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WP2 Standardisation of Offshore Energy System Testing

Final guidelines for test applicants

MaRINET2
D2.6

Status: Final

Version: 01

Date: 30/06/2021

MaRINET2

Deliverable 2.6:
Final guidelines for test applicants

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 731084.

Document Details	
Grant Agreement Number	731084
Project Acronym	MaRINET2
Work Package	WP2: Standardisation of Offshore Energy System Testing
Task(s)	T2.4: Best Practice Testing Guidelines
Deliverable	D2.6: Final guidelines for test applicants
Title	Final guidelines for test applicants
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File name	
Delivery date	
Dissemination level	Public
Keywords	Laboratory testing; field testing; guidelines; wave energy; tidal energy; wind energy; cross-cutting; electrical;

Document Approval Record		
	Name	**Date**
Prepared by	Frances Judge	25/06/2021
Checked by	Michael O'Shea	30/06/2021
Approved by	Michael O'Shea	30/06/2021

Document Changes Record			
Revision Number	**Date**	**Sections Changed**	**Reason for Change**

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List of Acronyms

ACoP	Approved Code of Practice
CDM	Construction Design and Management
CFD	Computational Fluid Dynamics
CoG	Centre of Gravity
DC	Direct Current
DOF	Degree of Freedom
ERP	Emergency Response Plan
FMEA	Failure Mode Effect Analysis
HIRA	Hazard Identification and Risk Assessment
IEC	International Electrotechnical Commission
IP	Intellectual Property
ITTC	International Towing Tank Conference
LOLER	Lifting Operations and Lifting Equipment
MEC	Marine Energy Converter
MRE	Marine Renewable Energy
NDA	Non-Disclosure Agreement
OPEX	Operational Expenditure
PTO	Power Take-Off
TA	Transnational Access
TPV	Third-Party Verification
TRL	Technology Readiness Level
WEC	Wave Energy Converter

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Executive summary

This report provides a set of guidelines to assist developers in getting the most out of transnational access (TA) and testing campaigns in general. The report is based on D2.2 Draft guidelines for test applicants which was produced in 2018 as part of MaRINET2. This updated report takes learnings from the TA campaigns conducted during MaRINET2 through feedback from participants and facility managers. Learnings from the round robin research programme are also incorporated. It is intended that this document will be used as a template to assist other facility types in producing their own recommendations.

In this guideline document, advice is given to assist developers in putting together a sufficiently detailed and well thought out proposal that will increase the likelihood of a successful TA application. Laboratory and field testing are then discussed with the view to providing potential users with key advice and information to design a successful test campaign and ensure delays are minimised during the testing phase. The goal is to ensure the users are well prepared before embarking on testing so that they get the most out of their allocated access.

1. Introduction

The aim of this report is to provide guidance for device developers or research teams that are planning a test campaign for an offshore renewable energy device. The report gathers learnings from the MaRINET2 Transnational Access programme, in which 173 users were granted access to facilities around Europe over the course of 5 calls. Both users and facility operators fed into this report. Learnings from the round robin test programme conducted as part of the research programme in MaRINET2 are also included where relevant.

1.1 MaRINET2 Transnational Access Summary

The MaRINET2 transnational access (TA) programme offered users free-of-charge access to the research and testing facilities of the MaRINET2 network over the course of the project. The test facilities included small- and large-scale laboratory facilities, as well as medium- and large-scale at-sea sites. The range of facilities available provided potential users with the capability to test technology relating to offshore wind, tidal, and wave energy, as well as electrical and grid integration, and cross-cutting technologies. There were 54 facilities available for physical testing in total. A detailed description of each facility is available on the MaRINET2 website[1].

There were five calls for access to the facilities over the course of MaRINET2, details of which are given in Table 1 below. Applicants were required to register on the MaRINET2 website and complete an online application form. The information required included the affiliation of the user(s), the choice of infrastructure and proposed period of access. Detailed information was required regarding the proposed work, the test plan, the technical requirements, and the anticipated outcomes. Discussions between the applicant and the facility manager were mandatory during the application phase to ensure the chosen facility was suitable for the proposed testing and to fine-tune the application.

After the end of the call period, each application was evaluated, and a selection procedure applied that considered the eligibility of the proposal and the technical feasibility. A scientific evaluation was then carried out and the final decision was made by a selection committee made up of experts in the area. Successful applicants were notified and subsequently contacted by the facility managers to begin the process of organising the test campaign.

A requirement of the TA programme is that on completion of testing, a short report must be produced by the applicant, highlighting the scientific output of the access received.

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

Table 1 TA call schedule

	Call period	Assessment	Selection decision	Access period
Call 1	10 April 2017 – 20 May 2017	22 May 2017 – 30 June 2017	5 - 7 Jul 2017	15 July 2018 – 15 Jan 2018
Call 2	15 Jan 2018 – 28 Feb 2018	1 Mar 2018 – 15 April 2018	15 – 18 Apr 2018	20 Apr 2018 – 30 Oct 2018
Call 3	1 Nov 2018 – 15 Dec 2018	17 Dec 2018 – 31 Jan 2019	2 – 4 Feb 2019	5 Feb 2019 – 5 Jul 2019
Call 4	15 Aug 2019 – 30 Sep 2019	1 Oct 2019 – 15 Dec 2019	16 – 18 Dec 2019	1 Jan 2020 – 30 Jun 2020
Call 5	1 Sep 2020 – 16 Oct 2020	19 Oct 2020 – 31 Dec 2020	4 – 15 Jan 2021	18 Jan 2021 – 17 Jul 2021

2. Proposal writing for access grants

Preparation of a good proposal was essential for a successful application to the MaRINET2 TA programme. This section provides guidance on how to prepare a good proposal for future calls for TA or other access grants in order to increase the likelihood of success.

Before preparing an application for access to a test facility, it is recommended that users familiarise themselves with typical testing procedures. This is discussed further in Sections 3 and 4. Useful references those listed in Table 2 for laboratory testing, and [1]–[3] for testing at sea.

For full details on the MaRINET2 application procedure, refer to the MaRINET2 website, and to the Transnational Access User Guidelines document [4]. This section provides additional recommendations for the application phase to supplement those provided in [4].

2.1 Consultation with the facility manager

As part of the initial application phase for access, the proposed user and the facility manager must communicate in advance of the application being finalised. This is important to ensure that

(a) There is allocation available at the user's facility of choice
(b) The facility is appropriate to carry out the desired test program
(c) Advice is received by the applicant on the proposed test program

As experts in device testing, the facility managers have a wealth of experience and knowledge to offer those planning a testing campaign, particularly those embarking on such a campaign for the first time. Proposals will only be successful if they are technically feasible; therefore, a detailed consultation with the facility manager is necessary to confirm that the proposal is in line with the capabilities of the facility.

2.2 Flexibility in facility choice

For TA programmes such as MaRINET2, applicants should not limit their application to a single facility. Should a facility be over-subscribed, only the top-ranking applications for that facility will be successful. To increase the chances of a successful application, it is recommended that the user apply to three different facilities that would meet their needs. For each focus area (i.e., wave, tidal, wind, electrical/grid integration, cross-cutting) facilities are grouped by their scale: small or large laboratory, medium-scale, or large-scale field site. It is recommended that applicants identify those facilities providing testing environments that are suitable for the technology readiness level (TRL) of the device of interest.

2.3 Proposal elements

Annotated photographs or figures should be included in the proposal which illustrate the concept to be tested. This makes it easier for the review committee to understand and assess the proposal, and thus increases the likelihood of success. It also aids the facility manager in identifying any potential issues with deploying or testing the device in the facility under consideration. If available, photographs of the scale model should be included to demonstrate the preparedness of the applicant.

When applying for access to a facility, inclusion of the proposed test plan is also beneficial. Evidence that the proposed testing campaign has been planned and is well thought out is key for a positive decision. This can be discussed with the facility manager during the application process. Include any documentation from previous studies, numerical or physical testing already carried out. This is extremely important to demonstrate the consistency of the proposed test program with the stage of development of the models being used. Provide as much detail as possible about what is required from the facility (wave conditions, acquisition and sensors, tools, etc.)

An application for access to a sea testing facility should show evidence that the logistics and health and safety issues associated with transporting, deploying, and maintaining a device at sea have been considered. This is discussed in more detail in Section 4.

2.4 Report writing after a successful campaign

MaRINET2 users were required to produce a short report after testing. The report should include a description of the concept being tested and the test campaign carried out. Results of testing and the main learning outcomes should also be included. Numerous reports of this nature that resulted from the MaRINET project are available for reference on the MaRINET2 website[2]. Figures and photographs that describe the concept and illustrate the testing should be incorporated where possible.

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

3. Laboratory testing

In this section general aspects that are in common with all marine energy devices are addressed. Theme-specific subsections (wave, tidal, wind) address aspects exclusive to that theme. Additional subsections are included that provide advice for testing electrical or cross-cutting components.

Wave basins, flumes and towing tanks can all be used for testing marine energy converters. Facilities available for TA in MaRINET2 can be broadly classified as 'small' and 'large' laboratories. Concept development, design validation and optimisation activities are generally carried out in small laboratories. These activities lead to TRLs in the region of 1-3. Large laboratories are generally used to advance to TRL4, verifying the performance of models in realistic seas, as well as performing component testing and power take-off (PTO) and control modelling.

3.1 Background research

As a general recommendation, users are advised to do some background research on tank testing techniques before embarking on a testing campaign. This is useful in terms of informing the proposed test campaign as well as avoiding past mistakes. Useful guidelines for tank testing for wave devices can be found in the reports listed in Table 2. A more comprehensive list of guidance documents has been published in [5]. It is also worthwhile asking the facility manager if any reports on similar test campaigns are available for reference.

Table 2 References for laboratory testing

Category	Reference
General	• All deliverables from the MARINET project are available at https://www.marinet2.eu/archive-reports-2/research-reports/ • A register of all ITTC guidelines is available at https://www.ittc.info/media/4251/register.pdf • EquiMar - Protocols for the Equitable Assessment of Marine Energy Converters [6] • D4.3 MaRINET2 Standard Testing Procedures Manual (due for publication in 2021) • MaRINET2 Deliverable D2.1: Test recommendations and gap analysis report [5]
Wave	• IEC TS 62600-103:2018: Part 103: Guidelines for the early stage development of wave energy converters – Best practices and recommended procedures for the testing of pre-prototype devices [7]

	• ITTC – Recommended Procedures and Guidelines: Wave Energy Converter, Model Test Experiments, Recommended Procedures and Guidelines [8] • European Marine Energy Centre (EMEC) guide: "Tank Testing of Wave Energy Conversion Systems", 2009 [9], • EQUIMAR Deliverable D3.4: Best practice for tank testing of small marine energy devices [10]. • IEA report: Guidelines for the development and testing of wave energy systems [11] • SuperGen report: Guidelines for the experimental tank testing of wave energy converters [12] • Marinet Deliverable 2.8 EC: Best Practice Manual for Wave Simulation [13] • Marinet D2.1 Wave instrumentation database [14]
Tidal	• IEC TS 62600-202: Marine energy – Wave, tidal and other water current converters – Part 202: Scale testing of tidal stream energy systems [15] • ITTC – Recommended Procedures and Guidelines: Model Tests for Current Turbines. 7.5-02-07-03.9 [16] • ITTC – Recommended Procedures and Guidelines: Uncertainty Analysis - Example for Horizontal Axis Turbines. 7.5-02-07-03.15 [17] • Marinet D2.18: Tidal Data Analysis Best Practice [18]
Wind	• Marinet D2.20: Report on Physical Modelling Methods for Floating Wind Turbines [19] • ITTC – Recommended Procedures and Guidelines: Model test for offshore wind turbines [20] • ITTC – Recommended Procedures and Guidelines: Floating Offshore Platform Experiments 7.5-02-07-03.1 [21] • ITTC – Recommended Procedures and Guidelines: Model Tests for Offshore Wind Turbines 7.5-02-07-03.8 [22]
Other	• Marinet Deliverable 4.01 EC: Tank test related instrumentation and best practice [23] • Marinet Deliverable 2.21 Review of Mooring Testing Systems [24]

3.2 Model design

A well-designed and appropriately scaled physical model is imperative for a successful laboratory testing campaign. The MaRINET project provided a best practice guidelines and lessons learned document for the construction of Wave Energy Converters (WEC) [25]. Although specific to the design and construction of WECs, the guidelines have a wider applicability to any device proposed to undergo tank testing and is a useful reference document. Some key considerations in the design and construction of a prototype device are outlined below. In general, it is recommended that model developers seek the advice of someone with previous expertise in model design and fabrication. Some test facilities have model design and construction services and can assist in model building.

3.2.1 Model accuracy and structure

The model structure should be kept as simple as possible. Determining the hydrodynamic properties of the model is a key outcome of tank testing, and unnecessary embellishments on a prototype may impact this goal. The design should ensure that the model is robust enough to survive transportation to the test facility, and that assembly upon arriving at the facility is as straightforward and as swift as possible. Complicated prototypes can lead to significant delays in model set up thus reducing the time allocated for testing.

The model must be accurate in terms of geometry and mass distribution. Small errors in the prototype may be very large when scaled up. Accuracy will most likely be achieved where the design is simple. Including components on the model that are not strictly necessary adds uncertainty, e.g., the mass distribution. It is generally preferable to keep the model as simple as possible, to reduce sources of uncertainty and the likelihood of breakages.

When dealing with floating devices, the hydrostatics of the model should be assessed numerically before testing to predict the expected centre of gravity, centre of buoyance, radiuses of gyration, metacentric height, and resonance periods. The mass of the model should be minimised to allow moveable ballast, e.g., lead weights, to be positioned to adjust the centre of gravity or achieve a level keel in the tank.

3.2.2 Water tightness and materials

The model must be watertight. To achieve this, unnecessary welds and joints should be avoided, and prefabricated beams/tube elements should be used where possible. It is strongly recommended that the water tightness of the model is tested before arriving at the facility. This can be done by floating the model in any body of water and checking for leaks. Adding weights to the model to artificially increase the draft and put pressure on the welds beyond what would occur during testing is a suggested method for ensuring water tightness and structural integrity.

When choosing the material from which to construct the model, it should be noted that the model will be in the water for a considerable length of time. Certain types of foam, aero-board and chip board will eventually take on water and swell and so should be avoided. Covering such materials with fibreglass or an epoxy coating may achieve water tightness, but this solution will likely result in a model that is vulnerable to damage during transportation and testing.

Non-corrosive material (plastics, wood, epoxy, polycarbonate, aluminium, stainless steel, aluminium, etc.) should be used throughout the model.

If the user is supplying any instrumentation in addition to what is available at the test facility, the user should ensure that it is watertight. If possible, instrumentation that has been certified waterproof by the manufacturer should be used. Other options include enclosing instruments in a watertight box, encasing devises in resin or moulding them in rubber.

3.2.3 Device scaling

The model must be built at a scale appropriate to the facility where testing is to take place. If the model is still at the design stage, it is recommended that the manager of the desired test facility is contacted well in advance of the call opening date, to discuss model scaling and allow time for fabrication. For already constructed models, it should be confirmed with the relevant manager that the facility is suitable for a device of that scale. The scale of the model should be identified in relation to the dimension of the facility in order to minimize flow confinement effects. This is particularly important when testing clusters or arrays of devices.

Scaling of structural properties is usually unnecessary. If it is deemed essential, it significantly complicates the construction, as well as the instrumentation required during testing.

Generally, tank testing of wave energy devices follows Froude similitude, whereas tidal device testing is primarily governed by Reynolds similitude and floating wind platforms are governed by both. These rules are not fixed, as oscillating water columns for example may also consider air compressibility, depending on the device scale. There is now a trend toward floating tidal energy converters, which must also take into account the effect of waves on the floating structure. Applying only Froude or Reynolds scaling will exclude the possibility of scaling to the other, and the scope and purpose of the tank testing must be well defined beforehand to avoid contradictions and scaling problems. For a detailed discussion on scaling, see the MaRINET Deliverable 2.13 [25].

3.2.4 Aesthetics

Applicants should note that testing provides an excellent opportunity to take photographs of the model in operation. Photographs and videos at this stage are very useful for marketing purposes, particularly when applying for future funding for further development and testing. Therefore, it is beneficial to design an aesthetically pleasing model; however, unnecessary embellishments should be avoided.

It is also recommended that the developer includes a raster grid on the model. This is a useful feature when it comes to interpreting images and videos.

3.2.5 Financial and timing considerations

Designing and fabricating a model takes time, therefore it is recommended that applicants already have a model designed, and if possible, constructed before applying for access to a test facility. Depending on the complexity of the proposed model and the proficiency of the team, the design and fabrication process can take 3 to 9 months. If time allows, it may be possible to get a model fabricated locally to avoid sending large models long distances. The facility manager should be able to advise on options for this. It should be noted that shipping abroad large and fragile models can be unexpectedly expensive and time-consuming. The risk of delivery delays should be adequately considered to ensure the model arrives at the host facility in advance of the scheduled testing time slot.

3.3 Moorings

The installation, testing and tightening of moorings is often the most time-consuming element of tank testing and should be given careful consideration. Once an application for access has been successful, the design of the mooring system should begin immediately, as it will be highly dependent on the facility where testing is to take place. The tank depth and area available for mooring spread will impact the design of the mooring system. A scaled version of a suitable full-scale mooring should be calculated, as it will significantly impact the device stability.

The mooring arrangement at model scale must be carefully calibrated. The numerical modelling of the system for comparison with the experimental results must rely on the scaled mooring as built and not on the theoretical design.

3.3.1 Catenary moorings

Catenary mooring systems cannot be accommodated in many testing tanks due to the large floor area they require; this should be discussed at the earliest opportunity with the facility manager. Springs can often be used in place of catenary systems; such an alternative should be designed, fabricated and tested in advance of arrival at the MaRINET2 test facility. Failure to do this may lead to a significant reduction in the time available for carrying out the proposed test campaign.

3.3.2 Mooring pre-tension

Mooring pre-tension will need to be adjusted during testing. Again, this is a time-consuming process which should be given consideration. Fixtures and fittings commonly used in the boating industry and available from chandleries can make the adjustment of pre-tensioned cables efficient and the final setting secure. On occasion, the model may have to be removed from the tank to adjust the model or instrumentation set up. Excessive downtime can be avoided by designing moorings that can be removed and reattached quickly and easily, without impacting the set pre-tension.

Mooring lines must be anchored. The simplest way of anchoring to the tank bottom is to use a lead weight of sufficient mass with a fitting to which the mooring line can be connected. Some tank facilities will provide attachment points on the tank floor. Check the situation with the facility.

Load cells will need to be connected at the anchor point for taut lines, or near the model for catenary lines. The preferred option should be identified, and provision made. The mooring loads expected for each mooring line during testing should be calculated. This information is very useful in the design of the scaled mooring system as well as for the selection of appropriate load cells.

3.3.3 Aerial mooring systems

Aerial mooring systems are a practical alternative to typical underwater moorings as they facilitate easier access to the anchoring points. This is where the mooring lines extend horizontally from the model to the side walls of the basin above and parallel to the water surface. This type of mooring system may be suitable when the focus of the tank testing campaign is on the hydrodynamics of the floater, rather than on the mooring system itself.

Linear aerial mooring systems were employed in both the wind and wave round robin test campaigns in MaRINET2 (see Figure 1). This system was chosen as it is independent of water depth and therefore could be installed in each of the facilities that participated in the round robin programme.

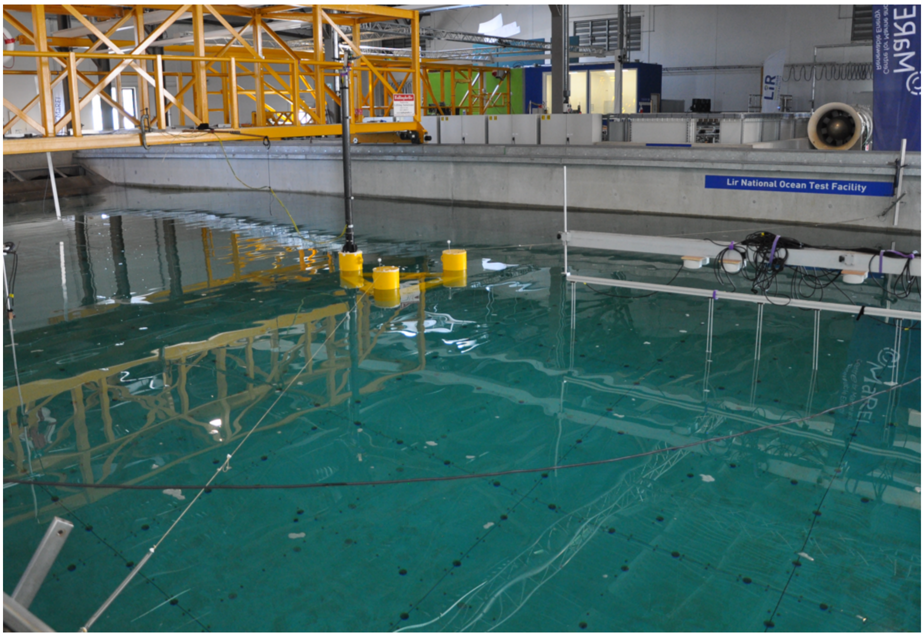


Figure 1 Aerial mooring system implemented for wind round robin tests

3.4 Rigid mounts

Rigid mounted structures are generally used for tidal turbines. However, some wave energy converter designs and offshore wind turbines can also be rigidly fixed.

Depending on the design, the model is kept fixed, and flush mounted on a truss frame over the test section of the tank. Similarly, in a towing tank installation, the model is supported by a structure fixed to the carriage frame. In recirculating tanks, the model can be mounted to the bottom of the tank or to a structure at the top of the tank, usually above the water level.

In all cases, the test-rig solution should be discussed in advance with the facility managers. Users should provide the facility manager with all information and data that are relevant for the realization of a robust, safe, and efficient installation of the model in the facility.

The loading on mooring lines as well as on supporting structures must be reasonably estimated. When dealing with large models, particular attention should be given to loads and bending moments generated by drag forces produced by immersed bodies such as struts, shrouds, and frames.

In most cases, device operation and performance is characterised by a number of sensors and measurement systems that are partly provided by the user and partly by the facility manager. Users' requests of equipment to be provided by the facility must be discussed in advance, including solutions to integrate sensors and data acquisition hardware.

3.5 Model set-up and dry tests

The complexity involved with model setup can vary considerably depending on the type and complexity of the device. Firstly, consideration must be given to the hydrostatic configuration of the device. The model will be likely be designed with particular mass properties (total mass, centre of gravity, moments of inertia) but these will usually require verification or adjustment prior to testing. The addition of motion capture markers, load cells, and other instrumentation may alter the mass properties. These additions, combined with instrumentation cabling, can be particularly significant on smaller models. Many laboratories will have a smaller trimming tank where the model may be ballasted with easy access and without holding up testing in the main tank(s). When designing the model consider locations for holding ballast, ideally with access that does not require removing the model from the water. As a rule of thumb, aiming for 10% of the model weight as ballast is usually sufficient for trimming and centre-of-gravity adjustment.

While total mass is relatively easy to verify, the centre of gravity and moments of inertia are more difficult. The laboratory may have access to a model swing or bifilar pendulum to aid in these measurements.

3.6 Instrument calibration

Where possible, instruments should follow the manufacturers calibration procedure. The laboratory may have the ability to calibrate some instruments locally (e.g., axial load cells or pressure sensors). However, the majority will require calibration offsite and this may only be conducted on demand. Therefore, it is essential to communicate with the laboratory what may be required well ahead of the test programme to ensure items are available in their calibrated state. If an uncalibrated device must be used this should be noted in the test notes.

All signals should be checked prior to testing and at regular intervals. Where possible, a known input (e.g., load) should be applied to check the instrument is performing consistently with its calibrated output. Any offset should also be noted or corrected. In some cases, this may require disconnecting the instrument from the model. A common example are load cells measuring mooring loads where a pre-tension exists. A practical approach is to disconnect the line (or manually de-tension the line) and take a "zero" measurement to quantify the offset. Without this approach it is not possible to distinguish between the offset and pre-tension. Accounting for offset is particularly important for submerged load cells where the static water pressure may exert a load on the device.

Note that all sensors used in a test campaign must be calibrated. This can take a significant amount of time and should be accounted for in the test plan.

3.7 Planning a test campaign

3.7.1 Discussions with test facility

A well thought out test-campaign is essential for getting the most out of the allotted time at the test facility. Users should consult the facility manager and agree a detailed test matrix, describing (where applicable) the wind, wave and current conditions required for each individual test, the test duration, and the total number of tests. The testing process is often subject to delays and may proceed slower than anticipated. Therefore, the priority of tests should be decided in advance. In the event that testing proceeds quicker than expected, some additional contingency tests should be included in the test matrix. Ensure that time is allocated to instrument and if necessary, spring calibration.

The consultation with the facility manager should include clarification on whether set-up and dismantling time is included in the access allocation. The user should know in advance whether any configuration changes will be required during the testing process and how long these will take to carry out. Any dry testing required should also be specified. The user should specify a list of preliminary checks to be carried out before testing commences (metacentric height, decay tests, etc.)

3.7.2 Numerical modelling

Ideally, all conditions that will be examined during laboratory testing should be simulated numerically beforehand. 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. Depending on the resources available however, detailed numerical modelling may not be possible. In the case of WECs, a hydrostatic analysis should be performed at a minimum.

3.7.3 Instrumentation requirements

It should be agreed with the facility manager what data will be collected during testing, for example, mooring loads, platform motions, accelerations, pressure, structural strain, wave height, etc. When determining the list and size of sensors required, it is recommended that the focus is on obtaining data that is really needed, rather than a lengthy list of desirable measurements. Excessive instrumentation causes delays, complications, and can lead to interference between sensors. Sensor sizing is also important; for example, a 500 N load cell may not provide accurate results for a mooring load range of 2-3 N.

It should be discussed with the facility manager what sensors are available, and whether it will be necessary to provide additional instrumentation. It is frequent that instrumentation is partly provided by the hosting facility and partly by the users. Typically, the former is used to characterise the operating conditions (wave pattern, current, wind speed, etc.) and the latter is embedded into the device to measure performance and response data. Requirements for the integration of sensor cabling and the data acquisition system should be discussed in advance with the facility managers. The full-scale measurement of sensors being used should be checked against the size of the models intended for testing.

Sometimes two data acquisition systems are used, one from the infrastructure and one from the visiting team. It is necessary to carefully prepare the synchronisation of the resulting data by a common trigger and at least a common channel that can be used to check and if necessary, adjust the synchronisation.

When using multi degrees of freedom sensors (six components gauge for instance), carefully check the orientation of the axis, distances, and signs of variables. This is particularly important when combining a six-component gauge and a six-component motion measurement system. Online analysis of the data after each test is a convenient way to avoid difficulties that may occur at the end of a testing campaign run as “blind” tests.

If filming of the testing is required, this should also be discussed and planned, to enable appropriate video camera set-up. Discussion with facility managers is strongly recommended to check that the model realization and installation will allow for adequate visualization of the phenomena of interest.

3.7.4 Cabling

Most sensors will have cabling connecting the sensors on or near the model to a power source outside the basin. Ensure that cables are supported so that they do not interfere with the motions of the device.

3.7.5 Decay tests

It is advisable to discuss with the facility manager in advance the options for carrying out decay tests. It may be more difficult to induce motion in larger models or where there are accessibility issues; for example, in basins without a movable floor, where decay tests must be carried out from a boat, footbridge or the basin sides. This can induce motion in additional DOFs to the one of interest which can affect the results. Pulley systems can be used to ensure motion is induced in one direction only, and to ensure consistency in the initial displacement. It is advisable to carry out several repeats of decay tests, to increase the confidence in the results.

3.7.6 Waves

3.7.6.1 Test durations

Test durations of 2-5 minutes are typically sufficient for tests involving regular waves, depending on the size of the basin and the potential impact of reflections. Irregular wave simulation durations depend on the scaling factor and the spectra used to generate the waves but are generally a longer duration than regular waves. The choice of spectra should be discussed with the facility manager. The proposed final site for model deployment may have a bearing on this decision.

It is important to consider the settling time between tests when planning out a test programme. Depending on whether there is active absorption or not in a wave basin, the settling time can be 5 to 10+ minutes, or even longer if standing waves develop. This will have a bearing on how many tests can be completed in one day. It is recommended that the facility manager is consulted in this regard to ensure the test programme is achievable.

Figure 2 Regular waves in a tank

3.7.6.2 Wave calibration

The waves proposed for the testing should be run and measured before testing commences with no model in the tank in order that that actual wave generated can be assessed with no model interference. Slight mismatches in the requested and actual wave produced in the tank are common. These mismatches can be tuned out by adjusting parameters in the tank; however, this is a time-consuming process and may not be necessary as it is much faster to adjust values in the numerical model. Generally, the best solution is to continue with testing and make a note of any discrepancies between the generated and desired wave field and adjust the numerical model accordingly.

The impact of reflections should be considered when performing wave calibration. This will vary at each facility and should be discussed with the facility manager. If it is the case that the desired analysis interval is not contaminated by reflections, the waves must be calibrated correctly for this analysis interval before the reflected waves reach the model location. In practice, this may only be possible for short period waves, as longer period waves will lead to a shorter analysis interval with no reflections. It may be useful to quantify the impact of reflections for over longer analysis intervals, in which case additional wave probes should be installed in the wave tank. The spacings of these probes can be calculated according to [26].

3.7.6.3 Breaking waves and survivability testing

The generation of waves that break across the model during testing should be considered carefully. Breaking waves can be difficult to model numerically and can result in unexpectedly high loads and motions. Breaking waves can be avoided in tanks by reducing the height of the waves. If part of the test programme is to test the survivability of the device, these tests should be run last to avoid down time from damage.

Figure 3 Short crested sea generation at ECN, Nantes

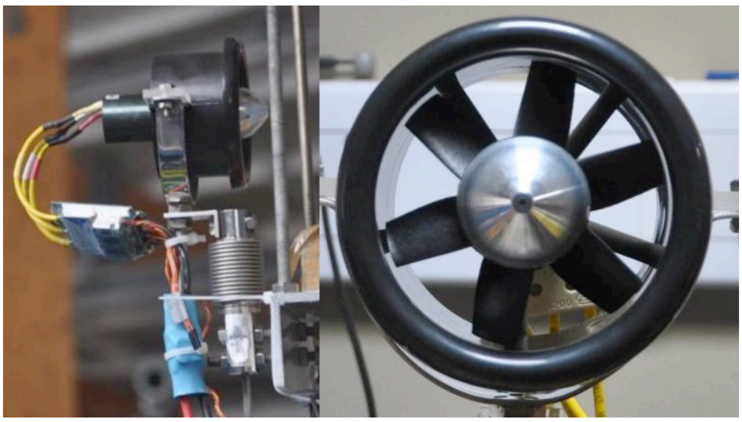
3.7.7 Wind

Generating a physical wind field in a laboratory setting requires large arrays of fans that can be expensive to operate. In addition to a bank of fans (with several fans in each row and column) above-basin wind generation systems typically include screens and honeycomb mesh to reduce the turbulence of the wind field produced, and a nozzle to direct the flow to the area where the rotor will be place. The wind field must be accurately measured and mapped to determine the best location for the model. A description of this process is given by [27]. Producing a high-quality wind field with accurate representation of the atmospheric boundary layer and turbulence is very difficult to achieve outside of a wind tunnel. Therefore, physical test campaigns often seek to emulate the thrust on the rotor only, as this is the most critical aerodynamic load when determining the platform motions.

There are a number of ways of simulating the effect of wind thrust on a model. These range from a simple hanging weight, to ducted fans, to a full scaled rotor with individual blade pitch control and a full dynamic control system. Detailed descriptions are given in the MaRINET Deliverable 2.20 [28] as well as by [29]. Generally, as the complexity of the above methods increases, so does the accuracy of the representation of the physics involved. However, there is a trade-off as the more complex methods require a longer set-up time, there is a requirement for additional data (e.g. atmospheric boundary layer details and a turbine controller) and more uncertainty may be introduced.

Hybrid testing is an alternative to full physical testing of a floating offshore wind model. It involves physical modelling of the hydrodynamic response to waves, but the aerodynamic loads are replaced by a numerically controlled actuator. The method allows real time combination of physical testing with numerical simulation. The hydrodynamic module of the numerical code is replaced with the real-time data from the motion tracking system in the basin. At each time-step, the code calculates the aerodynamic loads at full-scale which are then emulated by the actuator at Froude scale and applied to the model. Hybrid testing was first developed by CENER in Spain [30], and the actuators used have evolved from a single ducted fan to multi-bladed actuator capable of simultaneous loading in multiple DOFs, e.g. [31], who also describe a methodology for calibrating a multi-propeller actuator.

For early-stage research, the simpler methods are recommended and are the easiest to validate numerically. More sophisticated wind emulation should be considered for model designs that are well advanced. For a more detailed discussion on emulating aerodynamic forces and the associated scaling issues, refer to the discussion in Section 3.10.1.



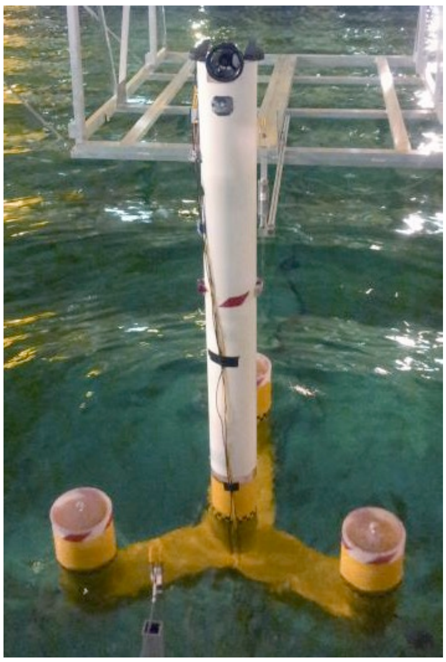


Figure 4 Ducted fan used for testing at UCC (left); and mounted on model (right) (Images taken from [28]*)*

Figure 5 Wind generation on a drag disk during hybrid wind/wave device testing at INSEAN (taken from [28])

3.7.8 Current

Tests in current tend to take one of two forms: devices where the current is integral to device performance (e.g., a tidal energy turbine); or situations where the current exerts an influence on seakeeping or some other key parameter (e.g. stability of a floating wind turbine or yaw of a wave energy device). The former will tend to require more energetic currents of the order of 1m/s for a typical ~1:20 scale model. Assuming Froude scaling this gives sufficient velocity range to cover a typical energetic tidal energy deployment site.

Froude scaling is typically employed in current testing in order to maintain similitude between current and wave loads. However, Reynolds scaling effects may be important, and tend to make testing with larger scale models (~1:20) preferable [32]. In the case of tidal turbines this typically leads to rotor diameters of between 1.0-1.5m.

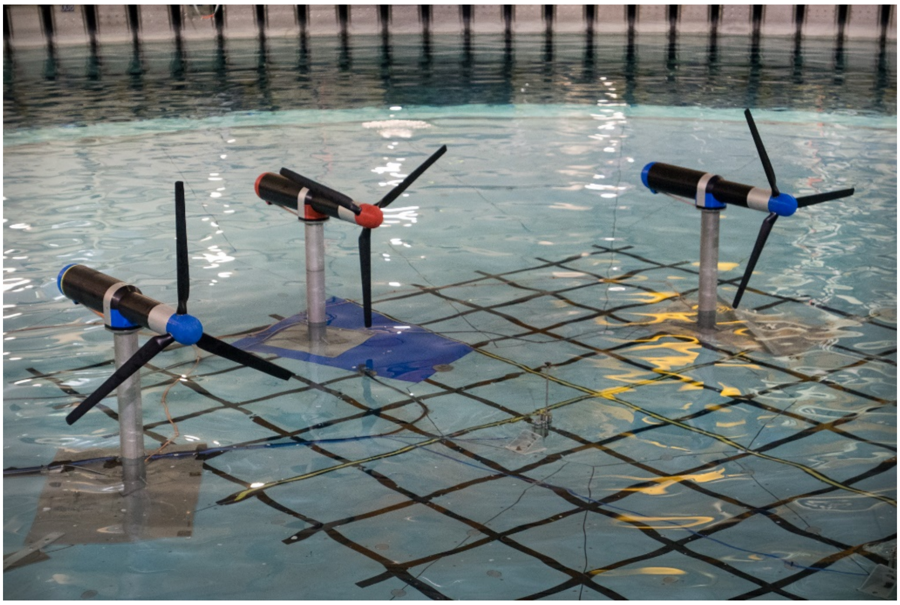


Figure 6 Three device tidal turbine array undergoing deployment in the FloWave Ocean Energy Research Facility, UK

Current may be defined in terms of speed (either depth averaged or a set position), direction, vertical velocity profile, and turbulence intensity. In the majority of facilities only a small number of these parameters will be independently controllable, typically speed and possibly direction. Adjustment of the velocity profile and turbulence intensity may be achieved through reconfiguration of the inlet system, and this is typically not a quick operation. The parameters will also tend to be dependent on the type of facility, with basins more likely to support variable direction, while unidirectional flumes may have more configurable inlet systems. When choosing a facility, the following should be considered: velocity range; test area size (e.g., for arrays); directionality of wave and current; representative velocity depth profiles and turbulence characteristics.

Test durations may vary significantly depending on the facility and the requirements of the model under test. However, durations of 3-5 minutes are typical for current only testing. This is driven by the time that stationarity can be assumed for the current measurement.

3.7.9 Combined wave and current

Current generation or simulation by towing determine different conditions for testing the effect of waves or onset flow turbulence on tidal devices. In a towing tank, regular waves generated in water at rest have a clean spectrum and this is independent of the current speed that is simulated by towing. Onset flow turbulence is nominally zero unless ad-hoc turbulence generation grids are installed upstream of the model, with additional set-up complexity. In water flumes or wave/current pools, the onset flow is naturally turbulent with intensity that can be gradually reduced with suitable grids. When wave generation is established, desired onset flow conditions can be influenced by uncontrolled turbulence induced by wave making devices.

Combined wave-current tests are challenging due to interaction modifying the target wave parameters. Even small currents will amplify or attenuate the wave height for opposing and following currents respectively. The input wave condition may be recalibrated to compensate, but there must be a clear rationale for this as it essentially changes the total energy in the system. One such rationale would be matching site data for a deployment location, where the wave height, current and directions are well defined. If only boundary conditions are known it may be more appropriate to leave the waves "uncorrected" and only vary the relative directions.

For seakeeping tests, for example on floating structures such as wave energy devices and floating wind supports, the currents are less energetic - typically <0.3m/s at model scale. Combined wave and current tests in a basin are typical in this scenario, providing space for representative moorings and changes to the relative wave-current direction.

Whether testing in a wave basin or towing tank, it is strongly recommended that when the objective is to analyse wave/current interaction or turbulence effects, the feasibility of requested testing conditions is discussed with the facility managers.

When creating a test matrix, note that for wave-current testing, the wave element of the test will tend to drive the duration.

3.7.10 Uncertainty analysis and repeat tests

It is recommended to incorporate uncertainty analysis into any test campaign. Sources of uncertainty encountered during tank testing can be categorised as model uncertainty, environmental uncertainty and measurement uncertainty.

Model uncertainty refers to the inherent uncertainty introduced by reducing a full-scale prototype to a simplified scale model which limits the accuracy with which a model can represent full-scale behaviour. It can be minimised by ensuring fabrication accuracy and appropriate scaling, as discussed in Sections 3.2, 3.9.2, and 3.10.1. Environmental uncertainty relates to the environmental conditions (i.e., waves, current or wind) generated in a laboratory setting. For example, the generation of a desired wave field is impacted by the tank shape, depth, and features such as beaches or absorbing paddles. Care must be taken during calibration to ensure that the desired conditions are achieved as closely as possible for the analysis interval of interest (see discussion in Section 3.7.6.2).

Measurement uncertainty can be quantitatively assessed in a laboratory test campaign but must be planned in advance. Every measurement made in a laboratory setting has an associated uncertainty and is therefore only an estimate of the 'true' value of that parameter. Uncertainty analysis can provide a lower and upper limit, between which the true value of a measurement lies and therefore gives an indication of the quality of the measurements made. To carry out an uncertainty analysis, several repeat tests must be performed (a minimum of 3-5) for a selection of test conditions (e.g., around the resonance periods). This allows the repeatability of the tests to be assessed which characterises 'random' uncertainty (sometimes referred to as 'Type A'), as well as providing back-up measurements should some discrepancies be discovered in the analysis stage. Systematic or 'Type B' uncertainty refers to bias errors that tend to remain constant. These cannot always be measured directly but are estimated from experience. During testing, data should be gathered on the precision of the instrumentation used as well as the calibration data. Descriptions of and methodologies for undertaking uncertainty analysis in laboratory testing of ORE devices are described by [33]–[37].

3.8 Testing wave energy converters

In addition to general aspects discussed in Sections 3.2 to 3.7, specific aspects for the successful testing of wave energy conversion devices at laboratory scale are addressed in this section. The portfolio of laboratory-scale testing facilities that are relevant for the characterization of these devices is given in Table 3 and reflects the list available through the MaRINET2 project website[3]. The list of facilities includes water flumes, wave/current basins, and towing tanks.

Table 3 Laboratory-scale testing facilities for wave energy devices

Tank size	Facility name	Location
Small	UCC MaREI Ocean Emulator	Cork, Ireland
	UCC MaREI Wave and Current Flume	Cork, Ireland
	AAU Wave and Current Basin	Aalborg, Denmark
	LABIMA Wave and Current Flume	Florence, Italy
	UEDIN Curved Basin	Edinburgh, UK
	MARIN Concept Basin	Wageningen, Netherlands
	MARIN Shallow Water Basin	Wageningen, Netherlands
	QUB Wide Wave Basin	Belfast, UK
Large	FZK Large Wave Flume	Hannover, Germany
	UCC MaREI Deep Ocean Basin	Cork, Ireland
	OCEANIDE_BGO FIRST Basin	La Seyne sur Mer, France
	UEDIN FloWave Ocean Basin	Edinburgh, UK
	MARIN Offshore Basin	Wageningen, Netherlands
	IFREMER Basin of Boulogne-sur-Mer	Boulogne sur Mer, France
	IFREMER Brest Deep Wave Tank	Brest, France

[3] http://www.marinet2.eu/facilities/our-facilities/wave/

	UoP Ocean Basin	Portsmouth, UK
	CNR-INSEAN Wave and Towing Tanks	Rome, Italy
	SSPA Maritime Hydrodynamics Lab	Sweden
	ECN Hydrodynamic and Ocean Engineering Tank	Nantes, France
	SSPA Towing Tank	Sweden
	UoP COAST Ocean Basin	Plymouth, UK

3.8.1 PTO design

Designing a suitable PTO for a scaled WEC can be complicated and must be considered very carefully. The key parameters that must be considered are

- Mass
- Friction
- Controllability

It can be difficult to design a PTO that is light enough to fit on a small-scale model without compromising the buoyancy and/or the performance of the device. The impact of friction becomes more pronounced at smaller scales and should be minimised by choosing for example the smallest bearings possible. Gearboxes should also be avoided at small scales as they introduce additional friction.

Control of WECs can be achieved at laboratory scale using PTO systems based on both linear and rotational motors. Conventional off-the-shelf rotational motors are designed for high speed, low torque operations. This at odds with the demands of wave energy devices, which are typically high torque, low speed operations. Linear motors provide excellent controllability at this scale. Stainless steel versions with dust and water ingress levels of IP69K are available tested up to one bar (10 m water depth). In the IEC 60529 rating system, IP6 refers to the product's ability to resist ingress of dust. The 69K refers to the product's ability to resist ingress of high temperature (steam) / high pressure water. Cogging and friction will still be prevalent, although feed forward control techniques can be used to compensate for this [38].

In rotational motors, servo motors represent the higher end models, although often a gearbox is employed. In the servo motor, an encoder is mounted to the motor, making highly precise and accurate position, speed, and torque control possible. More recently, brushless DC motors have been employed in tank testing set-ups (such as in the SQUID setup tested as part of the MARINET project and documented by [39]). A brushless DC motor focuses on speed control. If position control is not necessary, speed can be controlled with sufficient accuracy by a Hall Effect IC (magnetic sensor).

Clever methods of using a natural gearing system include the wire wrapped around a sector arc such as that used for the WEC element of a hybrid wind wave device tested under the

MARINET project [40], as shown in Figure 7. [41] incorporated a system whereby the relatively large translation movements of the guiding rod were grasped by a small diameter pinch roller, thus enabling a DC motor to be used for PTO.

Winding a rope around a spool is another way to utilise rotational motors although depending on the range of motion a gearbox may also have to be used. Regarding ropes, [42] states that as long as reasonable bounds are not exceeded, the winch radius is a powerful design-lever to minimise friction and optimise the drivetrain for the desired task. As a rule of thumb, the biggest winch diameter that can cope with the peak force in the system while applying the peak engine torque, is a good first approach.

Using a single rope for PTO would limit control studies to more phase-control based methods. Using several ropes, it may be possible to induce forced oscillations, thereby broadening the range of available control techniques at the cost of increased complexity. If the full device is to involve moorings in the PTO, it may require comment/justification as to the reliability of such an approach. A linear or rotational motor providing a reacting force against a fixed or referenced structure (e.g. a self-reacting point absorber) allows for a wide variety of control techniques to be investigated.

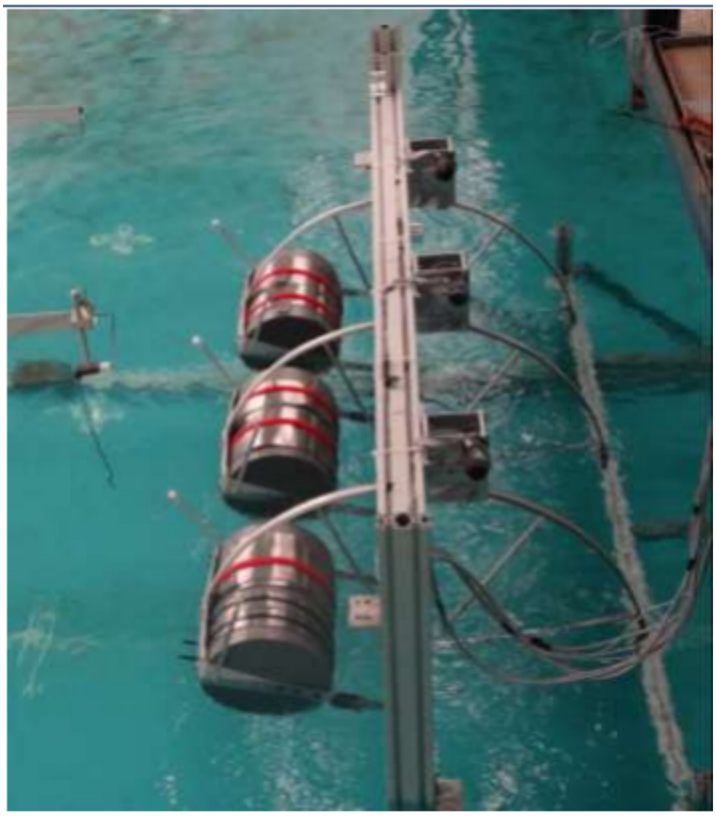


Figure 7: Model of scale1:30 WEC proposed for hybrid wind-wave device [40]

3.9 Testing tidal energy converters

In addition to general aspects discussed in Sections 3.2 to 3.7, specific aspects for the successful testing of tidal energy conversion devices at laboratory scale are addressed in this section. The terminology "tidal energy" here is used in a broad sense and includes any kind of technology aimed at the capture and conversion of kinetic energy from a marine current. The portfolio of laboratory-scale testing facilities that are relevant for the characterization of these devices is given in Table 4and reflects the list available through the MaRINET-2 project website.

Table 4 Laboratory-scale testing facilities for tidal energy devices

Tank size	Facility name	Location
Small	UCC MaREI Wave and Current Flume	Cork, Ireland
	LABIMA Wave and Current Flume	Florence, Italy
	MARIN Concept Basin	Wageningen, Netherlands
	MARIN Shallow Water Basin	Wageningen, Netherlands
	Cantabria Wave-Current Tsunami Flume	Santander, Spain
Large	IFREMER Basin of Boulogne-sur-Mer	Boulogne sur Mer, France
	CNR-INSEAN Wave and Towing Tanks	Rome, Italy

	CNR-INSEAN Circulating Water Channel	Rome, Italy
	UEDIN FloWave Ocean Basin	Edinburgh, UK
	MARIN Offshore Basin	Wageningen, Netherlands
	SSPA Maritime Hydrodynamics Lab	Sweden
	OCEANIDE_BGO FIRST Basin	La Seyne sur Mer, France
	UoP COAST Ocean Basin	Plymouth, UK
	NUIG Large Structures Test Cell	Galway, Ireland

Applicants to a TA program such as MaRINET2 can choose from three types of testing environments:

- Water flumes
- Wave/current pools
- Towing tanks

A fundamental prerequisite for the success of a proposed test campaign is that opportunities, limitations, and requirements of the different types of facilities are well understood.

In water flumes and wave/current pools, the model is fixed with respect to an onset current with imposed flow speed and, to some extent, turbulence intensity. Both seabed-fixed and floating devices can be studied. In some facilities, waves can be generated, and the effects of wave/current interactions can be investigated.

Different conditions characterise towing tanks. Here, the model is rigidly fixed to the structure of a towing carriage that moves along the tank at a set speed. The relative speed between the towed model and water at rest in the tank simulates an inflow current on the device. Several towing tanks are equipped with wave generators.

Ideally, water flumes and wave/current pools offer conditions that better reflect the operation of a tidal energy converter in a field site than a towing tank. However, the interplay of practical limitations existing in the different types of installations, determines a more complex scenario. The problem has been deeply investigated by the two round-robin tests on tidal energy devices carried out in the MARINET and MaRINET2 projects. Specifically, the former focused on a horizontal-axis tidal turbine in uniform flow [43], whereas the latter extended the analysis to operation in waves [44].

The findings from both MARINET and MaRINET2 round robin tests on tidal energy devices provide a unique reference for TA applicants on the impact of testing conditions offered by different facilities on the characterization of a tidal turbine:

- Reynolds number, onset flow turbulence and side-wall confinement effects on turbine thrust and power
- limitations in testing conditions for the study of tidal turbine operation in waves

This material integrates guidelines for laboratory testing of tidal energy devices that can be found in the Recommended Procedures and Guidelines "Model Tests for Current Turbines," by the International Towing Tank Conference (ITTC) [16] and the EquiMar Deliverable D3.4: Best practice for tank testing of small marine energy devices [45].

The main aspects that should be carefully addressed in the preparation of a testing campaign for a tidal energy device are described in the following subsections.

3.9.1 Tidal model design and accuracy of construction

A crucial aspect of a tidal testing campaign is to ensure that the model can resist the hydrodynamic loads generated during tests. The underestimation of loadings on model mechanical components is among the primary causes of failure in a tidal testing campaign.

There are several aspects that should be considered in order to achieve model reliability throughout the desired test program:

- Consider all types of loading: a model that is correctly dimensioned for the expected mean loads under steady operation can break because of intense transient loads. This problem is particularly frequent in vertical-axis and cross-flow turbines. Overloading can also occur when a turbine operates in off-design conditions.
- Consider all the mechanical components: typically, the blades and shaft are accurately dimensioned for the expected load range. Nevertheless, the model can suffer severe damage because of failure of the supporting frame or of components along the drive train.
- Consider the risks of specific conditions in the test matrix: if an existing model is being used, the capability to resist to high-loading conditions (e.g., high-torque, high-speed, transient flows) should be accurately analysed beforehand.

The simulation of test conditions by computational modelling (CFD, Fluid-Structure Interaction tools) can be very helpful to inform the correct design of the model and adequately choose materials and model manufacturing details.

Another important aspect is the accuracy of the model fabrication. A general reference for best practices in the construction of tidal energy devices can be found in the ITTC Recommended Procedures and Guidelines for model propellers [46]. Two main aspects should be considered. Lifting surfaces such as foils or blades are responsible for kinetic energy capturing. The hydrodynamic performance is dramatically affected by the manufacturing precision of these components. Particular care should be paid to the fabrication of leading edge and trailing edge regions, especially in case of very small models.

Accurate design and fabrication is also required to minimise friction among parts in relative motion that could otherwise lead to device performance results not representative of full scale conditions.

It is strongly recommended that design and manufacturing of models is undertaken by specialised and qualified companies. Facility managers can provide support by suggesting well-proven suppliers.

3.9.2 Scaling tidal devices

The primary goal of laboratory tests is to estimate from measurements at small-scale the performance of a full-scale device in a real field site. The selection of the best scale factor for the realization of the model device should be done by considering the dimensions of the hosting facility and the purpose of testing. When dealing with tidal turbine performance, the most important condition to ensure a reliable model-to-full scale extrapolation is the Reynolds number similitude. The goal is to maximise the product of model size and testing flow speed.

By considering model size, the dimensions of the facility test section, width and depth, the user should determine flow confinement (blockage) effects that may affect device performance. Theoretical methodologies to correct blockage effects in turbine performance measurements exist (e.g., [47]), but their validity becomes uncertain as the blockage factor increases. Moreover, general approaches to correct specific aspects like turbine wake expansion or blade cavitation do not exist. Other limitations with large-scale models can include too large rotor loads that are beyond the scale of the measurement systems provided by the hosting facility.

In facilities where large current speeds can be generated, Reynolds number similitude can be achieved also with relatively small models that are tested at high onset flow speed, while blockage effects are kept limited.

When a floating device is tested or the objective is to characterize the effects of wave/current interaction, Froude number similitude is also relevant. As Reynolds and Froude number scaling imply different conditions, it is important to define model scale and testing conditions that best match the primary objectives of testing.

3.10 Testing floating offshore wind devices

In addition to general aspects discussed in Sections 3.2 to 3.7, specific aspects for the successful testing of floating offshore wind devices at laboratory scale are addressed in this section. The portfolio of laboratory-scale testing facilities that are relevant for the characterisation of these devices is given in Table 5 and reflects the list available through the MaRINET-2 project website[4].

[4] http://www.marinet2.eu/facilities/our-facilities/ offshore-wind/

Table 5 Small- and large-scale offshore wind testing facilities

Tank size	Facility name	Location
Small	UCC MaREI Wave and Current Flume	Cork, Ireland
	LABIMA Wave and Current Flume	Florence, Italy
	MARIN Concept Basin	Wageningen, Netherlands
	MARIN Shallow Water Basin	Wageningen, Netherlands
	Cantabria Wave-current Tsunami Flume	Santander, Spain
Large	NUIG Large Structures Test Cell	Galway, Ireland
	CNR-INSEAN Wave and Towing Tanks	Rome, Italy
	OCEANIDE BGO FIRST Basin	La Seyne sur Mer, France
	UEDIN FloWave Ocean Basin	Edinburgh, UK
	MARIN Offshore Basin	Wageningen, Netherlands
	IFREMER Basin of Boulogne-sur-Mer	Boulogne sur Mer, France
	CNR-INSEAN Circulating Water Channel	Rome, Italy
	UoP Ocean Basin	Portsmouth, UK
	SSPA Marine Dynamics Laboratory	Sweden
	Cantabria Coastal & Ocean Basin	Santander, Spain

Readers should refer to [22] for specific advice in relation to conducting a test campaign on a floating offshore wind turbine.

3.10.1 Scaling wind devices

Froude scaling is used to achieve geometrical similarity between model scale and full scale. A geometrically scaled rotor using Froude scaling will have a lower Reynolds number at model scale comparted to a full-scale device, resulting in a lower lift coefficient and a higher drag coefficient. This will lead to a misrepresentation of the platform response to wind loading.

A low Reynolds number may be compensated for in a laboratory setting by increasing the applied wind velocity or adjusting the geometry of the rotor. Rotor thrust is the most critical aerodynamic load when determining the motions of floating platforms. Wind thrust can be emulated in several ways. A weighted pulley is the simplest method but can only model steady thrust loads and cannot emulate aerodynamic damping or the effects of turbine control. If a wind blower is available in the laboratory, a drag disk can be used to emulate the varying thrust on the rotor. Incorporation of a Froude scaled rotating mass can allow emulation of gyroscopic loads. Like the pulley system however, the drag disc method cannot simulate aerodynamic damping or turbine control.

Froude scaled rotors with a higher than Froude scale wind velocity can overcome the scaling mismatch, but motors are typically required to aid rotation and maintain the tip speed ratio (TSR). Performance-scaled turbines, where the blades have been geometrically modified, can be used to compensate for the low Reynolds number in a Froude scaled wind environment. This method can emulate aerodynamic loading, capture damping and the effect of blade pitch control while maintaining the TSR [48].

Hybrid testing is a useful means of overcoming the scaling issues introduced when testing a floating wind platform and can also be implemented in basins without a means of generating a physical wind field. As described in Section 3.7.7, it involves physical modelling of the hydrodynamic response to waves, but the aerodynamic loads are replaced by a numerically controlled actuator. The hydrodynamic module of the numerical code is replaced with the real-time data from the motion tracking system in the basin. At each time-step, the code calculates the aerodynamic loads at full-scale which are then applied by the actuator to the model at Froude scale.

A detailed overview of different methods of wind emulation and the issues with scaling is given by [29].

3.11 Testing electrical subsystems

The experience of both the MARINET and MaRINET2 projects has shown that the research and subsequent tests of the generator, power electronics and grid connection part are not yet a priority issue for technology developers. Generally, the tests at an electrical test facility are carried out when the device proof of concept has already been validated, and the technology has been proven to work in small flumes (Stage 1: Concept Validation). The use of electrical test facilities is introduced when the focus of the developer is moving to optimising the control and the challenges associated with grid integration (Stage 2: Design Validation and Stage 3: Sub-Systems Validation) [49]. It is important to note that control strategies may have a significant impact on the dynamics of the structure. Therefore, engaging in electrical testing early in the device development trajectory is considered good practice and is highly advised.

The portfolio of laboratory-scale testing facilities that are relevant for the characterization of these devices is given in Table 6.

Table 6 Small- and large-scale electrical testing facilities

Tank size	Facility name	Location
Small	UCC MaREI Electrical Laboratory: Microgrid; Medium Speed Rotary Emulator; High Speed Rotory Emulator; Linear Test Rig; Rotary PTO test rig	Cork, Ireland
	TECNALIA – Electrical PTO	Derio, Spain
	SINTEF Smartgrid Laboratory	Trondheim, Norway
	EMEC PTO test rig	Orkney, UK
Large	ORE Catapult HV Lab	Rome, Italy

The electrical testing facilities allow the testing of several aspects of the power conversion including components that constitute the drive train, the control unit and the control algorithms, the SCADA (Supervisory Control and Data Acquisition) system and issues related to power integration to the electrical grid.

Most of the electrical testing facilities are based on a Hardware-In-the-Loop (HIL) framework that consists of feeding back the modelled experiment with real measurements from the test rig and which must adapt its response in consequence. It integrates physical hardware and software models in a single closed – loop simulation.

The available electrical testing facilities can include:

- Electrical PTO laboratories
- MicroGrids
- Modelling computers with real time modelling capabilities and various I/O
- Motor to generator coupled test rigs, where the motor can emulate a turbine
- Advanced power converters to control machines or power flows to the grids/micrograms

From past experiences based on TA research using electrical test rigs, it has been found that users need at least two visits to the test infrastructures to complete a full test campaign: one to understand the test bench specifics and adapt the numerical models and another to perform the experiments. A test campaign in an electrical infrastructure is a long procedural activity where the main tasks are typically as follows:

- Pre-access preparation of the test: Before accessing the infrastructure, discussions with the infrastructure provider are required in order to obtain all the inputs needed to perform the tests.
- Adaptation of models: The mathematical models that represent the resource and the energy converter behaviour must be adapted to the electrical facility. Each facility may have a different simulation software and I/O acquisition boards. Usually users start at their institution, but this work needs to be finalised at the facility.
- Load and grid profiles: Discussion about the appropriate sea-state conditions to be tested. Prepare a detailed and realistic test plan with the infrastructure manager.
- Onsite preparation of tests: Final programming of the devices in the lab. Final programming of the proposed controls. Understanding the specificities and adapting the numerical models - typically one week – requires a high level of support from the facility manager
- Validation tests: Initial tests to analyse the performance of the facility with the device are undertaken.
    - The initial tests do not consider grid connection and generic controls can be used at this stage to perform general tests of the device.

  - Full tests: Once the device simulator's behaviour fully represents the behaviour of the mathematical models and/or the results of prior tests in the tank, the proposed controls can be tested.
- Battery of tests: typically, one week – requires only supervision while the tests are ongoing.
- Analysis and post-processing: Data post-processing, analysis, and reporting the main outcomes.

3.11.1 Remote access

As explained previously, testing in electrical facilities requires longer duration visits than is often anticipated, to learn how and what to test, prepare the facility and adapt the user's models. This can discourage some developers who may avoid performing these tests that they mistakenly believe are not important.

The provision by facilities of remote access would make electrical tests more accessible to many users. Work in [50] details the considerations and work required in order to turn an electrical test infrastructure into a remote access platform. The methodology and a real remote access case study to an electrical facility was conducted and recorded.

3.11.2 Scaling considerations

Electrical test rigs are not full scale and have physical limitations (speed, power, torque, inertia, etc.) that may not coincide with the models of the users, nor the reality they want to represent. Additionally, the input test data to the electrical test rig is often from physical tests of scaled models that need to be adjusted to the scale of the electrical test rigs. A report carried out in the FP7 MARINET project [51] provides guidance on how to address these scalability issues.

3.12 Testing cross-cutting devices

The portfolio of laboratory-scale testing facilities that are relevant for the characterization of these devices is given in Table 7 and reflects the list available through the MaRINET-2 project website[5].

Table 7 Small- and large-scale cross-cutting test facilities

Tank size	Facility name	Location
Small	UNEXE Dynamic Marine Component Test Facility	Exeter, UK

[5] http://www.marinet2.eu/facilities/our-facilities/cross-cutting/

	TECNALIA – Component Corrosion Test Platform	Basque Country, Spain
	CTC – Marine Corrosion Test Site 'El Bocal'	Santander, Spain
Large	NUIG Large Structures Test Cell	Galway, Ireland
	UNEXE Dynamic Marine Component Test Facility	Exeter, UK
	CTC – Marine Corrosion Test Site 'El Bocal'	Santander, Spain
	ORE Catapult Marine Facility	Blyth, UK

3.12.1 Structural testing of tidal blades

Guidance regarding structural testing of tidal blades is based on the testing of this nature carried out during MaRINET2. Full-scale structural testing of tidal stream blades under fatigue and static loading, in accordance with DNVGL-ST-0164 and IEC TS 62600-3, was offered to marine energy developers at the Large Structures Testing Laboratory at NUI Galway during MaRINET2. The Large Structures Testing Laboratory is comprised of a large reconfigurable test frame (10m x 6m 6m) along with a state-of-the-art multi-actuator load introduction system (with multiple servo hydraulic actuators up to 750 kN), which allows a very flexible test approach. The advanced actuator control system allows for a wide variety of load or displacement sequences across multiple actuators, which is suitable for static and fatigue testing. Data acquisition of up to 136 independent high-speed channels can be carried out simultaneously; displacement, force, acceleration, strain and other types of sensors are available to configure the test.

3.12.1.1 Test procedure

In advance of testing, a test procedure, which is an agreement between the Test Manager and the developer, must be completed in line with the DNVGL-ST-0164 standards and IEC TS 62600-3 specifications. This will include the blade geometry, the loading conditions, instrumentation requirement, testing programme details and expected load/displacements of the actuators.

3.12.1.2 Interfacing with the existing infrastructure

As each test is bespoke in nature, it is necessary to design and manufacture fixtures to interface between the tidal blade and the existing infrastructure (i.e., the actuators and strong floor). For a cantilever tidal blade, this usually requires a bespoke root connection to be provided by the developer that connects to our strong base or strong floor directly. Additional connections between the hydraulic actuators and the blade surface, which may take the form of steel/polymer clamps, contact pads (in compression) or steel ropes (in tension), are usually required and need to be designed (in conjunction with the Test Manager) and provided by the developer.

3.12.2 Component testing for moorings

Characterisation of mooring systems and components improves the confidence in the performance of the system to provide station-keeping for the MRE device. Physical testing in a test facility is a relatively inexpensive alternative to field deployment and this can be done for complete mooring systems (as described previously) or components such as fibre ropes.

Although most component test facilities provide a similar range of services, there can be a large variation in the test set-up and available instrumentation that may influence the implementation of test procedures and rope characterisation.

The mooring components of interest may either be innovative or based on established technology. Innovation in the component can be attributed to either the technology used or the intended application environment which leads to an increase in the associated risk. Physical testing provides an opportunity to advance the innovative technology along the technology readiness levels.

For most components with established technology, information provided by manufacturers does not fully characterise the materials for MRE use, therefore, laboratory testing using suitable load regimes must be conducted. These tests require specific test equipment that is available at very few independent test facilities. As an example, for fibre ropes, rope makers are unable to provide suitable characterisation data; only existing industry developers have access to such information, and it is not published to maintain competitive advantage. As a result, the designer of an MRE device must access available facilities to characterise the performance of ropes.

Some materials used for mooring synthesis, such as nylon for fibre ropes, display a change in strength and stiffness due to moisture absorption. These altered properties in the offshore environment must be accounted for during testing. Therefore, the developers should aim to choose a facility that can simulate the offshore application of the components during testing by either submerging or spraying the sample with water. Additionally, the component must be submerged in water prior to installation and bedding-in to allow for sufficient water ingress prior to testing so that the test results display the material properties for a submerged system.

3.12.2.1 Standard guidance

As a starting guideline, the specifications of the rope component from the supplier can be a useful indicator for the stiffness and strength of the rope. The specification sheet should be used to identify the material, its expected minimum break load and stiffness curve.

There is standard guidance available for most rope materials that can be used to inform the test plan. The developer must identify if they require any testing that needs to be done in addition to the standard testing. This may be useful when the standard guidance is based on application of the ropes in a different industry such as oil and gas. There might be additional failure modes that may be of interest for application in MRE that can also be added such as the influence of higher frequency loads on rope stiffness. To address this, additional dynamic tests should be conducted at a lower cycling periods of 3 -5 s to account for the effects on synthetic fibre rope performance.

In case no standard guidance exists for the material or component, a general test guidance can be used as a basis with suitable adjustments such as ISO 18692-1:2018 for fibre ropes.

3.12.2.2 Communication between facility manager and developer

Effective communication between the developer and the test facility manager is encouraged as this will provide each party with the opportunity to understand the requirements of the other. This should be done throughout the planning, testing and analysis stages. Physical presence of the developer at the test facility is also encouraged, as active involvement will facilitate smooth implementation of the test program by addressing any unforeseen obstacles.

At the outset of the test, the risk assessment should be thoroughly filled by the developer to inform the facility manager of any risks associated to the testing and possible mitigation methods outlined.

3.12.2.3 Test samples

Based on the expected test campaign, a suitable number of samples must be supplied by the developer to the test facility. In case of existing technology, testing multiple samples will provide an estimate of the uncertainty in performance characterisation. For innovative components, characterised by high risk of premature failure, providing multiple samples reduces the risk for delayed testing due to pre-mature failure of the specimen.

Rope sample terminations are a significant source of variation in performance metrics due to the stress concentration in the termination. The terminations for the different samples must be the same and in accordance with the requirement of the facility manager. Additionally, the length of the sample must be discussed based on the length of the test bed and the material properties of the sample to allow successful testing. In case of a more flexible hybrid rope, rope construction knowledge and rope yarn can provide information about single element properties. In the absence of this knowledge, an informed decision must be made to reduce the sample length sufficiently to ensure that a successful break test can be performed at the test facility.

The method of storage and delivery of samples to and from the facility should be agreed upon between the developer and facility manager keeping in mind the standard guidance. Similarly, the status of any overnight rest period during testing must be discussed based on the possible effects on the sample. As an example, will the sample be left submerged, connected to the rig and under tension.

3.12.2.4 Test plan

A detailed test plan must be drafted to ensure what tests will be conducted and what data will be collected. The developer must specify the type and frequency of data collected and enquire about the available instrumentation and their specification. Any additional equipment and instrumentation requirements must be discussed with the facility manager to avoid delays in testing. This is particularly relevant for innovative components as it is possible that traditional measurement equipment cannot be attached to the component. For suggested manual readings of an installed sample, it must be confirmed with the facility manager that it is safe to access the sample.

The test plan must account for the installation and de-installation period as these might vary between components. During testing, the collected data must be inspected regularly so that any inconsistencies can be identified and comparison with videographic evidence can provide evidence to the cause.

As part of the testing, standard guidance dictates that each sample is first bedded-in and then exposed to quasi-static and dynamic testing. It is recommended that for novel components where the minimum break load is unknown, a manual jog must be conducted first to prevent the premature failure of the component.

In order to ensure that the performance testing is based on the true material properties, the sample should be fully bedded in. Where no material-specific guidance is present, the load extension graph for the dynamic bedding-in cycles must be investigated to ensure that the sample is fully bedded in.

Quasi-static testing requires the sample to be held under a specified load for a specific time. The load range, duration of hold and number of quasi-static cycles must be specified in the test plan. For the dynamic testing, the test plan must specify the number, range, and frequency of load cycles.

It must be agreed with the test facility manager if a break test will be conducted on the sample. In case of a break test, suitable safety precautions must be taken, and the required measurements must be specified. While the load measurement is usually taken, the strain to failure requires special equipment. A non-contact extensometer would be required to measure the extension of the central portion of the rope to avoid introducing local stress concentrations (with clamps for example) and to avoid destroying the measurement device at failure.

3.12.2.5 Analysis

The analysis responsibility and methods must be agreed between the developer and the facility manager. While a stress-strain plot is standard in industry it leads to the requirement of a defined sample cross-section. For multiple samples, this introduces another variable that can be a source of error and force-strain plots can be used to present sample stiffness as an alternative.

3.13 Intellectual property

All MaRINET2 facilities have procedures in place to protect intellectual property (IP). These may include

- Exchange of non-disclosure agreements (NDA)
- Limiting access to the tank hall during testing
- The erection of screening around the tank during testing

If the model to be tested is IP sensitive, provisions to protect the IP should be discussed with the facility manager. If the model is not IP sensitive or is IP protected, 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 your design. For models that are not IP sensitive, there may be research opportunities at the test centre which can be used to further explore your concept. Again, the user is encouraged to discuss such opportunities with the facility manager. In general, it is recommended that some IP protection is 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.

3.14 Logistics and Health and Safety

Transporting and testing a model has logistical and health and safety implications which must be considered. It is recommended that models are loaded onto pallets for ease of transport. The dimensions and mass of individual components should be made available to the test centre so that an assessment of the lifting requirements can be made. Manual handling should be avoided where possible. Assumptions should not be made regarding the lifting capabilities available on site. If a crane or a forklift is required, it should be confirmed with the facility manager beforehand that these are available, and that the lifting capacity is adequate to meet requirements.

The user may be required to complete a Risk Assessment or Safety Statement before arrival at the facility; this should be checked in advance with the test centre. Depending on the rules of the facility where testing is to take place, the user may not be allowed to work in the tank or in the tank hall. This can be problematic if, for example, the assembly of the model is an intricate task. Therefore, it is advisable to check with the facility beforehand whether working on the model while it is in the facility is permitted.

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

It is recommended that delivery of the model to the facility is arranged for approximately one week before the allocated testing slot, to mitigate against delays and give time for preassembly. Once the model arrives, it should be immediately checked for any damage sustained during transportation, so that assembly can begin as soon as possible. Care should be taken when packaging the model prior to transportation as even minor damage can lead to significant delays. The model should be fully restrained, with no movement possible. The packaging itself should be robust (e.g., made of wood), and labelled as 'fragile' with 'this way up' arrows where appropriate. Any specialised tools or ancillary devices that may be necessary during assembly or testing should be packed with the model, as such items may prove difficult to source locally.

3.15 During testing

3.15.1 General recommendations

Users should bring the following to the test facility:

- Notebook
- Camera
- Warm clothes, depending on the local climate tank halls can be very cold
- Large external hard drive
- Laptop with numerical model if possible
- Any consumables required, e.g. tape, cable ties, ropes etc.

Users are encouraged to ask questions during the testing process; however, they should be aware that set-up is a very busy time so questions may be more welcome once testing has begun. A key component of MaRINET2 is cooperation and knowledge exchange, and facility managers possess a wealth of knowledge and experience that can be exploited by the users. It is also important to voice any concerns, e.g. relating to the testing or health and safety, so that these may be discussed and addressed.

Again, it is recommended to take photos and videos during testing as these are invaluable for reporting, as well as for marketing material. Before taking photos, however, check that there are no IP restrictions. Some aspects of the testing may be sensitive or there may be other models in the vicinity of the tank. Attractive pictures for marketing purposes can be difficult to take due to poor lighting and the layout of tank halls. Therefore, should high quality photographs be required, it may be worth hiring a professional photographer. The facility may be able to recommend someone local with experience of photographing in their facility.

3.15.2 Record keeping and data recording

Users should keep a log of the entire testing procedure, and document what happens on each day. In particular, any changes in set-up should be recorded. Small changes can have unexpected impacts that may only become apparent during post-processing of data. It is thus useful to have a record of what changes occurred and when, in order to determine the root cause of data abnormalities. It is also advisable to measure the mass and location of any ballast added to the model during set-up. This may be useful when performing numerical modelling at a later stage.

Photographs and video are an excellent method of documenting the tests, but it is important these can be correlated back to a particular test. This can usually be done by timestamps, but note that camera clocks can often be wrong. For video, it can be worth saying the test reference or parameters at the start of each recording. Where photos and video are recorded on personal mobile phones, it is important to collate these together with the project records at the end of the test.

Users should take note of any unusual behaviour exhibited by the model during testing and discuss it with the local expert, as it may be the case that the behaviour has been observed previously with other test campaigns. Alternatively, the examination of this behaviour may prove to be a good opportunity for further collaborative research.

Tank test facilities are typically part of larger research facilities. It is recommended that the user arrange a tour or meeting/presentation with a local business development or research officer. This may lead to further opportunities for the user.

Table 8 Record keeping and recommendations for data storage

Item	**Recommendation for applicant**
Test log	The user should maintain a daily test log that lists each test carried out and any notes or observations and documents any changes in setup.
File referencing	For data traceability, the user and facility operator should agree on how the files will be referenced. This referencing method should facilitate identification of the test, the date/time when the output file was generated, and the sensor from which the data was recorded.
Back up storage	In case of failure/destruction of the test output storage system, the user should verify with the testing facility that back-up storage is available and with sufficient capacity to store the data recorded during the test.

3.16 After testing

Once testing is complete, the model will need to be removed from the tank and dismantled. This process is generally much quicker than the set-up phase. The user should check for any changes to the model, e.g., damage to moorings, or whether the model has taken on water. Weighing the model before and after testing is useful in this regard. The location of any sensors that were applied to the model during testing should be marked. This can be useful when processing data later.

The user should retain all relevant documentation and if possible, any extra components that were used during testing, such as lead weights, swivels, etc. This may be useful when carrying out future testing, or to help understand the data in the post-processing phase. All data obtained during testing should be saved to a hard drive. Video files, in particular, require significant storage.

The model should be collected as soon as possible after testing is complete, as storage is often limited at tank testing facilities.

4. Field testing

4.1 General

The challenges of a field-testing campaign are far different from the ones experienced in tank test facilities. The increased size of the device, and the uncontrollable site conditions induce additional logistical issues to consider, before, during and after the test. The following sections provide general guidelines that test applicants should consider during the successive steps of an open field-testing campaign.

Testing at sea generally involves devices at a larger scale than those deployed in tanks. This, coupled with the nature of the sites, brings different logistical, and health and safety issues to the fore compared to those associated with tank testing. Wave Energy Scotland have produced a series of guidance documents relating to real sea deployments ([1]–[3]), and the user is encouraged to read these before undertaking a sea testing campaign. The MaRINET Deliverable 2.13 [25] contains some guidance on the construction of large scale WECs for testing at sea.

The field testing facilities in MaRINET2 are listed in the table below. They include both medium-scale and large-scale sites, suitable for testing devices at TRLs 5-9. Medium-scale sites are generally relatively sheltered with benign metocean conditions. These sites are typically used for devices built at 1:2 to 1:5 scale to bring devices to TRL 5-6. Large-scale sites are generally open sea sites that are used to test 1:2 to full scale devices. Testing at these locations aims to advance the device to TRL 7-9, where TRL 9 is a commercial unit.

Table 9 MaRINET2 sea testing facilities

Facility size	Site name	Location
Medium-scale (more sheltered sites)	Uppsala University Islansberg	Lysekil, Sweden
	EVE Mutriku Wave Power Plant	Mutriku, Spain
	EMEC Scale Wave Test Site	Orkney, Scotland
	EMEC Scale Tidal Test Site	Orkney, Scotland
	QUB Portaferry Wave Test Site	Portaferry, N. Ireland
	QUB Portaferry Tidal Test Site	Portaferry, N. Ireland
	DMEC Den Oever inshore test site	Den Oever, Netherlands
Large-scale (more exposed sites)	PLOCAN Marine Test Site	Canary Islands, Spain
	BiMEP – Biscay Marine Energy Platform	Armintza, Spain
	ECN SEM-REV Sea Test Site	Le Croisic, France
	EMEC Full Scale Wave Site	Orkney, Scotland
	EMEC Full Scale Tidal Site	Orkney, Scotland
	SmartBay Ireland Test Site	Galway Bay, Ireland
	DMEC Marsdiep Offshore Tidal Testing	Den Helder, Netherlands

Figure 8 Smartbay Ireland test site, Galway Bay, Ireland

4.2 Commissioning and installation

4.2.1 Lifting and Handling

As with tank testing campaigns, the delivery and handling of a device needs to be strategically planned from the outset. For medium to large-scale tests at sea, developers should consider producing a lifting and handling plan, which will ensure that the required onshore support facilities can be provided to meet the objective of getting the device deployed safely and cost effectively. The supply, manoeuvring, working areas and storage of devices and ancillary enabling equipment are key requirements to include within the plan.

Due to specificities of the device and the test site, it is recommended that the lifting and handling plan is agreed between the test facility and the test applicant. This requirement is outlined in Marinet2 deliverable D2.7-Final guidelines for test facilities.

As a minimum, the applicant should make sure the lifting and handling plan covers the following requirements:

Item	**Applicant requirement**
Delivery location	A clear mention of the delivery address near or in the test site facility. The location must be sheltered and offer sufficient space to store the device and the related hardware appropriately. Consultation with the test-site or the marine contractor to confirm availability of such facility/infrastructure is strongly recommended.

Logistic plan	A Time/Place/Freight company of the circuit followed by the device from its departure to the delivery. The objective is to provide traceability of the device and a clear expectation of the delivery date. More details regarding this item are given in section **Error! Reference source not found.** of the document.
Device technical details	The test facility or marine contractor may have the appropriate documentation ready that the applicant should fill to identify clearly the main aspects of the device. If that is not the case, the applicant should answer appropriately to all requirements of both parties regarding the device's specificities in terms of operation and handling. These items would include: - Size and geometry of the device, possibly synthetised in a set of drawings/datasheets - Lifting/Towing points and hardware of the device to be used by the marine contractor/Test site. (Section 4.2.2) - General recommendations from the applicant for transportation and commissioning of the model (Section **Error! Reference source not found.**) - List of components/subcomponents, their role, and additional spare if necessary

4.2.2 Commissioning and planning

A lack of appropriate planning can lead to unnecessary expense and delays, for example if equipment is mobilised with no provision made for where it will be stored or how it will be handled. Such a situation can result in a redesign of lifting methods and expensive lifting equipment sitting unused. Equally important is an understanding of all dynamic loadings including sudden loadings during transfer/recovery of device and equipment between lifting activities.

At low TRLs it is important to have an understanding of the structural integrity of the energy converter, its subsystems and components, and the mechanics of failure. Before marine testing, any structural changes, such as adding components or redesigning ancillary assemblies, should not compromise the structure or loading design.

The following are the critical requirements for lifting a device:

- Conduct a thorough hazard identification and risk assessment (HIRA) process as part of developing a lift plan and safe system of work.
- Lifting/winching/tag line points on the device are sized appropriately, certified and located optimally in an accessible position on the device/structure.
- Understanding of which areas on a device are sensitive to loading, with “no lift” or “no standing” clearly labelled.
- Available lifting and haulage capacity of local vessels is fully understood under static and dynamic conditions.
- Lifting transitions are considered (for example, from trailer to pier, from pier to water, from vessel to water).
- Device mass, centre of gravity and centre of buoyancy are fully understood and mitigated to avoid any interventions that would alter these parameters.
- Control of device and personnel is maintained during lifting/winching operations.
- Ensure regulations and standards are followed e.g. LOLER[7] if operating in the UK.

Below is a sample workflow that can be followed for organising and planning lifting activities.

[7] Lifting Operations and Lifting Equipment Regulations 1998 (LOLER): http://www.hse.gov.uk/work-equipmentmachinery/loler.htm

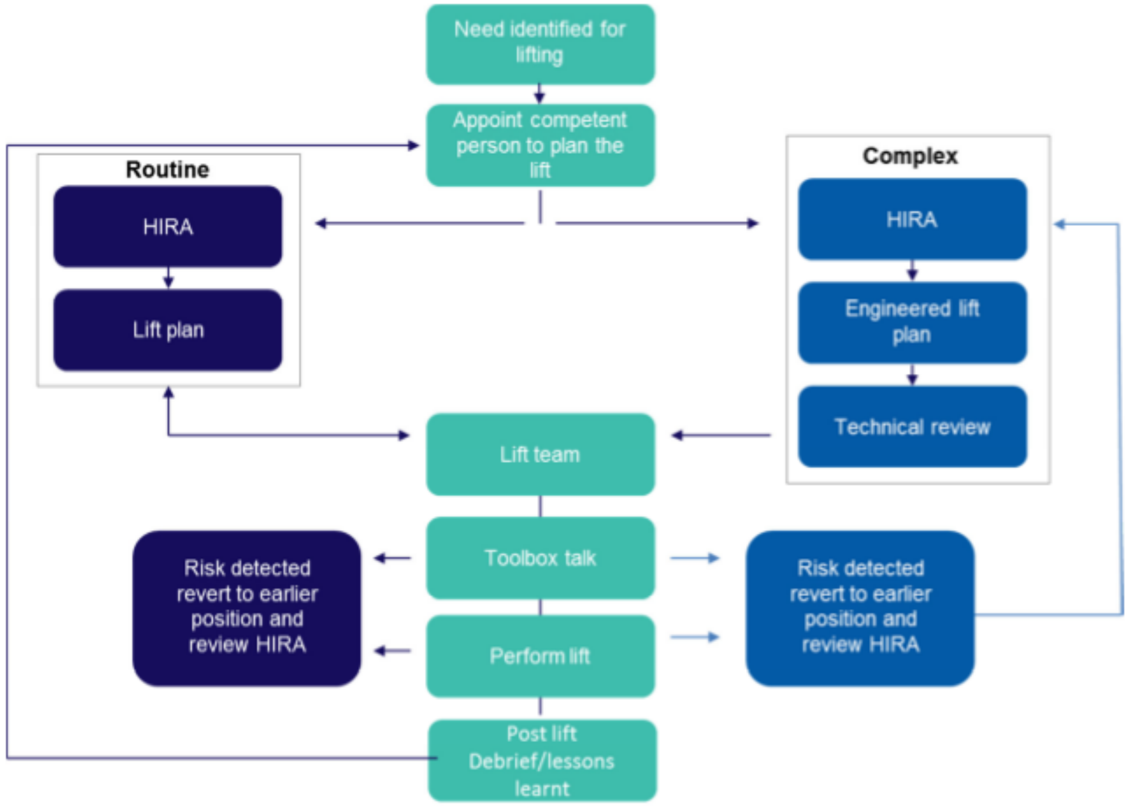


Figure 9 Workflow for planning lifting activities

4.2.3 Road transport and route planning

Road transport can be an issue for larger scale deployments when not addressed in good time with appropriate consultation. The size and weight of the load, in conjunction with the transport vehicle and trailer gross tonnages, should be understood and any required permits arranged. Roads at remote sites may also be limited in width and tight bends may cause issues. Therefore, doing an initial site review to plan the route is highly recommended.

Ideally, the road transport plan would include the route, expected times and dates and freight companies used for the transit.

It may be useful to include a transport management plan to capture the limitations and requirements of the local road conditions and capacities. Diagrams and drawings are excellent tools to visualise the transport routes.

It may be necessary to consider international custom controls if importing/exporting the device.

4.2.4 Risk management

Statistics from the Health & Safety Executive UK on injury, health and incident in 2012/2013 demonstrate the seriousness of appropriate device handling plans. The report states, 'injuries from handling, lifting or carrying' produced the most injuries in a single category followed by 'struck by moving objects',' slips',' trips', 'falls' and 'falls from height'. These four categories account for 90% of all injuries reported.[8]

A Hazard Identification and Risk Assessment (HIRA) should be carried out to identify the key risks involved in handling larger devices/subsystems or components onshore, from manufacturing site, to test location. The HIRA should include critical component risks (i.e. what is most likely to fail during handling/lifting of a device). For example, trailing cables are at high risk of damage during lifting operations.

4.2.5 Device installation

Offshore installation methodologies have not yet been standardised due to the variety of different designs still under investigation. It is considered essential that marine operations, including all support activities, are thoroughly assessed at the conceptual design stages to determine if a device can be safely installed with no or low risk to the environment.

It is essential that all users discuss marine operations with the test infrastructure before applying for access. There will be different marine operations provisions at these facilities and in many cases it is the user's responsibility to manage the installation of their device.

It is recommended that the installation plans be developed with the advice and support of marine contractors local to the deployment site, who have the onsite experience as well as understanding of the requirements for the safe securing and connecting of marine energy devices. Vital to informing the best installation methodologies will be their involvement in the technology risk assessments. Prior to the installation, inspections of the device and subsystem are recommended by the marine contractors to ensure safe installation.

The practicalities of installing any device or subsystem should be considered early in the design process. It is important to share this information with the test site. Past experience at EMEC includes a particular instance where a mooring system proved very difficult to install. Had a suitable review process been followed sufficiently early in the design process, a number of simple changes could have been made to ensure that the components were selected with attention to deployability and maintainability, and the number of days required for the task could have been drastically reduced.

[8] HSE UK Offshore injury, ill health and incident statistics. http://www.hse.gov.uk/offshore/statistics/hsr1213.pdf

As with the lifting and handling of the device onshore, electrical cables and umbilical lifts at sea are also a challenge, especially in near shore areas with wave action. The cables can undergo dynamic motions (e.g. twisting which result in kinks), which limits vessel movement during operations. It is advised to plan early reviews with contractors experienced in cost efficient cable laying and recovery activities.

In terms of connections, it is recommended to optimise and document a quick connection and disconnection plan as part of operational planning. The importance of ensuring the structural and mechanical protection of electrical connection systems should be in place prior to installation.

Identifying installation risk through HIRAs includes low and high-risk identification. For example, a low risk installation of a low weight device that can be efficiently towed to site, thereby improving OPEX costs. However, there are still negative risks associated with a low weight device if the CoG or ballast behaviour is not well understood. Incorporating risk management into the overall quality assurance processes has a positive influence, rather than restricting progress through the technology development programme.

The risk assessment for the installation procedure requires the design of the device or component to be finalised. This is occasionally overlooked as designs continue to be refined up to the last minute, which can have significant negative impacts on the ease of installation, and on safety factors of pre-installed equipment. If changes are made then a risk assessment is required based on the changes and the impact on the installation operations. Components are often not fully protected during assembly and installation and most failures can be avoided if properly secured, for example umbilical cables.

Figure 10 Scale WEC being towed to test site (Image from tidalenergytoday.com)

4.3 Marine operations

4.3.1 O&M

The planning of marine operations for deployment and recovery of the device is one of the main items to be covered prior to real-sea testing. Marine operations should, as far as is feasible, be based on the use of well-proven principles, techniques, systems and equipment[9].

Considerations for marine operations include:

- Data collection to determine local sea and weather conditions;
- Identification and selection of vessels suitable for location and task;
- Vessel audit and marine warranty surveys;
- Identification and selection of suitable ancillary equipment (e.g. towing);
- Determination of the limits for weather and sea states to conduct tasks;
- Development of safe work practices; and
- Training and competence requirements for project team working offshore.

[9] EMEC Guidelines for project development in the marine energy industry http://www.emec.org.uk/guidelines-for-projectdevelopment-in-the-marine-energy-industry/

Table 10: Operation management requirement for test applicant

Item	**Applicant requirement**
Consultation with Marine contractor	If a marine contractor is commissioned by the applicant, it should be made sure that the major items have been checked prior to deployment by both parties. These points include: - Availability of the appropriate vessels and equipment for deployment - Clear understanding of the Contractor's policy by the applicant's team members - Clear understanding of the device's specificities by the Marine contractor's team - Agreement of a method statement between all three parties (Applicant, test site and marine contractor), stating each other's role during deployment
Proper consideration of weather conditions	In addition to the previous points, the applicant, the test site and the marine contractor should agree on the risk assessment considering weather conditions during the deployment. A proper forecast of the weather conditions on site should be made available and consulted to decide the date and planning of the deployment. A consultation should be made to decide to what extent a deployment is judged unfeasible due to weather conditions, and a subsequent justification for when the conditions are judged acceptable.
Team qualification	In addition to the marine contractor team, the applicant might wish to send members of their team to be part of the deployment. In which case it is recommended that the applicant provides proof of the appropriate training and qualifications of the concerned team members. These proofs might be part of the requirements from the Marine contractor's internal policy and are detailed in section 4.3.3 of the document.

The importance of well-prepared marine operations documents covers all phases of the works, from start of preparations for the operation to completed demobilisation, including organisation and communication to familiarise personnel, is vital to long term cost reductions in OPEX. The O&M plan should include the following documentation:

- A description of procedures and acceptance criteria for testing/ commissioning of all equipment to be used for the operations
- Method Statements
- Description of vessels that are to be used
- Detailed procedures for all stages of the operation
- Hold and approval points and criteria for starting each phase of the operation
- Acceptable tolerances, monitoring and reporting details
- Verifications that the operations have been completed in accordance with the design and operational requirements.

Marine hazards are diverse in nature, and can be quite different from land-based risks that engineers are commonly more used to. They include:

- Loss of station keeping (e.g. mooring);
- Loss of structural integrity (e.g. hull, support structure failure);
- Loss of stability (e.g. ballast system failure);
- Collision (e.g. support vessel, passing vessel).

It is strongly recommended to use an O&M tool to help plan deployments. There are a number of O&M planning tools in existence and in development[10] that take hindcast data, along with detailed site data, and combine these with quality-controlled forecasts to provide a mission success chance. These tools can optimise operations within the expected weather windows, improving efficiency and cost-effectiveness. There are advanced tools are in the early stages of development, that promise to offer a significant input into the risk management of operations from both a H&S point of view, and an economic optimisation point of view.

When carrying out operations at sea, the local vessel operators who have an awareness of the site conditions and forecasts, will inform decisions at key 'break points' in the operations as to whether the best course of action is to continue, or move towards a "safe state" abandonment.

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[10] Examples of O&M planning tools available include: Forecoast Marine from JBA Consulting (http://www.forecoastmarine.com/), and Mermaid from Mojo Maritime (http://mojomermaid.com/)

It is emphasised for developers to undertake a pre-operations survey of equipment or components such as moorings before mobilisation to see if there is any risk of displacement or damage that could significantly affect operations. These inspections are cost saving measures and often overlooked during operations planning. Other inspections required by regulators would be of the seabed prior to deployment and a visual verification of seabed conditions after deployment.

4.3.2 Environment constraints

Open field testing implies a schedule of operation dictated by weather and site conditions. Considering specificities of the device and its integration, it is recommended that the applicant checks with marine contractor and test site personnel to estimate a safe and reliable deployment date and time given the environment conditions.

Table 11: Consideration of site conditions prior to deployment

Item	Recommendation
Tide table/Chart	The applicant should take into account the tide table/chart for successful deployments. It is recommended to operate during the timing of the neaps at the deployment locations. Consultation with the test site and the contractor should be carried out prior to deployment plan and method statement formulation.
Wave conditions	There might be a limit sea state or wave condition above which the marine contractor cannot guarantee security and/or integrity of the deployment operation. This should be checked prior to deployment, input will be required from the applicant regarding the past deployment operations during which deployment issues linked to wave conditions were reported.
Weather forecast	As for the two previous items, the weather (Wind, storm…) might compromise success of the deployment, and therefore the test. It is crucial to determine the appropriate weather window for deployment based on the tester's experience of its facility and the marine contractor recommendation.

4.3.3 Personnel

The tasks carried out during testing need some very specific skills and experience which few developers will have 'in house'. Sourcing guidance and advice from infrastructure managers/marine contractors/consultants or other competent persons is recommended where a developer may not have developed this experience internally. The building of these skills and experience internally within the device development company will occur over time if they choose to be involved with the operations, rather than contracting the complete operation out. Retaining experience and expertise in-house is invaluable for future design and development work

In order to ensure that personnel working offshore are suitably trained, competent and qualified to work safely offshore, certain training requirements need to be fulfilled. There are a number of training providers and qualifications available to ensure that all of those working offshore are suitable trained. Developers must confirm themselves which legal requirements are necessary for the work they are proposing to conduct.

Different individuals, companies and agencies bring different qualities and experience to a project. It is important to recognise this, and gain an appreciation of each parties' strengths and weaknesses. Ensure that the right combination of skills, experience and competencies are available, both within the lead organisation and within the wider support team, and adjust the requirements at each point in the technology development pathway.

An example of this can be shown in mooring design, specification, procurement and deployment. Moorings require a certified review of the hold capacity versus the anticipated loadings, so the expertise of a certified Third-Party Verification (TPV) organisation is essential (required for insurance and marine licencing). This will provide information on the design loads but gives no indication as to how easy it is to deploy, which vessels can carry out the work, and its ease of maintenance. To determine these often overlooked aspects, dialogue is needed with appropriate supply chain members during the design phase. During the deployment of the moorings, there are industry best practices regarding connections such as shackles, and this requires input from experienced contractor. Considering verification and ease of installation at the appropriate stage is an important part of risk management and optimised procedures.

Table 12: Recommendation on personnel mobilisation regarding three parties for the applicant

Item	**Applicant requirement**
Applicant personnel	The applicant should make sure that their personnel involved in any task included in the deployment and test plan are duly qualified. The marine contractor and the testing facility's policies might require proof that the applicant's team members can participate in the tasks. These proofs may consist in training and academic records suited for the operation. In expectation of these requirements, applicant should keep traceable records of their personnel training and competency.
Test site personnel	It is expected that qualified personnel will be mobilised by the test site to perform the required operation and analysis tasks. Most test sites best practices include a traceable record of the personnel members

	qualification and competency. As a part of the test, these evidences might be included in the reports.
Marine contractor personnel	In advance to deployment and recovery operations, the applicant should enable contact with the marine contractor and exchange regularly with the team to keep the planning updated. This requirement regards mostly how the applicant should keep in touch with the contractor's team, particularly in addressing the main steps of the operations appropriately. - Exchange with the Marine contractor's chief of operation prior to deployment/recovery and agree on the method statement. - Exchange with the personnel member responsible of the inventory/equipment in order to answer the needs of the operations - Exchanges with the planning director to decides the milestones for deployment and operations

4.3.4 Recommendations for vessels hire

All phases of a marine renewable project in open water will involve vessel-based activities necessitating selection of the most suitable type of vessel for each phase.

Vessels will be required that are suitable to deploy/retrieve the device, for cable laying and other offshore installation works. Devices and subsystems will be deployed in areas that maximise their potential, which by necessity will mean large waves, potentially significant tidal flows, and short duration weather windows. Currently there are few, if any, purpose-built vessels for these environmental conditions and therefore, early work will be required to identify suitable vessels[11].

Identification of the appropriate vessel will be based on the test facility's recommendation considering the information the applicant will deliver.

[11] RenewableUK Vessel Safety Guide 2015. https://c.ymcdn.com/sites/www.renewableuk.com/resource/collection/AE19ECA8-5B2B-4AB5-96C7ECF3F0462F75/Vessel_Safety_Guidance.pdf

Table 13: Deployment considerations for test applicants

Information	Detail
Vessel management	Vessel operators should provide an indication of how the vessel will support the deployment procedures. This review should be at a sufficiently early stage in device design so that changes can still be made if necessary. It is important to note that gradual changes in design over time can lead to increases in mass or similar limiting factors that can have step change impacts on the type of vessel required and therefore, the cost of hiring marine services. The applicants should make sure that the challenges regarding the device handling and commissioning have been clearly transmitted to the marine contractor. This information will help in an appropriate choice of the vessel used for deployment. Examples of offshore vessels used for installation at the EMEC sites for example, have included: • Multicats • Gantry Barge • Tugs • Jack-up barge • Heavy Lift Vessels
Deployment budget	Installation costs can be a significant proportion of the device development budget and may escalate due to several factors such as weather downtime, multiple deployments due to equipment failure or poorly planned procedures. The approach to installation should therefore be prioritised and included in the design stage in order to minimise costs. There should also be a realistic approach taken to the possible escalation of costs, essentially preparing the budget to include contingency. An appropriate reserve fund specific for any decommissioning should be established.
Installation scope	If intending to keep all marine operations within the readily available and cost-effective equipment capabilities of a local marine contractor, then it is again important to scope all activities well in advance of final detailed design to ensure this equipment has sufficient capacity. As an example of the cost reductions that may be possible, the Orkney Vessel Trials, completed in 2013/14 and utilising 20 local organisations, demonstrated that developers could save up to 70-80% on installation costs by utilising

	a gantry barge and other local vessels rather than commissioning large dynamically positioned offshore construction vessels.

Given the one-off unique nature of the installation operations and the potential difference in scale of moorings/foundations etc., it is not unusual for developers to charter a larger scale vessel that may appear better suited for the task at hand. A warning when using this approach is that a non-local vessel operator may have reduced understanding of local conditions and restrictions. Contracting a marine consultant with experience of the specific site conditions to oversee the operations is one way to reduce the likelihood of costly mistakes.

4.4 Device design

When designing electrical connections and moorings, consideration should be given to their safe and practical installation and access for maintenance. At the conceptual design phase, it is recommended that the designer creates a high-level overview of the cabling, moorings and/or foundation configurations for the device. The cost and time associated with complex installations for connections and moorings systems can be avoided, by engaging with a marine contractor following completion of concept design.

In general, the applicant should record appropriately the specificities of the device in an understandable way. Consultation with the test facility and the marine contractor to ensure transparency might be needed.

The international electrotechnical commission did release technical specifications related to design requirements of the MEC. These documents outline the main challenges the applicant should face during development of the MRE model.

- IEC TS 62600-2: Design requirements for marine energy systems (International Electrotechnical Commission, 2016)

- IEC TS 62600-3: Measurement of mechanical loads (International Electrotechnical Commission, 2020)

At the marine testing phase, it is recommended to produce an FMEA and develop a predictive maintenance programme for the device subsystems, and that mooring construction, assembly and testing takes place onshore as far as possible. Third party verification of the subsystems should be carried out and certified prior to installations.

4.5 Managing change during field testing

Intense short-term activities such as those that characterise the early stages of ocean energy testing hold numerous risks and tend to involve one-off type scenarios. These need active and continual management to help ensure all risks are minimised and opportunities are realised. Given the stringent demands on the project team due to the varied one-off scenarios, it is important to recognise where the team is lacking in experience and knowledge. Developing a capabilities matrix is helpful at this stage.

4.5.1 Planning ahead

There are very few plans that remain unchanged after exposure to weather, daylight, equipment reliability and theoretical rather than practical design specifications. Small changes can and should be managed on an ad hoc basis during operations by competent staff, with input from all involved parties present. There must however be an awareness that a certain level of change renders a procedure invalid, and operations must be halted to allow for a more detailed review in the calm of a non-operational environment. All changes to procedures however small should be captured for inclusion in later versions of operations.

It is important to try to create contingency plans to provide immediate guidance during an operation for when deviations from procedure occur. While the exact details of a failure may often differ from the contingency scenario, the approach to resolving a similar issue with regard to health safety and project risk management will be of use in the field.

4.5.2 Record keeping and data storage

Unexpected events might be observed during the test. As-laid survey reports for seabed assets are invaluable later in operations as they can define the exact layout of cables, chains, anchors and other mooring components. These can change by tens of metres from the documented intended locations. Often, this has no significant impact other than difficulty of finding them later but unless it is recorded, the risk from assuming its location will remain. Having a detailed chart showing the exact as left/as laid locations of all seabed assets is very valuable to developers and marine contractors who often need to find clear seabed to place temporary moorings. Poor survey and maintenance of records can lead to incidental damages. It is also important to re-run device simulations/calculations to ensure that the dynamics and structural loads are not adversely affected by misplaced anchors, for example.

Recording deviations from the planned activities is of value in terms of adjusting future procedures, or for re-evaluating the capabilities of vessels, contractors, and equipment.

The table below references the items covered in deliverable 2.7 of Marinet2 regarding the same subject. The requirements linked to data handling for test facilities are similar to the ones recommended to the applicants. It is assumed that the applicants would have to follow data handling policy of the test site. However, the process should be checked and approved by both parties prior to starting the test.

Table 14: Records and data storage recommendation for test applicants

Item	Recommendation for applicant
Back up storage	In case of failure/destruction of the test output storage system, the applicant should verify with the testing facility that a back-up

	facility is available and with sufficient storage to retrieve the data recorded during the test. If it is the tester's responsibility to make sure that enough space is available for the amount of data, advise from the applicant regarding the best back-up storage solution considering the file format is recommended.
File referencing	The file referencing is also directly linked to the tester's SCADA system and storage policy. For data traceability, both parties should agree on how the files will be referenced. This referencing method should allow to uniquely identify the test and the date/time when the output file was generated.
Traceability	This item constitutes an addition to the previous point regarding file identification. Depending on the test plan, the number of sensors can increase significantly from one test to another. It is recommended that the output file name from each sensor includes a reference allowing to the instrument that generated it to be identified directly (Serial number, for example)
Major event record	As described above, unexpected events are a part of the test. The date of their occurrence and their impact on the test process/results should be noted and reported. It is expected, as mentioned previously, that a risk assessment would be performed on the test prior to starting it. If an unexpected event (Not considered in the risk assessment yet) occurs during the test, the applicant should take that in account for risk assessments dedicated to future tests.

4.5.3 Component and subsystem failure

When testing new technologies, it is important to recognise that failure of components or subsystems is inevitable and forms an essential learning aspect of the product development cycle. FMEA is an integral reliability assessment process and should be detailed down to the component level and understood well before marine operations begin.

However, once at the test infrastructure, capturing and analysing the details of any failure is an important part of this cycle, and one that can be left aside in the rush to prove full system capability. To illustrate, previously developers have been noted to continually replace a failed bearing with identical components, without appearing to analyse wear patterns and failure modes in order to specify/develop new and improved bearings for inclusion in the device. While it is recognised that this can often be a stop gap to keep a test programme on track, as it is not always possible to redesign/fabricate/procure bespoke items quickly, this should not be the final solution. Including costs for failed component testing/analysis will secure greater knowledge for the developer, including informing and adding greater certainty to the preventative maintenance plan. For earlier designs, using conservative standard, marinised components will mitigate against the high-risk failure mode such as corrosion if you are conducting marine trials.

A procedure should be put in place to capture the detail of a failed component, to ensure the comprehensive review of a failure and to outline proposed remedial action. In addition to component or system failure, there is also procedural failure to be considered. This can be recorded through daily reporting logs, incident reports, or through the analysis of video recording of operations. The feedback of where procedures have failed is critically important in the updating of the risk register, and the procedures themselves.

EMEC, for example, has a failed component capture, and handling procedure in place to ensure that components are not 'binned'. The challenge is to ensure that a budget is in place for analysis of failures and the data captured in a database like the WMEP[12] wind reliability database or OREDA[13] reliability database for the Oil & Gas sector. A dedicated reliability database for wave and tidal energy would prove beneficial for the ocean energy sector.

4.6 Safe operations

It is of prime importance to ensure that the hazards, opportunities, and uncertainties associated with all programme activities are identified, understood and managed appropriately and that where necessary, suitable mitigation and insurance has been put in place. The risk register is a singularly important live document that should be updated whenever a new risk, or means of mitigation, is identified.

A complete, well-presented risk register is a first step toward a strong health and safety culture. Furthermore, it may lead to lower insurance premiums as insurers have more confidence in the level of planning being applied.

One considerable addition to the H&S burden on site can be pressure to perform. Where possible, users should try to disconnect the day-to-day operations from the financial pressures within the company. The danger of this has been shown in the previous experience of developers where pressure to perform and maintaining an unrealistic schedule has resulted in mishap or failure rather than the goal of success leading to revenue. The coupling of energy generation revenues directly to the technology development pathway should be avoided where possible, through guided negotiations with investors or funding bodies.

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[12] Fraunhofer Wind reliability database http://windmonitor.iwes.fraunhofer.de/
[13] OREDA Offshore Reliability Database for O&G http://www.oreda.com/

4.6.1 Construction, Design and Management Regulations

Regulations concerning occupational health, safety and welfare are in construction and are relevant for higher TRL tests. They place responsibilities in relation to management arrangements and practical measures on a range of construction project participants, including clients, designers, and contractors. For example, the Construction Design and Management (CDM) regulations[14] will apply to work carried out on sites in the UK. Similar regulations apply in other countries and should be investigated by the user.

Together with the supporting Approved Code of Practice (ACoP), they maintain the broad level of implementation for H&S. ACoPs provide guidance on compliance with general H&S regulations. The following are examples of regulations relevant to the UK. Users should research the relevant regulations in other locations.

- The Health and Safety at Work Act (1974)[15]
- The Management of Health and Safety at Work Regulations 1999
- The Reporting of Incidents, Disease and Dangerous Occurrences Regulations 1995
- The Control of Substances Hazardous to Health Regulations (updated in1999)
- The Noise at Work Regulations 1989
- The Provision and Use of Work Equipment Regulations (PUWER)
- The Lifting Operations and Lifting Equipment Regulations (LOLER)
- International Convention for the Prevention of Pollution from Ships (MARPOL)
- The Diving at Work Regulations 1997
- The Electricity at Work Regulations 1989
- Safety of Life at Sea (SOLAS)
- Code of Safe Working Practices for Merchant Seamen
- Confined Spaces Regulations 1997

The ACoP covering The Diving at Work Regulations 1997[16] is the commercial diving projects offshore ACoP. It is prudent to investigate the associated ACoPs for any of the above regulations.

4.6.2 Emergency response/reporting

The management systems put in place at the start of a company's development project should include clear sections on emergency response at each point during the test schedule. At early development stages this will likely be very light, and in accordance with emergency procedures at the test tank. However, as the technology progresses to at-sea test sites, there

[14] Construction, Design and Management Regulations 2015 http://www.hse.gov.uk/construction/cdm/2015/index.htm
[15] Health and Safety at Work Act 1974 http://www.legislation.gov.uk/ukpga/1974/37/contents
[16] Diving at Work Regulations 1997 http://www.legislation.gov.uk/uksi/1997/2776/contents/made

will be a significant jump in complexity and risk, and the resultant need for increased documentation is evident.

All O&M plans should have operational contingency plans in place for each step in the procedure and sitting behind these contingencies should be an emergency response plan (ERP). This is for use when the situation changes from a means of making project progress, to the safeguarding of personnel and equipment. The ERP should have a detailed process worked out well in advance, and contracts put in place for any additional equipment or vessel hire required. These contracts should cover details like call out rates at various levels of notice, for different times and of different levels of equipment/vessels.

There are responsibilities regarding the reporting of incidents to the authorities, often determined by the impact it has on the persons involved (see CDM Regulations 2015).

5. Conclusion

This document provides guidelines for users applying for an access grant for testing, or for planning a test campaign using the experience gained in the MaRINET2 TA program. Guidance is given on the key features of a successful proposal. Recommendations are then made for applicants that have been successful in their proposals and are embarking on a test campaign, either in a laboratory or at sea. Laboratory testing and sea testing present different challenges, and users are strongly encouraged to research the testing methods and logistical issues involved for both types of campaigns. References are provided for useful sources of information. A well-informed developer is more likely to conduct a successful testing campaign and avoid past mistakes. At all points, communication is key for efficient and well-run tests.

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