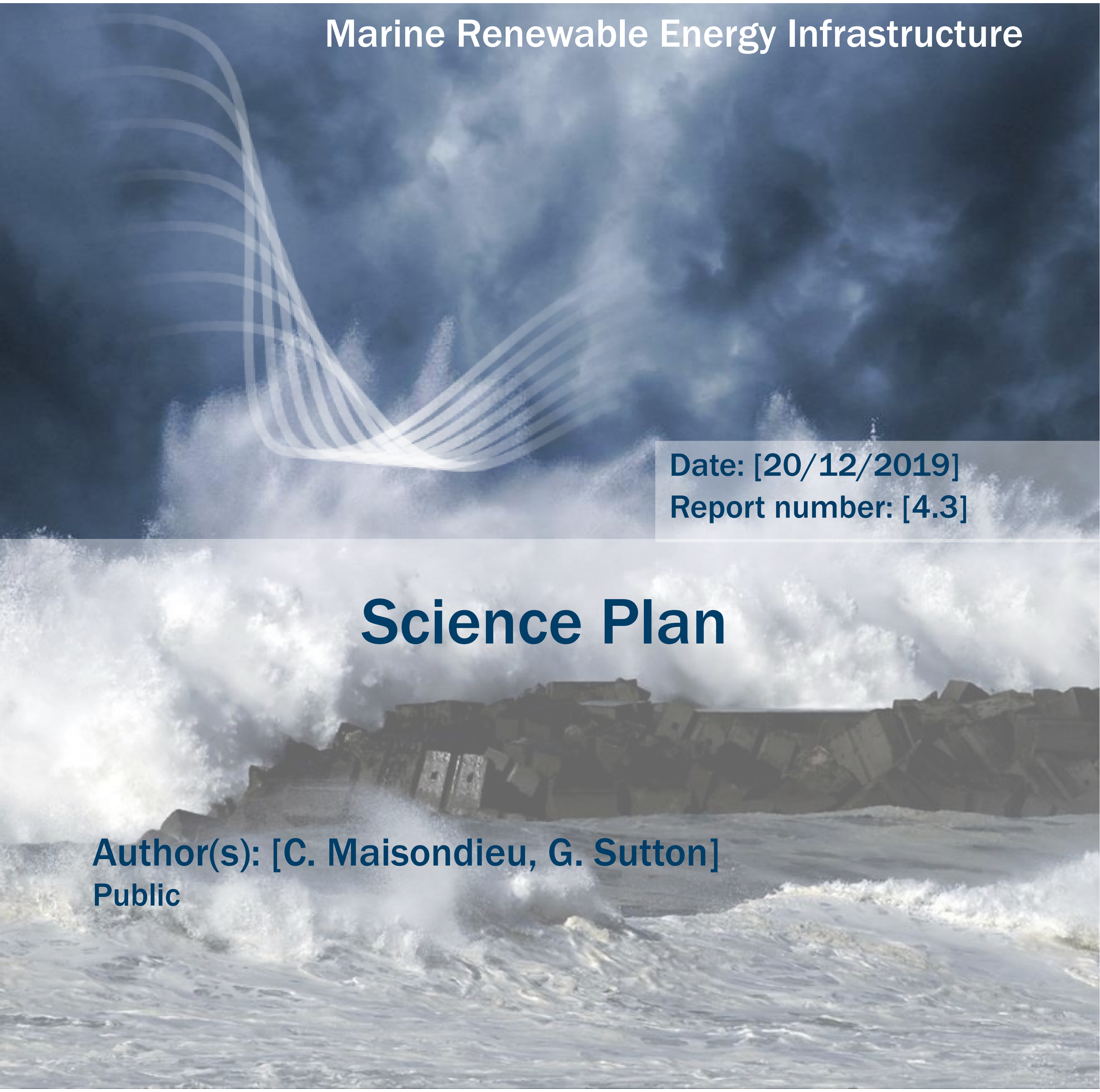
marinerg-i

Marine Renewable Energy Infrastructure



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Abbreviations

DRI	Distributed Research Infrastructure
ORE	Offshore Renewable Energy
LCOE	Levelised Cost Of Energy
WEC	Wave Energy Converter
ISSC	International Ship and offshore Structures Conference
TRL	Technology Readiness Level
ITTC	International Towing Tank Conference
IEC	International Electrotechnical Commission

Preface

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Appendix

Executive Summary

MARINERG-I will create and implement an international programme of research, development, observation, and modelling to advance progress in harnessing Offshore Renewable Energy to increase energy autonomy and reduce greenhouse gas emissions.
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1. Introduction

1.1. About this document

The document provides the rationale and direction for the scientific activity to be conducted within the Pan European Distributed Research Infrastructure (DRI) MARINERG-i, which aims to support the development of Offshore Renewable Energy (ORE) at European and global levels. It is intended as a living document which will be updated periodically in order to maintain currency and relevance. This first generation MARINERG-i Science Plan is designed to support the MARINERG-i bid to be placed on the 2021 ESFRI roadmap.

1.1.1. Method

The Science Plan has been developed in parallel with the Design Study (D4.4) and Business Plan (D8.2) as key interrelated elements of the MARINERG-i INFRADEV project. A collaborative design process has ensured that key stakeholders in all participating countries have contributed to defining end-user requirements, and to ensure relevance and applicability in terms of their own research facilities. Dedicated workshops and meetings were used to elaborate the scientific agenda as well as an iterative reporting procedure involving all partners for the definition and elaboration of the research themes.

1.1.2. Scope

The Science Plan considers ORE technologies and their relative competitiveness at all Technology Readiness Levels from proof of concept and design optimization right through to the full operational scale (TRLs 1-9), thus taking into account the current and future requirements of a broad range of end-users and developers. This integrated approach is designed to specifically address the twin overarching long term DRI goals which are to reduce the Levelised Cost of Energy (LCoE), and to reinforce investor trust and confidence in ORE technologies.

In the context of MARINERG-i, Offshore Renewable Energy is regarded as including three major technological fields, defined by the mechanical uptake and conversion of the energy flux associated with environmental flows, namely: wave, tidal and wind. These technologies can potentially be linked in a combined approach which optimises the exploitation of the resource while contributing to a reduction of the LCoE (e.g. through efficiencies in cable laying and grid connection for example).

The Science Plan also considers the electrical and grid connection aspects of the ORE devices as well as cross-cutting technologies. ORE technologies based on thermodynamic exchanges such as Ocean Thermal Energy Conversion (OTEC), Sea Water Air Conditioning (SWAC) or salinity gradient are considered outside of the primary focus of MARINERG-i. However, contribution to the development of these technologies through MARINERG-i can be considered where common research topics can be addressed (mooring and floating structure design, new materials, monitoring, energy storage…).

1.1.3. Context

The ocean energy industry estimates that 100GW of wave and tidal energy capacity can be deployed in Europe by 2050, meeting 10% of Europe's current electricity needs (ETIP ocean 2019). Wave and tidal technologies even though at different TRLs are trailing offshore wind, having yet to achieve large-scale deployment. The marine environment is harsh and creates highly challenging conditions in terms of reliability, survivability and maintenance of wave and tidal devices.

While fixed offshore wind is significantly more developed than the wave and tidal sectors, and is approaching a point where it is cost-competitive with fossil fuels, reductions of the LCoE are still being sought through the development of wind farms with larger turbines, further from the shore. The current push is for floating offshore wind platforms which are beginning to enable large scale energy production in deeper waters. The scientific challenges associated with all of these developments is considered herein.

Overall, the MARINERG-i Science Plan is a strategic research agenda that considers ongoing EU coordination/roadmap initiatives (Ocean Energy Roadmap, Set plan/ETIP Ocean/ ETIP Wind, etc.), as well as end-users requirements identified during the discovery phase of the MARINERG-i INFRADEV project.

MARINERG-i will work towards the achievement of European renewable energy targets and, in particular, contribute to the development of the blue economy by supporting the commercialisation of floating wind, tidal, wave and combined energy technologies and ensure their competitiveness in the energy market.

MARINERG-i will thus be well positioned to address aspects of the following key global environmental issues:

- Carbon free Energy
- Climate Change
- Sustainable Development of our Seas and Oceans

The Research Infrastructures contributing to the MARINERG-i DRI will thus need to continually innovate in order to push the boundaries of what can be achieved or learnt from pre-commercial testing of ORE technologies, and to keep step with industry requirements.

1.1.4. Document structure

Section 1 provides the background and context for the key scientific questions relating to Offshore Renewable Energy development which have been grouped under four main headings as Research Themes, and which are presented in Sections (2-5):

- Theme 1: Resource characterisation and environmental loading
- Theme 2: Design, Power Take-Off and performance characterisation/optimisation
- Theme 3: Cross-cutting and material testing
- Theme 4: Research for testing

Section 6 provides an overview of the Science Plan implementation, considering all aspects regarding MARINERG-i governance and project management as well as communication and outreach, relationship with other organisations, education and capacity building.

1.2. Summary of MARINERG-i high level objectives

The objective of MARINERG-i is to become the leading internationally Distributed Research Infrastructure in the Offshore Renewable Energy sector. Its integrated nature and coordinated approach will accelerate the development and deployment of wave, tidal, offshore wind and combined energy technologies. The MARINERG-i DRI will help maintain Europe as a global leader in this emerging and constantly evolving industry. In addition, MARINERG-i will strengthen European, scientific and engineering excellence and expertise as its combined facilities represent an indispensable tool to foster innovation across a large variety of ORE technologies through all key stages of technology development.

MARINERG-i will build on the existing community developed in the FP7 MaRINET and H2020 MaRINET2 projects, to create a global scientific community with a broad base of expertise and knowledge across disciplines, that has at its disposal the facilities, tools and e-infrastructure necessary to support research in ORE as a core activity within ocean and engineering science. This structured community will address fundamental questions within clearly identified research themes and across all the levels of technological development that will help accelerate ORE development.

1.3. MARINERG-i organisational structure

As a Distributed Research Infrastructure, MARINERG-i will consist of a Central Hub and interlinked National Nodes all gathered under a unique banner. It will have a recognised legal status and will operate under a clearly determined governance structure that defines the responsibilities and competences necessary to guarantee efficient coordination. Interconnections between National Nodes and with the Central Hub will allow the implementation of a dedicated user programme providing a single point of access for all users. The unique access policy will ensure that the most appropriate support is given to users to help them achieve their research and development aims.

1.4. Rationale for a MARINERG-i science plan

1.4.1. Requirements for a trans-national Distributed Research Infrastructure.

Designing and optimising ORE devices is a long term process requiring cross-sectoral and multi-disciplinary approaches. Europe is the leader in the development of ocean energy technology (ETIP Ocean 2019) and there is a clearly identified need for a structured approach that brings together the resources necessary to consolidate this leadership and help the ORE industry reach its goal of significantly contributing to global power production. The integrated approach envisioned for the development of the MARINERG-i transnational Distributed Research Infrastructure is in that perspective extremely beneficial:

- The MARINERG-i DRI offers the capacity for strategic planning of research facilities across Europe so as to avoid redundancies and/or gaps across the TRL map while offering more visibility to researchers and ORE technology developers.
- Bringing together a large number of engineers and scientists, the MARINERG-i DRI will create a cohesive scientific community with core strategic objectives focused on improving services, identifying the relevant questions and approaches to answer them and ultimately enable the development of the ORE sector.
- Developing and securing a sector such as the ORE industry is a long-term process requiring important resources. The MARINERG-i DRI will bring together the critical mass of knowledge, skill and resources necessary to sustainably address the issues raised by the constantly evolving ORE sector.
- Trans-national collaboration conducted within the MARINERG-i DRI coordinated structure will enhance and optimise testing processes through the common

implementation best practice. This will reduce lead-times and testing durations, while also reducing time wasted in repeating work within individual facilities. Sharing experience and learning will maximise return on investment and impact in terms of Key Performance Indicators (KPI) (innovation, clusters, economic development, jobs) through improved efficiency and optimisation of resources.

1.4.2. Scientific rationale

Oceans represent a huge source of renewable power which can fulfil a substantial part of the global energy requirement when harvested sustainably. Advanced offshore technologies and practices e.g. particularly from the Offshore Oil & Gas industry can be applied in the ORE sector. However only a very limited number of offshore renewable energy converters are connected to the grid and contributing to global power production despite the high number of research programmes conducted at the national and international level over recent few decades and involving both academia and the industry. This apparent low rate of return on investment is associated with several main factors including :

- Environmental and social license to operate. Identification of such impacts is an essential part of the development process that must be explored, potentially through long duration staged assessment procedures. It can be noted that these societal and environmental issues should be factored in and researched in tandem with the technical issues.
- Economic issues are also fundamental as energy costs must be kept low and a high level of reliability must be guaranteed to reinforce investors' trust in the ORE industry at all stages of development.
- Extracting energy from the ocean in order to sustainably provide power to the grid requires extremely complex technological and engineering capability and the development of new knowledge and skills with which to address fundamental questions at all the key stages of development

The following list provides an example of some of the key generic questions that MARINERG-I Scientific and engineering research agenda addresses:

- Whilst the overall levels of offshore power availability are high, how it is distributed in time and space is still poorly described and highly unpredictable. How can we account for this random variability, and more specifically how do we correctly account for the directional and spectral distribution of the energy within a sea-state when designing a wave energy converter?
- Tidal currents are predictable however, can we actually measure and predict the effects of turbulence-induced variability and can we reproduce these phenomena at a reduced scale? Are secondary effects being neglected in the design parameters (wave-current interaction, bathymetry, etc)? How do we understand and replicate multi-element array effects in test facilities?
- How can a device produce useful amounts of power of reasonable quality in its intended deployment locations while being able to withstand the extreme conditions it will face over its lifetime? Will it be capable of sustaining production continuously and autonomously for extended periods without maintenance?
- Can full scale devices be cost effectively manufactured, handled, deployed and operated using existing affordable techniques and equipment?

- What are the underlying design principles that will drive convergence towards the most effective devices across the sectors and design classes?
- Could the development of novel materials and sub-components yield to new paradigms in the design of Offshore Energy Converters?
- How can open sea environmental conditions be realistically and accurately reproduced at reduced scale in a laboratory, combining waves and currents, waves and wind or the three forcing fields together?
- How can integrated cross-scale validation studies be designed and implemented so as to guarantee the continuity and validity of the assumptions made in the performance/behaviour assessment process of a technology?
- Do existing measurement techniques and monitoring procedures provide the level of accuracy required to apprehend and understand the physics at stake? New instrumentation and methods might be necessary for enabling more advanced understanding of technology behaviour, present and future.
- How useful can be Software in the loop and Hardware in the loop processes to circumvent the difficulties in replicating at reduced scale complicated aerodynamic and hydrodynamic loading as well as in simulating the behaviour of Power Take Off (PTO) systems.
- Sophisticated and powerful numerical approaches with combined aero/hydro/servo/elastic modelling are now being developed. How can experimental testing facilitate their validation and integration so as to maximise the understanding of technology behaviour?
- Are the existing facilities adapted to the assessment of innovative technologies and how could the portfolio of European facilities be consolidated? For instance for testing performance and behaviour of hybrid (e.g. floating wind/wave) designs which blend partially incompatible theoretical approaches?

Figure 1: Storm wave (Copyright ©Rachael Talibart)

1.5. Summary - Research Themes

Based on the foregoing rationale it is clear that MARINERG-i needs to tackle a broad range of fundamental questions whose answers are needed to support the ORE industry through all the stages of development along the path to deployment and production.

A science and engineering R&D program divided into four main themes provides a convenient structure within which to consider the main groups of technologies associated with extracting energy from waves, currents and wind; and the necessary learning process based on testing at all scales from the controlled environment of the laboratory to the real open sea conditions of the test sites. The structure of these four themes is summarised below and presented in detail in the following sections 2 -5:

THEME 1 - Resource characterisation and environmental loading

- *Wave resource – A spectral description of complex sea-states*
- *Tidal resource – A more accurate description of the flow turbulence*
- *Wind resource – The flow variability in the lower boundary layer*
- *Coupled environmental conditions – Adapted monitoring strategies*
- *Biofouling – Monitoring of impact on ORE devices*

THEME 2 - Design, Power Take-Off and performance characterisation/optimisation

- *Hydrodynamics – Flow kinematics and interaction with structures*
- *Power transfer systems – Systems configuration and optimisation*
- *Power Take-Off and electrical – Energy conversion, current transmission*
- *Control strategies – Converters arrays and grid connection*
- *Numerical/Physical coupling – Scale effects, CFD resource*

THEME 3 - Cross-cutting and material testing

- *Materials – Long term reliable material data*
- *Moorings and dynamic cables – Environmental dynamic loading*
- *Electrical connectors – Solutions to reduce CAPEX and OPEX*
- *Maintenance and Operations – Reliability and cost reduction*
- *Biofouling – modelling and prediction/ Monitoring of impact on ORE devices*

THEME 4 - Research for testing

- *Reproducing environmental conditions at reduced scale – Scaling effects and limitations*
- *Development of measurement systems and procedures – Transient and non-linear conditions*
- *Monitoring*
- *Development of new facilities – wave/current/wind combinations*

The four key research themes are summarised in Figure 2.

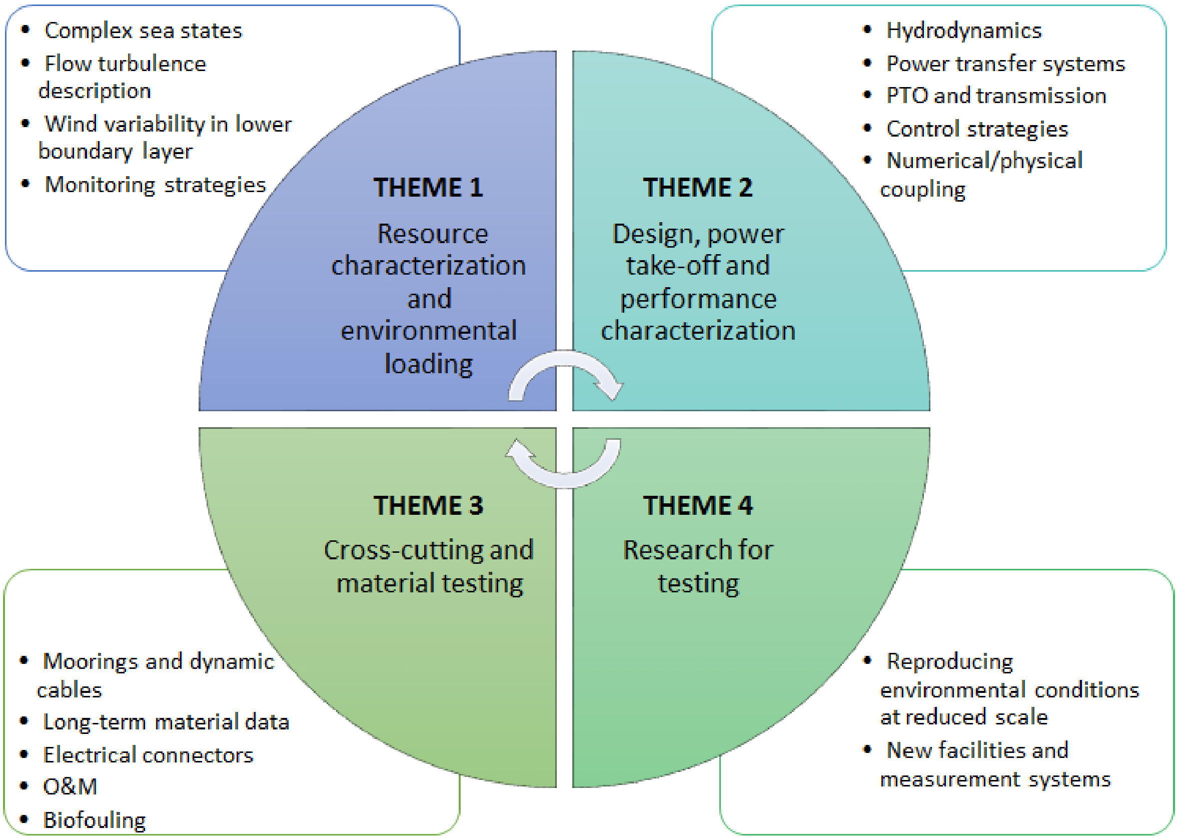


Figure 2: Science Plan Research Themes

2. Theme 1 - Resource characterisation and environmental loading

A major part of available marine energy actually arises from solar radiation, transferring large amounts of energy to the Earth's atmosphere and surface area, whether over continents or over oceans, and by gravitational interactions with neighbouring astral bodies and satellites. This makes it “permanently” renewable. The mapping of this marine resource available for conversion has already been conducted at the global [1] [2], [3], regional and local levels, [4], [5], [6], for offshore wind, wave or tidal energy and various references [7], [8], indicate that its potential could cover a significant part of the electricity needs of the earth population. When considering resource characterization, the general features of the distribution of marine energy are well known together with the associated benefits and relative disadvantages: Tidal energy, pseudo-periodic by nature, can be considered relatively predictable. Its exploitation is however currently restricted to the geographical areas of limited extension where current velocities are high enough. Offshore winds are statistically higher and less turbulent, having less wind shear than onshore winds. They however show a large variability at all time scales and rise from random processes. As a consequence, waves resulting from the interaction of the lower atmospheric layer winds with the ocean surface globally show the same unpredictable variability from inter-annual scales to the duration of a few wave periods that contribute to making this resource quite difficult to harness.

Resource mapping is both relevant and essential for the planning and optimization of the deployment of marine energy converters. It enables developers to optimize energy extraction, as well as ensuring that technologies are designed to be accessible and survivable on a given site.

Indeed, structural interaction with the marine environment is complex and designing a device requires an accurate description of this environmental forcing. Sea-states for instance, result from the superimposition of locally generated wave systems and remotely generated swells, so that the wave energy is distributed in both frequency and direction. Wave Energy Converters (WECs) endeavor to optimise this complex wave distribution whilst energetic tidal currents are usually affected by a large to medium scale turbulence that can potentially reduce turbine efficiency while accelerating their structural ageing. Similar challenges have been identified in the offshore wind sector. In addition, these three “forcing fields” are coupled by nature and in most cases it is their combined action on the structures that should be taken into account in order to develop optimal designs with best efficiency.

Providing an adapted characterisation of this environmental loading is a key element to produce an optimal design of offshore renewable energy converters. This requires availability of relevant datasets, either obtained from measurement, in-situ or remote, or from modelling. It also necessitates the elaboration of adapted data processing and analysis procedures allowing for a better knowledge and description of the relevant physics. In the context of the research programs involving testing at open sea test sites or in controlled research laboratories, this also requires the development of adapted monitoring tools and procedures aimed at identifying and reducing uncertainties on the metocean conditions and environmental forcing.

Considering the objective of MARINERG-i to contribute to the acceleration of the deployment of offshore renewable energy converters through testing of devices at all stages of development, developing a capacity to characterize more accurately the environmental loading on structures at the scale of a test site or a production site is a key requirement. Indeed, a capability to deliver an accurate description of the input to the general design and engineering problems would help reduce the uncertainties and improve the reliability and resilience of the systems. Therefore, new monitoring and measuring equipment as well as processing methods are required to tackle complex issues which cannot be resolved with existing tools. Indeed, acquisition of the information necessary for understanding the considered phenomena and validate their replication at reduced scale in tanks requires the development of new measurement technologies and processing methods.

2.1. Wave resource

The global theoretical wave energy potential is high (32 PWH/year [1][8]), compared to the worldwide electricity consumption, but its distribution is relatively uneven and widespread across the oceans. Also depending on the location, time variability, including seasonality and inter-annual variability can also be relatively high. As a consequence, some of the most interesting areas for wave energy extraction are not necessarily correlated with the most energetic areas with the largest raw resource [9]. When considering the development of wave energy converters, it is clear that technology convergence, similar to wind energy, is not yet close and technology costs are still high when calculated based on the produced power (Levelised cost of Energy).
Assessment of the potential wave energy production, especially when considering the MARINERG-i objectives, requires two major competences:

- A capacity to provide an accurate description of the resource and wave loading.
- A capacity to accurately assess the performance of a wave energy converter in given environmental conditions.

These two topics are linked as, in order to provide accurate information on the environmental loading, one has to clearly understand the way the device interacts with its environment.

The main objective of the design process is to develop devices having an optimal efficiency when in operation while having the capacity to survive the most extreme conditions. In the case of WECs, this is a relatively complex problem to solve. Indeed, the moving parts of the device must be light and compliant enough to respond to the mild to moderate wave conditions prevailing most of the time and around which the device power production is tuned but also be strong enough to resist the extreme loading associated with storms. Even though the highest or the most damaging wave do not necessarily happen during the most severe storm, the probability of reaching the survivability limit of the structure is associated with the occurrence of the strongest wave events. Thus the design process requires the estimation of weather conditions having return periods longer than the expected lifetime of the structure itself. Recorded wave time series having a sufficient duration to allow a realistic extrapolation of these extreme values are rarely available and commonly using hindcast time series is the only option. These hindcast datasets are generated using numerical models which are calibrated and validated against in-situ measurement data provided by buoys or remotely sensed satellite data, themselves also calibrated against reference buoy measurements.

This validation process is usually based on the evaluation of the relative error between the buoy data and the model data, assessing standard error estimators considering only

[1] PWH/year = PetaWattHour/Year=10^{15} WattHour/year

global parameters such as significant wave height, energy and peak periods or mean direction. However this approach does not allow a complete validation of the model as it does not provide a full insight in the capability of the model to accurately describe the spectro-directional distribution of the energy within a sea-state [10]. Directional spectra provide the most comprehensive information on the wave energy distribution and are relevant to the design of marine structures and more specifically to optimize WECs [11], [12]. The quality and accuracy of wave spectra estimation is of prime importance to reduce uncertainties on the wave loads acting on structures and their response as all sea-states parameters used in design will derive from these functions. Attempts have been made to characterize uncertainties associated with measured wave spectra [13]. However, definite conclusions are still hard to draw as data provided by wave-buoys has associated uncertainties.

Indeed, procedures and processes necessary to recover wave information from recorded time series of the dynamics of a wave buoy are complex and major uncertainties remain, whether it is considering the short term measurement of the free surface elevation necessary for input to control methods [14] or wave to wire approaches [15], the identification of steep and breaking waves or the longer term estimation of the spectrum characterizing a sea-state. For instance, the coupling with the dynamics of the mooring can influence the response of the float itself, especially in sea-states with high waves inducing circumvention of the crest or breaking waves submerging the float; signal processing requires filtering, hence alteration of the information; and methods used for recomposition of the directional spectrum itself are to be used with caution [16].

An efficient way of optimizing WECs in terms of power extraction is to design these systems together with the associated control procedures so that their response is efficient and optimal over the widest span of the encountered sea-states spectral bandwidth. Hence, WEC design requires a proper description of the actual wave energy spectral distribution within sea-states, especially in areas with wave climates dominated by complex sea-states - superimposition of one wind-sea and one or more swells. Indeed, analytical spectra such as JONSWAP or Pierson-Moskowitz functions are not adapted to the description of multimodal sea-states. Their use for the evaluation of the response of a structure as for instance when assessing the power extracted by a wave energy converter, might introduce a rather significant bias [17].

A global high level of occurrence of multimodal sea-states is recognized and the local co-existence of swells and wind sea have a rather large regional variability. In the case of such complex sea-states, directionality, characterised by the direction of propagation and directional spreading of the waves as well as the relative direction of propagation between the various wave systems becomes an important parameter for WEC designers.

The methods developed for the identification of wave events simultaneously occurring at a given site [18] can provide new approaches for a description of the time evolution of complex sea-states by events. They are potentially suitable for engineers when estimating devices fatigue ageing [19] and are also adapted to the management of operations or optimisation of the production as they can contribute to optimize the forecasting of the time intermittency of the resource [20]. However, such methods still require the development of statistical analysis procedures providing parametric outcomes adapted to the needs and tools of the sector.

Marine operations, whether for deployment, recovery or maintenance, account for a large part in the costs associated with the development and exploitation of WEC farms [21]. Hence optimising the management of such operations is a key element in the reduction of the LCOE. Optimal planning of these operations requires a characterisation of the wave climate not just at the scale of the production site itself but more preferably considering the whole regional area including the location of the port facilities and the transit route for the supply and operation vessels. Hence, local monitoring is no longer sufficient and regional characterisation of the wave climate becomes necessary. Therefore in-situ measurement data can be merged with model data and potentially other sources of information offering global or regional coverage, such as satellite and HF radars.

Indeed, the wave buoy, even though being the reference is not the only measurement device providing relevant information on waves. Acoustic Doppler Current Profilers (ADCP), originally designed to measure current velocity profiles are now adapted to the measurement of wave kinematics when placed on the sea-bed in shallow to intermediate waters and provide relevant spectro-directional information [22]. Their use in deeper waters however requires the deployment of a mooring line and is more complicated as compensation for the mooring dynamics is to be implemented and is often an additional source of error.

The ability of wave acquisition stereo-video systems to characterise the space-time evolution of waves over a limited area was demonstrated about a decade ago [23] and recent developments showed the relevance of this method for the identification of breaking waves [24]. The method is however not yet adapted to continuous site monitoring due to data storage and processing limitations as well as a relative sensitivity to environmental conditions

In spite of some interesting results, developments are still necessary to confirm the ability of HF radars to retrieve reliable estimates of the wave parameters [25] especially in areas were the presence of currents or obstacles such as islands complicates the calibration/validation process.

X-band radar is considered as a more reliable remote sensing technology for the assessment of wave parameters, even though improvements are still thought in complex coastal areas [26].

Satellite remote sensing offers a valuable source of information for sea-state characterisation [27]. Long duration time series of significant wave height derived from altimeters are now available. Spectro-directional information can be retrieved, still with some limitations, from Synthetic Aperture Radars (SAR). However, because of its discretisation in time (return period of 10 to 35 days) and space (intertrace up to 300 km) in addition to its lower quality in coastal areas, satellite remote sensing data is not the most adapted for wave resource characterisation. Still, it offers a relevant reference for model data validation as well as for data assimilation in hindcasting and forecasting models.

Elements discussed indicate that in spite of an already existing relatively good knowledge of the global wave resource, research and development is still needed to provide engineers and developers of Wave Energy Converters a refined and accurate characterisation of the wave energy distribution. This is necessary to reduce uncertainties hence contribute to largely reduce the LCOE by optimising the efficiency of the devices while improving their capacity to resist the harshest conditions and reducing the need for maintenance operations.

The activity conducted as part of the MARINERG-i research program will contribute to the improvement of the wave loading characterisation for design considering both technological and theoretical developments. It will take advantage of the availability of open sea testing sites to define and test monitoring methodologies and procedures also adapted to the long term monitoring of production sites. The challenges that will be addressed include:

- Improvement of the local in-situ wave measurement capacity (wave buoy, ADCP, disruptive technologies) with focus on the spectro-directional characterisation and large and steep wave measurement.
- Improvement of technologies and processing methods for remote sensing at a local or regional scale (X-band radar, stereo-video,…)
- Multi-sensor multi-source sea-state characterisation using collocation methods
- Spectro-directional validation methods for the calibration and validation of hindcast wave models
- Development of methods for real time interaction between wave gauge and WEC to enable optimal control and maximize power production…

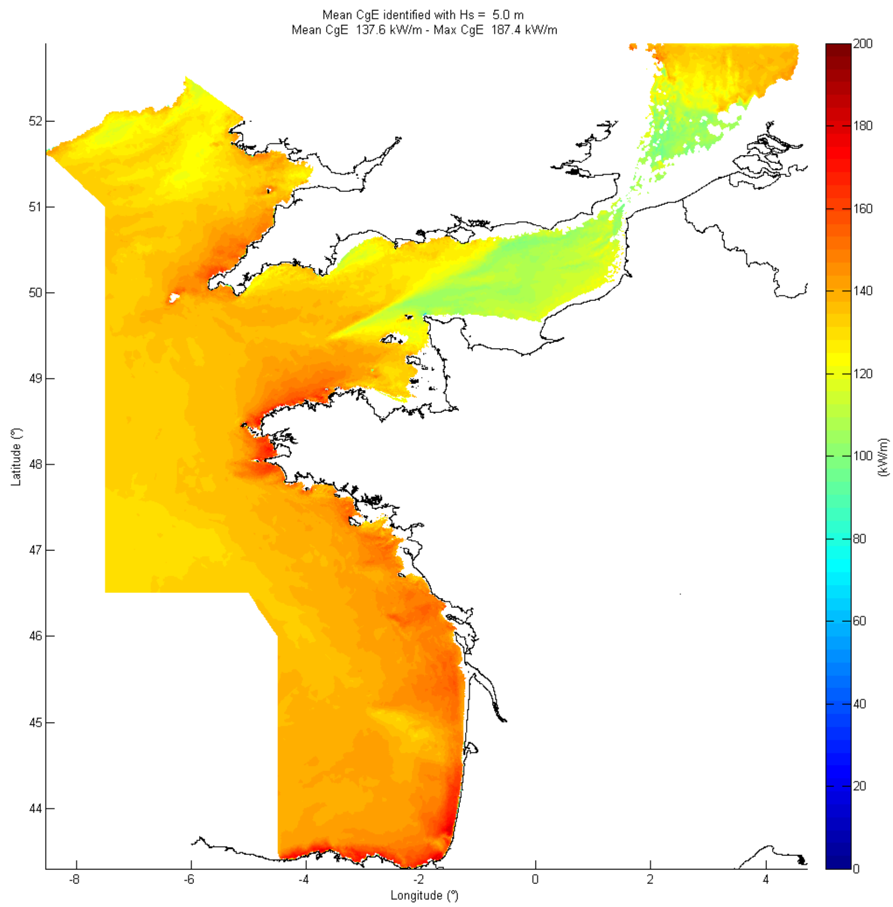


Figure 3: Mapping of wave energy flux CgE for Hs~5 m (from [28])

2.2. Tidal resource

The hydrokinetic energy of the tidal currents has been identified as a valuable resource for the production of electricity by means of Tidal Energy Converters (TEC), whether considering horizontal or vertical axis turbines or more ground breaking technologies such as kites, oscillating foils or membranes [29]. A clear advantage of the tidal energy for electricity production is its pseudo-periodic cycle that makes it remarkably predictable.

Many studies have been conducted worldwide to map the tidal resource and the most relevant sites have been clearly identified [30], [31], [32]. These are globally located in coastal areas where water depths are limited and tidal currents can be accelerated as the result of specific topographical and bathymetric contours such as narrow straits or channels. An important feature of the flow identified at these highly energetic sites where current velocities higher than 2.5 m/s are regularly observed, is its high level of turbulence. Advected turbulence structures are observed at various scales contributing to the strong variability of the flow both in space and time. The characterization of this turbulence induced variability, random by nature, is an important requirement for TEC design as it will have an impact on both the efficiency of the devices and their structural ageing. On this latter topic, structural fatigue can be triggered by unsteady loadings and, considering high variability, transient phenomena such as cavitation or impulse loading can lead to integrity failure of the rotor and of other components on the drive train.

The influence of turbulence on the efficiency of tidal turbines as well as the additional mechanical loading it induces on the structures has been widely investigated over the last decade, mainly through experimental testing in current flumes [33], [34], [35] as well as numerically, using Computational Fluid Dynamics (CFD). However characteristics of the turbulence to be generated in the inflow, whether it is for replication at reduced scale in a flume or for modelling, is still relatively approximate as the uncertainties on the variability of the flow at real scale sites are still quite large. Indeed, the phenomena associated with the production, propagation and dissipation of the turbulence are relatively complex and directly affected by the local environment, including variable bathymetry and incoming waves. Furthermore, existing systems deployed for in-situ measurement of current velocities are not yet ideally suited for an accurate characterization of velocity fluctuations in time and space. Indeed, although Acoustic Doppler Current Profilers (ADCPs) are well adapted to the measurement of mean flow velocities, developments are still needed both on a technological level (increased number of beams, increased sampling frequency etc.) and post-processing methods and techniques.

Existing 4-beam and 5-beam ADCPs do not allow a proper assessment of the whole set of metrics (Reynolds stress, isotropy, intermittency,...) [36] necessary to characterize fully turbulence and procedures combining multiple ADCPs [37] still remain complex to implement in such energetic environment. Parasitic Doppler noise affecting the identification of the higher frequency turbulence increases the uncertainty on the turbulence dissipation [38] and no satisfactory methodology has been identified to clearly separate wave kinematics from turbulence in the inertial subrange where the large turbulent structures are the most likely to interact with the TEC structure [39]. In addition, the validity of the assumptions made to develop the signal processing methods used to assess the flow velocity and variability still need to be fully validated for energetic environmental conditions. For instance, the extension of the measurement volume delimited by the acoustic beams has the magnitude of some structures developing in the inertial subrange and the validity of the “frozen field” approximation [40] is probably relatively conservative for the considered sites and flow conditions.

In comparison to ADCPs, Acoustic Doppler Velocimeters (ADV) offer a more accurate assessment of the local flow velocity and a higher sampling frequency allowing a more efficient noise reduction. However, the measurement they provide is only local and the deployment of a large number of sensors would be necessary in order to assess the time and space variability of the flow. This would represent a rather complex and costly procedure from an operational point of view in the considered environment.

ADVs are otherwise extremely valuable for flow measurement in current flumes, together with other methodologies based on optical techniques using lasers, such as Laser Doppler Velocimetry (LDV) or Particle Imagery Velocimetry (PIV). These techniques are very efficient and accurate in the controlled environment of a laboratory but no satisfactory solution has as yet been developed that would allow their implementation in the rougher conditions taking place at tidal test or production sites.
Actually testing at reduced scale in a controlled environment - when open sea testing would be complex and would require costly marine operations - still constitutes an important and interesting approach for improving our knowledge on energetic flows variability and interactions with structures, especially if coupled with numerical modelling and CFD. For instance, recent studies conducted at the laboratory scale have provided interesting insights into the onset and evolution of turbulence induced by bathymetric obstacles, in the form of boils convected downstream and propagating in the whole water column up to the free surface [41]. In the same manner wave loading in the presence of current can be investigated [42], [43]. The influence the wake of TECs has on the variability of the natural ambient flow and the efficiency of downstream converters is a challenge that can also benefit from laboratory testing [44], [45], [46].

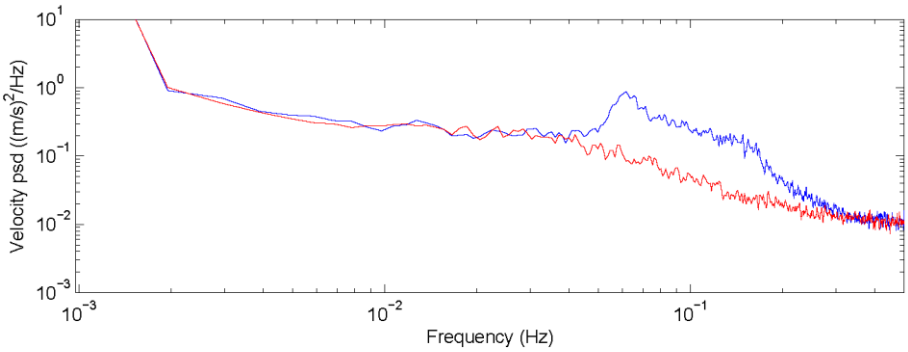


Figure 4: Current velocity measurement spectral density with (blue) and without (red) waves - (After [39])

However, efforts should be made to pursue investigations for the development of new methodologies adapted to the challenge of monitoring in an energetic environment, possibly taking advantage of techniques already developed by other research communities. For instance attempts have been made to adapt a fast-response, multi-hole pneumatic probe - a measurement technique well established in the turbomachinery for unsteady flow measurement- so as to design a low cost device that would cover the frequency range required for tidal turbine applications [47].

As seen from this brief overview, solution to a number of challenges are required in order to provide the accurate characterization of the resource and flow variability at energetic tidal test and production sites such that to reduce the uncertainties on the actual loading acting on TECs. Key elements identified are the lack of adapted monitoring devices and procedures as well as the complexity and costs of the marine operations necessary for the deployment and recovery of the instrumentation. Fortunately, in the context of the MARINERG-i Distributed Research Infrastructure this can be partly mitigated by resorting to available reduced scale testing facilities so as to improve the general knowledge and offer solutions beyond the existing standards and guidelines. More specifically developments on tidal resource characterization conducted as part of the MARINERG-i research program should address the following topics:

- Improvement of the local in-situ current measurement and monitoring capacity (ADCP, ADV, ground breaking technologies) with focus on the space-time variability of the flow.
- Improvement of monitoring procedures (deployment, multi-sensor approaches,…)
- Improvement of the general knowledge on flow variability combining open sea monitoring and experimental testing at a reduced scale.

2.3. Wind resource

According to the Global Wind Energy Council, the global offshore wind capacity installed at the end of 2017 reached 18,814 MW of which 84% (15,780 MW) was in Europe. The global offshore wind resource has mainly been investigated combining satellite remote sensing data with hindcast datasets generated using numerical atmospheric models [48], [49]. The information derived from space borne remote sensors is however relatively limited. Scatterometers only provide wind velocity assessment at one given elevation, usually the 10 m reference height, which is not suitable for power assessment at turbine hub elevation, hence requiring correction. Synthetic Aperture Radars (SAR) which can provide relatively accurate information on wind velocity and on wind direction has a resolution of about 500 m so that only average space estimate are provided. In addition return period of the satellites does not allow a proper assessment of the diurnal variability of the wind flow [50]. This information is certainly of relevance for the planning of offshore wind farm siting. It does not however provide all the information necessary to assess the efficiency of the turbines and the actual loads acting on the structures, whether floating or fixed in the sea-bed.

It is largely acknowledged that one of the main advantages of deploying wind turbines in offshore locations is that the wind velocity is on average higher and steadier with lower wind-shear above the oceans than on onshore terrain [51]. Thus offshore wind farms generally have higher production levels and potentially lower turbulence-induced fatigue on the structures.

As for tidal or wave, reducing the uncertainties related to the characterisation of this resource, considering both the power production potential and the design conditions [52], is of prime importance for reducing the LCoE so improvement of the monitoring tools and procedures is still needed.

Masts equipped with cup anemometers are considered as the reference for in-situ measurement of wind velocity, turbulence and variability. However with the deployment in deeper waters of higher turbines with a larger sweep, the size and deployment cost of such monitoring structures appears a major limitation to their operational implementation. More recent remote sensing technologies based on optical techniques such as Lidars (Light detection and ranging) or acoustic techniques such as Sodars (Sonic detection and ranging) which provide measurements of the wind profiles are offering a promising and economically competitive alternative to the offshore masts [53], [54].

Lidars measurement principle allows for a relatively accurate assessment of the wind velocity in the atmospheric boundary layer and up to the height of the turbine hub. Because of the temporal and spatial averaging induced by the processing, turbulence remains difficult to capture but is not out of reach if proper calibration/validation against reference cup anemometer can be conducted. In addition, the Lidar itself must be placed on a reference platform and for a floating support, the compensation for the dynamics of the

platform is an additional constraint which must be thoroughly dealt with in order to reduce errors [55].
Support to the development of adapted monitoring tools and procedures for in-situ wind monitoring is the most relevant task to be developed as part of the MARINERG-i DRI research programme and will make use of the capacities available at the test sites:

- Improvement of the local in-situ wind measurement and monitoring capacity (Lidars, Sodars, ground breaking technologies) with focus on the space-time variability of the wind flow.
- Improvement of monitoring procedures (deployment, multi-sensors approaches,…)
- Wind shear measurements and analysis at extreme Atlantic sites

2.4. Joint Environmental Conditions

Even though marine structures are constantly submitted to the joint action of the wind, waves and currents, these three environmental variables and the associated parameters are most of the time considered independently in the design process. In most cases, coupling is considered weak enough so that the processes can be separated and a first order estimation of the conditions can still be provided. Even though there is strong evidence that coupling can play a significant role in the properties of one or the other parameters of interest (atmospheric and oceanic turbulence, sea surface disturbance, etc.) these effects are hardly accounted for in the current state of the art for best practices [56].
When considering joint environmental conditions for the design of marine structures, two different aspects of the problem are to be addressed. On the one hand, the alteration of the environmental variables induced by the physical coupling such as current induced wave refraction also potentially affecting wave breaking distributions and on the other hand the response of the structure to the combined action and loading induced by the wind waves and current which becomes of prime importance when considering extreme conditions [57].
In both cases specific monitoring protocols must be developed to gather co-located and simultaneous measurements of the environmental parameters. The open sea test sites available in the MARINERG-i DRI are an essential support to the development of such advanced monitoring strategies. Programs involving the deployment of state-of-the-art sensors will be implemented to build the long term time series of joint parameters. These databases will be used as references for the development of adapted statistic and stochastic approaches for the characterization of the response of ORE devices to joint environmental forcing.

3. Theme 2 - Design, Power Take-Off and performance characterisation/optimisation

A key objective of the design and optimisation process for marine structures and Offshore Renewable Energy (ORE) devices is the identification of the responses, whether structural or dynamic, to environmental loading. The development of new approaches and adapted methods to improve characterisation of non-linear behaviour associated with extreme loading or dynamics in water is needed to improve the assessment of structural reliability.

Such new methodologies should be adopted at all stages of development, from small to larger scales and with the consideration of multiple units ultimately forming arrays.

Advancements in the areas of power take-off and control methods are critical for the efficient operation and survivability of ORE technologies. The MARINERG-i DRI will prioritise the development of power take-off and control strategies that will increase power production, regulate and decrease loading, reduce fatigue or improve survivability. Control methods are also required for the optimisation of arrays of devices. Research gaps and actions that are required once multiple units are connected to the electrical network must also be informed.

Combining the numerical and experimental approaches is required for the development and design of marine structures and ORE systems. The MARINERG-i DRI will facilitate advancement of numerical modelling approaches by facilitating access to and use of data from physical testing for calibration and validation purposes. Intricate and powerful numerical approaches with combined aero/hydro/servo/elastic modelling are being used nowadays. It is important to develop methods so that physical model testing approaches are in tune with these advanced numerical models. This will ensure proper validation of the models and maximise the understanding of technology behaviour, particularly at small scale before significant development funding is required for larger-scale open sea testing.

This chapter aims to identify the research gaps and challenges as well as the actions required to move forward into the development of efficient and cost-effective ORE solutions, where ORE consists of Wave, Tidal and Offshore Wind Energy . It has been divided into four main topics: i) hydrodynamics, ii)power take-off and control, iii) electrical and grid connection and iv) numerical and physical coupling.

3.1. Hydrodynamics and power capture

In this section, the research challenges associated with the characterization of the action of the flow on devices and the influence these devices may have in return on the flow are investigated in the view of the assessment of the power capture.

3.1.1. Wave

Wave energy conversion can be achieved by extracting the energy from wave fields using several techniques; e.g. oscillating water columns, point absorbers and attenuators, to name a few. Each design has its own implications and when deployed as multiple units the associated challenges increase considerably. Many classifications are proposed in the literature [1], based on the working principle, type of PTO or even water depth (shoreline, Nearshore or Offshore); however the majority of WECs can be further split into two major classes according to the captor size: small and large devices.

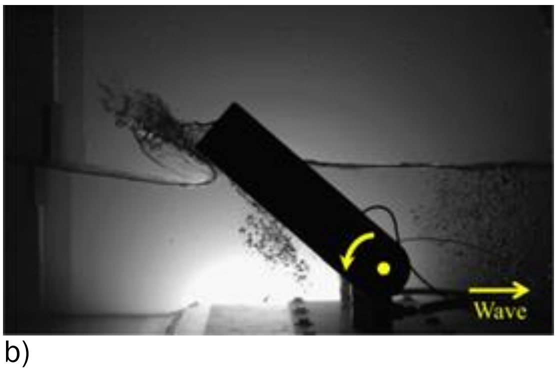
The first category includes smaller converters, usually point absorbers, in which the characteristic captor size (or floating surface) is much smaller than the length of the predominant incoming waves. Such concepts are typically axisymmetric (although not necessarily), with diameters between 10 and 14 m; thus their capacity to absorb wave energy does not depend on the direction of the incident waves. The second category comprises larger devices, with characteristic length of the principal axis not negligible when compared to the predominant wavelength. Essentially, this group includes terminators and attenuators; the main difference between an attenuator and a terminator is that the incoming wave angle varies by 90 degrees. Therefore, a terminator can become an attenuator (and vice-versa) depending on wave climate conditions and mooring configuration.

Hydrodynamics is a main driver to the optimization of WECs design and capture width. Identification of the hydrodynamic loading and associated dynamic and structural responses will allow optimization of the geometry of the device combined with the most adapted Power Take-Off system and mooring layout yielding the highest power extraction capacity. Challenges exist in the characterization of the hydrodynamics associated with large waves in energetic sea-state as complex non-linear effects come into play that are difficult to model or to properly assess at reduced scale. These however affect the characterisation of the structural ageing, reliability and ultimately survivability of the devices hence is a topic that must be properly addressed. In addition, the diffraction-radiation issues associated with the deployment of WEC farms and potentially affecting the global power extraction still remain challenging and should receive more attention.

Wave Energy Converters (WECs) typically contain moving parts that undergo large amplitude motions in order to produce energy. In real seas, such motions are nonlinear, as the result of multi-directional sea-states and large amplitude waves acting on the device in the presence of mooring lines, a Power Take-Off (PTO) mechanism and control systems.

The majority of the WEC concepts, except for instance fixed Oscillating Water Columns (OWCs), include a moving part undergoing large amplitude motions, in heave and/or pitch/roll. As the order of magnitude of the motion can be as large as the draft of the floater, standard linear or weakly non-linear approaches are not suitable for accurately describing the hydrodynamic behaviour of such structures. Large amplitude motions, relative to the free surface, can rapidly lead to slamming events. It has been shown in the naval industry that slamming events reduce the amplitude of pitch motion of surface ships [2]. For example, as illustrated in Figure 5a below, the SeaREV [3] device exhibits slamming loads as soon as the pitch angle exceeds 10°. Flap-type devices such as the Oyster concept (Figure 5b) are also subject to strong water impacts due to the combined motions of the structure and of the free surface.

a)



b)

Figure 5: a) Water impact on the SEAREV Wave Energy Converter due to large amplitude motion (Babarit et al., 2019). b) Water impact on the Oyster Wave Energy converter due to wave and body motion (Wei et al., 2016).

An efficient way of extracting large amounts of power form the incident wave field consist in deploying a large number of WECs arranged in farms using a particular geometrical configuration [4]. Within such arrays, the wave field around an individual WEC is modified in all directions as the result of wave-WEC interaction so that additional hydrodynamic interactions take place between the WECs (so-called “near field effects”). These interactions between neighbouring WECs alter the incident wave field so that the overall power output of the WEC farm is not ultimately equal to the power output from an individual WEC, times the total number of WECs.

In addition, the wave field at large distances downstream a WEC farm is typically a region of reduced wave energy density. This is the so-called “far-field effects” or “wake effects” which may affect coastal processes, neighbouring activities and other users of the sea, other marine energy projects, coastal eco-systems and even the coastline and coastal defense structures. In spite of the development of some research projects (e.g. PerAWaT, [5], WECwakes, [6]), challenges associated with the development of WEC farms have only received little attention so far. Testing of arrays at reduced scale in a wave tank is indeed challenging because of the necessarily limited size of the available facilities, and deployment of arrays at open sea test sites even though considered necessary to produce data required to validate numerical models capable of simulating the associated hydrodynamics, e.g. wake effects [7], [8]; [9] is still too expensive to be envisioned as a standard practice.

A good understanding of the large amplitude motion hydrodynamics is necessary in order to accurately predict the hydrodynamic loads that structures must sustain and to accurately estimate the power that can be extracted from the relative motions of the moving elements of the device. Although still poorly apprehended by the ORE community, such high hydrodynamic loads and associated non-linear responses are expected to limit the power production and alter the structural integrity of the devices. In the conceptual phase, a feasibility assessment is required for understanding the limitations of the wave energy converter design for the prevailing sea-states at the site of interest. Therefore interactions between mooring system, floater and Power-Take-Off system (PTO) are to be investigated. This feasibility assessment can be conducted by means of experimental and/or numerical simulations to give insight into the operational envelope of the WEC. Various system configurations can be evaluated and compared to key performance indicators such as loading on critical parts, maximum operability, survivability and energy yield. Field-testing of WECs in real sea states with monitored mooring systems will produce data that can be used to improve understanding of the hydrodynamic forces acting on devices, improve power capture prediction and validate numerical models.

Understanding the interaction between WECs within an array is crucial to make the step towards the commercialisation of WEC technology. Therefore, methods are to be developed, involving coupling with numerical modelling so as to circumvent the scalability issues induced by the limited testing area available in wave tanks on the one hand and the high costs preventing from conducting systematic testing at full scale on the other hand.

Figure 6: A 5x5 WEC array tested during the WECwakes project (Stratigaki et al., 2014, 2015) at the DHI wave basin within the European Hydralab IV Programme.

3.1.2. Tidal

Understanding the hydrodynamics of the fluid flow affecting the performance and loading of tidal energy converters is one of the most challenging and relevant topics within the tidal energy community. In this section "tidal device" is used in a broad sense and encompasses devices operating in both tidal (bi-directional) streams, where ebb and flood phases are cyclically repeated, and in unidirectional flows as in the case of salinity or temperature-driven ocean currents (i.e., the Gulf stream) or rivers.

Tidal energy production sites are characterised by energetic flows associated with strong variability and turbulence that may alter tidal devices efficiency and induce structural loading. Seafloor relief is a major cause for the onset of such flow variability. For instance, it has been observed [10], [11] that the presence of obstacles on the seabed, either bathymetric (e.g. rocks) or artificial (e.g. cylinder rooted in the seabed) can produce dynamic turbulent structures (i.e. horseshoe vortices) or transmitted/reflected wave frequencies which will directly impact the power production performance and structural ageing of the tidal devices. Methodologies and procedures adapted to the assessment of these impacts are being investigated but still require improvement [12] [13] and, as already pointed out in theme 1, there is also a need for improvement of tools and methodologies for a better identification of the turbulence and flow variability at small and large scale [14]. These site features may inform the practicalities of using a specific tidal device (e.g. rotor, oscillating foils and multiple variations of blade shapes).

Technology solutions designed to capture the energy of an onset current are inherently conditioned by the directionality of the flow. The power capture capability of actual tidal devices is typically maximized by orienting blades such that their leading edge is always facing the onset flow. This can be achieved by blade pitch or rotor yaw control. Some technologies avoid the mechanical complexity of pitch and yaw control by adopting blades whose sections are shaped as bi-directional profiles having identical leading and trailing edges [15]. Each technology implies specific fluid-dynamics features to be appropriately characterized by model tests from the early stage of design. This flow directionality also generates hydrodynamic effects generated when the turbine is positioned downstream of the structural support developing shadow effects on blades, depending on their position relative to the mounting frame [16], [17.

Methods for improving the quality of the flow around blades either considering rigid or flexible profiles have been given a lot of attention but optimization of the fluid-structure interaction remains a challenge for tidal energy applications. Some technical solutions are proposed which include the use of compliant coatings on tidal turbine blades [18] so as to reduce skin-friction drag and subsequently improve the performance or the reduction of the loading by passively deforming the blade surface using friction force. Other methods include the use of bend-twist composite blades to shed loads but preserve an optimum performance of the rotor [19] the use of leading-edge tubercles like the ones seen on humpback whales' fins [20] or the use of endplates and winglets to improve the power capture of devices.

Another aspect worth investigation is the onset of cavitation over the blades. The occurrence of vapor voids at the leading edge of the blades is due to the local low pressure triggered by high speeds or by local roughness. This phenomenon is common in propulsion systems because of the high rotational speeds. In tidal turbines, the scale of the rotor induces high tip velocities, which combine with periodic static pressure variations during the rotation and high incoming flow turbulence to create the conditions for cavitation onset. Cavitation is characterized by strong unsteadiness and is known to generate broadband noise and erosion, and can possibly lead to structural failure through fatigue and material pitting. Another consequence linked to cavitation is the noise radiated into the far field and the possible impact on the marine biosystem. It is also an important aspect to consider in the case of turbines arrays, as cavitating tip vortices can propagate for long distances behind the rotor and impact the downstream rotors, affecting their performance and integrity.

Investigations related to blockage effects impacting the performance assessment of tidal devices at reduced scale are still ongoing. It has been found that even at the lower-limit of blockage magnitudes (~5%), the performance of a device may still be affected by the tank proportions [21]. This matter is of great importance when aspects related to wave interactions on turbine arrays are under investigation since turbulent boundary layers induced by free surface effects develop on side walls.

Studies related to tidal arrays are also of critical importance [22], [23]. Model tests at reduced scale have demonstrated the effects of wake diffusion and dissipation mechanisms in the performance of the multiple devices. However model tests on clusters of devices yield flow confinement issues that may be present even in the largest facilities existing worldwide. Some studies demonstrate that arrays can be very efficient if their arrangement is optimized to maximize the energy harvesting from upstream turbines wakes [24]. However, research in this area is required.

As seen from this review, many research topics are still to be investigated to improve efficiency and reliability of tidal devices. It can be noted that knowledge transfer from the more mature technology sectors on marine propulsion systems and wind energy could contribute to achieving significant progress in some of the aforementioned topics. Also, new multi-disciplinary approaches to tidal turbine design should be considered for specific topics such as the study of blade flexibility effects to increase performance and alleviate loads on blades, where classical hydrodynamics aspects should be addressed in combination with hydro-elasticity and materials. Interdisciplinarity could also play an important role when investigating the interaction between seabed morphology and flow topology as this topic is also central to coastal and offshore engineering, as is the effect of structural elements (such as posts or rotor masts) on seabed scouring and erosion.

Main considered research topics include:

- Impact of turbulence flow variability on tidal devices efficiency and ageing
- Influence of bathymetry and surface roughness on flow variability and modeling at reduced scale
- Optimisation of blades profiles and fluid-structure interaction
- Interaction between tidal turbines in array, combining numerical modeling and testing
- Influence of cavitation on efficiency and ageing of turbines and blades

3.1.3. Offshore wind

In comparison to wave and tidal energy, technologies for harnessing offshore wind energy are already in a quite mature state. Fixed offshore wind farms have already reached TRL 9 and have been in commercial operation since 2001. By the end of 2017 offshore windfarms with a total power of 18800 MW were installed worldwide with about 80 % of those in Europe, in particular in the North Sea in maximum water depths up to about 55m.

The major research gaps and challenges relate to achieving cost reductions through the optimisation of components (or development of innovative new components) and methods. Specifically, in relation to the foundation platforms there has been much work to extend the range of existing fixed foundations to deeper water that has led to the XL and XXL monopiles and there are fixed solutions now being developed for 100m depths. However the main focus of activity is on floating platforms as floating wind is on the cusp of large scale deployment and there is a lot of R&D being undertaken on platforms with different stability principles (barge, semi-submersible, Tension Legged Platform (TLP), Spar and hanging pendulum). There is also development on self-yawing multi rotor platforms with a view that design and logistics issues associated with large turbines can be overcome using these platforms. All these different concepts have to be proven and tested in advance of field deployment, which require theoretical development, various numerical simulations and in particular laboratory experiments. Wave and wind loads are surely dominant and most important to be studied in this context, but currents are particularly important for self-yawing structures to ensure that the platform does not become misaligned with the wind. As is the case for floating wave and tidal energy devices the dynamics of mooring lines, power cables, anchors and soil structure interaction are also important design considerations for floating wind platforms and turbines (see Theme 3).

The generation of wind loads on floating test structure in itself is very complicated and a new area of research despite the long-time experience with wind tunnels. The major challenge is the correct reproduction of a scaled down local realistic turbulent wind field with gusts and its interaction with the rotor in particular if it is actually rotating. An alternative approach involves artificially replicating the wind forces using a ducted fan or drone using a control system that accounts for the motion of the platform. These systems for replicating the effect of wind on floating structures require further testing and validation which will need innovation in terms of developing new testing methodologies and consequentially adaption of testing facilities.

Proposed research/actions for offshore wind include:

- There are only very limited number of testing facilities worldwide in which both waves and currents can be generated simultaneously but the range of conditions that can be tested without tank effects is very limited. So the addition of wind loading through wind generation over the tank or use of a fan/drone on the model creates a very complex test environment that has not yet been properly developed.
- Structural design optimisation needs further work where extreme environments such as highly nonlinear waves and breaking waves impact complex foundations such as jacket or truss structures with many individual members that experience time-shifted loads and sheltering effects. These cannot be assessed properly yet in the design due to the limited number of studies that are currently available.
- Research and development at large scales must require the involvement of commercial parties where novel data acquisition procedures can be implemented; or data gathering through monitoring at or around pilot or operational systems, preferably on a long term can be undertaken. The former is particularly helpful for a rapid development of new technologies like floating wind turbines or suction buckets, as potential scale effects can be widely excluded and testing in a natural environment might reveal aspects which had not been considered at previous scales, but are crucial for the design.
- Long term monitoring programs, are also necessary to confirm results from laboratory investigations or to identify scaling effects.

3.2. Power take-off and Control

Power Take-Off (PTO) systems considered here are the mechanisms used to convert the energy captured from the device (i.e. rotor, buoy, etc.) into another form of energy; e.g, electrical or mechanical depending on the device scale and type. Control strategies are also considered in this section, as they have a great influence on the power capture efficiency and load damping, along with the PTO design.

3.2.1. Wave

The classification mentioned in section 3.1.1 drives the selection of the most appropriate PTO equipment. It may be assumed that small devices must have, in principle, high velocities, to compensate the low excitation forces acting on the captor (due to its small size), in order to maximize the energy absorption. This means that these concepts need to operate at resonance (or close to it), which confines the PTO equipment to systems suitable to work at high velocities as, for instance, direct drive linear generators, rack and pinion mechanical systems or air turbines in the case of floating OWCs, where high pressures in the chamber can only be achieved near the resonance of the water column or/and the hollowed structure.

In contrast, large devices are typically subjected to very high forces and small velocities, which means that hydraulic systems (apposite for small displacements and high loads) are usually more suitable for this type of applications. The drawback of this sort of PTO equipment is the high number of components (valves, seals, hydraulic accumulators, hydraulic hose pipes, etc.) and the reduced life time (maximum number of cycles) of some of those components (e.g. standard seals can typically withstand a much smaller number of cycles than the level required for offshore energy applications), which may increase maintenance frequency and consequently increase the costs. However, hydraulic systems potentially enable energy storage and so contribute to improve the quality of power produced.

Devices that use direct drive (e.g. linear generators) may be more efficient because they imply fewer conversion stages (i.e. less energy loss) and require less maintenance of auxiliary systems. They have however no provision for any energy storage to smooth the output (less critical in arrays) and they are usually heavy and costly. When using hydraulic systems, accumulators and short-term energy storage can be used to provide a smoother output power [25], [26], [27]. However, the hydraulic device must be enclosed, and care has to be taken to design the seals of the main cylinder, while the electric system offers the possibility of designing a flooded system.

Ultimately, with regard to the capacity to absorb energy, there are also some distinctive characteristics between categories. Typically, point absorbers have a narrow absorption bandwidth centred at the resonance frequency, and therefore correctly tuning the system (in accordance with the most energy profitable sea states) is crucial to optimize energy production. Usually, to tune a point absorber two techniques are combined. The device is designed (mass, stiffness, damping) so that its resonance frequency be in the frequency range of the peak frequency of the predominant sea-states. In addition, control strategies are developed to allow dynamic adjustment of the PTO load to the sea conditions [28].

Control strategies can be based either on reactive control which consists in adjusting the PTO reactance to cancel the intrinsic system reactance or on phase control where the oscillatory velocity is imposed to be in phase with the excitation force and the modulus of the PTO load equal to half of the excitation force.

Attenuators and terminators have normally a much wider absorption bandwidth hence, they are not as dependent as point absorbers on complex control strategies. This advantage is counterbalanced by the fact that their PTO equipment is often more complex and requires higher levels of maintenance.

Proposed research/actions include:

- Further research is needed coupling numerical and experimental assessment to improve control strategies
- Permanent-magnet materials and new electromagnetic topologies are required as they offer better prospects where the electrical direct drive PTO offers no intermediate steps between the primary interface and the electrical machine.

3.2.2. Tidal

The PTO along with an adequate control strategy serves to set specific loadings to build performance curves of a tidal stream converter. PTO applications for small scale tidal turbines can range from resistance loading (i.e. passive systems such as hydraulic dampers), back to back power converters, generic “off the shelf” motors, to the rarely utilisation of generators which in contrast, are widely used at large scales.
To date, most of the experimental research undertaken at small scale focuses on the use of speed-controlled techniques to set the load required for a particular operation point. In the case of a generic horizontal or vertical axis tidal turbine, optimal blade pitch, and rotor velocity are set based on the incident flow velocity in order to maximise the power extraction. The control techniques are usually based on standard feedback to control the pitch actuators and the torque in the rotor in order to achieve the desired pitch angle and/or rotor speed. The manipulated variable for the pitch control is the power to the pitch actuators (voltage and/or current). For torque control, either the back-to-back (B2B) power converter (where one is used) or the generator excitation can be used as control actuators.

Multi-pole generators can be used as a direct drive system and replace gearboxes components that have one of the highest failure rates in the wind industry. These failures mainly result from the mechanical stresses that individual components must withstand; e.g. in the drivetrain bearings and seals where constant lubrication is required for such underwater low speed high torque applications. Potential shocks induced by debris impacting the turbine or the loading induced by flow turbulent structures that may damage the mechanical components of the PTOs are also to be considered. Thus, ensuring the optimal design and performance of the bearing system is crucial to the reduction of the LCOE from this technology.

When a tidal turbine reaches its rated power, the turbine must be ‘depowered’ in order to avoid exceeding any rated specifications. In this situation, it is not required to maximise power conversion and, for variable pitch turbines, blade pitch can be adjusted in order to limit power converted or excessive loading on the system which may be related to complex flow turbulence structures. Therefore PWM control methods - similar to the stepping brake in ABS system - can be implemented.
Proposed research/actions include:

- The application of efficient planetary gears, direct drive, hydraulic systems, pneumatic systems, to the latests techniques adapted from the wind industry; e.g. the use of magnetic gears [29 – 32], should be further investigated
- Novel control methods could improve the power capture and reduce expected loadings on the tidal converter. The energy output of an array could be optimised by fine-tuning each individual array member to work coupled to the surrounding

members and environment rather than setting up each device as stand-alone. An in-depth analysis of the differences between control methods has yet to be performed.

3.2.3. Offshore wind

Modern wind turbines typically have control systems that maximise energy capture by adjusting the yaw position and optimising the rotational speed of the generator. The generator speed is used to control the collective pitch angle of the blades when operating above the rated wind speed, to regulate the rotational speed once the rated power is reached. The pitching of the blades to the feathered position (i.e. 90∘) is used as the main braking system to bring the turbine to a standstill in critical situations. Other control systems include vibrational damping in both the tower and the drivetrain, and individual blade pitch control.
Passive control systems are not controlled by operators or automatic systems, but are part of the blade structure and can be used to prevent flow separation and erosion of turbine blades. Vortex generators have been used on blades for many years, but are still being studied and refined e.g. the low drag vortex generator system of [33].
Examples of active control systems include circulation control, where compressed air is used to dynamically adjust the aerodynamic performance of the blades; and individual pitch control, which controls power production and the loading on the blades by pitching them individually [34].
These control systems however do not take into account the effect that the wake evolution from neighbouring turbines has on the loads and production of the turbine in the wind farm.

Proposed research/actions include:

- The development of smart rotor technology that combines passive and active control systems with novel sensor technologies will facilitate the deployment of larger turbines both onshore and offshore, by reducing the weight and the loading on the blades.
- Improvement of the stability of offshore wind turbines through the incorporation of both passive and active damper systems.
- Integration of design approaches of control systems in floating wind farms [35].
- Associated commonalities between the wind and tidal industry are evident and thus learning procedures and advancements in both sectors should be examined appropriately.

3.3. Electrical and grid connection

Most of the ORE devices currently connected to the grid are offshore wind turbines. However, in the medium-long term innovative solutions will be required to effectively connect to the grid multiple types of devices deployed at greater distances from the shore. This section intends to showcase the challenges associated with electrical connection, control and grid connection in the ORE industry.

3.3.1. Direct Current Solutions

High voltage direct current (HVDC) systems are practical to transmit large amounts of power to shore over long distances. HVDC technology is however mostly relevant for the largest offshore marine power park modules - mostly offshore wind in the near future - and for plants where physical limitations related to employability of alternating current technology exist. In the long term however, deployment of other technologies at large scale will possibly require HVDC power transmission technology, providing existing challenges are properly addressed. Identified challenges include decoupling of the offshore electrical alternating current system from the main electricity grid and stability issues requiring development of adapted power electronic converters.

Proposed research/actions include:

- Laboratory testing also considering real time simulations can contribute to assessing the interaction between ORE devices and direct current based electrical system so as verify the direct current concept, reduce skepticism, and therefore bring the technology closer to the market.
- Full-scale component testing requires implementation in commercial applications. Investigations of complex issues appearing on larger systems, however, are beyond the feasibility of full-scale testing and can be addressed with scaled laboratory prototypes. In particular, the possibility of combining components of multiple vendors is an important topic, which has already been considered in the BESTPATHS project, but requires further research.

3.3.2. Alternating-Current Solutions

Alternating Current (AC) transmission options such as LFAC (Low-Frequency AC) transmission, operating typically at 16.7 Hz, are considered competitive for interconnection of offshore wind farms at distances of 50-200 km offshore compared to voltage source converter (VSC) High Voltage Direct current (HVDC) [36].
Contrarily to HVDC, LFAC doesn't require installation of an offshore converter station. There exist however design challenges for the low-frequency transformer and associated platform.
Current access to medium and high voltage testing is limited, with additional requirements involving safety areas, equipment, certification and training due to the increased risk of hazards.

Proposed research/actions include:

- Advanced modelling work combined with knowledge and input from marine spatial planning regulations, could help determine the most suitable and cost-effective electrical layout and technology for potential installations. Developing high voltage test capacity and expertise together with improved electrical system modelling equipment and software is needed to support research in this area.

3.3.3. Holistic Wide-Band Control Systems

A common practice when investigating the interaction between the electrical system and the control process of an ORE converter is to assume that the electrical system is ideal and stable or at least to consider that all electrical stresses are kept within defined limits. However, potential deficiencies of the electrical system must be considered when designing the control system.

Electrical deficiencies can include component failures in the electrical systems which may dictate an unplanned immediate shut-down or resonances in the electric system that can ultimately lead to oscillations within the marine energy converter control systems. Many of these challenges only appear in up-scaled arrays, and they might not be observable for a single prototype. The control process of each single device should account for these array-interactions to avoid any potential problems when the converters are integrated to the electrical grid.

All possible failures in the electric system need to be managed, especially considering the fact that auxiliary equipment might be required depending on the supply of electric power.

Understanding of the capabilities and limitations of control from commercial power converters to these ORE devices is important as these usually depend on the electrical layout; e.g. varying distances between the generator, power converter, and grid and different transmission types and ratings between all potential ORE projects which will vary the control options.

Resonance is a common problem related to cable-based electricity collection grids of offshore wind power plants and will likely affect other marine renewable conversion technologies.

The transmission to the onshore electricity grid gets more challenging with increasing power and with increasing distance from shore. Interactions of power park module and transmission cable are possible and have to be investigated.

Proposed research/actions include:

- The electricity collection grid with all its components and the offshore energy converters have to be modelled in detail with wide-base models to capture possible excitation of resonances. The same applies to the transmission system that connects the power park module to shore.
- At a later stage of development, the power and control hardware can be tested in the loop, while the electricity grid and primary energy carrier are covered with real-time simulation. Whether the mechanical parts of the marine energy converter can be part of the test, or if they have to be part of the real-time simulation is a question of practical feasibility.

3.3.4. Grid Connection

In real environments grid deficiencies are likely to appear; e.g. grid frequency disturbances, short circuits or other voltage fluctuations, and the need for reactive power. Challenges associated with these features are outlined as follows.

All electricity-generating facilities that are connected to the power grid need to fulfil the requirements set out in grid codes. The grid-interfacing part of an offshore energy converter (most likely a power electronic converter) must have a suitable control system that is designed according to the specifications of the grid code. This is generally not a problem, but as this control has consequences on other parts of the ORE converter, all implications of the grid code are compliant with the control features and it must be verified that any complication potentially arising can be handled effectively (e.g. power dissipation during grid faults).

The provision of ancillary services to the electricity grid (any functionality other than supplying harvested energy) has become a hot topic for wind and solar power as it can create additional revenue. Other marine energy converters could also provide such services, improving the financial feasibility of deployment. Providing such services is, however, not the primary focus when developing new ORE converters; therefore, potential conflicts such service provision controls of the grid-interfacing converter may have with other aspects of the design must be investigated.

Grid code compliance is not an issue for single devices but is relevant to arrays. The installation of additional hardware at the point of common coupling on previously non-compliant ORE converters may be a pathway to achieving compliance.

Proposed research/actions include:

- Grid-interfacing devices of ORE converters (in most cases a power electronic inverter) have to be exposed to grid code compliance tests. Thus, the control has to be designed according to the requirements of each specific site to meet compliance. In addition, other grid-focused control functionalities for ancillary service provision must be developed and tested.
- Electric power hardware and control hardware can be in the loop, while the electricity grid and primary energy carrier are covered with real-time simulation. If the mechanical parts of the marine energy converter can be part of the test or if they have to be part of the real-time simulation is a question of practical feasibility.
- Regarding arrays, different strategies to meet compliance are available but they should be compared and tested before being implemented.

3.4. Numerical/ physical coupling

Coupling experimental and numerical techniques is still a largely untapped approach worth dedicated research efforts. Numerical models such as high-fidelity Computational Fluid Dynamics (CFD) models provide virtual testing tools that can be used for studies that should be too complex, dangerous, expensive or simply impossible using physical models tested in a laboratory or at sea. For instance, physical constraints related to flow confinement at laboratory scale or budget issues for tidal site testing, seriously limit knowledge obtained from model tests that can be used for array mapping while virtual models of arrays can be developed using CFD and applied to analyse device-device interactions to optimize spacing and to account for site-specific conditions like bathymetry, current profiles and turbulence.
In return, the physics implemented in numerical models often requires simplifications based on theoretical assumptions so as to limit or reduce computational costs and accurate experimental data is needed to calibrate these models and validate the domain

of validity of the considered assumptions, especially when considering non-linear dynamics.
Recently developed real-time physical/numerical coupling techniques such as software-in-the loop approaches offer promising alternatives especially when multi-physics processes are involved. Further research and development is however needed in order to circumvent issues related to real-time processing.

3.4.1. Wave

It has been demonstrated that viscous effects play an important role in the energy conversion of offshore renewable converters [37]. The state-of-the-art numerical methodology that relies on potential flow theory assumes fluid is inviscid and the most widely used option to incorporate the viscous drag effect is the application of the Morison equation. The drag coefficient required for the Morison equation can be quantified using small-scale tests or by the use of CFD; however, its extrapolation to full scale is still a challenge because of the nonlinear nature of the drag force. Further research is needed in this area.
Numerical wave simulation is performed using a variety of methods and both Lagrangian and Eulerian approaches are used to solve the Navier-Stoke equations (NSEs) which could provide a full description of fluid flows. The Eulerian approach has been applied for decades to study waves and is considered mature. Nevertheless, Eulerian methods still face the challenge of simulating large deformations and violent surface interactions, which require special meshing techniques on the surface boundary. On the other hand, Lagrangian approaches are naturally suited for large deformation problems since they require no special treatment for monitoring and recreating the free surface, e.g. Smoothed Particle Hydrodynamics (SPH) models[38], [39], [40.
Moreover, solving the NSEs numerically requires an enormous computational effort; therefore, simplifying assumptions of varying significance are made, depending on the problem being solved and the computing resources available. Numerical modelling of WECs is typically carried out using low-fidelity hydrodynamic models based on linear wave theory, e.g. linear potential flow. The advantage of such tools is their computation speed, but the underlying assumptions and simplifications limit their capacity to simulate nonlinear behaviour. CFD models provide a much more rigorous treatment of the NSEs and are capable of capturing nonlinear behaviour, at the cost of significant computational effort [41].
Investigating the response of WECs in arrays requires both a capacity to properly model the non-linear behaviour of the devices and to propagate realistic wave fields over a large domain. In order to circumvent the inherent computational costs numerical modelling methodologies based on coupling techniques are developed which combine the advantages of wave-structure interaction solvers (such as those based on BEM, CFD, SPH) for evaluation of the near-field and the efficiency of wave propagation models for assessment of the far-field [42], [43]. These models still include a number of assumptions and further research is needed, requiring the integration of field/laboratory data for the calibration and validation of the models. [44] pointed out the benefits of using Particle Imaging Velocimetry (PIV) data to improve CFD modeling for the simulation of devices having a highly non-linear dynamics. However, a high-fidelity numerical representation of a WEC will be undermined by low-fidelity models of the subsystems; therefore, improvement is needed in the representation of elements such as PTOs, moorings and control systems. This requires high quality validation datasets, necessarily obtained from dedicated measurement campaigns both at reduced scale in wave tanks and in the real

conditions of an open sea test site so as to guarantee proper validation of non-linear behaviour and scale effects.

Proposed research/actions for numerical/physical coupling activities for the design of WECs include:

- Improvement of CFD models for the non-linear response of devices in waves
- Contribution to the development of efficient Numerical Wave Tanks
- Development of near-field/far-field coupled approaches
- Improvement of hybrid testing methods (software in the loop, etc.)
- Elaboration of measurement datasets and dedicated procedures for calibration/validation of numerical models

3.4.2. Tidal

The numerical resolution of the Navier-Stokes equations allows detailed investigation of the mechanisms governing onset flow kinetic energy conversion. Reynolds-Averaged Navier-Stokes (RANS) models, Detached and Large Eddy Simulation (respectively, DES and LES) fall within this class [45]. Detailed characterisation of the hydrodynamic interaction between a tidal device and the surrounding flow are however achieved at the cost of complex computational set-ups requiring expert users and high-performance computational resources.

In parallel, methodologies based on simplified mathematical models provide useful tools to estimate system performance under given operating conditions at reduced computational effort. Blade Element Methods (BEM) derived from wind turbine aerodynamics are widely used [46]. Alternative approaches include Vortex Methods (VM) and Boundary Integral Equation Methods (BIEM) [47]. The computational efficiency combined with full automatisation of the whole computational set-up make those models suitable for the recursive calculations that are necessary for device design and optimization studies. The coupling of CFD solvers for viscous flows and simplified models (BEM, BIEM) provides computational tools capable to simulate complex problems at reasonable computational effort [48]. The reliability of fast, design-oriented software still requires improvement that can be achieved through extensive validation studies using experimental data as benchmarks.

An area where virtual modelling demonstrates its power is the analysis of problems where phenomena requiring different scaling laws come into play. An example is the case of tidal turbines operating in the presence of waves [49]. Testing physical models at small scale in a wave tank is an option; it is however not trivial as turbine performance scales with the Reynolds number while surface waves scale with the Froude number and these two scaling laws are inconsistent between each other at reduced scale. Computational modelling can be performed at full scale, thereby overcoming this issue. Moreover, numerical results can inform procedures to correct model test data affected by non-consistent Reynolds and Froude scaling.

A similar situation occurs when fluid-structure interaction (FSI) significantly affects the hydrodynamic response of a device. This is the case for instance for turbines using blades built with lightweight materials like composites or specifically designed to modify their shape during operation. The hydroelastic behaviour of blades has to be accounted for in the design, and tests performed at small scale may fail to provide correct information because of the difficult scaling of dimensions, material and dynamical properties [50].

FSI is an example where different simulation tools, addressing different processes - fluid-dynamics and structural response for instance - are combined to study multi-physics problems. Model integration can also be exploited to investigate interactions between subsystems composing a tidal device. For instance, hydrodynamics software can be combined with models describing the PTO response and control strategies to analyse and optimize the tidal device at the early stages of the design process, thereby overcoming difficulties inherent to small scale testing in wave and flume tanks.

However, reducing the complex physics governing tidal energy conversion into mathematical and computational models implies approximations based on theoretical assumptions having limited domains of validity that need to be clearly defined and understood. In particular, CFD models used for analysis and design of tidal systems are largely based on commercial software developed for other applications like turbomachinery, marine propulsion and wind energy. A strong effort is required to enhance modelling capabilities in order to accurately describe peculiarities of tidal energy converters. In this context, the collection and sharing of experimental datasets for tidal energy CFD validation represents an area where research infrastructures are expected to play a significant role in the short term. It is important that these datasets include both model scale and full-scale conditions so as to tackle the scaling related issues.

Further work related to the advancement of numerical model and experimental coupling approaches has thus been identified as follows:

- Onset flow turbulence: CFD models provide satisfactory description of boundary layers and wake flows; however, suitable models must be developed to avoid numerical dissipation across the computational domain of the turbulence intensity imposed at the inlet, considering both model and full scale.
- High-Reynolds number flow: improve capability of RANS models to simulate full-scale flows characterised by Reynolds number in the order of $10e^7$ with very thin boundary layers around turbine blades.
- Optimisation of computational efficiency of fluid-structure interaction.
- Improvement of methods for computational grid generation: overlapping grids, adaptive mesh algorithms.
- Implementation of control strategies into numerical modelling.
- Improvement of the capability of fast, design-oriented models to describe loads fluctuations induced by unsteady and non-homogeneous onset flow
- Coupling of fast, design-oriented models with CFD solvers for fast modelling of tidal arrays using approaches generalising standard actuator disc models
- Limitations related to physical assumptions of the operational environment: controlled fluid structures, constant and defined bathymetry.
- Devices impact on the environment: develop and validate turbine wake/seabed soil interaction models, hydro-acoustic models in order to predict device noise footprint potentially harmful for sea wildlife.

3.4.3. Offshore wind

The development of numerical models for the optimisation of offshore wind conversion is heavily focused on coupling hydrodynamic models that can represent a floating platform with aerodynamic models that accurately represent the performance of wind turbines during various points of operation. A shortfall of these numerical models exists due to the lack of experimental data and the difficulties associated with gathering the information; e.g., generating representative wind loading at laboratory scales.

Combining physical testing of offshore wind platforms with real-time numerical simulation is an increasingly popular method of simulating wind thrust in the laboratory in the absence of a wind field. In this type of testing, typically known as *real-time hybrid testing*, *Hardware-in-the-loop* or *Software-in-the-Loop*, [51] the response of the platform is measured experimentally and passed to a numerical model that simulates a full-scale floating wind turbine. The numerical model calculates the aerodynamic loads on the turbine tower resulting from a hypothetical wind field, the motion of the platform and the numerically simulated turbine control algorithm [52], [53]. The calculated wind thrust is fed back to the actuator (often a ducted fan) in the laboratory and applied to the physical model. An example of such a numerical model is FAST, a computer-aided engineering tool developed by NREL, which couples models representing aerodynamics, hydrodynamics, control and electrical system dynamics and structural dynamics in the time domain.
Combined physical-numerical testing can resolve one of the technical challenges associated with laboratory testing of offshore wind turbines, namely, the Froude-Reynolds conflict where the scaling of the model based on the Froude number produces equivalent hydrodynamic forces, but out of scale aerodynamic forces at the rotor, similar to the problem encountered for tidal energy applications. Reynolds number, which governs the aerodynamic forces, is usually not kept constant. However, other challenges with real-time hybrid testing exist; these include:

- Time delays from numerical simulation, data transfer and the actuator response. The time-delay may introduce additional damping or spurious energy that may cause instabilities. A delay compensation strategy is necessary.
- Physical limitations of the actuators to emulate the high frequency loads that are important in the design of certain types of offshore wind turbines including tension-leg platforms and monopiles.
- The accuracy of the aerodynamic loads is limited by the simplifications and uncertainties in the numerical model. Uncertainties can be attributed to both the input wind field characterisation (such as a lack of full-scale data) as well as aerodynamic load modelling (simplification and assumptions, accuracy of numerical solvers).

Limitations in the capabilities of the numerical models in use at present must be overcome, in addition to improving the methods for generating accurate wind thrust in the laboratory (e.g. the use of multi-rotor devices).

4. Theme 3 – Crosscutting and Material Testing

In the context of the MARINERG-i Science Plan, crosscutting encompasses a broad range of transverse activities addressing technological issues associated with the development and deployment of offshore renewable energy converters, which are relevant for the three considered offshore renewable energy fields: wave, current and offshore wind. Main identified topics to be addressed include:

- Development of new materials
- Ageing of materials in the marine environment
- Moorings
- Dynamic cables
- Electrical, connectors,
- Maintenance and Operations,
- Biofouling

In addition to specific research programs developed within the MARINERG-i DRI to address these cross-cutting challenges, it is foreseen that this activity will require the development of new measurement techniques and possibly new instrumentation and methods for enabling more advanced understanding of technologies behaviour. This will include close interaction with the environmental monitoring enhancement programmes identified in theme 1.

4.1. Materials

The increased use of new lower cost materials such as composites or polymers is a promising alternative being investigated so as to reduce LCoE and optimise device weight and performance. However, longer term performance, durability and the ageing of such materials in the marine environment need to be proven. These key elements for the reliability of the devices and their sub-components still represent major unknowns and require specific research.

There are at least three major challenges facing the end user who needs to optimize materials for ORE in order to reduce costs while ensuring long term durability:

- Obtaining reliable data for in-service loads
- Obtaining relevant long term material data, including coupling effects
- Testing to validate lifetime model predictions.

The first point is absolutely fundamental to any material related activities. If loads cannot be clearly defined then, material components - composite blades, anchoring systems or Power Take-Off lines - cannot be correctly dimensioned. This will result in either premature failure or overdesign. While resource predictions can indicate global conditions at a particular site, it has been clearly demonstrated that local effects such as turbulence will also contribute to loading. This requires the development of specific instrumentation as already pointed out in Theme 1 on resource characterization and environmental loading. An example is the measurements made on the Alstom 1 MW DeepGen-IV tidal turbine at EMEC within the ReDAPT project [1] which were specially designed to record velocity perturbations with a relatively high spatial and temporal resolution. Such data must be

correlated with structural response measurements, on device structures such as turbine blades, floaters, PTO or mooring systems, in order to be able to provide benchmark loading spectra which can be used to define laboratory tests, both on materials and structures.
The second point concerns the material tests. If an appropriate loading sequence can be defined then the aim of these tests is to establish safety factors with respect to material damage development and failure. Several laboratories perform such tests in Europe, for example, for fibre reinforced composite components [2-4], or ropes for mooring systems [5,6]. A major requirement is that coupling be correctly integrated in these test campaigns, so that for example cyclic tests are performed in water and at appropriate temperatures [7]. Accelerated testing is frequently used to reduce testing time but may be unnecessarily severe when elevated temperatures are applied. Data on loading other than tension or flexure are very rare; for example, there are few guidelines which enable impact or erosion to be accounted for and these may be critical aspects for long term durability. Coatings may be applied to limit these factors but their long term durability is rarely addressed. There is a need for standard test procedures to evaluate materials for ORE and these must be linked to realistic loading conditions.
The third point concerns lifetime prediction. While there have been several large programmes directed towards wind turbine blade lifetime prediction [8] these do not require coupling with water effects. There is some literature in this area but more work is needed to validate the many assumptions employed. Any modelling results must be compared with test results and this requires an open access database. Existing wind turbine and tidal turbine blades test facilities should provide urgently needed fatigue loading response data at full scale. The round robin exercises currently being performed within MaRINET2 should help to orient the testing requirements and to the definition of agreed test protocols which are essential for the generation of relevant and valuable data sets.
The identified test facilities to be made available as part of the MARINERG-I DRI allow for the development of research programmes adapted to respond the challenges here above identified for the improvement of the efficiency and durability of materials in the marine environment. The main scientific objective is the elaboration of benchmarking programmes combining component testing on dedicated test benches and long term testing campaigns at open sea test sites following specific monitoring protocols so as to create the databases needed to elaborate adapted recommendations and guidelines. Procedures for the development of adapted sensors for the characterization of both the structure and materials response and the environmental loading will also be implemented jointly with the research activity identified in the other themes for the improvement and standardization of the instrumentation and testing procedures.

4.2. Moorings and dynamic cables

Moorings necessary for station-keeping of floating structures and dynamic cables used to transfer the power generated by the ORE devices to the subsea network and to the grid, in spite of their clearly different functions share some common points. Both, having one fixed end point on the seabed are submitted to the environmental loading all along the water column and to the dynamics of the floating structure to which they are connected near the surface. Both are also identified as significantly contributing to the costs associated with maintenance and operation, hence as being good targets for improvement (reliability, ageing) inducing substantial reduction of the LCoE.

4.2.1. Moorings

There is considerable current interest in the use of novel mooring systems for ORE structures. The main emphasis is on synthetic fibre ropes [9], for floating wind, but the much more dynamic environment of all ORE applications compared to the offshore oil and gas industry has led to the need for damping to reduce peak loads. This can be introduced through the choice of a more compliant material, through design, or by inclusion of specific damping elements. In all cases the main difficulty resides in guaranteeing long term reliability. While polyester has been extensively studied and is now widely used in deep-water moorings offshore, the durability of alternative low stiffness materials such as nylon for catenary moorings or high modulus fibres for TLP platforms has not been established. More work is needed, both in material testing and in gathering data from tests at sea, in order to validate mooring line modelling and to define more realistic test programmes. Specific problems such as snap loading [10] and water diffusion/stress coupling also require further investigation. The development of mooring line modelling codes which include both viscoelastic and load-history dependent material behaviour should also be a priority.

The dynamics of floating bodies and especially ORE devices are influenced by their mooring systems. Motions and structural loads are closely related to the resonant periods and damping from the aerial and underwater components including the mooring lines which particularly play an important role in the low frequency dynamics.

The low frequency drifting behavior and ultimate resistance are also key points in the case of offshore farms when the relative positions and the reliability of the floating devices are part of the overall efficiency and safety. Although numerical modeling has reached a consistent level of accuracy, experimental modeling at reduced scale remains necessary in sufficiently large basins able to simulate detailed mooring configurations and the actions of waves, wind and even currents. Complementary data from full scale are useful to calibrate the numerical results and evaluate the possible scaling effects. The development of suitable instrumentation for the *in situ* monitoring of mooring loads and motions is therefore important.

4.2.2. Dynamic cables

Dynamic cables are the components of the power transfer line running from the floating offshore renewable energy converter (whether considering wave, tidal or wind energy converter) down to the seabed and the hub connecting to the grid. This section of cable is submitted at its upper end to the dynamics of the converter responding to the environmental loading. It is also submitted to the forces associated with the wave kinematics and currents all along the water column. All this dynamic loading induces various constraints on the cable and mostly cross-sectional stresses which are largely contributing to its fatigue ageing, potentially increasing the risks of failures and decreasing its expected service lifetime. Dynamic cables are relatively complex structures composed of various elements (conductors, insulation screens, optical fibre units, armor, etc.), all assembled together under an outer jacket and all having various mechanical and structural properties. In addition, various sub-elements including buoyancy components, bend stiffeners and bend restrictors or cable protection panels can be added as mitigation solution to the dynamics induced by the environmental loading.

Even though a significant number of failures are reportedly due to installation procedures [11], there is still a need for a reduction of the uncertainties on the estimates of environmental and dynamic loading and their influence on the dynamic cable ageing during its long term operational phase.

The identified challenges regarding umbilicals-structure interaction and their influence on ageing and reliability can be addressed through multi-staged approaches combining component testing on dedicated test benches and testing at reduced scale in wave tanks. This requires the development of specific guidelines on scaling and similitude effects adapted to the considered materials and structures. In parallel, databases are to be created from in-situ monitoring campaigns conducted at open sea test sites to calibrate the models and evaluate the possible scaling effects.

4.3. Electrical connectors

Connectors are used to connect power cables to subcomponents of the electrical equipment or cables to cables so as to build the subsea array necessary for transmission of the electrical power produced by ORE Converters to the onshore grid. Non-permanent connection is needed in many cases so as to allow easy recovery of the ORE devices or components during maintenance operations. Therefore, specific connectors adapted to the constraints of the marine environment are necessary.

Even though different technologies should in principle be available from the offshore Oil & Gas industry, they are in many cases not adapted to the required power and voltage levels. Another critical barrier to the utilization of these connectors in the marine energy sector is their high market price which is not in favor of a reduction of the LCoE.

The main drivers identified by the end-users for the development of new adapted connectors include:

- A reduced CAPEX of the connectors so as to reduce the LCoE
- An easy and quick connection and de-connection procedures so as to lower OPEX by reducing the needs for highly qualified manpower and limiting expensive offshore working time while increasing the probability of suitable weather windows for marine operations
- A capacity to enable remote coupling and de-coupling so as to increase personnel safety by avoiding potentially dangerous transition of personnel from work boat to device and also to decrease cost for ROV operations in case of submerged devices

In addition research activity is still to be conducted so as to develop connectors adapted to the electrical specifications of the ORE sector. In particular, it has been noted that more development on cable-device connectors is needed than on cable-cable-connectors and that focus should be made on connectors for AC power transmission.

Identified research paths for the development of electrical connectors include:

- solutions adapted to recently proposed voltage for offshore wind farm array cabling: 66 kV [12]_in Europe and 69 kV in US, standard voltage was formerly 33 kV in Europe and 34.5 kV in the US [13],[14]
- solutions adapted to power level of modern large offshore wind turbines: 10 to 12 MW. This will cover the power requirements of the largest available tidal devices and future wave devices: 1.5 MW (AR1500, HS1500, mWave, CETO 6 Mk.2), 2 MW (AR2000, Orbital O2, ATIR), 3.6 MW (Poseidon P80) and possibly 9 MW peak power (GWave PGV)
- assessment of the wet-mate and dry-mate approaches for cable-cable connections.

The testing and monitoring capacity offered at the various open sea test sites available in the MARINERG-I DRI will contribute to support this research activity for the development of adapted connectors and standardized practices for connection procedures.

4.4. Maintenance and Operations

One of the key requirements to contribute to the reduction of LCoE is to guarantee the continued operation of the ORE devices once deployed. Therefore, adapted maintenance programs and associated operations are to be implemented. Some expertise in the management of marine operations and maintenance programs is transferable from the Oil & Gas industry which has already developed procedures and equipment, including support vessels. However, because of the diversity of ORE designs, it is likely that highly specific operations and maintenance procedures will be needed so as to keep the devices operational all year long while keeping low operation costs and considering safety of personnel as a priority.
In the context of the MARINERG-i DRI research activity, a contribution to reducing costs associated with Operations & Maintenance could mostly be based on developments for:

- Improving the reliability of the devices and their components
- Reducing the costs of offshore operations

Improvement of the reliability of ORE devices is, as already discussed in the previous chapters a key objective of the MARINERG-i Science Plan. This will be achieved through components testing so as to improve reliability prediction, contribution to the development of new technologies and materials aiming at replacing less reliable components and the development of adapted in-situ monitoring procedures and systems allowing for earlier warning of failure risk. Reducing the cost of marine operations can be achieved through many diverse contributions including testing of cost-efficient connecting disconnecting procedures and systems, development of adapted ROVs and author autonomous underwater vehicles for on-site inspection, development of planning tools for operations introducing weather window estimates based on local and regional monitoring.

4.5. Biofouling

Marine biofouling comprises hard-fouling organisms (calcareous organisms such as barnacles, mussels and tubeworms) and soft-fouling organisms (non-calcareous algae and invertebrates such as soft corals, sponges, anemones, tunicates and hydroids). Over 4000 organisms are responsible for biofouling [15], [16], [17].
Biofouling is a complex multistage dynamic process that involves continuous colonization by micro (e.g., viruses, bacteria, cyanobacteria, fungi, protozoa, diatoms and other microalgae) and macrofouling organisms (larger organisms, e.g., macroinvertebrates, macroalgae) (e.g., [18], [19], [20]). Colonization is greatly dependent on the type and number of organisms (whose settlement is independent of one another) that could attach to or colonize the substratum (but also by several complex environmental and biological interactions during colonization). Also, the absence of a stage does not impede the occurrence of another stage (e.g., [21], [22], [23]).
The composition and abundance of biofouling communities varies greatly, geographically (e.g., between different latitudes), seasonally (e.g., winter versus summer communities) and locally (e.g., at different depths or levels of exposure). Biofouling is dependent on many

abiotic factors such as seawater temperature, hydrodynamic conditions and depth ([24], [25], [16]) and biotic factors such as biology (e.g., larval development mode, period of recruitment), cues (chemical signals) and interactions (e.g., competition, predation) (e.g., [26], [27], [28]).
Despite a great effort has been devoted to the biofouling issue, there is still a paucity in understanding biofouling growth (e.g., biofouling composition, organisms' weight and size, impacts) and, most important, predicting biofouling in a certain location accurately is still complicated. Nevertheless, some trends in biofouling composition have been identified worldwide (e.g., [28], [29], [30]; [19]; [31];[24]) and the OCEANIC project has developed a European Biofouling Database which is updated frequently (oceanic-project.eu/biofouling-database; [32]).

Biofouling affects all kind of structures deployed at sea, including moorings and foundations or submarine cables. In time, its growth will increase the devices structural mass, components diameter and surface roughness, resulting in increased drag and inertia and loss of performance of the devices. Furthermore, biofouling may promote corrosion (e.g., microbiologically influenced corrosion; the devices or their coatings may be damaged by the organisms or upon their removal; some organisms, e.g. some bivalves and bryozoans, can use chemical substances for drilling substrates, in cases accelerating corrosion of materials). In all cases, biofouling will induce alterations in the materials causing a reduction in their integrity and longevity.

Marine structures such as ORE devices, although serving a different primary purpose, can be regarded as artificial reefs creating new surfaces on which the organisms attach, settle and grow [33], [34]. Therefore, such structures may act as promoters of ecosystem diversity and function, and often present communities more diverse and abundant that those in the surroundings (natural reefs and soft substratum) [35]. Additionally, this may result in fish attraction and aggregation when compared to surrounding soft-bottom areas [33].However, offshore structures may contribute to the propagation of non-native species (NNS) in the marine environment, serving as 'stepping stones' for the organisms [35], [36]. The introduction of NNS often impacts biodiversity, habitats or ecological processes, and it may pose great ecological (e.g., by competition, predation and/or exclusion of indigenous organisms) and economic (e.g., in the aquaculture sector, with production loss caused by impaired growth of the target species) threats.

Offshore maintenance is a costly and difficult process. For instance, maintenance, repair and inspection need to be carried out *in situ* during the service life of the setup, as these structures are settled to optimally perform from 10 up to 30 years. Accordingly, several methods/technologies may be used to control (prevent or remove) biofouling offshore. However, impacts caused by biofouling are varied and often device- and site-specific, making extremely difficult to rely on a single, best, method to control biofouling.
To avoid greater problems, usually observed when biofouling is allowed to grow for long periods (e.g., several months, or years), prevention is probably the best. This can be achieved will physical cleaning (e.g., frequent grooming with Remotely Operated Vehicles), which needs to be performed very regularly (e.g., every month, or earlier, depending on the device). The best prevention methods that don't imply regular monitoring may be anti-fouling coatings which prevent the organisms' attachment and growth. Several solutions are already in the market. However, none is capable to prevent all kinds of biofouling (e.g., some are specific to barnacles, which are one of the most problematic source of biofouling)

since each organism presents unique features (biology and ecology) and specific impacts to the MRE sector.

Elements presented here above show that biofouling is a complex process that can be considered from different angles when considering its impact on marine structures. Combining the capacity associated with the open sea test sites and specific facilities for testing of materials in the marine environment, the MARINERG-I DRI offers a real research support to contribute to better predict and model biofouling composition and its impacts, either on the response and integrity of marine structures or on the environment.
More specifically, the geographically distributed test sites will allow characterisation of the biofouling growth under different conditions through research programs aimed at:

- Assessing biofouling in different regions (e.g., warm vs cold)
- Assessing biofouling in sites with different exposure levels to oceanic conditions within region
- Assessing biofouling at different depths within/between sites/exposure levels
- Assessing biofouling growing in different materials (e.g., metal, plastic)
- Assessing the efficiency of different anti-fouling solutions (e.g., chemical, biological) within/between sites

5. Theme 4 - Research for testing

Test facilities are an essential part of the process to develop commercially viable offshore renewable energy technologies. Testing at a reduced scale allows developers to refine ideas, optimise device and subsystem design, and ultimately, reduce the cost and risk of full-scale deployments at sea. Laboratory testing aims to simulate real-world conditions in a controlled setting in order to conduct repeatable experiments with minimal uncertainty. However, real sea-states and wind regimes are highly dynamic and nonlinear, and can only be approximated in the laboratory. As ORE devices progress through the TRLs, larger scale laboratories and open sea test sites are necessary to further develop the design of sub-systems and evaluate the device performance and survivability in real seas. Testing at sea brings different challenges relating to instrumentation, monitoring, device deployment, operations and maintenance.

This chapter examines the challenges faced by existing infrastructures and offers perspectives on the research required to improve testing capabilities in laboratories and in the open sea. The focus in this chapter is on the test facilities; challenges relating to the design, set-up and operation of ORE devices including moorings and materials are discussed in detail in earlier chapters.

5.1. Reproducing environmental conditions at reduced scale

Laboratory facilities for testing ORE devices typically comprise wave basins, current flumes, towing tanks and electrical laboratories. Some research centres offer additional facilities for performing corrosion and materials testing, and test rigs for applying tensile or compressive forces to mooring lines, for example.

For wave basin tests, devices are positioned in a section that often has a movable floor to facilitate testing at different depths. Wave generation is generally achieved through piston or flap-type wave makers that can move independently of one another to generate uni- or multi-directional waves. The paddles move according to a pre-calculated displacement time-series, which generates waves of the desired amplitude, frequency, angle and phase. In most wave basins, the paddle signals are calculated by specialised software that allows the user to define the desired sea state.

Wave basins typically have a beach at the opposite end from the wavemaker. A well designed beach will absorb most of the energy generated by an experiment. Reflections will occur however off the side walls, the paddles, the device itself, and to some extent the beach, which can quickly impact the wave field. State of the art wave basins have forced feedback absorbing wavemakers that absorb incoming (reflected) waves by measuring the force acting on the paddle face or the free surface elevation along the paddle and controlling the paddle velocity to compensate [1]. In this way, experiments can be run for longer without being significantly impacted by reflected waves. Active absorption technology has the additional advantage of decreasing the time it takes the water to settle between tests.

Figure 7 Deep ocean basin at the Lir National Ocean Test Facility, Cork, Ireland]

There are two types of infrastructures for simulating current in a laboratory: current flumes and towing tanks. Towing tanks are equipped with a carriage that tows the model in still water to generate flow past a device. Current flumes typically have a flow circulation system in which current is generated by thrusters in a closed channel beneath the open channel test section. Curved vanes direct the flow from below into one end of the open channel and back down at the other end. Grids can be installed in flumes to alter the turbulence levels to simulate site conditions. Flumes provide a better representation of a tidal site for testing turbines, but are less common and therefore towing tanks are often used instead.

Many towing tanks and flumes are also equipped with wavemakers for combined wave and current generation. However, few facilities are capable of producing conditions suitable for high-quality experiments involving wave-current interactions (e.g. tests with tidal turbines) due to issues with turbulence and scaling.

There is a range of methods for simulating wind thrust on a model, from a simple hanging weight to a full-scaled rotor with individual pitch control and a dynamic control system. The more complex methods are generally more accurate, but are compromised by the inability of most wave tanks to generate representative wind fields (e.g. that take account of atmospheric boundary layer effects). Software-in-the-loop (SIL) systems, in which a thruster (e.g. a ducted fan) is controlled in real time by an active control system, can be used to simulate wind thrust in the absence of a wind field.

Hexapods are used in some laboratories to perform forced oscillation tests on ORE devices. They are equipped with six actuators that can generate motions in any direction or orientation (i.e. 6 degrees of freedom).

Aside from in laboratories, scaled testing is also carried out at sea in relatively sheltered test sites, for example SmartBay in Ireland, and EMEC in Scotland.

Scaled testing of both tidal and floating wind platforms presents challenges due to the application of two different scaling laws. Froude scaling applies to wave induced motions, whereas Reynolds scaling applies to hydrodynamic and wind loading on tidal and wind turbine blades respectively. Both methods are applicable but not compatible in a tank-testing scenario, resulting in compromises that can have an effect on scaled model performance. An overview of these challenges is given in Theme 2 as well as by [2], [3], [4] and [5] among others.
When performing laboratory testing of floating wind platforms, the use of software-in-the-loop (SIL) systems allows scaling to be dictated by the hydrodynamics only. However, improvements need to be made to the numerical models controlling these systems to overcome physical challenges such as generating adequate forces in the direction of interest.
Scaling difficulties also arise when inertia and elasticity of system components must be accounted for, e.g. when testing the mooring system of a floating device, or the hydroelastic response of turbine blades. The scaling of material properties and hydroelastic behaviour is an example of new challenges introduced by advancing technology (e.g. composite blades).

Wavemakers in laboratories are often limited to linear or weakly nonlinear wave generation. It is only recently that researchers managed to reproduce the so-called Draupner wave at laboratory scale [6]. The controlled generation of breaking waves and highly nonlinear waves remain highly challenging and needs to be improved.

Long duration simulations in wave basins are subject to contamination by reflections off the basin walls, the beach (if present) and the paddles. Active absorption is a feature of the wave generators in many modern wave basins; however, absorption is typically effective only for low-frequency waves. Beach installations in basins can absorb high-frequency components and tend to reflect long waves; however, their effectiveness is dependent on the beach slope, material, and the wave field characteristics. Research is required into more advanced absorption techniques that can be both retrofitted in existing basins, and incorporated in new basin design.

Minimising contamination from reflections will be particularly important when carrying out scaled testing of arrays.

The accurate representation of wind loading on a floating test structure is complicated and a new area of research despite the long-time experience with wind tunnels. The major challenge is the correct reproduction at a reduced scale of a local realistic turbulent wind field with gusts, and its interaction with a rotor, in particular if the rotor is in motion. SIL systems replicate the wind forces with a ducted fan or drone using a control system that accounts for the motion of the platform. However, these systems require further testing and validation. Improvements must be made in developing systems that generate adequate forces in the directions of interest, and in the numerical models that control these systems.

Load fluctuations associated by wave-induced perturbations of the onset flow are responsible for structural damage of blades and other components. Research to date aimed at combining waves with current in a laboratory setting has shown that towing tanks can provide high-quality wave spectra but the interaction of wave-induced motions with the current is inherently missing. On the other hand, wave makers in flume tanks may introduce uncontrolled/unrealistic turbulence structures in the flow and the quality of wave patterns can be affected [7]. While a number of research infrastructures have the capability to combine waves and current, only a small fraction are suitable for quality wave/current interaction studies.

One of the challenges to be faced when testing tidal devices in a towing tank is that the water is at rest and hence the inflow to the turbine has nominally zero turbulence; whereas in open water tidal sites, turbulence intensity of 5-15% is very common. Onset flow turbulence has a limited impact on power output but plays a critical role in a number of aspects, notably structural safety issues related with fluctuating loads [8] as well as shedding and diffusion of rotor wakes in arrays, or onset of cavitation [9]. Flumes are more straightforward in this regard, as eddies are naturally present in the flow and simple grids can be used to alter natural turbulence levels.
For turbine array studies, special attention must also be paid to the persistence of artificially generated eddies at large distance downstream the rotor in the wake field. Specifically, cavitating vortices can have serious impact on the structural integrity and performance of the downstream turbines.

Onset flow turbulence and wave/current interaction are examples of factors producing non-homogeneous inflow to the turbine, a condition leading to loading unsteadiness and possibly cavitation-related effects such as noise and material ageing. Other factors include seabed roughness and morphology and the shear profile of the onset flow, as well as the wake shed by upstream devices in an array. Modelling such effects in a laboratory environment is very important in order to understand how inflow variations result in fluctuating loads acting on device components like blades, supporting structures and drivetrain parts. Field-testing and CFD modelling has shown that non-homogenous inflow increases fatigue and the risk of damage and system failure [10]. Investigating these aspects at laboratory scale is a key device development and progression through the TRLs.

Enhanced testing capability in non-homogeneous transient flow is also necessary to improve power control strategies to maximize power output and system safety for operation in real conditions.

Large models introduce a problem in terms of blockage when tests are performed in the confined flow of a towing tank or a flume. Considering a 5% blockage as an upper limit for acceptable flow confinement effects on turbine performance, many hydrodynamic facilities routinely used for ORE applications do not provide satisfactory conditions for model rotors with a diameter of greater than 0.5 m. Therefore, accurate methodologies must be introduced to correct results of model tests carried out in non-negligible blockage conditions. An example of research in this area is the Round Robin test conducted in the FP7 MaRINET and subsequent H2020 MaRINET2 projects where the effects of flow confinement on horizontal-axis turbine performance are addressed [11].

Little consideration to date has been given to the impact that increasing realistic laboratory testing methods have on uncertainty. For example, when testing floating wind systems, the more complex the wind emulation system is, the more uncertainty is introduced due to the increased number of variables. Both ITTC and ASME [12] have published guides for the quantification of uncertainty in the laboratory; however, these have not been implemented in a systematic way. Researchers at NREL [13] have attempted to identify sources of uncertainty associated with hydrodynamic testing of a floating wind platform. [14]

examines the uncertainty introduced by introducing wind thrust and gyroscopic rotor loading, with a view to informing the round robin testing due to be conducted in 2019/2020 as part of the H2020 MaRINET2 project.

Failure mechanisms relating to different types of corrosion (e.g. uniform, marine, pitting, galvanic, cavitation, hydrogen embrittlement, etc.) are at present not well understood and require research. Research is also necessary to improve understanding of how combinations of factors causing material degradation, e.g. the combined effects of corrosion and fatigue, the combination of composite ageing and fatigue or the biofouling growth. For further information on the challenges relating to material testing, refer to Theme 3.

Proposed research/actions for the reproduction of environmental conditions at reduced scale include:

- Improve wind emulation using SIL systems by improving the numerical models used to control them. Investigate the use of multi-rotor devices (similar to drones) for simulating wind thrust.
- Improve wind generation capabilities in wave tanks to recreate a realistic shear layer.
- Investigate the use of wind tunnels in parallel to wave basins, whereby an instrumented turbine in the wind tunnel provides wind thrust forces, which are applied to a floating turbine in a wave basin using an active control system.
- Develop improved methodologies for generating nonlinear and breaking waves
- Improve beach design and active absorption technology to minimise reflections.
- Develop methodologies for testing arrays in wave basins that minimise tank effects.
- Develop improved methods for generating waves in the presence of currents that are representative of real sea conditions.
- Develop techniques to reproduce tidal-site turbulence in towing tanks e.g. by installing grids or obstacles in front of the turbine to obtain different turbulence intensities. Characterise the turbulent flows behind these grids to determine how these properties change downstream.
- Develop techniques to study seabed morphology changes replicating real sea conditions
- Validate existing blockage correction procedures using experimental data and CFD predictions and extend their validity to include special cases like rotors in proximity of free surface, or interacting rotors in arrays.
- Put in place a standardised approach for the assessment of the experimental uncertainty associated with physical testing of ORE devices and investigate ways of reducing the uncertainty associated with tank testing at low TRLs.
- Develop methodologies for simulating material failure mechanisms.

5.2. Development of measurement systems and procedures

Resistance-type probes are typically used to measure wave heights in laboratories. They operate by measuring the current that flows between two stainless steel wires that pierce the water surface. The measured current is converted to a voltage that is directly proportional to the immersed depth. Servo wave gauges are the preferred resistance-type measurement system in salt-water basins due to their non-corroding single platinum probe. Capacitance-type gauges operate by relating changes in capacitance to changes in water depth.

An overview of non-intrusive wave measurement methods is given by [15]. These include acoustic probes and laser-based optical sensors, such as optical triangulation wave probes, laser slope gauges and LiDAR (Light Detection and Ranging). Particle image velocimetry (PIV) is a state of the art optical measurement and visualisation technique of fluid flow. The principle of operation is that the fluid under examination is seeded with microscopic tracer particles, and the motion of these particles is illuminated with a laser and recorded photographically. Image processing software is then used to determine velocity and other parameters such as vorticity and turbulence.

Laboratory facilities that have a wind generation system (e.g. a blower) are generally equipped with a wind measurement system. Cup-type or propeller-type anemometers can measure the average speed in one direction, but ultrasonic anemometers are the preferred wind measurement system in a laboratory environment. LiDAR can also be used to characterise wind fields in a laboratory.

Instrumentation typically employed in the laboratory to measure flow velocity at a single point include pitot static tubes, flowmeters or ultrasonic flowmeter sensors (e.g. Acoustic Doppler Velocimetry (ADV)). Laser Doppler Velocimetry (LDV) and PIV can be used in a flume to achieve high-resolution water velocity measurements in two dimensions. Acoustic Doppler Current Profilers (ADCPs) provide flow characterisation in three dimensions.

Optical motion capture is commonly used in the laboratory to measure the motion of a device undergoing testing (e.g. Qualisys). It can be used to track the position of fixed points with 6 degrees of freedom. Wiring is not required for these systems as the motion is tracked with cameras mounted around the wave basin. The technology can also be implemented underwater.

Other commonly used measurement equipment include load cells and pressure sensors that can be installed on ORE devices and mooring lines.

Resistance-type probes are the most common method for measuring wave heights in laboratories; however, they present some significant disadvantages. Frequent calibration is necessary, and large measurement errors can occur if the gauge is moving relative to the water surface (i.e. in towing or wave-current experiments), or subject to large hydrodynamic loads caused by high-amplitude waves. Non-intrusive wave measurement methods such as optical triangulation wave probes, laser slope gauges and LiDAR can produce good results; however, they lose accuracy when measuring steep-sloped, nonlinear waves. Particle Image Velocimetry (PIV) systems produce high-accuracy measurements in a 2D plane, but are costly to set up in the laboratory and are unsuited to breaking waves and large wave field measurements. As methods for the generation of nonlinear and breaking waves improves, it will be necessary to develop innovative and cost-effective techniques for high resolution measurements of the wave field and wave kinematics. Adapted methods for accurate measurement of directional sea states in a wave tank also require development and improvement [16].

The measurement of extreme wave loads at model-scale is challenging due to the small size of the models. As laboratory wave-makers are limited as to the size of the waves they

can generate, the model scale must be reduced in order to obtain wave amplitudes comparable to extreme wave heights at full scale. This makes force and pressure measurements difficult as the quantities being measured are very small.
LiDAR is becoming more common as a method for measuring the wind field at wind farm sites; however, these systems must typically be fixed on solid ground for high quality measurements. Floating solutions have emerged as a cost-effective solution compared to met-masts for wind resource assessment for offshore wind farms. However, further research is required in this area, particularly in terms of obtaining data and developing methodologies in the laboratory for validating the LiDAR measurements at sea and quantifying the uncertainty associated with different sea states.
Challenges associated with the measurement of both flow and turbulence at tidal sites are discussed in Theme 1. In energetic environments, both ADCP measurements for example are often contaminated by Doppler noise. Improvements in ADCP technology are required (i.e. increased number of beams and higher sampling frequency) as well as methods to post-process the data.

Proposed research/actions for the Development of measurement systems and procedures include:

- Develop improved methodologies for the characterisation of the flow and the free surface elevation in tanks and flumes, including directional properties.
- Develop procedures for improved load measurement at reduced scale.
- Conduct research into laboratory-based methodologies for validating floating LiDAR measurements and quantifying the uncertainty.
- Develop improved instrumentation and methodologies for characterising flow and turbulence in energetic environments.

5.3. Monitoring

Reliable and safe operation of ORE devices requires continuous device performance control as well as the ability to check the integrity of components. Full-scale ORE devices are typically equipped with sensors to acquire, store and transmit information on the site conditions as well as electrical and mechanical subsystems and components, e.g. strain gauges on tidal turbine blades. Recent advances in smart health monitoring systems allow the detection of material failures in the early stages of deterioration. The implementation of these systems is expected to improve system reliability and facilitate the optimisation of maintenance schedules.
Measurements relating to tidal currents, waves, and wind as well as electricity generation are used as inputs to control strategies that are used to reduce peak loads and improve reliability, as well as optimise the power output of the ORE device.
Mitigating the impact of variable environmental and operating conditions is an important adjunct to health monitoring. Widely-banded passive controllers [17] and semi-active controllers [18] are examples of mitigation measures; however, further physical testing of these controllers is required.

ORE devices are deployed in remote environments with difficult access and variable meteorological conditions that can affect the reliability, operation and behaviour of mechanical, structural and electrical components. Where deployments occur in areas subject to high winds and seas, relatively few weather windows exist in which operators can carry out essential maintenance or repairs, often resulting in lengthy downtime. Reliable monitoring is therefore essential to identify deterioration, avoid major failures and reduce the cost of energy generation, during testing at TRL 5-9, as well as for commercial deployments.

The current state of the art technology in the area of fault detection exists in the offshore wind and solar sectors; therefore adaptation is required for the wave and tidal sectors. Across all sectors, however, the efficacy of these systems must be improved. As more data on component and system reliability is generated, methods and tools must be developed that can process complex data resulting from varying environmental and operating conditions, e.g. by applying wavelets [19] or artificial intelligence and machine learning techniques to the design fault detection and condition monitoring systems.

The use of wireless sensors may provide a solution to monitoring components of ORE devices where wired instrumentation is impractical or difficult to install. Unobtrusive wireless sensors can be embedded in the components so that they can monitor and wirelessly transmit data on a variety of structural parameters. The integration of wireless sensors with memory and processing capabilities to perform computational activities can alleviate the burden on wireless communication. In other words, data from on-board sensors, or within the sensor network should be pre-processed (also known as in-network processing), to reduce the communications traffic within the wireless sensor network [20]. Further research is required in this area.

There is currently a lack of data on the long-term impacts of ORE technologies flow regimes, sediment transport, habitats and wildlife. Lengthy monitoring and data gathering exercises are required in this regard.

The development and testing of advanced condition monitoring, fault detection and control strategies at reduced scale will rely on accurate reproduction of realistic environmental conditions in the laboratory, as discussed in earlier sections.

Proposed research/actions for improving monitoring capacity include:

- Develop condition monitoring systems that in addition to measuring the performance of device components, also measure site conditions and allow the operator to change control strategies remotely.
- Develop in-built networking and communications systems for improved operations and maintenance of farms of ORE devices
- Investigate the use of wireless sensors as a solution to monitoring ORE devices.

5.4. Development of new facilities

The MaRINET2 consortium provides a good overview of the state-of-the-art facilities available in Europe at present, particularly for small-scale testing. It is composed of 37 institutions offering access to 54 different ORE test facilities across 12 EU countries, details of which can be found on www.marinet2.eu. Many of these facilities were adapted from other applications (e.g. coastal engineering research) to accommodate the needs of the ORE industry. A smaller number were built specifically for ORE research; these include laboratories in Plymouth, Edinburgh, and Cork, and a multi-purpose offshore platform, test site and observatory in the Canary Islands. Open-sea, grid connected test sites for ORE research are available at EMEC (Scotland), SmartBay (Ireland) and BiMEP (Spain). Very large-scale test facilities in Europe include the Large Wave Flume (GWK) at the University of Hannover, which is the largest publicly accessible research facility in the world, measuring 307 m long, 7 m deep and 5 m wide.

Profiling conducted in the MARINERG-i project of European research facilities resulted in Figure 8 below. The figure shows the numbers of large and small laboratories, and large/medium scale open sea test sites as well as illustrating the testing capabilities available for wind, wave and tidal devices, as well as electrical and cross-cutting technologies.

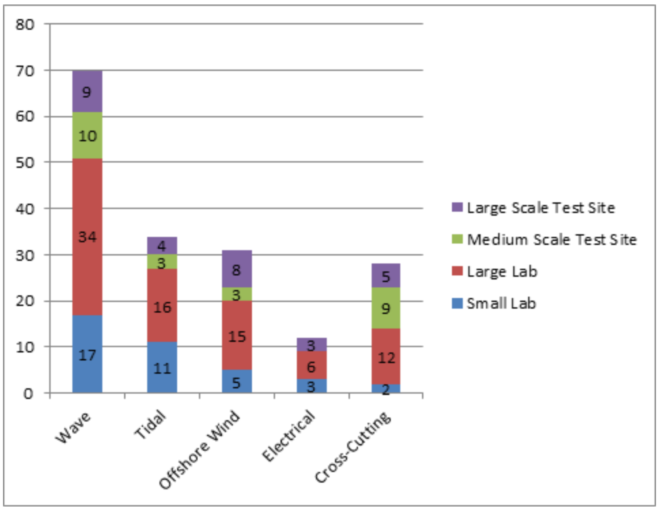


Figure 8 European research facilities, by scale and type (MARINERG-I profiling study)

The increasing demand for accurate and comprehensive testing is already stressing the existing portfolio of test infrastructures beyond their capabilities. As new technologies are developed, new, more advanced testing capabilities are required. It is expected that the demand for offshore test sites and larger test tanks will increase with the evolution of projects towards higher TRLs.

The construction of new facilities specifically designed for ORE applications will most likely be necessary in the long term to keep pace with the requirements of the ORE sector. Purpose-built large-scale test infrastructures should have the ability to reproduce real sea conditions in a laboratory environment through simultaneous generation of waves, wind and currents and address the issues raised in the previous sections such as improved representation of combined wave-current and wind-wave conditions.

Wind tunnels may play a greater role in the future when it comes to the application of realistic wind thrust in physical test involving floating platforms. New ORE test facilities may investigate the possibility of using instrumented wind turbines in wind tunnels to obtain realist load profiles, which can then be applied to a floating turbine in a wave basin where the hydrodynamic and structural response is measured and fed back to the wind tunnel in a 'facility in the loop' system.

The ability to control turbulence as well as the capability to modify the geometry or overall dimensions of the test section would provide maximum flexibility for testing a range of devices, and enable the performance of complex and innovative tests.

Minimising contamination from wave reflections in basins is important when carrying out long duration experiments involving ORE devices. This becomes critical when carrying out scaled testing of arrays of devices in order to identify the impact the array has on the wave field. This may require a concept design for a MARINERG-i infrastructure capable of testing arrays at model scale, where the impact of reflections is kept below a critical threshold. Similarly, the study of tidal device arrays requires the construction of suitable facilities able to accommodate a number of devices to minimise scaling issues while providing adequate

flow structures. Methodologies for testing devices in wave basins that minimise tank effect must be developed.
The development of facilities for more advanced electrical testing can be achieved by consolidating and improving the facilities currently available in many testing infrastructures. Consultation with electrical contractors and consultants may provide practical advice for the physical implementation of different circuit configurations and the use of off-the-shelf equipment when developing ORE prototypes. More hydraulic testing facilities are required, as well as linear generators for testing. Aside from improved physical test facilities, improved modelling capabilities should also be prioritised.
As the construction of new facilities carries a high capital cost and will likely require financing from industry, in the shorter term, existing facilities should be upgraded and retrofitted with new equipment, and advanced testing methodologies must be developed to enhance the support that laboratories can provide to the ORE industry.

Proposed research/actions for the development of new and adapted research facilities include:

- Create a long term strategy for the construction of purpose-built large-scale test infrastructures with advanced capabilities for reproducing complex environmental conditions, including wind-wave, and wave-current interactions.
- Put in place a shorter term strategy to upgrade/retrofit existing facilities with new equipment. For example, grids to provide turbulence control in wave flumes,and advanced wave absorption technology to minimise reflections.
- Investigate the expansion of existing open sea test sites and the development of new sites with grid connections and adapted logistics capacity. For further details relating to electrical connectors, maintenance and operations, refer to Theme 3.
- Develop advanced testing methodologies and standardised procedures to enhance the support that laboratories and open water sites can provide to the ORE sector

6. Implementation of the Science Plan

The MARINERG-i Distributed Research Infrastructure will stimulate and support the development of advanced technologies for harnessing Offshore Renewable Energy, pursuing the need to attain a more carbon neutral, sustainable and autonomous energy supply. It will therefore bring together a selected set of research facilities so as to build the critical mass of knowledge, skill and resources necessary to sustainably address the issues raised by the constantly evolving ORE sector. It will facilitate and mediate the exchange of knowledge and expertise, data, and human capital in ORE between these research entities, stakeholders and other interested parties. It will coordinate on a centralised basis the usage of the distributed testing infrastructures for use by qualified European and international scientific communities, facilitating and streamlining user access to the facilities, engineering research, quality validation and analytical services, and databases, through a common web portal and e-infrastructure.

Already identified scientific questions to be addressed through the MARINERG-i research programs were presented in the previous chapters, classified under four main themes. The following sections will outline the main elements of implementation of the MARINERG-i Science Plan.

The MARINERG-i DRI will run in the long term following a staged evolution described in section 6.2 and according to an operating approach detailed in section 6.3, with a focus on the implementation of the access program. The organisation of the governance and project management related to the coordination of the scientific activity, as described in the statutes, are recalled in that same section. All the aspects related to communication and outreach, training and capacity building as well as connections with other organisations and programmes, which are key elements to the development of this scientific plan at the European and International level, are presented in section 6.4 and subsequent. Finally, anticipated benefits are highlighted in section 6.5.

6.1. Fundamental questions

The acceleration of the development of the ORE industry is obviously driven by the necessary need to lower the Levelised Cost of Energy (LCOE). Many approaches may lead to an optimised exploitation of the offshore renewable energy but some have been clearly identified as priorities: There is a need to reduce uncertainties on a wide range of parameters so as to improve the reliability and efficiency of the devices; harsh marine environment are not yet characterised with enough accuracy. The spectro-directional distribution of the energy within complex sea-states, crucial for the optimisation of WECs is not accurately described; turbulence associated with energetic tidal currents is not well known and reasons for this include the lack of adapted sensors and measurement procedures; identification of the wind flow variability in the lower boundary layer above the ocean and up to turbine hub height is also constrained by the capacity to develop and deploy at sea cost-effective profiling sensors. The joint assessment of these coupled forcing fields, of major importance when assessing hybrid systems, still requires adapted monitoring strategies. The characterisation of the environmental loading is addressed in THEME 1 while the monitoring and sensor development issues are addressed under THEME 4 together with the problem of reproducing environmental conditions at reduced scale. Indeed, the design and optimisation of ORE devices is a multistage process requiring the physical processes at stake, whether considering hydrodynamics, power transfer, power take-off and control strategies being identified and understood in the controlled environment of a laboratory before machines and sub-systems being tested in real conditions at open sea test sites. Performance optimisation is addressed in THEME 2 while all the research to improve the testing capacity, involving monitoring and reproduction of the environmental conditions at reduced scale is conducted in THEME 4 under which future needs for adapted research facilities is also investigated, considering the long term objective of the MARINERG-i DRI. Also clearly identified as offering potential for innovation and ground breaking developments in the longer term, cross-cutting issues are addressed in THEME 3.

6.2. Timeline

It is foreseen that the MARINERG-i DRI will operate over a multi-decadal period as on the one hand, designing and optimising ORE devices proves to be a long term cross-sectoral and multi-disciplinary process and on the other hand, once achieved the primary objective of having devices deployed and connected to the grid, contributing to the global power production, the ORE industry will continuously seek new solutions to improve and optimise its production capacity while reducing the LCOE, also considering new production areas and potentially ground-breaking technologies, beyond solutions already envisioned such as the hybrid systems.
The development of the MARINERG-i DRI itself, is a long and clearly established process with different stages and milestones along the path to the creation of the MARINERG-i European Research Infrastructure Consortium (ERIC), the legal ESFRI structure allowing for the operation and management of the DRI.

The Science Plan will be implemented according to a staged development plan following the phases identified in the MARINERG-i progressive business model:

- Foundation
- Expansion
- Operation

In the first phase of the implementation, the DRI will include established ORE infrastructures and facilities for the testing of offshore wind, wave and tidal energy technologies at all stages of development (TRL1-9), selected and configured to service the existing service demand. It is foreseen that the elaboration of this structure will take advantage of the advanced community established under the MaRINET and MaRINET2 programs and considering the level of engagement of each partner country.
This founding structure will establish the organisation necessary to ensure the operability of the high quality scientific and engineering services necessary to support the development of advanced technologies for harnessing Offshore Renewable Energy. It will more specifically establish the service offering streamline access to the test facilities and develop the capacity for coordinating the storage and use of the data, considering both scientific data and associated metadata necessary to inform partners and other stakeholders as well as to inform the longer term development strategy.

The objective of the second phase is to consolidate the DRI by including additional ORE research infrastructures so as to expand the offer of services made available by MARINERG-i and match the demand of the ORE industry. By identifying the limitations and possible points for improvement associated with individual facilities, the distributed configuration will expand and optimize the spectrum of capabilities to provide enhanced services to enable technology and sub-system development and proofing.

This expansion could potentially include niche infrastructures (e. g. ROV R&I, etc.). This stage requires the development of the operational capacity of coordinated management through the regional groups so as to consolidate the access services and to develop standards through exchanges and collaborations between facilities.

Finally, the operational stage will start within the fourth year after the beginning of the foundation process with the official launch of the MARINERG-i ERIC. At this stage the operation and management of the scientific activity will be entirely conducted according to the governance and operational structures as defined in the MARINERG-i ERIC statutes. An expansion of the DRI will still be possible, including the international infrastructures necessary to service the global market and adapt to the evolving demand. Such evolution would be conducted according to the requests from the end-users and the recommendations of the advisory committees, following a periodically updated Long Term strategic Plan.

6.3. Governance and operation

Since MARINERG-i will be established as a European Research Infrastructure Consortium (ERIC), the governance arrangements will follow the ERIC guidelines and be grounded in legal statutes and associated contracts. The governance structure as defined in the currently established legal statutes shall consist of:

- An Assembly of Members
- A Central Management Office lead by a CEO
- A Scientific, Technical and Ethics Advisory Committee
- An Executive Committee
- Service Groups

MARINERG-i CEO and Central Management Office (CMO) will be responsible for the day-to-day operations of the MARINERG-i entity, making decisions on daily operations to efficiently deliver the MARINERG-i ERIC.

The CMO will take responsibilities for informing and leading the wider international promotion of the MARINERG-i ERIC; co-ordinate the engagement of the infrastructures delivering access and services on behalf of the MARINERG-i ERIC; and lead the formation of the MARINERG-i ERIC through the contracting of participating infrastructures.

It will also be supported by the Scientific, Technical, Quality and Ethical Advisory Committee (STQEAC) which will provide independent advice and feedback on the focus and performance of the MARINERG-i ERIC. This will be made up of invited International experts in the respective areas of the STQEAC.

The operational structure comprises, in addition to the main office, the distributed facilities made available for access and usage by qualified European and international communities, supported by the Service Groups, organisational units tasked with specific activities of transversal interest.

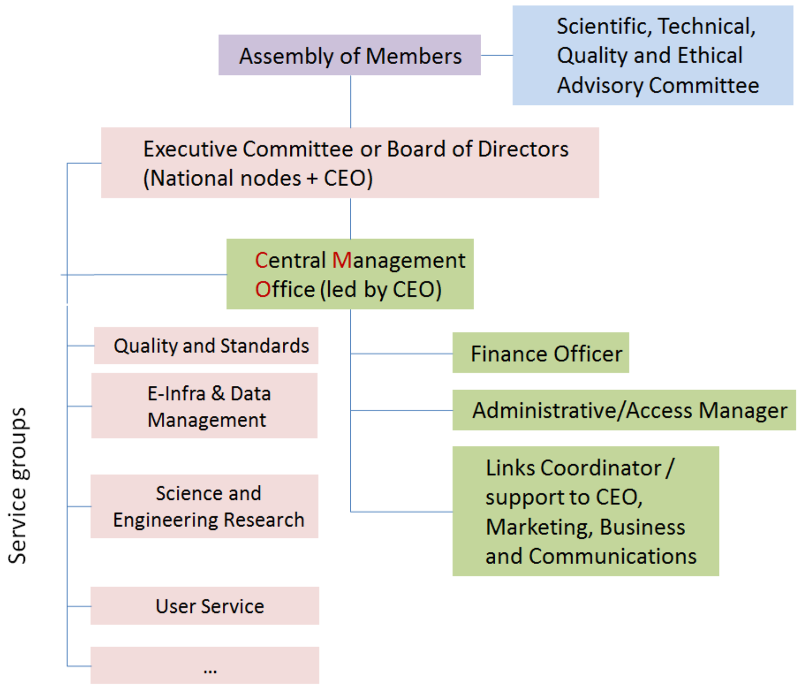


Figure 9: MARINERG-i proposed governance structure

6.3.1. Service Groups

The Service Groups are distributed organisational units located in one or more countries. They are in charge of carrying out specific activities of transversal interest classified in five different categories:

The Science and Engineering Research Service Group is responsible for supervising, implementing and reviewing technological, engineering and standardisation practices across the DRI. This Service Group works to implement interoperability & best practices, and to foster convergence towards mature technologies and develop improved testing & operating methods.

The Quality and Standards Service Group develops and implements the MARINERG-i quality and standards policy and procedures, and is responsible for strategic standardization planning processes, auditing and compliance.

The E-Infrastructure and Data Management Service Group is responsible for developing and implementing the MARINERG-i data policy to ensure effective curation and controlled access to data & analytical services (including remote access).

The Users Service Group supports Scientists and Companies who wish to physically or virtually access infrastructures and/or data archives to perform experimental testing or other R&D purposes.

The Marketing, Business Development & Communications Service Group is responsible for promoting the MARINERG-i brand worldwide, to facilitate the exchange of information inside the scientific community and to attract new users and stakeholders.

The contribution of the operational structure to the implementation of the Scientific Plan with the aim of supporting the development of advanced technologies for harnessing ORE will mostly focus on two main tasks:

- Coordinate the usage of the distributed testing facilities made available in the MARINERG-i DRI, facilitating and streamlining user access to these facilities and associated services (engineering research quality validation and analytical services, databases)
- Ensure over the long term the high quality of the MARINERG-i scientific and engineering services, defining an overall strategy, setting up a common and recognized standard of research across Member States, outlining future scientific developments and assessing the achievement of the scientific objectives.

6.3.2. Access management

A substantial part of the available research time of the facilities being part of the MARINERG-i DRI shall be offered to the international research community. The access to the facilities shall be open to researchers, engineers, scientists and students conducting research programs based on experimental testing of offshore wind, wave, tidal and hybrid energy devices at all stages of development (TRL1-9) and aiming at developing optimized converters and sub-systems, hence, contributing to the deployment of ORE production devices.

This access can range from simply providing access to the equipment, right through to a full-suite of testing support services, more directed towards specific industrial client's needs. Testing support services leverage in-house knowledge in order to provide added value to equipment access, and can include:

- Test design and preparation
- Model design and instrumentation
- Experimental and technical support during testing
- Post-processing of testing data and analysis
- Validation and benchmarking of results

These services can be provided for both laboratory and open-sea testing sites and adapted to the technology development stage and scale.

The granting of access is to be based on competition and peer-review of applications after a fair and transparent procedure. The criteria for the competition shall be scientific excellence and importance in relation to MARINERG-i ERIC strategies, as decided by the Assembly of Members. Selection criteria for access shall be established in accordance with the advice of the relevant scientific community. For instance, selection criteria could be defined so as to allow the assessment of the capacity of the applicant to provide a realistic development plan from TRL 1 to TRL 5.

It must be noted that in this stage-gate development process it can also be extremely valuable to directly engage with the developers, especially in the early stages of development so as to help capitalize on the outcomes from their testing, provide guidance and orientation at each stage so as to facilitate and accelerate evolution to the next stage and the transfer to the most adapted testing facility, from the small Lab all the way to the large scale test site. Therefore, a comprehensive development protocol is needed, as part of the code of practice shared by the MARINERG-i members.

As the objective is to contribute to the development of the international ORE market, a proportion of the access time shall be made available to researchers from states that are not Members of the MARINERG-i ERIC.

Access will be coordinated and managed through a streamlined application process mediated by the common access portal, developed as part of the MARINERG-i e-Infrastructure.
This platform will allow the integrated view of infrastructure availability necessary to manage the access in order to match users' requirements, ensuring quick access and helping to alleviate oversubscription to well-known facilities by directing users to equally suitable facilities available within their time-frames.
Support will be provided to users by the Users Service Group so as to help them determining the most appropriate testing facility according to:

- the technology type,
- the Technology Readiness Level,
- the test scope and objectives;
- the developer's location, timeline and available funding mechanisms;
- the availability of relevant testing facilities.

The evaluation of the most appropriate facility together with the definition of the most relevant testing plan will be conducted according to the defined standard and guidelines and following the recommendations of the properly established stage-gate process (Figure 10).

All relevant information on technical, financial and legal matters related to the access of the infrastructure as well as contacts and access procedures will be made available on the access portal so as to facilitate the application process, thereby reducing the administrative tasks and procedures while optimising response times.

A detailed Access Policy applicable to users and approved by the Assembly of Members, will be made publically available.

Figure 10: Development stages and TRLs for wave energy devices

6.3.3. Coordination of the research activity

In order to ensure over the long term the high quality of the MARINERG-i scientific and engineering services, a dedicated research programme will be implemented, taking advantage of the critical mass of resources that the MARINERG-i DRi will bring together.
Aligning with the priorities identified by ongoing EU coordination/roadmap initiatives (Ocean Energy Roadmap, Set plan, ETIP Ocean, ETIP Wind), this research programme will be coordinated according to the overall strategy established through the adoption of a periodically updated Long Term Strategic Plan. The updates will be based on the assessment of the achievement of the scientific objectives and of the capacity to transfer knowledge and technology to the industry. They will contribute to the outlining of future scientific developments. Finally, this coordinated approach will foster the setting of the common and recognized standard of research across Member States necessary to ensure the quality of the offered services.

The MARINERG-i strategic research agenda combines fundamental science addressing a wide range of key disciplines (hydrodynamics, statistics, materials …) and applied science and engineering. Indeed, the questions raised in the scientific rationale and the issues discussed in the four identified research themes (sections 2-5) clearly indicate the need for both new theoretical developments and technical innovations. In that matter, the research activity jointly conducted between the industry and the academia, through testing and proofing of new ideas and concepts at all stages of development, will constitute a constant support to the development of innovative approaches and theories or even changes of paradigms that will drive the evolution of the strategic plan.

A key element to the success of MARINERG-i is a capacity to develop a common code of practice based on established best practices and common standards so as to ensure the quality of MARINERG-i member facilities as well as the consistency and comparability of these facilities. This code of practice will foster convergence and harmonisation in approaches to research, design, testing methods, practices and procedures. Hence will contribute to the de-risking of the technologies and will increase the investors' confidence in the ORE market. Indeed, standardization of testing and results, along with better operational data, will allow technology developers to de-risk the technology sooner, leading to a reduction of the financial hazard. This will enable technologies to progress towards higher TRL testing and proofing programs sooner and with lower risk.

As the availability of such a code of practice is crucial for the coordination of the research activity from the very beginning of the operation of the MARINERG-i DRI, a specific approach will be implemented by the Quality and Standards Service Group. The standardisation outcomes of the MaRINET and MaRINET 2 projects together with the efforts of the individual infrastructures will be condensed, analysed and validated by MARINERG-i to produce consensual and unified Best Practice testing guidelines. These will be implemented throughout the distributed infrastructure in order to establish testing consistency across all the facilities that represent the MARINERG-i DRI.

The testing and research activity generates large sets of data. Many of which should be considered as reference data and as such be made publicly available together with the metadata necessary for their exploitation by the ORE research community. Hence coordination of the storage and use of the data, including references to testing protocols, profiles of facilities and equipment, will be conducted with the support of the E-Infrastructure and Data Management Service Group.

It has been observed that the development of ORE devices requires a cross-sectoral and multi-disciplinary approach. It is obvious that, in spite of a careful profiling and identification of the relevant facilities required to build the most adapted DRI, the MARINERG-i portfolio will not have the capacity to cover the whole range of research activity necessary to support the development of the ORE industry, especially during the early phases of the development plan of the DRI. Hence, coordination with other external international initiatives, and more specifically ESFRI's should be sought so as to fill the potential gaps (for instance in the domain of offshore wind or electrical and electro-technical), while guarantying the requested quality of service according to recognised standards.

Figure 11 provides a schematic view of the proposed coordination of the research activity.

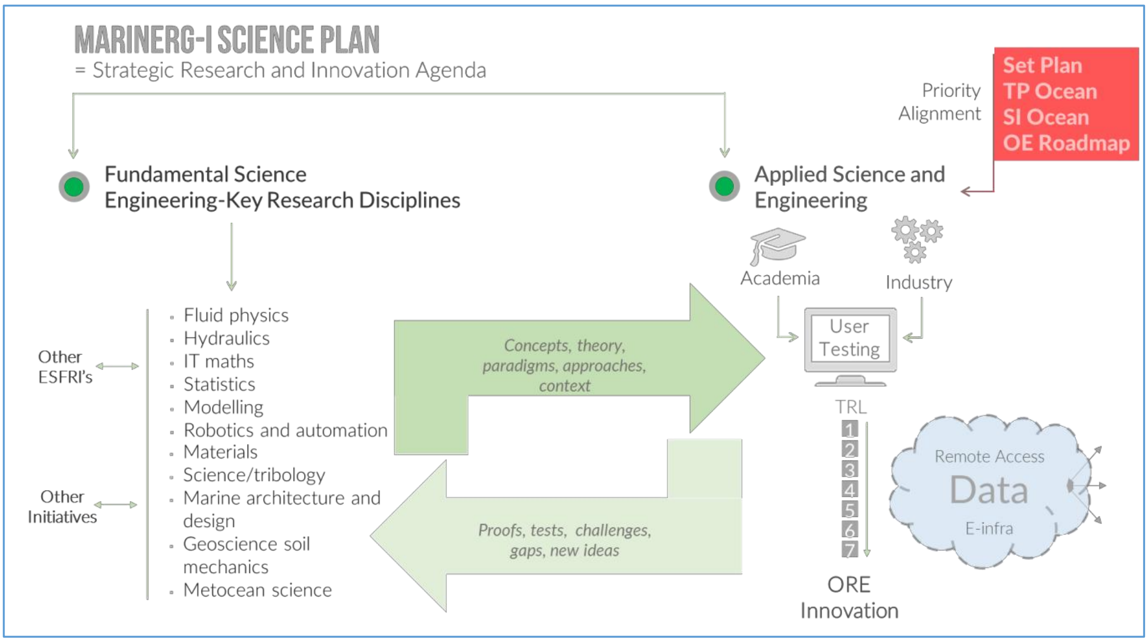


Figure 11: Coordination of the research activity

6.4. Exchange and communication capacity

In order to achieve its objective to accelerate the development of the ORE sector and to enable the commercialisation of ORE technologies, MARINERG-i will provide coordinated services and scientific research that respond to the short and long-term R&D needs of the industry. These services are intended to address the requirements of different user groups which include: technology developers (industrial and academic), the research infrastructures themselves, researchers from both academia and industry, certification/standards bodies, supply-chain stakeholders (components, construction, grid and logistics), technology users, investors and financing bodies, funding agencies and policy makers at the national and European level.

Developing a capacity to exchange and communicate with such a broad range of stakeholders is necessary to:

- facilitate and mediate the exchange of knowledge and expertise, data, and human capital in ORE between the MARINERG-i operating entities and the stakeholders;
- build the research capacity necessary to stimulate and support the development of advanced technologies for harnessing ORE;
- inform and contribute to the updating of ORE policy and market development in Member countries.

6.4.1. Data management capacity

The MARINERG-i e-Infrastructure will be the main supporting tool implemented to ensure effective curation and controlled access to data, knowledge resources and analytical services. Under the supervision of the E-Infrastructure and Data Management Service Group, this common portal will:

- enable for users access to facilities and services offered by the MARINERG-i DRI;

- grant structured access to publicly available data produced at test sites and facilities, including advanced metadata tools for data discovery and utility assessment;
- support e-brokerage services to facilitate permitted access to proprietary data and data-products under secure controlled conditions;
- allow remote access to testing procedures in real-time (virtual access), which would remove many practical and financial barriers to access.

In conformity with the MARINERG-i ERIC data policy, access to research results and data shall be free and open, taking into account any third party Intellectual Property Rights, secrecy and confidentiality restraints. In this regard, the MARINERG-i ERIC will ensure the integrity of Intellectually Property (IP) at all times, adopting a common, trusted approach to IP management.
The data preservation policy will be compliant with international standards and European standards for Marine data. The overarching MARINERG-i e-Infrastructure will be aligned with existing initiatives frameworks at the EU level, including the European Open Science Cloud, and the EUDAT collaborative Data Infrastructure. Where possible, and especially for all the aspects related to marine environmental data, it will interconnect with other clearly identified European services such as EMODnet, COPERNICUS[2] Marine Environment Monitoring Service or other ERIC such as EMSO[3].

6.4.2. Collaboration and networking

Collaboration between the members of the MARINERG-i DRI is needed to create the critical mass necessary to support the development of the ORE industry, to ensure the operational and scientific integration of the Research Infrastructures, producing new synergies, to maximize the use of the added value generated by the infrastructure services and to increase the existing level of knowledge and expertise.

The internal web portal developed as part of the e-Infrastructure will be the main networking support promoting collaboration at a technical level. This collaborative platform augmented with a specific framework and protocols for remote access and monitoring, will facilitate communication and networking between facilities. It will support employee exchange, education and training programmes, hence will contribute to the promotion of knowledge transfer.

It has been noted that the because of the identified need for a cross-sectoral and multi-disciplinary approach, collaboration with other organisations, programmes and international initiatives, including ESFRI's, should be sought so as to complete the MARINERG-i offer in terms of research capacity and knowledge. Hence a specific collaborative approach will be developed with a clearly identified network of such initiatives so as to guarantee a wider and more complete offer with a referenced quality of service in line with recognised standards.

[2] http://marine.copernicus.eu/
[3] http://emso.eu/

6.4.3. Communications and Outreach

The Marketing, Business Development & Communications Service Group is responsible for promoting the MARINERG-i brand worldwide, to facilitate the exchange of information inside the scientific community and to attract new users and stakeholders.

It will ensure that all research results and data be largely disseminated to the scientific community and beyond, to the policy and funding agencies and to the wider civil society, so that they can play an active role in the Offshore Renewable Energy policy development, on the basis of up-to-date knowledge and information.

It will encourage users of the MARINERG-i ERIC research results to make their own research results publicly available and shall request users to make suitable publicity about the access provided to them within the MARINERG-i ERIC (in all publications dealing with results and knowledge generated by or within the MARINERG-i cooperation, MARINERG-i ERIC shall be duly acknowledged.).

It will contribute to the promotion of innovation, knowledge and technology transfer and will act as an advocate for the scientific and engineering community involved in ORE research, innovation and testing.

6.4.4. Education and capacity building

The capacity to develop the critical mass of knowledge, skill and resources necessary to sustainably address the issues raised by the constantly evolving ORE sector has been clearly identified as an important vector of success. Knowledge is to be shared not only within the MARINERG-i DRI but also with the users and with the other identified stakeholders.

MARINERG-i will support and encourage employee exchange, education and training programmes. This will enhance the availability of highly skilled and experienced staff and will contribute to the development of a coherent scientific/technical community. It would also promote knowledge transfer, an inter-disciplinary approach and transparency to facilitate learning and improvement. Staff exchange between MARINERG-i and industry could be supported by funding schemes such as the RISE program (Marie Sklodowska Curie (MSC) actions).

MARINERG-i will deliver user training and education programmes to optimise expertise and skills. In particular, this will help make the most efficient and effective use of testing facilities. Support to users could also be made individually, providing advice on request in developing long-term testing plans that will consider the most efficient path to move through the TRLs.

At the intersection between research and industry MARINERG-i also has the capacity to contribute to education and training of graduated students in participating to targeted Innovative Training Networks (ITN-MSCA).

MARINERG-i shall, as appropriate, encourage researchers to use MARINERG-i ERIC results in their higher education programmes.

The MARINERG-i e-Infrastructure will be used to facilitate the development of virtual services, webinars and other teaching/instructional resources that will be made available to participating infrastructures in order to provide added-value services to the users and other stakeholders.

6.5. Anticipated Benefits

The main goal of the MARINERG-i DRI is to support the Offshore Renewable Energy industry in the development process necessary to design and optimise the technologies which ultimately will be deployed at sea to contribute to the global power production and fulfil decarbonisation and energy supply issues.
The Scientific Plan implemented by the cohesive research community operating the MARINERG-i DRI will contribute to the fulfilment of these objectives by facilitating and streamlining access to research facilities and associated services and by ensuring over the long term a high quality scientific and engineering research programme.

The primary beneficiaries of the MARINERG-i Science Plan are the end-users: developers, researchers and industry stakeholders.
The streamlined access to the research facilities is an efficient and timely process for technology developers wishing to develop their concepts across different TRLs. The collaborative, multi-disciplinary and comprehensive support provided by the MARINERG-i Service Groups will help them avoid or mitigate the wider barriers to implementing their products. Guidance provided along the staged test process will help identify and solve potential issues earlier, accelerating development and innovation. The standard procedures implemented in all the facilities will allow for objective assessment and fair comparisons of devices and technologies. This will build confidence in results and reduce risks, hence contribute to establish the investors' confidence necessary to move forward along the path to industrialisation and commercialisation.

The critical mass of resources and knowledge brought together within the MARINERG-i DRI will provide synergies and access to opportunities unavailable to single entities or small groups. The augmented level of expertise and knowledge as well as the shared scientific strategic objectives will build a stronger research capacity, in favour of the acceleration of the development of the ORE industry. Collaboration and the application of best practices will enhance and optimise the testing processes and procedures, reducing lead-times and testing durations. The improved efficiency and optimized resources will maximise return on investment and impact in terms of KPI's (innovation, clusters, economic development, jobs…).

Directly connected to the sector's industrial development roadmap, the MARINERG-i DRI will act as a European hub for maturing technologies, affirming the European global leadership position in this sector and informing development of the international ORE market.
The MARINERG-i strategic research agenda and periodically updated strategic plan, informed by the data and services made available through its associated e-Infrastructure will constitute a European reference providing a unique strategic consulting capacity with respect to the state of the art and upcoming developments in ORE to national and European agencies, as well as to industry stakeholders (organisations, consortia, joint-ventures and companies). MARINERG-i will both inform and act as a vector for research

policies in ORE. It will be instrumental in developing a common understanding and achieving European strategic objectives and research agendas.

7. Conclusions

This science Plan has been elaborated so as to provide the rationale and direction for the scientific activity to be conducted within the Pan European Distributed Research Infrastructure (DRI) MARINERG-i, which aims to support the development of Offshore Renewable Energy (ORE) at European and global levels.

This Science Plan considers ORE technologies and their relative competitiveness at all Technology Readiness Levels from proof of concept and design optimization right through to the full operational scale (TRLs 1-9), thus taking into account the current and future requirements of a broad range of end-users and developers.

In addition to economic issues and the necessity to reduce the LCoE the extreme complexity of the technological and engineering issues faced by the ORE industry to extract energy from the ocean and to sustainably provide power to the grid has been identified as a main driver for the definition of the MARINERG-i research agenda.

A broad range of fundamental questions whose answers are needed to support the ORE industry through all the stages of development along the path to deployment and production have been identified. These will be tackled according to a clearly established science and engineering R&D program divided into four main themes which provides a convenient structure within which to consider the main groups of technologies associated with extracting energy from waves, currents and wind; and the necessary learning process based on testing at all scales from the controlled environment of the laboratory to the real open sea conditions of the test sites.

The MARINERG-i DRI will run in the long term following a staged evolution enabling the capacity to develop the critical mass of knowledge, skills and resources necessary to sustainably address the issues raised by the ORE sector. The identified governance structure and associated operational organization, supported by dedicated Service Groups, are designed to support the implementation of the Science Plan. The development of a user program with a clearly defined access policy is at the heart of the coordination of the scientific activity, aimed at fostering the development of optimized converters and sub-systems, hence, contributing to the deployment of ORE production devices. This coordinated approach will also foster the development of the training, communication and outreach programs necessary to improve the global capacity and to connect with other organisations and programs, which are key elements to the development of this scientific plan at the European and International levels.

The identified scientific agenda and the key elements of its implementation presented in this Science Plan are considered the most relevant and best suited to achieve MARINERG-i objectives to accelerate the development and deployment of wave, tidal, offshore wind and combined energy technologies, to become the leading internationally Distributed Research Infrastructure in the Offshore Renewable Energy sector; hence, to help maintain Europe as a global leader in this emerging and constantly evolving industry.

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