in materials testing. It is noted that a description of failure mechanisms related to the different corrosion types is not found in current standards and guidance for MECs. In addition, it is specifically found that combinations of effects are not well covered, namely:

- The combination of composite ageing and fatigue
- The combination effect of wear with corrosion or fatigue

Moorings/support

A standardised approach of mooring system testing has not been formalised for MEC devices internationally partly due to the lack of convergence to a design solution and insufficient field deployment experience.

Grid/electrical

There is no exclusive standard of test methodologies for grid connected marine energy converters. In the more established wind industry, there is an international standard of power quality assessment for grid connected wind turbines.

It is also noted that due to the differing grid normative for various locations, grid integration controls will be site-specific and will range significantly. This is something not well covered by guidance, yet will play an important role in the MRE sector.

11.4 Progression from laboratory to the ocean

As mentioned in Section 11.3.1, an interesting gap identified is the lack of guidance on progressing from low TRL to high TRL. The particular challenge is in progressing from a controlled laboratory setting to a highly uncontrolled, hostile, ocean environment.

Technology development must be at the forefront of TRL progression, yet a number of additional considerations arise when moving up TRLs, including practical aspects such as logistics, operations and health & safety, but also the approach to risk and learning. It may be that with a more joined up approach, more can be learnt during scaled testing which can help ease this process. This may include incorporating specific tests for marine operations, an increased focus on de-risking materials, or may be the inclusion of more site-specific environmental conditions to de-risk device response and performance.

It is hoped that the collation of guidance carried out in this report, and the identification of key gaps, can provide the basis for, and stimulate the development of a guidance document that aims to address the specifics of TRL progression.

12. Conclusions

As a nascent industry, international standards have yet to be developed for the marine renewables sector. The Technical Standard IEC TS 61400 for windfarms has been extended to include offshore variants, and the IEC technical committee TC114 is developing Technical Standard 62600 on wave, tidal and other water current converters (see section 2.2 of this document). There is also a wide range of less formal guidance on testing of marine renewable energy device, particularly for wave and tidal energy. This has been developed as part of the European funded EquiMar and MaRINET projects, as well as from other institutions including universities and test facilities.

The relevant published standards and guidance documents for testing marine renewable energy devices have been summarised in sections 4–12 of this document, covering the whole range of device types and technology readiness levels. Gaps in these guidance documents have been identified through the review process, and via a questionnaire sent out to MaRINET2 test facilities.

It is highlighted that there is a need for additional standards on a number of topics, including the PTO subsystem (scaling, simulation at model scale, and performance prediction/ assessment), plus standards for moorings and cable systems. In particular, it is noted that there is a lack of guidance on how to transition between TRL levels, dealing with progressing from controlled laboratory setting to the uncontrolled marine environment.

The summary of available guidance and gaps identified in this document will be a useful resource to those involved in testing marine renewable energy, and will help guide future work on standardisation in the sector.

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Appendix A. Questionnaire for MaRINET2 test facilities

A.1 Purpose

Each of the test facilities involved in the MaRINET2 project responded to a questionnaire designed to collate testing parameters, practices, and sources of guidance used. This feeds into deliverable D2.1 Test recommendations and gap analysis (this report), plus internal deliverables D2.2 Draft guidelines for test applicants, and D2.3 Draft guidelines for test facilities. It will also feed into WP6 on E-Infrastructure.

A.2 Methodology

A web-based questionnaire was sent out in June 2017 to each of the test facilities involved in the MaRINET2 as trans-national access (TNA) providers (both physical and virtual). These are predominantly tests tanks, field test sites, and component test facilities as shown in Table A.1. A full list of facilities contacted is included in Table A.2, with details of these facilities available on the MaRINET2 website[viii].

The questionnaire had questions on six aspects relating to testing and test requirements:

1. Facility type and test parameters
2. Standards and guidance
3. Testing support
4. Physical conditions
5. Instrumentation and data requirements
6. Model installation/integration and operations

As this questionnaire was designed for responses from various test facilities, all questions were optional, and did not necessarily apply for all facilities. The total number of responses therefore varies by question. The results in section A.3 are reported by number of responses, not percentage of facilities. In this analysis, many of the responses are grouped by facility type to facilitate comparison. As there is only one wind tunnel, this is grouped with other facilities. The questions included and wording thereof were developed collaboratively by WP2 and WP6 partners.

Table A.1: Breakdown of facility types contacted

Facility type	Number contacted[ix]	Percentage[ix]
Test tank (flumes, towing tanks, wave basins)	20	38%
Wind tunnel	1	2%
Field test site	16	30%
Component test facility	12	23%
Other facilities	14	26%
Total number of facilities	**53**	

[viii] http://www.marinet2.eu/facilities/

[ix] Some facilities offer more than one type of service, and are shown in each category.

Table A.2 Full list of facilities contacted

Facility Name	Type
Aalborg University (AAU) Wave & Current Basin	Wave Basin
Biscay Marine Energy Platform (BiMEP)	Field test facility
CENER (VIRTUAL): Windbench (VIRTUAL)	Other
CNR-INSEAN: Circulating Water Channel	Wave Basin
CNR-INSEAN: Water Towing Tank	Wave Basin
CTC: Marine Corrosion Test Site “El Bocal”	Field test facility
DMEC (former TTC): DenOever	Field test facility
DMEC (former TTC): Marsdiep	Field test facility
DTU: Windscanner	Other
Ecole Centrale de Nantes (ECN): Hydrodynamic and Ocean Engineering Tank	Wave Basin
Ecole Centrale de Nantes (ECN): SEMREV	Field test facility
EMEC: Full Scale Tidal (Fall of Warness)	Field test facility
EMEC: Full Scale Wave (Billia Croo)	Field test facility
EMEC: Integrated Monitoring Pod	Other
EMEC: Tidal Scale (Shapinsay Sound)	Field test facility
EMEC: Wave Scale (Scapa Flow)	Field test facility
EMEC: WEC PTO	Component test facility
EVE: Mutriku Wave Power Plant	Other
University of Edinburgh (UEDIN): FloWave Ocean Basin	Wave Basin
FZK: Large Wave Flume (Grosser Wellenkanal, GWK)	Wave Basin
Ifremer: Basin of Boulogne sur Mer	Wave Basin
Ifremer: Basin of Brest	Wave Basin
Ifremer: HOMERE Hindcast Database	Other
Ifremer: Material Testing Facility	Component test facility
MARIN: Concept Basin	Wave Basin
NTNU: Skipheia Met Station	Other
NUI Galway: Large Structures Test Cell	Component test facility
OCD: BGO	Wave Basin
ORE Catapult: Blade Test 1	Component test facility
ORE Catapult: CPTC Energy Link Lab	Component test facility
ORE Catapult: Marine Test Site	Other
Queen’s University Belfast (QUB): Portaferry Tidal Test Site	Open water test facility
Queen’s University Belfast (QUB): Wide Wave Tank	Wave Basin
SINTEF: Smartgrid Lab	Component test facility
SmartBay: MARETS	Open water test facility

Facility Name	**Type**
SSPA: Maritime Dynamics Laboratory, Towing Tank and Cavitation Tunnel	Wave Basin
University of Surrey: Enflo Wind Tunnel	Wind Tunnel
TECNALIA: Component Corrosion Test Platform	Component test facility
TECNALIA: Electrical PTO Lab	Component test facility
University College Cork/MaREI: Deep Ocean Basin	Wave Basin
University College Cork/MaREI: Ocean Emulator	Wave Basin
University College Cork/MaREI: Wave & Current Flume	Wave Basin
UC-IHC: CCOB	Wave Basin
University of Edinburgh (UEDIN): Curved Tank	Wave Basin
UL: MRE-ROV	Field test facility
University of Exeter (UNEXE): DMaC	Component test facility
University of Exeter (UNEXE): FaBTest	Open water test facility
UNIFI-CRIACIV: Wind Engineering Laboratory	Other
UNIFI-LABIMA: WCF	Wave Basin
UoP: Ocean Basin	Wave Basin
UoS: Kelvin Hydrodynamics Lab	Wave Basin
UU: Islandsberg	Field test facility
WAVEC: Pico Plant	Field test facility

A.3 Summary of results relating to facility practice

The findings from a subset of the questions are reported in this section. More detail on the responses regarding standards and guidance used by facilities is given in section 2. Data from the questionnaire will also feed into other MaRINET2 deliverables.

A.3.1 Device model scale and technology readiness levels tested

The range of (model) scales and development TRL tested at each type of facility are shown in Figures A.1 and A.2. Unsurprisingly, test tanks are typically testing smaller models, with field tests sites testing at (close to) full-scale. TRL is a subjective measure however and there may be a tendency to over-estimate the TRL of laboratory scale devices. It is also unlikely that low TRL devices are being tested at field sites.

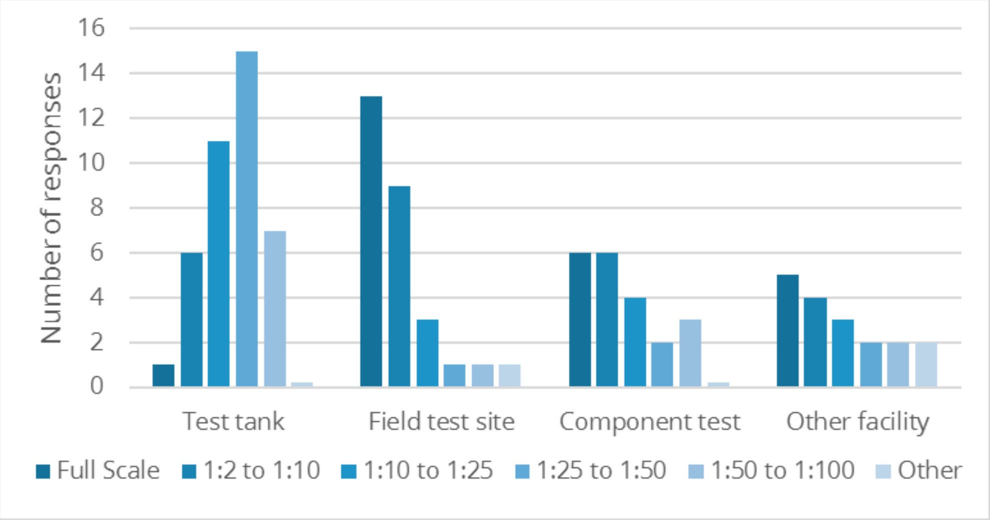

Figure A.1 Questionnaire responses to Q5) "What scales do you typically test at? (Select all that apply)"

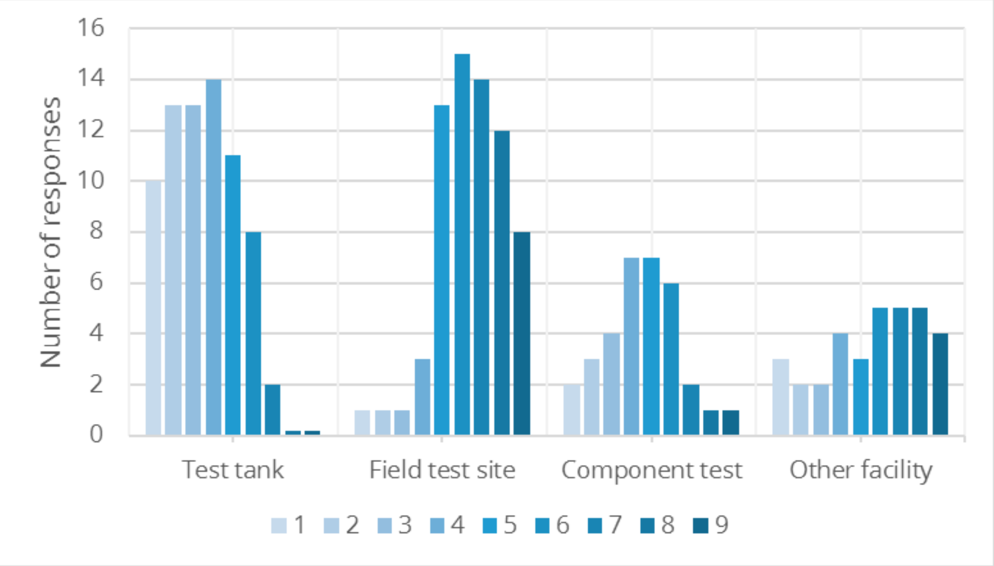

Figure A.2 Questionnaire responses to Q6) "Which technology readiness level (TRL) are you typically testing? (Select all that apply)"

A.3.2 Level of support offered by facility

The level of support offered to clients was broken down into three sequential stages: pre-test, during testing, and post-test support and analysis. The majority of responses were from facilities that offer detailed technical support throughout the testing process, with a smaller number only offering basic advice. Few respondents offer a full service with no user involvement.

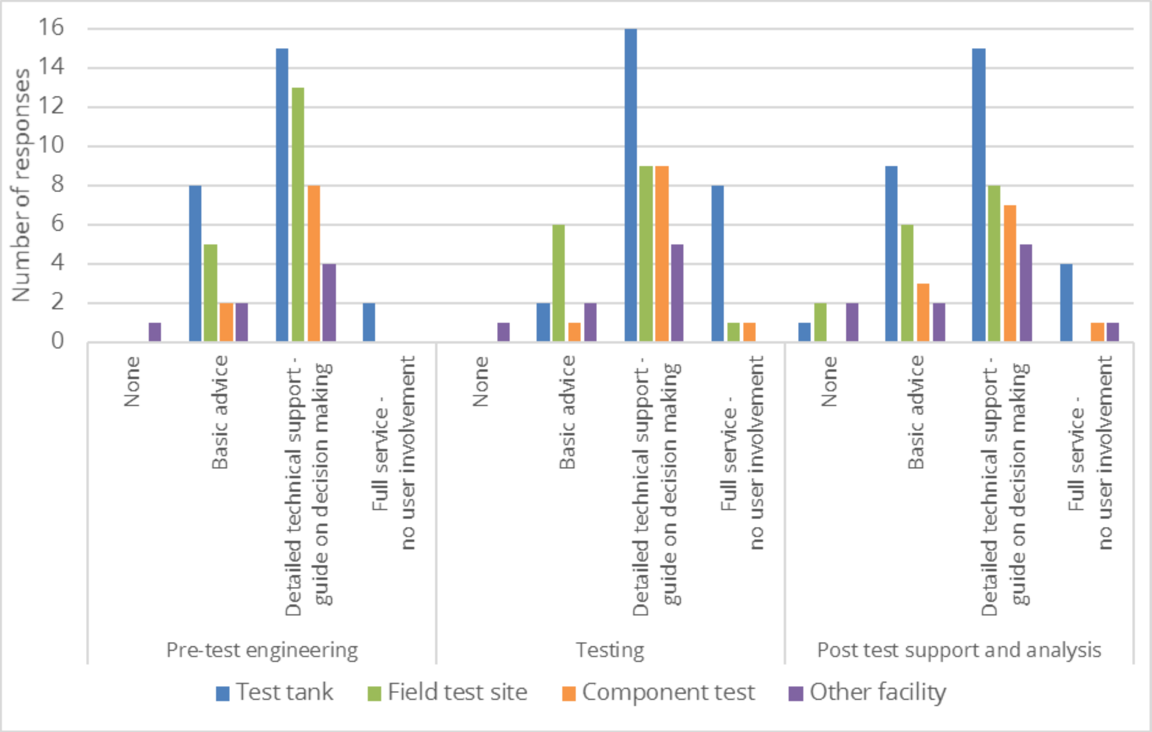

Figure A.3 Questionnaire responses to Q10) "Which statement best describes the level of support that is typically offered?"

A.3.3 Instrumentation and data requirements

The majority of facilities (77%) have some form of data acquisition (DAQ) system. A third of respondents (34%) report having had some limitations with data acquisition, with just over half (57%) reporting never being limited by their DAQ. A breakdown of limiting factors with number of responses by facility type is shown in Figure A.4

Most facilities store data on a server in addition to PC internal hard drives, as shown in Figure A.5. The vast majority of facilities (89%) have some form of backup in place, as shown on Figure A.6.

Figure A.7 shows the data types that are transferred to users immediately after testing (i.e. before pre-processing) and after pre-processing.

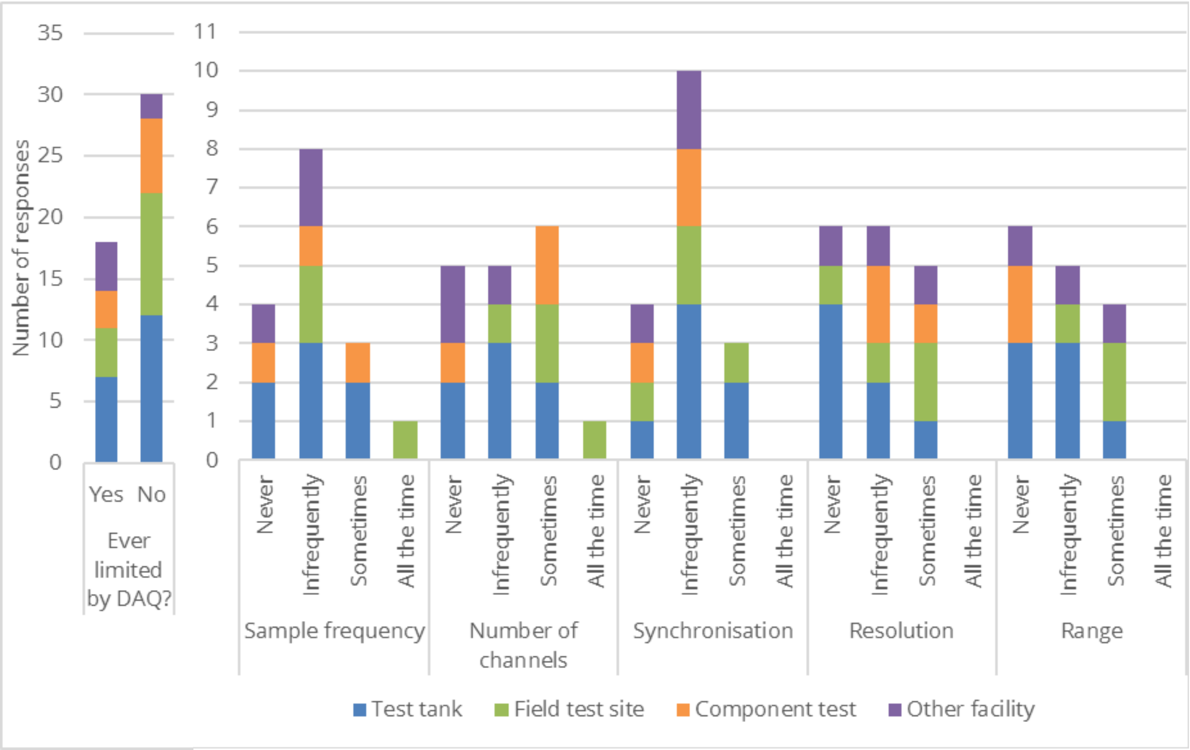

Figure A.4 Questionnaire responses to Q19) Have you ever been limited by your data acquisition system? If so, what is the limiting factor and how frequently does it happen?

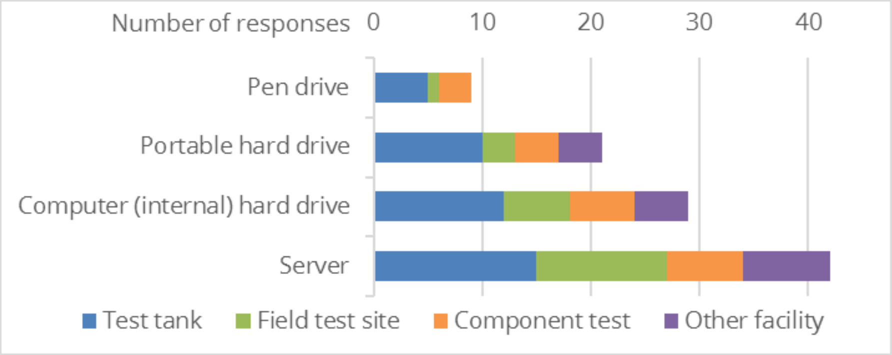

Figure A.5 Questionnaire responses to Q31) How is user data stored? (select all that apply)

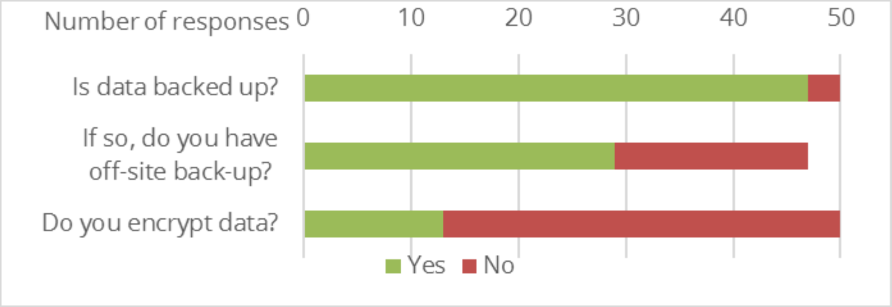

Figure A.6 Questionnaire responses to Q32) Is data backed up? If so, do you have off-site back-up? And Q33) Do you encrypt data?

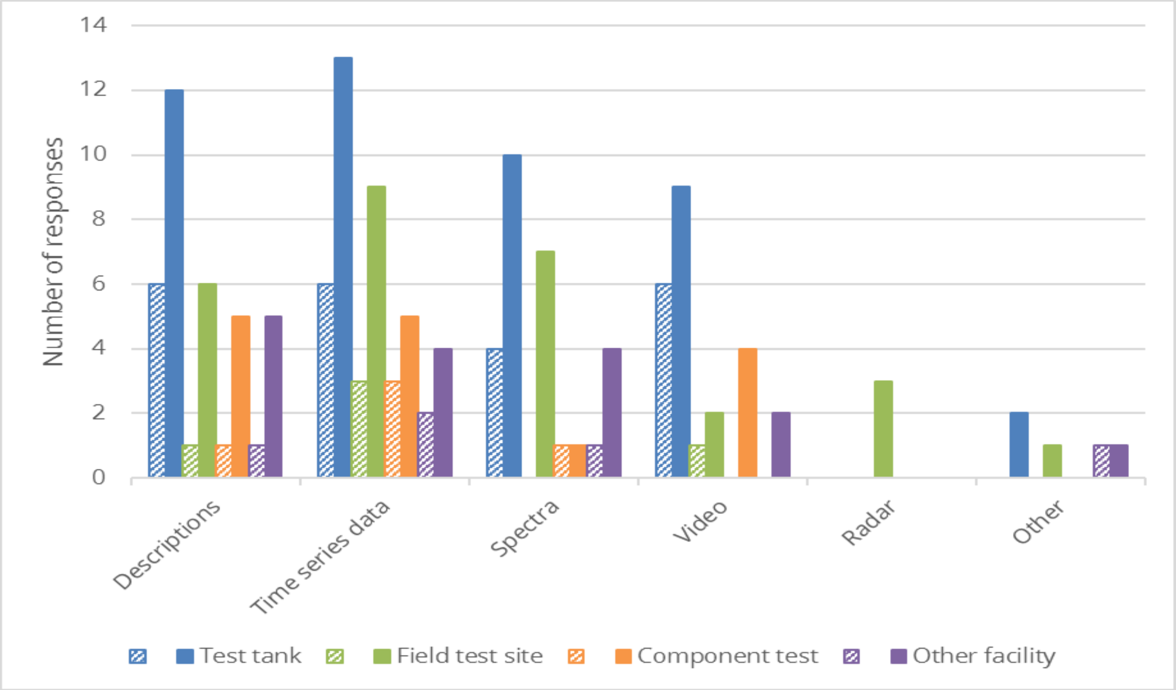

Figure A.7 Questionnaire responses to Q35) Which data types are transferred to users (a) immediately after testing (i.e. before pre-processing)? [hatched bars] and (b) after pre-processing? [solid bars].

Appendix B. Tabular summary of key topics covered by guidance documents

Key topics covered:	**Technology**			**Environmental conditions**				**Testing**																
Report Title	**WEC**	**TEC**	**OWT**	**Wind**	**Wave**	**Current**	**Resource assessment**	**Lab testing**	**Field testing**	**Test facilities**	**Development progression**	**Test programme**	**Scaling considerations**	**Scale model**	**PTO/control**	**Mooring/support**	**Electrical/grid**	**Component testing**	**Materials testing**	**Measurement/ instrumentation**	**Data analysis/ storage**	**Numerical modelling**	**Environmental/ ecology**	**Standards**
MaRINET 1 Project Deliverables																								
D2.01 Wave Instrumentation Database	✓				✓			✓	✓											✓				
D2.02 Collation of Tidal Test Options		✓				✓		✓		✓		✓	✓											
D2.03 Review of Relevant PTO Systems	✓	✓	✓												✓		✓							
D2.04 Collation of Offshore Wind-Wave Dynamics			✓	✓	✓								✓											✓
D2.05 Report of Instrumentation Best Practice	✓							✓						✓	✓									
D2.06 Report on Offshore Wind System Monitoring Practice and Normalisation Procedures			✓	✓		✓		✓						✓		✓			✓	✓				
D2.7 Tidal Measurement Best Practice Manual		✓			✓	✓		✓	✓				✓	✓										
D2.8 Best Practice Manual for Wave Simulation					✓			✓	✓	✓	✓	✓	✓											
D2.09 Standards for Wave Data Analysis, Archival & Presentation					✓				✓											✓	✓			✓
D2.10 Best Practice Protocol for Offshore Wind System Fluid-Structure Interaction Testing			✓	✓	✓			✓		✓		✓		✓										
D2.11 Best Practice Manual for PTO Testing	✓	✓	✓	✓	✓	✓		✓			✓				✓		✓	✓				✓		
D2.12 Collation of Wave Simulation Methods	✓				✓	✓		✓		✓			✓							✓				
D2.13 Collation of Model Construction Methods	✓							✓	✓				✓	✓	✓							✓		
D2.14 Wave Data Presentation & Storage Review					✓			✓	✓												✓			✓

Key topics covered:	Technology			Environmental conditions				Testing																
Report Title	**WEC**	**TEC**	**OWT**	**Wind**	**Wave**	**Current**	**Resource assessment**	**Lab testing**	**Field testing**	**Test facilities**	**Development progression**	**Test programme**	**Scaling considerations**	**Scale model**	**PTO/control**	**Mooring/support**	**Electrical/grid**	**Component testing**	**Materials testing**	**Measurement/ instrumentation**	**Data analysis/ storage**	**Numerical modelling**	**Environmental/ ecology**	**Standards**
D2.16 Tidal Test Parameter Overview		✓				✓		✓		✓														
D2.18 Tidal Data Analysis Best Practice						✓		✓	✓				✓	✓						✓	✓			
D2.19 Generation of a set of typical dynamic load regimes for common conversion devices	✓				✓			✓							✓									
D2.20 Report on Physical Modelling Methods for Floating Wind Turbines			✓	✓	✓			✓		✓			✓	✓	✓									
D2.21 Review of Mooring Testing Systems								✓	✓				✓			✓		✓	✓					
D2.23 Review of Tow Tank Limitations		✓			✓	✓		✓		✓														
D2.25 Review Best Practice Standard for Electrical PTO Systems	✓	✓	✓					✓		✓	✓				✓		✓	✓			✓			✓
D2.26 Collation of European grid codes																	✓							✓
D2.28 Protocol for Model Construction	✓							✓			✓		✓	✓						✓				
D2.29 Report on Comparative Testing of Tidal Devices		✓						✓		✓										✓				
D4.01 Tank test related instrumentation & best practice				✓	✓			✓						✓						✓				
D4.02 Report on dynamic test procedures	✓	✓	✓					✓		✓	✓		✓	✓	✓		✓							✓
D4.03 Report on grid integration & power quality testing	✓	✓														✓	✓							✓
D4.04 Report on low frequency response and moorings								✓	✓					✓		✓						✓		
D4.05 Report on non-intrusive wave field measurement					✓			✓	✓											✓				

Key topics covered:	**Technology**			**Environmental conditions**				**Testing**																
Report Title	**WEC**	**TEC**	**OWT**	**Wind**	**Wave**	**Current**	**Resource assessment**	**Lab testing**	**Field testing**	**Test facilities**	**Development progression**	**Test programme**	**Scaling considerations**	**Scale model**	**PTO/control**	**Mooring/support**	**Electrical/grid**	**Component testing**	**Materials testing**	**Measurement/ instrumentation**	**Data analysis/ storage**	**Numerical modelling**	**Environmental/ ecology**	**Standards**
D4.06 Data reports and data bases on coastal & offshore wind measurements				✓					✓											✓				
D4.07 Best Practice Report on Environmental Monitoring & New Study Techniques	✓	✓							✓											✓			✓	
D4.08 Database for environmental monitoring techniques & equipment									✓											✓			✓	
D4.09 Report on remote underwater motion measurement								✓	✓											✓				
D4.10 Report on Real Time Estimation of Incident Waves	✓				✓										✓									
D4.11 Report on new instrumentation and field measuring technology for tidal currents		✓			✓	✓		✓	✓	✓										✓				
D4.12 Report on design and accuracy of the sensor and SHM-system			✓					✓								✓			✓	✓	✓			
D4.13 Report on field test buoy research					✓	✓			✓							✓				✓				
D4.14 Report on demand side grid compatibility																	✓							✓
D4.15 Report on numerical methods for PTO systems	✓	✓	✓										✓		✓		✓	✓				✓		
D4.16 Report on options for full-scale wind resource surveying				✓					✓											✓				✓
D4.17 Report on environmental monitoring protocols									✓											✓			✓	

Key topics covered:	**Technology**			**Environmental conditions**				**Testing**																
Report Title	**WEC**	**TEC**	**OWT**	**Wind**	**Wave**	**Current**	**Resource assessment**	**Lab testing**	**Field testing**	**Test facilities**	**Development progression**	**Test programme**	**Scaling considerations**	**Scale model**	**PTO/control**	**Mooring/support**	**Electrical/grid**	**Component testing**	**Materials testing**	**Measurement/ instrumentation**	**Data analysis/ storage**	**Numerical modelling**	**Environmental/ ecology**	**Standards**
Equimar Project Deliverables *(deliverables relevant to testing only, for a full summary see http://www.equimar.org/equimar-project-deliverables.html)*																								
D1.1 Global analysis of pre-normative research activities for marine energy	✓	✓			✓	✓	✓	✓	✓		✓												✓	✓
D1.2 Recommendations from other sectors															✓	✓	✓		✓	✓	✓		✓	
D2.2 Wave and Tidal Resource Characterisation					✓	✓	✓													✓	✓			
D2.3 Application of Numerical Models					✓	✓	✓															✓		
D2.4 Wave Model Intercomparison					✓		✓															✓		
D2.6 Extremes and Long Term Extrapolation					✓		✓														✓			
D2.7 Resource Assessment Protocol					✓	✓	✓				✓										✓			
D3.1 Identification of Limitations of the Current Practices Adopted for Early Stage Tidal and Wave Device Assessment	✓	✓						✓	✓		✓				✓	✓						✓		
D3.2 Concept Appraisal and Tank Testing Practices for 1st Stage Prototype Devices		✓						✓	✓			✓			✓			✓						
D3.3 Assessment of current practice for tank testing of small marine energy devices	✓	✓			✓	✓		✓		✓			✓	✓						✓	✓			
D3.4 Best practice for tank testing of small marine energy devices	✓	✓						✓				✓									✓			
D4.2 Data Analysis & Presentation To Quantify Uncertainty	✓	✓		✓	✓	✓									✓		✓				✓			
D4.3 Test Sites Catalogue	✓	✓			✓	✓	✓		✓	✓														
D5.1 Guidance protocols on choosing of electrical connection configurations									✓	✓							✓							✓

Key topics covered:	**Technology**			**Environmental conditions**				**Testing**															
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D5.2 Device classification template	✓	✓													✓	✓								
D5.3 Protocols and guidance for device specification and quantification of performance	✓	✓			✓	✓	✓																	
European Marine Energy Centre (EMEC) draft standards and guides in 2009, for wave and tidal energy. *(see http://www.emec.org.uk/standards/) Six of these have been submitted as a suggested work programme for IEC TC 114, marked *.*																								
1. Assessment of Performance of Wave Energy Conversion Systems*	✓				✓	✓	✓													✓				
2. Assessment of Performance of Tidal Energy Conversion Systems*		✓			✓	✓	✓														✓			
3. Assessment of Wave Energy Resource*	✓				✓		✓													✓		✓		
4. Assessment of Tidal Energy Resource*		✓				✓	✓													✓	✓	✓		
5. Guidelines for Health & Safety in the Marine Energy Industry	✓	✓							✓															
6. Guidelines for Marine Energy Certification Schemes*	✓	✓																						
7. Guidelines for Design Basis of Marine Energy Conversion Systems*	✓	✓														✓	✓	✓	✓				✓	
8. Guidelines for Reliability, Maintainability and Survivability of Marine Energy Conversion Systems	✓	✓																						
9. Guidelines for Grid Connection of Marine Energy Conversion Systems	✓	✓															✓							
10. Tank Testing of Wave Energy Conversion Systems	✓				✓			✓	✓	✓	✓	✓	✓	✓						✓	✓			

Key topics covered:	**Technology**			**Environmental conditions**				**Testing**																
Report Title	**WEC**	**TEC**	**OWT**	**Wind**	**Wave**	**Current**	**Resource assessment**	**Lab testing**	**Field testing**	**Test facilities**	**Development progression**	**Test programme**	**Scaling considerations**	**Scale model**	**PTO/control**	**Mooring/support**	**Electrical/grid**	**Component testing**	**Materials testing**	**Measurement/ instrumentation**	**Data analysis/ storage**	**Numerical modelling**	**Environmental/ ecology**	**Standards**
11. Guidelines for Project Development in the Marine Energy Industry	✓	✓					✓																✓	
12. Guidelines for Manufacturing, Assembly and Testing of Marine Energy Conversion Systems	✓	✓																	✓					
International Towing Tank Conference (ITTC) – Recommended Procedures and Guidelines *(key documents only, for a full list see https://ittc.info/downloads/quality-systems-manual/recommended-procedures-and-guidelines/)*																								
7.5-02-01-01 Guide to the Expression of Uncertainty in Experimental Hydrodynamics								✓		✓										✓	✓			
7.5-02-07-01.1 Laboratory Modelling of Multidirectional Irregular Wave Spectra					✓			✓												✓	✓			
7.5-02-07-01.2 Laboratory Modelling of Waves: regular, irregular and extreme events					✓			✓												✓				
7.5-02-07-03.7 Wave Energy Converter, Model Test Experiments	✓				✓			✓		✓	✓	✓	✓	✓	✓	✓				✓	✓			
7.5-02-07-03.8 Model Tests for Offshore Wind Turbines			✓	✓	✓			✓		✓	✓	✓	✓	✓	✓	✓				✓	✓			
7.5-02-07-03.9 Model Tests for Current Turbines		✓				✓		✓		✓	✓	✓	✓	✓	✓	✓				✓	✓			
Other guidance																								
UEDIN Best Practice Guidelines for Tank Testing of Wave Energy Converters [36]	✓				✓			✓		✓			✓	✓	✓					✓		✓		
OES IA Guidelines for the development & testing of wave energy systems [5]	✓				✓			✓	✓		✓	✓												
SuperGen Marine Guidance for Numerical Modelling in Wave and Tidal Energy [33]	✓	✓											✓									✓		