



Strategic Research Agenda for Ocean Energy

European Technology and Innovation Platform
for Ocean Energy

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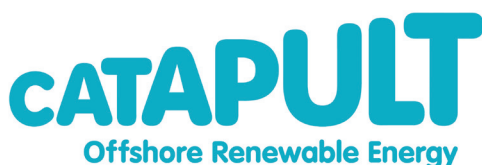
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I. Executive Summary



Sabella D10 tidal turbine deployed off Ushant Island

Europe needs ocean energy

Ocean energy: a significant part of the EU power mix

Ocean energy is abundant and geographically diverse. Under the right political and economic conditions, it is estimated that wave and tidal energy alone could meet 10% of the EU's power demand by 2050 through the deployment of 100GW of capacity¹.

In the same time frame, 30GW of tidal range power plants and 30GW of salinity gradient power plants² could be connected to the European power grid. While ocean thermal power plants significantly increasing local supply of electricity in the EU's overseas territories and reducing their energy bills.

A new industry for Europe

European companies and European research are at the forefront of ocean energy development. The European Commission's Joint Research Centre calculated that,

today, 45% of wave energy companies and 50% of tidal energy companies are from the EU³. With ocean energy markets rapidly developing around the world, from Canada to Chile and from Indonesia to Japan, improving the focus of ocean energy R&I programmes can help ensure that European industry benefits from its first-mover advantage and confirm its world leading position, tapping large export markets.

European investments, regional development and local jobs

The development of ocean energy will lead to an emergence of a truly pan-European supply chain. Leading companies in the sector can already be found across Europe, including in land-locked countries such as Austria and the Czech Republic.

Moreover, ocean resources have to be tapped locally which means ocean energy farms and power plants are deployed in coastal areas, some of which have suffered

¹ SI Ocean. Market Deployment Strategy. 2014

² TP Ocean Research. 2016

³ European Commission - JRC. Ocean Energy Status Report. 2014

economic downturn over the past years. The development of ocean energy will breathe new life into existing port and marine infrastructure and complement Europe's regional growth agenda.

A step-change in tackling climate change

Ocean energy uses natural ocean resources to produce electricity without depleting them.

Successfully tapping the many energy resources of Europe's seas and oceans will lead to a step change in the energy transition that Europe is undergoing. After wind and solar, a new generation of renewables must be developed to reach Europe's full decarbonisation potential.

Ocean energy a key part of Europe's future energy mix

To develop ocean energy's full potential, the cost of electricity from the technologies needs to come down and tend towards a level of €c10/kWh or lower.

To achieve these ambitious goals, ocean energy R&I needs to:

- **Improve reliability and survivability of ocean energy devices**
High reliability and survivability will ensure ocean energy devices can deliver electricity consistently over the life-time of projects, attracting and protecting investments.
- **Reduce the perceived risk of ocean energy technologies**
The high capital expenditure needed to develop an ocean energy project, coupled with operating uncertainties typical of new technologies increases the perception of risk for investors. Reducing technology risks will reduce investor risk perception, leading to easier and cheaper access to private capital.
- **Reduce technology costs**
Through technology testing and deployment, installation learnings, and operational know-how costs will start reducing, bringing down overall project costs

and, therefore, the cost of electricity produced by ocean energy devices.

- **Improve reliability and survivability, reduce technology risks and then bring down costs... in that order!**
Ultimately, ocean energy technology and risk perceptions will improve significantly, as more and more ocean energy devices are deployed. This requires a number of first-of-a-kind and demonstration projects that, as for other energy technologies, will require public support.

As deployment increases, both manufacturing and installation processes are standardised and industrialised, unfolding the paths to cost reductions.

RD&I funding is crucial for the ocean energy industry to meet its objectives and support €1bn of investments in 12 priorities and 54 actions

Striking the right balance between demonstration and scaled testing

At this stage of the sector's development deploying devices and pilot farms is key to move forward. Real sea deployment is fundamental to improve knowledge of ocean energy device behaviour. Operational data from the real sea environment is needed to perfect devices and generate the learnings to improve logistics and processes.

Testing scaled models and components in test facilities, on the other hand allows simulating conditions that might take many years of real sea testing to achieve. This avoids making costly mistakes and accelerates technological progress.

RD&I programmes need, therefore, to strike the right balance between lab and scaled tests and full-scale deployment in real sea conditions.

The ocean energy sector has identified 12 priority research areas and proposes 54 research and innovation actions applicable to one or more ocean energy technology to meet these challenges. The research areas have been attributed indicative budgets that industry,

national authorities and the European Commission need to commit to finance the RD&I programmes. These are summarised in the table below.

In all, it is expected that rolling-out the actions in this Agenda will generate around €1bn in investment over the coming 4 to 5 years, borne by the industry, national and European authorities. These actions cover three main RD&I categories:

- **Stepping up deployment to validate data and improve data collection**

Data from full-scale demonstration – both single devices and devices in arrays - is required to enable commercial future investments in ocean energy projects. As for other technologies a number of iterations of full scale prototypes and tests are required to reach a stage where commercial investors feel the level of risk is acceptable.

- **Improving materials to survive the sea environment**

Components and systems used in ocean energy converters need to be compatible with the marine environment and resist corrosion and the heavy loads they are subject to. Using, developing and improving the right materials is key to making ocean energy devices survivable and reliable to produce energy at acceptable cost.

- **Developing a bespoke ocean energy supply chain**

Due to the limited number of devices and projects deployed to date, ocean energy does not yet have a full, dedicated supply chain. Using machines, vessels and tools that are not fully fit-for-purpose can slow the sector's progress and increase costs. The

development of bespoke manufacturing procedures, vessels and installation techniques, therefore, needs to go hand-in-hand with the industrialisation of the ocean energy sector.

Although great effort has been put into prioritising the research areas highlighted in the table in the next page, tackling one does not mean that others do not or need not be looked at. Achieving full industrial maturity will require advancing in all the areas identified.

A first Strategic Research Agenda

This first ever European Strategic Research Agenda for ocean energy is the result of the work of TP Ocean – the European Technology and Innovation Platform for ocean energy. TP-Ocean is a network of over 220 ocean energy experts and professionals from 150 organisations across Europe. TP Ocean was officially recognised in November 2014 by the European Commission as an official industry stakeholder in its Strategic Energy Technology Plan (SET-Plan).

Whilst a considerable effort has gone into defining this Strategic Research Agenda, it is the first of its kind resulting from a collaborative process covering the five ocean energy technologies. Much of the focus of this Agenda is on wave and tidal stream technology since there is a higher degree of activity in this area. As such there may be areas of research that have not yet been identified or need a greater focus as the sector continues to develop. It is likely therefore that this Agenda will continue to evolve with further dialogue within TP Ocean and the ocean energy community.

TABLE 1: PRIORITY AREAS FOR OCEAN ENERGY RESEARCH, DEVELOPMENT AND INNOVATION

SRA section	Priority area description	Priority level
●●● High priority ●● Medium priority ● Low priority		
1.1	Deploy demonstration projects to generate learnings necessary for commercialisation	●●●
2.3	Validation of components and sub-systems	●●●
2.4	Increase yield with improved power take-off	●●●
2.5	Control systems to increase reliability and survivability	●●●
3.2	Reduce uncertainty, risk and cost of foundations, anchoring systems and cables	●●●
4.1	Building a case for investment, including LCoE analysis	●●●
1.2	Technology development through validated numerical models and small-scale prototypes	●●
2.1	Develop high quality seaworthy materials	●●
2.2	Condition monitoring systems to optimise operation and maintenance	●●
3.1	Access to ocean energy sites, design adapted processes and vessels	●●
4.3	Standards, health, safety and environment	●●
4.2	Develop manufacturing expertise for ocean energy	●

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II. Ocean Energy Technologies

Five resources, five technologies, five opportunities to harness the power of the seas

The European ocean energy sector covers five different technologies harnessing different ocean resources. Each ocean energy resource is unique; tidal currents and the difference between sea level at low and high tide are driven by the rotation of the moon around the earth; waves are created from the transfer of energy from the wind to the sea; OTEC (Ocean Thermal Energy Conversion) including SWAC (Sea-Water Air Conditioning) exploits temperature differences in the ocean and salinity gradient exploits the osmotic pressure between seawater and fresh water. As ocean resources are driven by different natural phenomena, the patterns in which they produce electricity are different and, often, complementary to each other and to other renewable energy technologies such as wind or solar.

Ocean energy projects are typically intended to be deployed for at least 20 to 25 years. For tidal range projects this increases to over 60 years.

Tidal Stream

Tidal stream converters harness the flow of the currents to produce electricity. Energy output is determined by the speed of the currents. Tidal turbines can be fixed to the sea bed or floating. A number of devices have undergone full-scale testing and the first farms are under development.

Tidal Range

Tidal range uses the difference in sea level between high and low tides to create power. Tidal range technology uses the same principles as conventional hydropower and requires a barrier to impound a large body of water. This water is forced through turbines inside the structure using the pressure difference between the upper and lower reservoirs. The difference between high and low tide, as well as the size of the area of impounded

water influence power production. Tidal range is the more established ocean energy technology, with the first projects generating power since the 1960s.

Wave

Wave energy converters derive energy from the movement of waves. Energy output is determined by the height and period of the waves. Wave energy converters can be placed in different areas – on the shoreline, near-shore, typically in depths less than 20m, or offshore in greater depths. A wide variety of concepts exist, able to harness energy using different mechanisms. A range of prototypes has been deployed, nevertheless, further technology development, testing and demonstration are required prior to industrial roll-out.

Ocean Thermal Energy Conversion

Ocean Thermal Energy Conversion (OTEC) exploits the temperature difference between deep cold ocean water and warm surface water. It can be used to produce electricity via heat-exchangers. In this set-up, the technology is naturally dedicated to tropical and equatorial seas and oceans where high temperature differences will yield the most electricity. Similar technologies can be used to cool buildings, this is called Sea-Water Air Conditioning or SWAC. A number of OTEC demonstration plants are being developed in EU overseas territories. A full-scale SWAC plant has been commissioned in the French Mediterranean town of Marseille.

Salinity Gradient

Salinity gradient power generation utilises the difference in salt content between freshwater and saltwater to provide a steady flow of electricity via osmosis or Reversed Electrodialysis.

It is suitable for areas where fresh water and salt water meet, such as deltas or fjords. Consequently deployment potential is significant around Europe, however, further technology development is required to bring salinity gradient to maturity.

Technology and R&D requirements

The level of development of each ocean energy technology and its consequent R&D requirements is assessed using the Technology Readiness Level (TRL) scale that underlines the European Commission's Horizon 2020 programme⁴.

To bring ocean energy to full industrial roll-out, devices need to go through various development and demonstration phases and be deployed on a pre-commercial scale. The challenge for the ocean energy sector is to bridge the gap between TRLs 6, early R&D and prototypes, and demonstration and pre-commercial levels 7, 8 and 9. To do this, there is a need to increase the amount of operational data from real sea deployment. This will help demonstrate and validate the models, concepts, components, manufacturing and installation processes that work well and which areas require improvement.

If each ocean energy technology is to advance, it is necessary to ensure that funds and finance – both public and private – are allocated to priorities enabling the sector as a whole, and each technology individually, to move forward.

Moreover, since there is, as yet, no proven technological concept for some ocean energy technologies, it is necessary to modulate support where it remains desirable to bring forward different sub-categories or technological concepts.

Deploying and testing to improve performance

In wave and tidal stream energy a small number of full scale prototypes have been built, deployed and tested including some small-scale farms. A number of further farms are currently under construction. The primary objective for full-scale prototypes (or pilot projects in the case of OTEC and Salinity Gradient) is to demonstrate 'appropriate performance', such that investment in a first farm of multiple devices (or larger pilot projects) can be commercially justified - albeit that this will still require some degree of public support.

'Appropriate performance' is somewhat subjective but includes assessments of power performance - demonstrating the ocean energy device's 'power curve' – how much power it produces in certain ocean conditions. In this way the likely annual energy production for a particular site (and resource) can be estimated. For tidal energy such information could be obtained over a tidal cycle whereas for wave energy a full year of testing may be required to cover the majority of sea states experienced.

Performance is contingent on device availability; what the likely down time of a device or plant is likely to be as a percentage of time. Availability is affected by the device or plant's survivability and reliability.

Survivability is generally considered to be the ability of an ocean energy converter to withstand extreme events



Scotrenewables Tidal Power tidal turbine at Harland & Woolfe Shipyard, Belfast

⁴ See annex 3.

in the ocean energy environment, typically related to extreme weather conditions. Storms may produce exceptional loads as a result of extreme wave, wind or tidal heights or a combination of these. An assessment can be made of what loads an ocean energy converter needs to be able to withstand (or have a strategy to avoid) in relation to the probability of the event occurring during the intended lifetime. For example, a marine structure may be designed to meet a '1 in a 100' year event, provided that its design incorporates a certain factor of safety. Similar assessments are also made in other industries such as offshore oil and gas platforms, nuclear power plants and so forth.

For commercial roll out of marine energy technologies it is important that the risk of non-survivability is adequately mitigated so that projects can be appropriately insured at an economically viable cost. This can be achieved by following certain design standards, model testing, numerical simulations and by following acceptable procedures for hazard identification, design and operations such as installation and maintenance. Whilst there are parallels with other industries in the marine environment there are also important differences that require such standards and procedures to be improved through learnings from deployment at sea.

In terms of the cost of energy, survivability can be considered a 'binary' factor: if a device is not survivable for the intended economic lifetime, then an acceptable LCoE will not be met. Whereas the safety factors and risk criteria may vary, the need for survivability applies equally to wave, tidal stream, tidal range, OTEC and salinity gradient projects. Although survivability as a concept relates to the entire ocean energy system, the type of materials, components and systems used may also have an impact on this inasmuch as premature failure or faulty operation may compromise the device.

Reliability on the other hand, relates to the system's ability to generate when required over the project lifetime. As a criterion it is a subset of a measured parameter known as availability: the percentage of time that the device is able to generate over the course of the year. Availability however also depends upon *accessibility* - how easy it is to access the device when required, and

on *maintainability* - how easy it is to maintain the device once it has been accessed. Clearly the more reliable the system is, the less important it is to have good accessibility and good maintainability. On the other hand, whilst it is possible to achieve high reliability, it may be more costly to achieve.

Reliability may be improved by careful system design to ensure that a single failure does not significantly impact operation; such work is called Failure Mode Effect and Causality Analysis (FMECA); again there is a balance between the deployment of dual or multiple redundant systems, reliability and cost.

Generally reliability is driven by the most vulnerable component or subsystem. If this is known then the device design can take this into account and either focus effort on improving the component or mitigating the effect of failure. Where this is not known, data on certain critical elements may be in some cases obtained from accelerated lifetime testing on land. Ultimately however it is only when the unique combination of components and systems are placed in operation in the sea that the reliability of the system may be fully verified. Indeed sometimes quite trivial components can cause unforeseen issues with high impact. Similarly systems may sometimes be 'over-mitigated' as testing may show certain elements to be more reliable than anticipated. In both cases knowledge and feedback from testing is vital such that systems may be improved to reduce cost and increase reliability by building on this hard won experience.

The key issues in ocean energy devices relating to reliability are:

1. Ensuring that best practice from experience is followed where possible to use the most appropriate materials, components and subsystems;
2. Ensuring that design takes into account FMECA principles;
3. Ensuring that components and systems are tested to provide reliability data and inform system design.

Reliability and availability are intimately connected, with survivability being a pre-requisite. In general, the higher the availability, the higher the quantity of energy produced, or yield. Increasing the yield has a direct impact on cost of energy (LCoE) reductions.

Up-scaling and industrialising

It should be noted that the challenges of prototype projects involving new technology are numerous - such that the parameters above need to be interpreted in light of these rather than applying 'absolutes'. In other words, a poor headline figure for availability (and annual energy production) during prototype testing does not necessarily translate to a larger project as these may be a result of logistical and financial constraints which may be able to be better addressed in a larger scale project.

For example, a 500MW offshore wind project will have a dedicated team of technicians who have the sole objective of keeping availability high. They will operate on shifts to provide continuous cover. A dedicated O&M base will help to facilitate this. Dedicated vessels will be kept on permanent standby ready to intervene at the earliest possible opportunity in case of a fault. Such vessels will be designed for the application to maximise accessibility, with well-established procedures for doing so in certain weather conditions. A large stock of spares will be kept to ensure minimum downtime. Standard operating procedures evolved over time will ensure maintenance activities can be carried out quickly. Fault diagnosis will usually be relatively straightforward, based on experience of similar faults.

In the case of a prototype ocean energy project many of these factors will be different, in particular since it may not be economical to provide the cover that a commercial project can enjoy and also because the primary output of a prototype project is knowledge rather than the revenue from energy production (which may actually be lower than the cost of operation due to large fixed costs with prototype projects).

With the relatively high cost of full-scale demonstration projects there is a need to better correlate the performance of numerical and physical models and scale

prototypes with full-scale devices, such that simulation and testing at scale can be done effectively.

Ultimately certification of the full-scale device in relevant environment is a prerequisite to develop commercial projects.

Summary of priorities, objectives and actions

The five different ocean technologies have different requirements for their development, although there are synergies between them. TP Ocean's SRA chooses to focus on four research themes across all the ocean energy technologies, highlighting technology-specific points where necessary.

1. Demonstration, Testing and Modelling.
2. Materials, Components and Systems.
3. Installation, Logistics and Infrastructure.
4. Non-technological issues.

Each theme is dealt with in a dedicated chapter that is further divided into overarching **priority areas**, **objectives** to be met when addressing the priorities and research and innovation **actions** that should be carried out. Moreover, for each theme the amount of investment in research and innovation needed and its potential to reduce ocean energy costs are estimated.

1



GE Alstom tidal turbine

1. Demonstration, Testing and Modelling

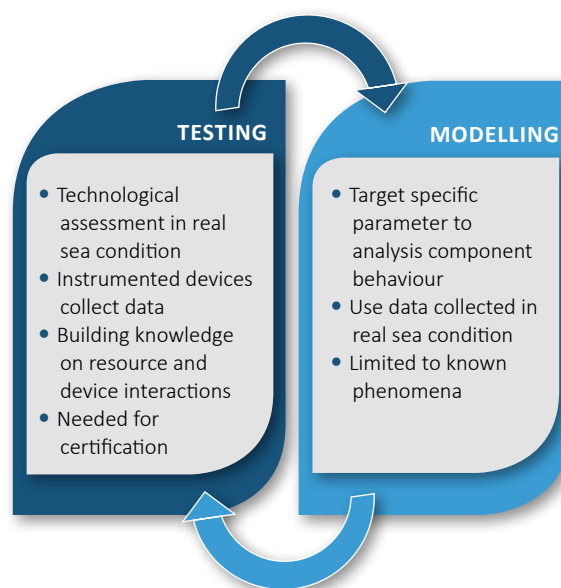
TABLE 2: COST REDUCTION POTENTIAL AND ESTIMATED RESEARCH & INNOVATION BUDGET: MATERIALS, COMPONENTS AND SYSTEMS

CAPEX reduction potential	Medium
OPEX reduction potential	High
Estimated budget for 2018-2020	<p>Total € 670m</p> <ul style="list-style-type: none"> • Pilot project support € 150m • Early commercial farm deployment Cost: € 500m • Farm design & modelling tools Est. Cost: € 10m • Site characterisation Est. Cost: € 10m • Grid services and inter-farm interactions Cost: € 50m • Grid Integration assistance, on- and offshore Cost: € 15m

FIGURE 1: LINK BETWEEN TESTING AND MODELLING ⁵

Single devices and devices in arrays need to be deployed in real sea conditions. Through accumulation of operating hours, performance can be determined and optimised. This will allow technology certification, the creation and validation of high definition models necessary to design the next generation of ocean energy projects.

The continued refinement of components, devices and array systems will drive down costs and increase the bankability of ocean energy projects as has been seen with other energy technologies.



Research priorities for Deployment, Testing and Modelling			
●●● High priority ●● Medium priority ● Low priority			
1.1	Deploy demonstration projects to generate learnings necessary for commercialisation	●●●	2018
1.2	Technology development through validated numerical models and small-scale prototypes	●●	2019

⁵ TP Ocean Research. 2016

CROSS TECHNOLOGY

Full scale power plant for OTEC, salinity gradient and array of full scale devices for wave and tidal stream have to be demonstrated in real sea conditions. The feedback from these first pilot projects will allow development and improvement of components and sub-systems towards certification. Further, this data can be used to validate numerical models and accelerate device and components improvement via R&D.

Standards and certification on how to testing devices and array will be needed. Also a sharing process that supports the prime movers needs to be put in place.

TIDAL STREAM

Modelling turbulence and other complex phenomena induced by the tidal devices improves the understanding of how currents interact with the blades and the device which is necessary to develop optimal designs for arrays and farms.

Numerical models that simulate these interactions need to be validated with real sea data from pilot projects.

WAVE

Modelling the wave resource with real measurement is necessary to further develop control systems and optimise wave PTO yield.

Numerical modelling of the PTO is difficult due to the effect of scaling-up: full-scale deployment is, therefore, needed to collect data and develop testing methods.

TIDAL RANGE

Resource measurement of sea beds should include to include sediment size and coverage.

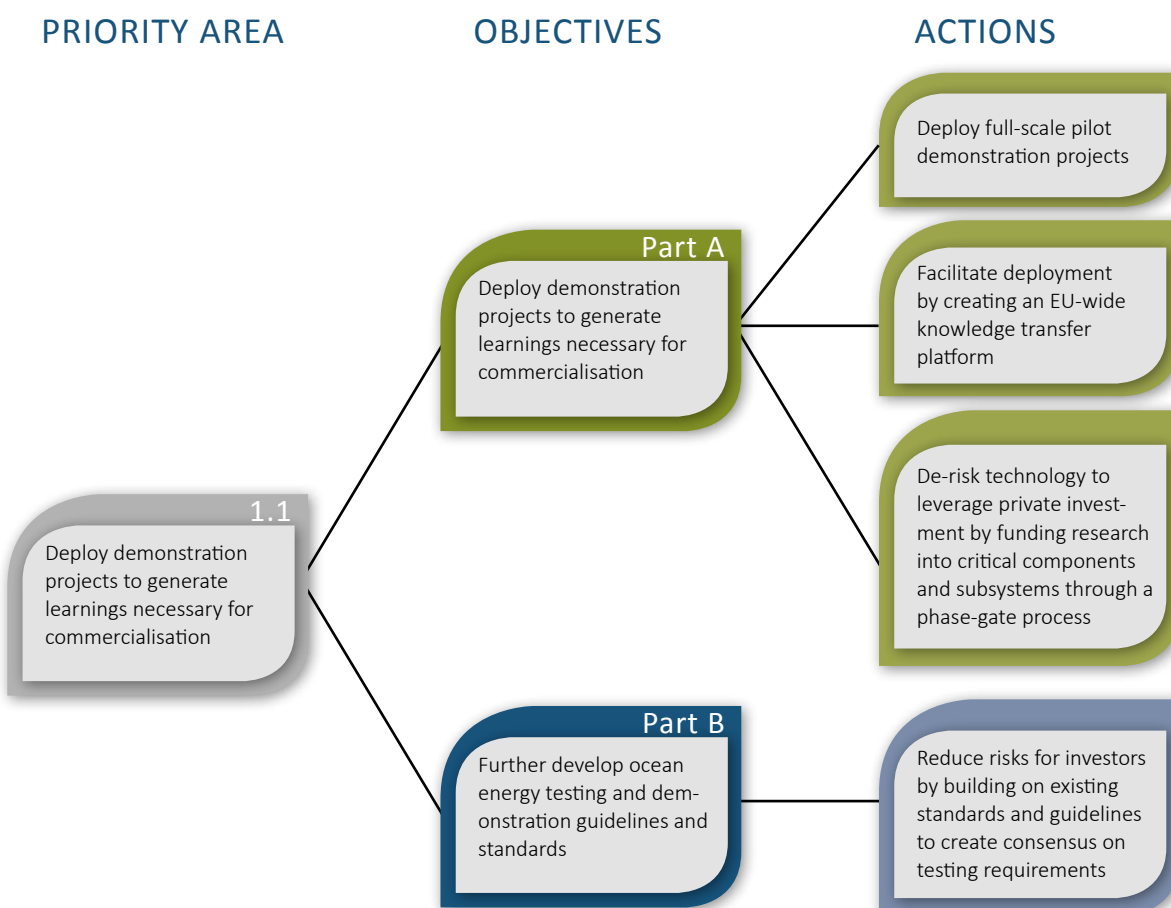
OTEC

Testing in real sea conditions to optimise heat exchanger performance and then scale-up.

SALINITY GRADIENT

Testing technology to demonstrate at larger scale, reaching 1MW plant capacity.

1.1 Deploy demonstration projects to generate learnings necessary for commercialisation



To enable commercial investments in future ocean energy projects, data from full-scale demonstration in the relevant sea environment of single devices and devices in arrays is required. Similar to the development of other technologies a number of iterations of full scale prototypes and tests may be required before reaching a stage where commercial investors feel the level of risk is acceptable.

The path to commercial readiness requires testing scale devices, full scale prototypes and pilot farms. However, progression through these steps is not necessarily linear, a number of iterations at each stage may be necessary making use of the data obtained. Rolling out

projects commercially will also depend upon the specific circumstances of the market (price obtainable for generated electricity and costs inherent to the project's specific location) and not only whether the technology performs but whether the return on investment meets an acceptable threshold. As is the case with other energy technologies, competition is likely to result in pressure to continue to drive down costs, which will lead to continued improvements and a need for further prototypes for new generations of machines. However, the key objective for ocean energy technologies at this point in time is to meet the commercial investment criteria for initial pilot projects.

The build and test of full-scale prototypes is relatively costly and with multiple units in arrays even more so. As such, it is imperative that data from demonstration devices and projects is available to ensure that pitfalls can be avoided. However, diversity can also be a strength inasmuch as it makes sense to evaluate different concepts. A balance must, therefore, be struck between multiple projects which help increase knowledge and the funding available.

Whilst some data from demonstration devices and projects is available, it is limited and has not been adequately collated. This slows progress in research and development. The accumulation of device operating hours from single devices and arrays will produce the required data and facilitate the design of future devices and farms. For wave and tidal stream technologies, the final product will be the development of an ocean energy farm consisting of multiple devices. In the case of tidal range it will be multiple turbines contained within a single structure. For OTEC and Salinity gradient larger installations will be developed.

Tidal stream or wave energy farms are composed of many devices interlinked to one another that may have an effect on each other's performance. For OTEC, Salinity gradient and Tidal Range, a full-scale power plant will not be constituted in an array. The farm includes installation, O&M and grid connection. These are required to prepare the deployment of commercial projects.

The development of a new technology is not linear. Some components are developed more rapidly than others. However, it is not possible to fully develop certain components or subsystems without similar progress in other connected components. Experience from demonstrators will mean that research and innovation will go backwards and forwards from sea deployment to design of individual components or subsystems to optimise them as greater experience in real sea conditions is gained.

Challenge: Testing at full scale, in a real sea environment and in arrays is required to validate technology and meet commercial investment criteria, enabling further cost reduction. The results of these tests should

be shared within the industry to accelerate technology development and the establishment of guidelines and standards to facilitate the transferability of the knowledge creation.

Part A. Prove technology to meet commercial investment criteria

Deploy full-scale pilot demonstration projects

Ocean energy devices need to be deployed at full-scale in arrays in real sea conditions. The main objective of this demonstration is to assess technologies and decrease risks in project development.

Each technology has a different focus area; differently designed and harnessing different ocean resources. Nevertheless, certain experience from full-scale testing and array testing can provide knowledge for all or several technologies.

A project or device's full scale can vary significantly within a same technology depending on the target market, from a few kilowatts to multi-megawatts.

Facilitate deployment by creating an EU-wide knowledge transfer platform

Tests gaining specific feedback on reliability, survivability and device and resource behaviour need to be shared with the whole industry. Common issues identified can, then, be addressed and specific R&D programmes will help resolve generic engineering problems. See also 2.5 Part B, publicly available database on failures.

The technology design tested is based on theoretical knowledge and laboratory experimentation. Testing in real sea conditions at full scale is ultimately the only way to validate these assumptions and optimise devices. The same is true for deployment in arrays, as the latter can lead to interactions between devices and necessary testing of other elements, such as cabling and power transmission components. Energy yield may also be improved by optimising the projects architecture.

There are five main ocean energy technologies, each may have sub-categories. According to the location

of the device, designs are appropriate for either near shore or deep-sea or may be floating, subsea or bottom fixed. Where there are similarities, knowledge transfer can be encouraged.

There are also technological challenges being looked at in other energy or marine industries that can lead to useful transfer of knowledge. Challenges linked to floating platforms, for instance, are shared with the floating offshore wind sector.

In a competitive market there is little *prima facie* incentive to share information and learnings, even for non-commercially sensitive data. Data sharing mechanisms, therefore, need to take account of businesses commercially sensitive information, particularly to reduce the risk of the first mover. The protection of commercially sensitive information is key to the participation of the industry to this type of mechanism.

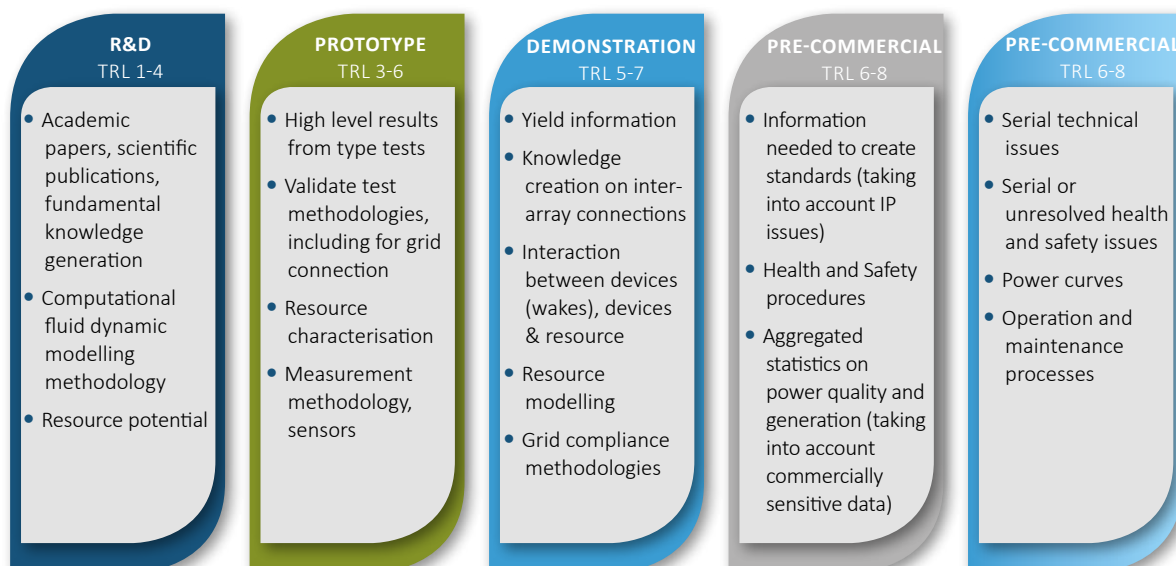
Public funding programmes could, therefore, include incentives for project developers to disseminate good

practices, successful processes and generic problem solving. See also the sharing mechanism recommendation in the Ocean Energy Forum Roadmap⁶: “Establish a Europe-wide industry-run platform where data in standardised and anonymous form are fed in by project and device developers. Public or EU-funding for individual projects could be made conditional to fully participating in the data and knowledge platform. Clear rules to protect intellectual property rights are required to ensure full industry buy-in into the system.”

The dissemination will focus on mutually beneficial results across industry, with relevant data, such as success and failing components or processes, data and knowledge about critical aspects for cost reduction and so forth.

The information to be shared differs depending on the where the technology is in its development phase.

FIGURE 2: SHARING MECHANISM BY PHASE⁷



⁶ Ocean Energy Forum. Ocean Energy Strategic Roadmap. 2016

⁷ TP Ocean research 2016.



Carnegie Wave Energy's CETO5 wave energy convertor under tow to deployment site

Moreover, there is further potential benefit of transferring technology and knowledge from other industrial sectors – aerospace, automotive, defence, marine & maritime, space and transport. Many of these sectors have components and processes that could be adapted to meet the affordability, reliability, survivability and performance requirements of the ocean energy industries.

De-risk technology to leverage private investment by funding research into critical components and subsystems through a phase-gate process

To use the funding efficiently to develop the technology steadily from early stages to commercial roll-out a phase gate approach may be helpful to concentrate funding on the most promising concepts. A phase gate approach, for components, sub-systems, devices and array enabling technologies could be used to determine further access to funding according to agreed performance indicators. These performance indicators could be determined by an independent multi-disciplinary panel of experts, or from the TP Ocean group. Technology developers would, then, need to demonstrate that the technology is on course to meet satisfactory performance indicators to access further funding.

Ideally with successful development of components, sub-systems, devices and array enabling technologies, the fruit of this research should be able to be exploited (albeit on a commercial basis) in such a manner so as to move the whole sector forwards. This would encourage successful technologies to converge and promote the establishment of standards.

However, it should be recognised that there is a balance to be struck between the needs of investors to realise

a return on investment through protection of intellectual property and a sector wide need to disseminate the data from development; if the balance is wrong then private sector investment would not be forthcoming.

See also the Ocean Energy Forum Roadmap on the phase gate approach for the development of innovative technologies in ocean energy.

Part B. Further develop ocean energy testing and demonstration guidelines and standards

The applicable guidelines, standards and procedures for testing and demonstrating ocean energy technology are relatively limited. Currently there are only contributions to the establishment of widely accepted standards. Further developing widely accepted guidelines will enable coherent development and assessment of technologies and avoid unnecessary costs.

Reduce risks for investors by building on existing standards and guidelines to create consensus on testing requirements

Existing guidelines, such as EMEC's *Improvement to and Communication of Existing Rules and Guidelines* or work that has begun at the International Electrotechnical Commission (IEC) to develop standards and guidelines for ocean energy. A consensus on testing requirements will facilitate knowledge sharing through comparable test result data sets and reduce the risk for future investors in the technology.

1.2 Technology development through validated numerical models and small-scale prototypes

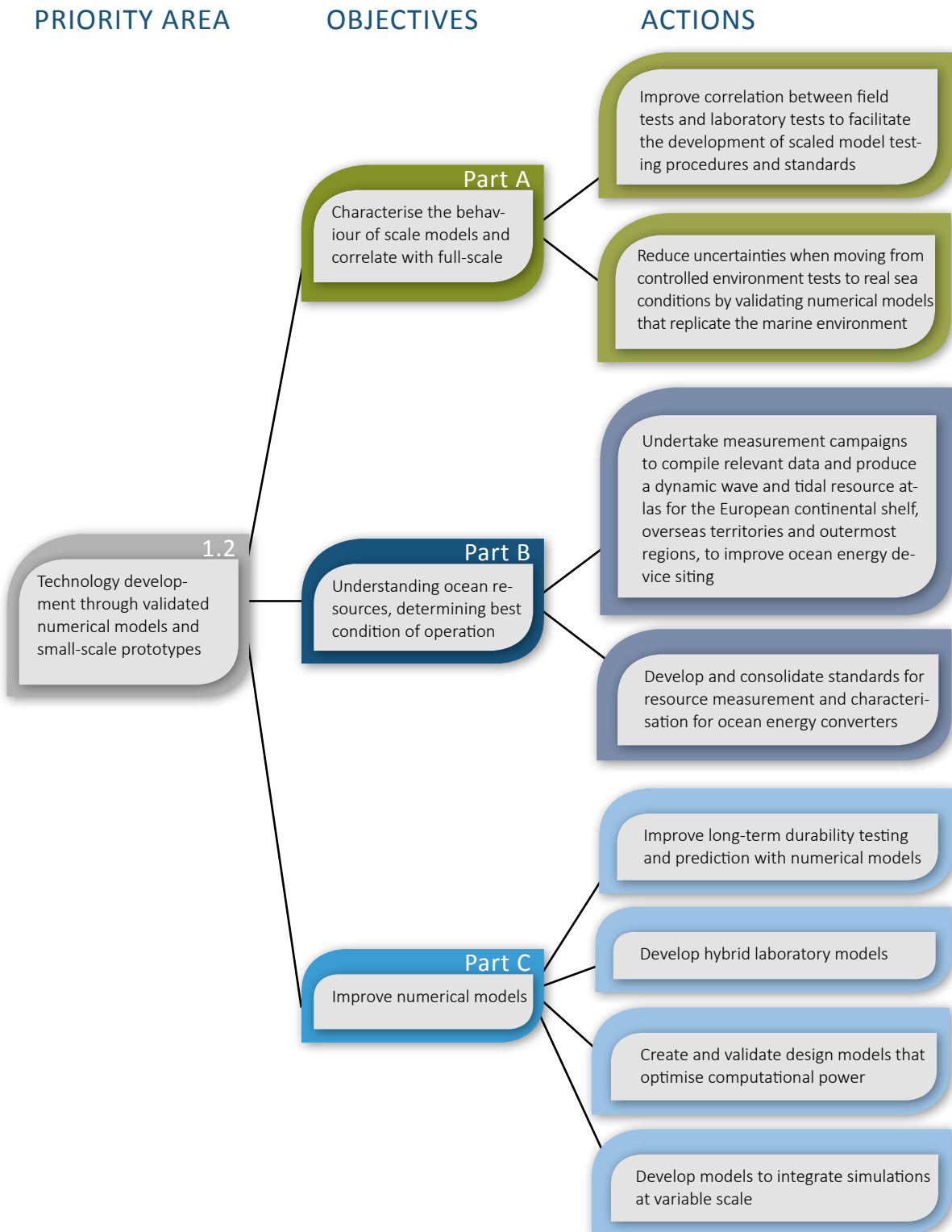
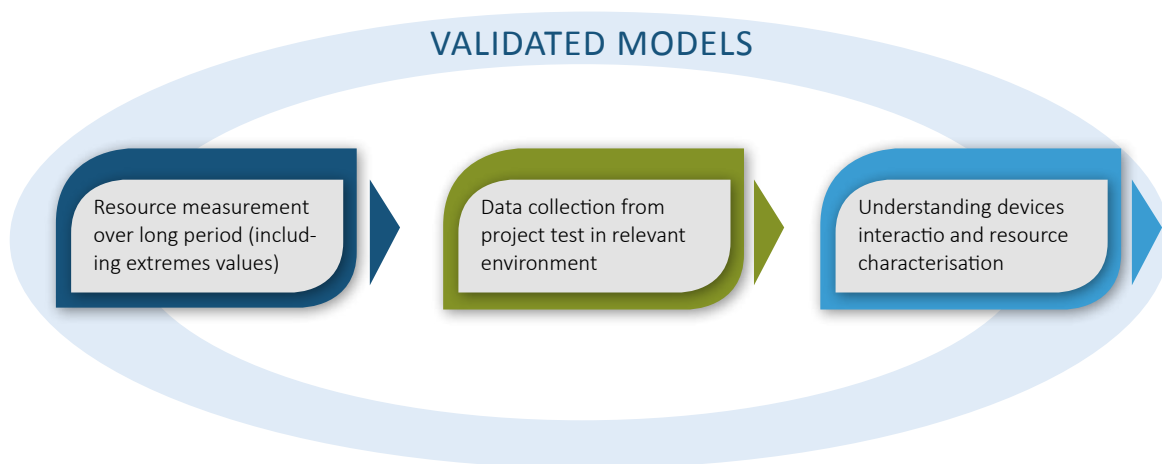


FIGURE 3: VALIDATED MODELS⁸

From laboratory to validation of the system in a relevant marine environment, extensive tests are required. Development of device prototypes can be costly as full-scale components are not readily available and require specific designs and bespoke manufacturing. To reduce the cost of technology development, developers use both small-scale prototypes and numerical models.

To design a prototype, assumptions need to be drawn from theoretical analyses. Part of this exercise is to understand the limitations of the tools in representing the complexity of waves, currents and subsea conditions.

For less developed technologies, small-scale prototypes can be cheaper and quicker to deploy as they require less expensive components and can be assembled in the laboratory. The objective is not to validate an economic model but obtain proof of concept for the device as a whole or for its critical components.

Validated numerical models are a way to carry out early explorative testing of concepts at a minimum cost. A numerical model requires exact data on the behaviour of the resource, and precise information on device design and operating mode to formulate accurate conclusions. The validation of a numerical model means that results are in correlation with the tests in its real sea conditions.

Challenge: There is a limit to what can be achieved by testing small scale prototypes and running numerical

models. The behaviour of a full-scale prototype in real sea conditions is different from the results obtained with down-scaled devices or models. Understanding how the behaviour differs, known as the “scaling-up” effect, allows for the improvement of down-scaled testing and models and greater correlation between the latter and real behaviour of full-scale prototypes, facilitating future device design processes.

Part A. Characterise the behaviour of scale models and correlate with full-scale

Improve correlation between field tests and laboratory tests to facilitate the development of scaled model testing procedures and standards

Small scale model tests are typically performed in laboratories (wave tanks, flume tanks...). The complexity of real operating conditions experienced during prototype testing at sea cannot be reproduced. Fluid-dynamics affecting system behaviour will be missed depending on the capability of the scaled model tests. This will limit the description of the correct behaviour at full scale.

However testing in idealised conditions at laboratory scale allows separating physical features characterising operating conditions that cannot be observed individually in real conditions. This allows clear identification of the relationships among specific conditions and their impact on device operation.

⁸ TP Ocean Research. 2016

Reduce uncertainties when moving from controlled environment tests to real sea conditions by validating numerical models that replicate the marine environment

Designing numerical models that accurately reproduce the interaction between the resource and the ocean energy device over a long period of time, including extreme events such as storms, will facilitate moving from scaled testing in controlled environments to full-scale testing in real sea conditions by reducing uncertainties on how the devices will behave. Once suitable characterisation of the resource has been established, the necessary parameters can be translated from lab-scale to field-scale.

To achieve this, understanding real sea conditions parameters and characterising device operation in real conditions is essential to improve the numerical models. The relative youth of the ocean energy industry means that there is little real data on resource/device interaction with consequent knowledge gaps on:

- array lay-out design and the simulation of the complex phenomena specific to arrays (such as wake effects, resonance, turbulences);

- device and component performance in their relevant sea environment;
- resource behaviour and extreme situations such as during storms with high waves, strong currents;
- long term effects of sea deployment on devices and components;
- impact on the environment.

With validated data, relevant environment conditions can be replicated in small-scale tests, reducing uncertainty when moving from controlled environment tests to relevant environment tests, mitigating the “scaling-up” effect.

Part B. Understanding ocean resources, determining best condition of operation

Unlike in conventional power plants, where the operator can determine how much fuel is burnt, it is not possible to control ocean energy resources such as waves or currents. Consequently, ocean energy devices have to adapt to the resource and surrounding environment. Characterising the latter is, therefore, essential



Corpower Ocean's wave energy convertor



Tocardo T1 tidal turbines in the Afsluitdijk (Netherlands)

to optimise deployment, reducing capital and operating costs and increasing yield.

Understanding resources sufficiently well to enable accurate positioning of commercial systems is a key requirement especially for tidal stream devices which are very sensitive to current velocity. A positioning error with a tenth less velocity could represent a third less of energy extraction. Due to the youth of the sector, there is insufficient data on the complex interactions between ocean energy devices, array of devices and the marine resource, particularly as regards long-term effects. This constitutes a hurdle for the sector's development.

Undertake measurement campaigns to compile relevant data and produce a dynamic wave and tidal

resource atlas for the European continental shelf, Overseas Territories, and Outermost territories, to improve ocean energy device siting

The same wave and tidal resources have the potential to reach coastal areas at a different intensity and time, over a period varying between hours to days. Accurate predictions of how waves, currents and tides move across the sea basin will permit synchronisation of ocean energy farms to the resource and smoothen output variability through their aggregation.

Whereas forecasting of certain resources such as tides is relatively straight forward, wave resource forecasting is more complex. Analysing wave propagation will, furthermore, facilitate strategic wave energy site selection over a large sea area, further synchronising power production between wave energy farms.

A systematic and coherent collection of data on seabed properties (such as sediment size and coverage, rock density...) and water column as well as ocean energy resource mapping (waves, tides, currents, salinity) across the EU, would serve the dual purpose of

1. facilitating selection of appropriate sites for ocean energy device deployment and inform maritime spatial planning exercises, identifying zones for ocean energy deployment; and,
2. providing useful input data for ocean energy resource modelling, necessary when developing an ocean energy project.

Deploying measurement buoys is one way of collecting the relevant data but is, nevertheless, a costly operation. Moreover, buoys cannot cover the vast areas of ocean resource available to ocean energy deployment. The operational data from deployed buoys, therefore, needs to feed into resource numerical models for optimisation and ultimately validation.

Develop and consolidate standards for resource measurement and characterisation for ocean energy converters

Collection of data and data collection tools for ocean energy resource characterisation can differ. Consequently, data is often not comparable across ocean energy projects or measurement campaigns. To ensure compatibility of data and complementary analyses across Europe, standards have to be developed and recognised.

Certain standards on resource assessment and device characterisation such as IEC already exist. However there is no consensus on all the necessary parameters to evaluate the resource. For example, there is no clear suggestion for measurement of the wave energy period, a common standard for developers and numerical modellers is needed.

Part C. Improve numerical models

Numerical models are used to analyse ocean energy resource (waves, currents, salinity, ...) and provide data for simulating device deployment. Their objective is to

predict the behaviour of a single device or of devices in arrays.

Models can also be used to predict how certain materials or components will react over time, as there is, currently, limited experience of full-scale devices deployed over many years.

Numerical models are, therefore, a relatively cost effective way to predict the functioning of ocean energy devices to optimise design. After a device is deployed, the real data collected can be fed back to the numerical model to sharpen it further.

Improve and validate numerical models to permit accurate prediction of ocean energy devices' long-term durability and operation

Long-term durability testing and prediction with numerical models

Improved methods to test and model the durability of materials, components and long-term effects will improve prediction of how deployment in real sea conditions over many years will affect deployed devices.

Hybrid laboratory models

Control systems and mechanical structures are generally designed in parallel. Ultimately, however, testing the control systems will only be possible when the device is operating. Thus control system errors are likely to occur during operation at sea. Hardware In the Loop (HIL) modelling, where physical subsystems are combined with software simulation can reduce testing costs and improve control system efficiency as devices are scaled-up.

Optimise computational power

Three-dimensional numerical models that capture the resource and its complex interaction with ocean energy devices require intensive computational power. Optimising the level of detail for each parameter can improve modelling techniques, simplifying models while retaining sufficient accuracy to ensure reliability.

Each technology's focus area needs to be clearly identified to allow the creation of optimised numerical models that capture the most important parameters as a first step to simplifying the models.



DCNS OpenHydro tidal turbine

2. Materials, Components and Systems

TABLE 3: COST REDUCTION POTENTIAL AND ESTIMATED RESEARCH & INNOVATION BUDGET: MATERIALS, COMPONENTS AND SYSTEMS

CAPEX reduction potential	Medium
OPEX reduction potential	High
Estimated budget for 2018-2020	Total € 150m <ul style="list-style-type: none"> • Technological Research – Devices, components, materials Cost: € 140m • Monitoring and Analysis Cost: € 10m

Components and systems used in ocean energy converters need to be compatible with the marine environment and resist corrosion and the heavy loads they are subject to. Using, developing and improving the right materials is key to making ocean energy devices survivable and reliable to produce energy at acceptable cost.

Ocean energy converters typically need to be designed to produce for at least 20 years. Lack of experience over such a period of time means that there is little data on device and component reliability and survivability. This

means that there is a knowledge gap on avoiding failure and reducing down-time over the life-time of ocean energy projects.

Ensuring the robustness of device components and sub-components for saline and/or sub-sea environments, reducing stress and structural loads placed on the devices and structures and preventive maintenance, are fundamental to increasing the reliability of ocean energy devices.

Research priorities for Materials, Components and Systems			
●●● High priority ●● Medium priority ● Low priority			
2.1	Develop high quality seaworthy materials	●●	2018
2.2	Increase yield with improved Power Take-Off	●●●	2018
2.3	Validation of components and sub-systems	●●●	2019
2.4	Control systems to increase reliability and survivability	●●●	2018
2.5	Condition monitoring systems to optimise operation and maintenance	●●	2020

CROSS TECHNOLOGY

Reliability is fundamental for all ocean energy technologies. Project life cycles are long and the environment they operate in is challenging. Maintenance operations can be difficult and devices subject to biofouling. Extended component and sub-system resistance is, therefore, essential.

Survivability is particularly challenging for ocean energy technologies that may be placed in highly energetic locations where extreme weather conditions may significantly increase the loads experienced.

TIDAL STREAM

Tidal turbine blades are made of composite material to ensure the correct levels of rigidity at the lowest possible weight. Blade edges can erode rapidly, facilitating water ingress, accelerating fatigue and the risk of failure. Improving the seaworthiness of blade materials will reduce the likelihood of failure.

Whereas designs for tidal stream PTO have been relatively well demonstrated, further performance improvements are required to reduce down-time and improve productivity.

WAVE

Cyclic loading and extreme wave conditions impact wave devices' resistance and survivability. New materials, such as reinforced concrete, may help to reduce cost.

The development of control systems that accurately monitor wave conditions and respond dynamically to them can mitigate adverse impacts and reduce fatigue.

SALINITY GRADIENT

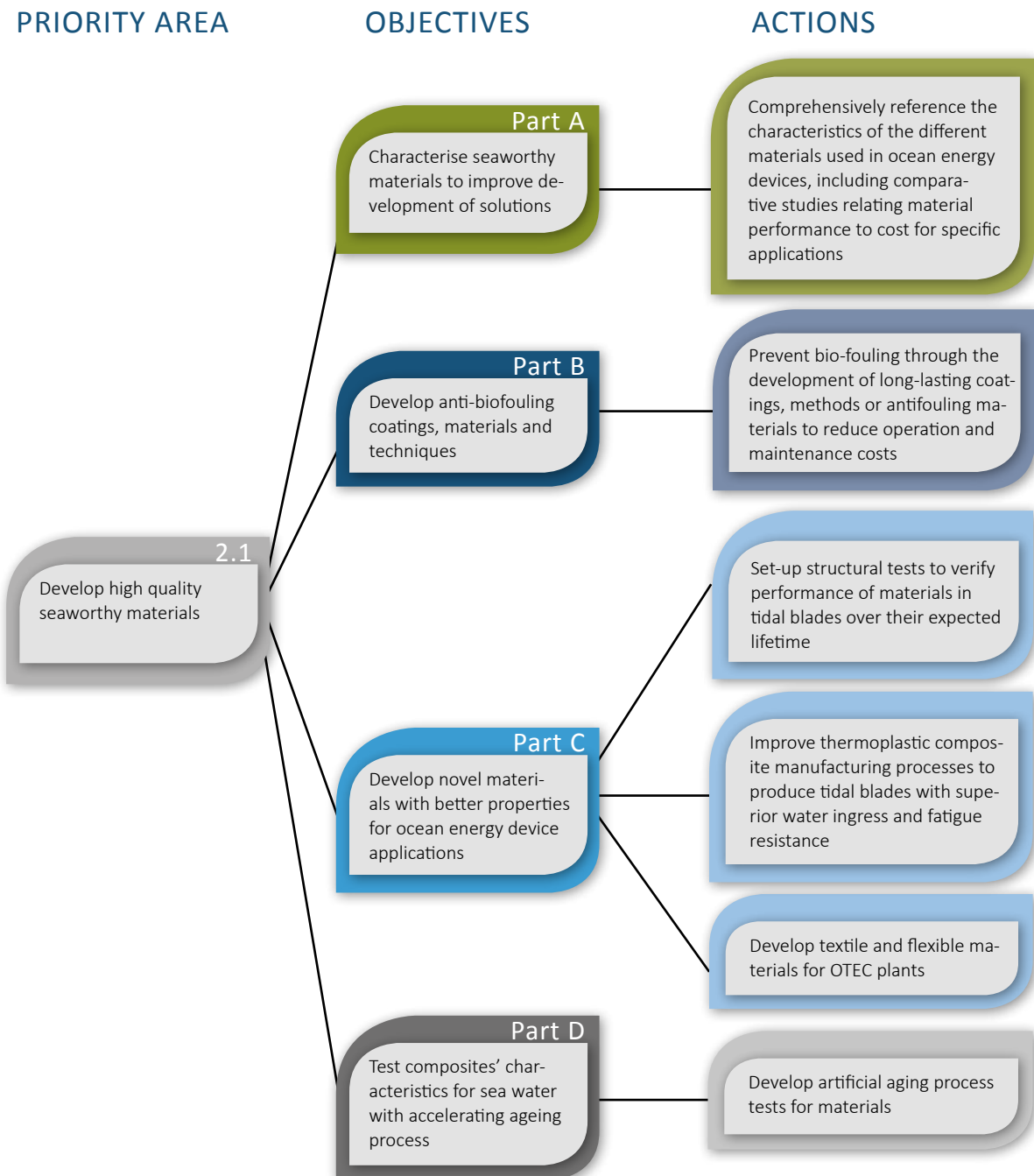
Membranes are critical components in salinity gradient power plants.

Osmotic membranes are exposed to loads and require high mechanical resistance. Reverse Electrodialysis membranes require low electrical resistance to increase the plant's yield. A stack's design and configuration will also substantially affect performance.

OTEC

The large structures in OTEC plants, such as the deep water pipes, are particularly exposed to loads. These, therefore, need to be sufficiently resistant and flexible. Development of new materials, less affected by fatigue, will increase the reliability of OTEC plants.

2.1 Develop high quality seaworthy materials



High levels of stress, tension and torsion on ocean energy devices generated by loads, water ingress, erosion from sand, salt and seawater combined makes the sea a hostile environment for structural materials. The resistance of the materials to the elements has a direct impact on system lifetime and maintenance intervals.

Ocean energy devices need to absorb recurring loads, such as the usual and repetitive movement of waves or water in a current. These are known as cyclical loads. Cyclical loading over time will create fatigue in components and the device as a whole.

To reduce an ocean energy device's downtime and, therefore, improve its power output and overall performance, it is necessary to reduce the need for maintenance over the device's life-cycle. This can be achieved through use and development of materials that are durable in sea conditions. To improve the economics of an ocean energy project, the choice of materials will be dictated by the relationship between the latter's up-front development costs and their maintenance costs over the project lifetime.

Significant experience has been accumulated by other offshore industries with many materials used in ocean energy. How reinforced concrete or steel, for instance, reacts to long-term exposure to sea conditions is well understood. This is not necessarily the case for other materials commonly used in ocean energy devices, such as composite materials. The focus of research in this context needs to be on materials that help to sustain an ocean energy converter's life cycle of more than 20 years.

Challenge: Development and characterisation of cost effective innovative materials for ocean energy converters and components in seawater that are resistant to biofouling, corrosion and erosion and able to withstand maximum loads and fatigue loading experienced during the OEC lifecycle.

Whilst many solutions already exist that are utilised in marine applications there may be the opportunity to reduce CAPEX and OPEX by the use of alternative materials and utilisation of new surface coatings.

Part A. Characterise seaworthy materials to improve development of solutions

Comprehensively reference the characteristics of the different materials used in ocean energy devices including comparative studies relating material performance to cost for specific applications

The characteristics required of materials used in ocean energy devices should be defined, taking into account elements such as resistance to bio-fouling, maximum tension, torsion, water ingress resistance, long term fatigue, rigidity and weight. However, such a characterisation of materials for ocean energy devices comes with uncertainties, such as the effect of fatigue over the life cycle. The development of reliable methods and tools to characterise novel materials is, therefore, also required.

It is particularly important to include in the database experience from tests and deployments in relevant sea conditions. Whereas, for example, there is a good understanding of how reinforced concrete ages in seawater, there is little available information on its application to a tidal turbine's foundation, nacelle or wave device. In this domain, research and laboratory testing are also of importance (see enabling action: "Test composites' characteristics for sea water with accelerating ageing process").

Part B. Develop anti-biofouling coatings, materials and techniques

Manual maintenance operations to remove biofouling on ocean energy devices are costly and require extended device down times.

Prevent biofouling through the development of long-lasting coatings, methods or antifouling materials to reduce operation and maintenance costs

The surface preparation of materials during device fabrication may increase longevity and increase resistance to corrosion and bio-fouling. This may be particularly important for tidal turbine blades, salinity gradient and OTEC. New methods of surface preparation may help to increase their durability and longevity and help minimise maintenance costs.



Andritz Hydro Hammerfest tidal turbine ready for deployment at the Meygen Project in Scotland

Structures exposed consecutively both to sea water and air, so called “splash zone” are particularly exposed to corrosion and biofouling. The devices’ moving parts are particularly sensitive to the phenomenon as the accumulation of micro-organisms can increase loads on components and interfere with contact between surfaces reducing mechanical performance and productivity of the device.

Bio-corrosion that occurs in metallic device and mooring systems in contact with the seabed caused by

bacteria on the metallic oxide may limit the lifetime of the component. Currently, designing over-dimensioned components extends their lifetime. However, this procedure increases a device’s manufacturing costs and, therefore, can significantly impact the cost of electricity produced. Further development of corrosion and bio-corrosion resistant materials will reduce the need to over-dimension components and reduce costs. Similarly methods such as impressed current and controlled release of anti-biofouling agents may be improved to reduce build and operational costs.

Part C. Develop novel materials with better properties for ocean energy converter applications

For certain ocean energy converters, new cost-effective and manufacturing processes would significantly improve performance. Rigid materials, for instance, may not always be the best option to resist the loads certain devices or components are exposed to.

Moreover, tidal stream blades have been manufactured using composite materials. These have not been readily used in the past in underwater applications. Consequently, there is little information on the durability of the materials once exposed long-term to the sea environment.

Set-up structural tests to verify performance of materials in tidal blades over their expected lifetime

There are a number of learnings from the use of composites in wind turbine blades that the ocean energy sector can build on. However, these are limited as water is denser than air and the loads to which ocean energy devices are exposed are different. Moreover, the porous nature of composite materials gives them a tendency to absorb the surrounding seawater, increasing their weight and loads over their lifetime.

More water-resistant denser materials are, therefore, required. Polymers could offer an alternative, but the – albeit – limited experience in their use in tidal applications to date indicates that polymer blades are subject to erosion.

To determine and develop the best materials for blade manufacturing, specialised structural testing facilities and design methodologies capable of simulating loads and erosion over the expected lifetime of a blade are required.

Improve thermoplastic composite manufacturing processes to produce tidal blades with superior water ingress and fatigue resistance

Thermoplastic, or polymer, composites have improved resistance to seawater impregnation as they reduce the amount of water that enters the laminate,

improving the materials reliability and its recyclability at end of life.

Existing thermoplastic polymer composite systems cannot, however, be moulded in sufficiently thick sections (around 100mm) over the required length for tidal turbine blade manufacture (that can be around 10m).

Further development of thermoplastic composites manufacturing processes for tidal turbine blades will need polymer composite materials to produce thermoplastic composite blades with superior water ingress and fatigue resistance.

Develop textile and flexible materials for OTEC plants

OTEC plants have a long and large cooling pipes necessary to reach cold waters at great depths. These are inevitably subjected to strong loads, causing stress and fatigue, especially around joints. High mechanical resistance is, therefore, needed to mitigate the latter on the plant structure.

Flexible materials, such as textiles or elastomeric materials - that also resist corrosion, biofouling and ultraviolet rays from the sun - could increase the reliability of cooling pipes by reducing stress and fatigue on joints. These materials could also find applications in umbilical cables of other ocean energy floating devices.

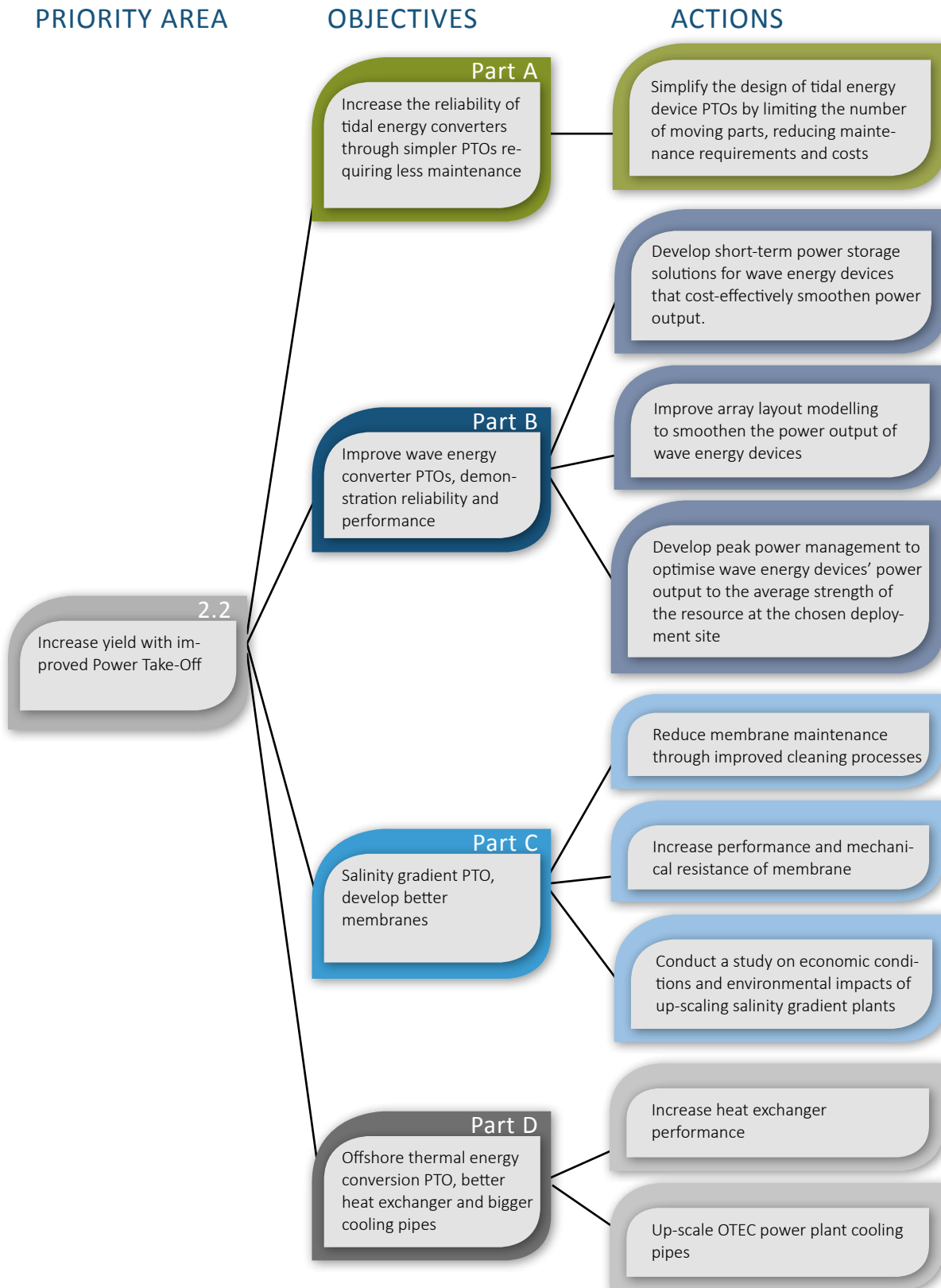
Part D. Test composites' characteristics for sea water with accelerating ageing process

To understand the long term effects of corrosion, erosion, and biofouling and sea water immersion with cyclic loadings on components and materials over the life time of an ocean energy project, tests in relevant sea environments need to be carried out long periods of time.

Develop artificial ageing process for testing materials

Test times can be reduced by developing artificial ageing processes. Development and generalisation of electrochemical accelerated ageing techniques could provide accurate data on how materials react in sea conditions in the long-term over short test periods, reducing, thus, the development lead-times for new materials.

2.2 Increase yield with improved power take-off



The Power Take-Off (PTO) for ocean energy devices is the mechanism that extracts energy from the resource. PTO is not a component in itself but a systems composed of several components. There are a multitude of PTO designs for use in different resources.

The PTO system needs to be reliable, as any failure directly impacts power production. Consequently, PTO performance, survivability and reliability are fundamental to the economics of an ocean energy project.

The technical maturity of the PTO varies between ocean energy technologies. Tidal range technology was first deployed in 1966, and borrows heavily from traditional hydro turbines. There are, therefore, few technical challenges related to the power production systems. Tidal stream technologies have successfully demonstrated PTOs during sea trials. However, further improvement is needed to improve the technology's economics. The other ocean energy technologies require further research and development on their PTOs, including being tailored to their respective resource at different locations.

Challenge: optimisation of PTOs to improve performance, reliability and survivability, to capture the most energy per unit cost. Further testing to demonstrate technology is needed, particularly in wave and salinity gradient.

Part A. Increase the reliability of tidal energy converters through simpler PTOs requiring less maintenance

Many PTOs developed for tidal energy have been demonstrated in real sea conditions and their design successfully validated. A further reduction in maintenance costs and increase in device availability will pass by a further simplification of PTO designs.

Simplify tidal energy device PTOs by limiting the number of moving parts, reducing maintenance requirements and costs

Reducing the number of moving parts in the PTO reduces the risk of component failure. For tidal stream turbines, simplifying PTOs could provide a solution to increase reliability.

Part B. Improve wave energy converter PTO, demonstration reliability and performance

Designs for wave energy PTOs have not converged to the extent they have in tidal and there remain a number of different designs. Generally, however, reliability and performance need improving.

Waves have multiple angles and different variables (time between waves, size, weight, speed, shape etc.) that can affect their interaction with wave energy devices. This multilinear characteristic of the resource is particularly difficult to model numerically (see 1.2) or capture physically. Consequently, understanding the resource and, therefore, how to optimise PTO design is challenging.

Develop short-term power storage solutions for wave energy devices that cost-effectively smoothen power output.

Conversion of the wave movement into electrical energy is difficult due to the large range in size of the wave's oscillations. Wave energy converters will generate power throughout the movement of the wave, but register a peak during a very short time (of perhaps just a second), then a new peak will come later as a new wave reaches the device. Because little electricity can be generated during this relatively long lull, power-smoothing mechanisms are required to even out power production. Short-term storage is a possible solution.

Coupled to storage systems, a wave energy device with a lower rated capacity can have the same or greater power output than a device with larger capacity. Devices with a storage mechanism will deliver power to the grid more smoothly, reducing incidences of peaks and troughs during production. Storage systems can, therefore, also reduce the need for larger electrical components such as generators or power converters.

Tidal turbines would also benefit from the development of short-term storage. However, due to the greater regularity of tidal movements, this action has been more closely linked with wave energy in this SRA.

However, short-term storage solutions increase device capital costs. The extra cost of the storage system needs to be balanced with the cost of increasing electrical components' size to deal with peaks and troughs in power production where there is no storage capability.

Improve array layout modelling to smoothen the power output of wave energy devices

The PTO's performance is not, however, solely impacted by the design of the single device, but also how devices are laid out across an array. Understanding interactions between wave energy devices in an array and optimising array design is, therefore, also a key to smoothing power output.

Develop peak power management to optimise wave energy devices' power output to the average strength of the resource at the chosen deployment site.

Wave energy converters are affected by a large range of wave amplitudes. Peak power management can avoid designing ocean energy devices with unnecessarily expensive power electronics.

Part C. Salinity gradient PTO, improve membrane performance

Increasing the performance of membranes and improving resistance to biofouling are the key issues to be tackled to increase the performance of salinity gradient plants. The theoretical maximum capacity of a salinity gradient plant's membrane for osmotic pressure is around 6 kilowatt per meter square. Currently results from prototypes are under half of this capacity.

Increase performance and mechanical resistance of membrane

In osmosis, a stronger membrane will allow increasing both the reliability and plant's yield. New materials and manufacturing processes should, therefore, be developed to increase the membrane's mechanical resistance.

For Reversed Electrodialysis, membranes with ultra-low electrical resistance will increase both the fuel-efficiency and the plant's yield. New materials and processes are, therefore, required to decrease the membrane's electrical resistance.

Reduce the maintenance of the membrane through improved cleaning processes

Membranes need to be cleaned regularly to maintain their optimal yield. During use, membranes collect dirt and bio-fouling that reduce the osmotic pressure on the surface of the membrane in osmosis and reduce the ion exchange rate in Reversed Electrodialysis. New cleaning processes or treatment of the water stream need to be developed to increase intervals between maintenance operations.

Conduct a study on economic conditions and environmental impacts of up-scaling salinity gradient plants

Up-scaling salinity gradient plants to significantly increase their production capacity is critical to fully exploit the technology's potential. However, the economic conditions for and advantages of upscaling as well as the environmental impact of large salinity gradient plants is largely unknown.

Part D. Offshore thermal energy conversion PTO, better heat exchangers and bigger cooling pipes

The key challenge to improving OTEC power plants' performance is an improvement of the heat exchanger. Furthermore, to upscale power production from ocean thermal energy, the cold water collector pipes need to be enlarged and lengthened, which remains a manufacturing and materials challenge.

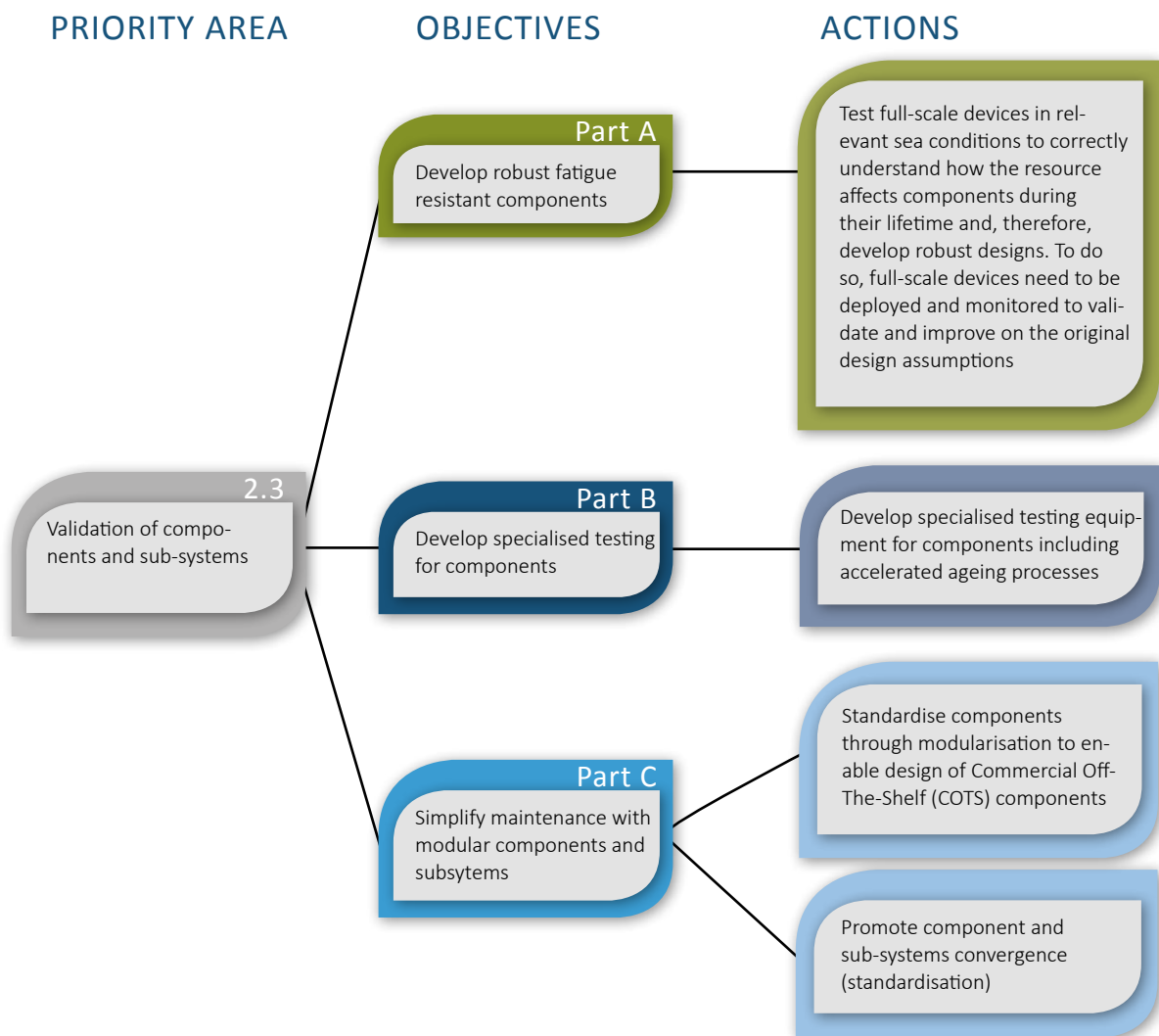
Increase heat exchanger performance

The relatively small temperature difference between hot surface water and deep sea cold water (around 20°C) requires the development of highly efficient heat exchangers.

Up-scale OTEC power plant cooling pipes

By increasing the volume of water intake, OTEC power plants can reduce the capital expenditure, improving the economics of the project. Larger cold water pipes are required to increase the volume of coldwater streams in the plant's PTO. The significant up-scaling of the cold water pipe poses both a manufacturing and a use of materials challenge.

2.3 Validation of components and sub-systems



Ocean energy devices are exposed to strong ocean forces: waves, currents, tides and forces specific to the layout of the arrays. Improving knowledge of the necessary component characteristics will improve component and overall device reliability. Ocean energy devices have to cope with constant variations in the resource, making it more complicated to design components than in other marine sectors. Experience shows that existing commercial off-the-shelf (COTS) components used in other off-shore activities do not necessarily offer the right level of reliability when used in ocean energy devices, due to the harsher conditions than they were originally designed for.

Challenge: Characterisation of loads to allow the Commercial Off-The-Shelf components manufacturers to develop off-the-shelf components that meet the strength and durability requirements of the ocean energy industry.

This is particularly relevant for commonly used components and sub-systems, such as connectors and cables. However, many components are device specific, consequently, technology convergence needs to occur to encourage COTS manufacturers to develop, where possible, new technologies for ocean energy and reduce the premium of developing specific components for specific devices.

Part A. Develop robust, fatigue resistant components

Certain components are in the front line in terms of exposure to loads, corrosion and biofouling. By effectively resisting or mitigating these phenomena, they can reduce fatigue and exposure of the device as a whole.

Test of full-scale devices in relevant sea conditions to correctly understand how the resource affects components during their lifetime and, therefore, develop robust designs. To do so, full-scale devices need to be deployed and monitored to validate and improve on the original design assumptions

Component design must take into account fatigue to reduce or mitigate damage. Use of specific materials and designs can improve component behaviour. For

example, the characteristics of material or the shape of a tidal energy device's blades will directly impact their resistance to fatigue and performance at a specific site.

The layout of the devices in arrays can also mitigate effects of physical phenomena, such as wakes that increase fatigue on components, at the same time array layout can similarly positively impact performance and power yield.

Specific components can be used to mitigate fatigue and increase reliability, for example, systems attached to mooring lines that reduce, restrict or prevent oscillations can decrease stress and fatigue on the other components.

Part B. Develop specialised testing for components

Due to the cost of testing at sea, complimentary component and subsystem testing on land is required. Nevertheless, real environment tests for components and sub-systems cannot be entirely replaced and remain essential for validation and standardisation.

Develop specialised testing equipment for components including accelerating ageing processes

To reduce component and subsystem failures, tests in ocean conditions are required. Rigs using new methods focusing on components that are particularly sensitive to failure and "mission critical", such as, bearings, connectors, cables, blades, membranes, sensors, and cables replicating sea conditions, are required.

Tests should include accelerated life testing, which creates a testing environment that is able to more rapidly simulate the life cycle loading on a device, or components. This is particularly important as the long term effect of being exposed to aggressive sea conditions on components is uncertain. Accurate accelerated life testing will improve component design allowing for a reduction of conservative margins and, therefore, reducing component costs.

Part C. Simplify maintenance with modular components and subsystems

Standardise components through modularisation to enable design of Commercial Off-The-Shelf (COTS) components

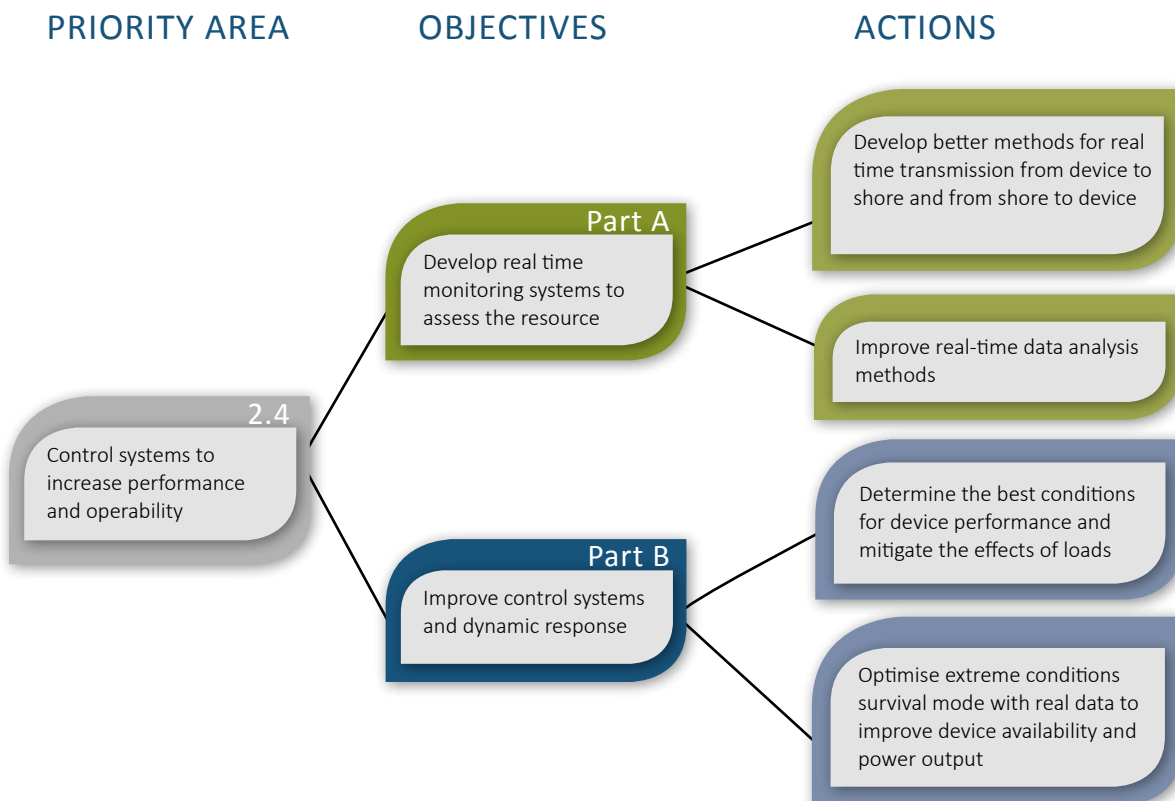
Carrying out maintenance or repairs on an ocean energy device can be a costly operation due to the complexities of accessing devices and its components at sea. Designing components and device sub-systems in a modular way – whereby they can be removed from the device

and re-inserted easily after maintenance -, can reduce maintenance costs and device down-time, increasing its availability.

Promote components and sub-systems convergence (standardisation)

Convergence of sub-system designs will facilitate the development of modular components compatible within the same technology family. This will lead to greater standardisation of components and enable the development of off-the-shelf solutions.

2.4 Control systems to increase performance and operability



Extreme weather conditions, such as during storms, or other natural phenomena can, over a short period of time, increase loads on ocean energy devices that need to be equipped to resist these extremes. The cumulative effect of the stresses, tensions, cyclic and extreme loadings, corrosion, biofouling, etc. increases material fatigue on the devices' components.

Control systems are mechanisms that engage a dynamic response in the components to the resource to which they are exposed. They can be used to mitigate fatigue and damage that waves or currents create on the device and its components, thus increasing the survivability and reliability. Control systems also improve synchronisation with the resource to optimise performance. There are a multitude of possible dynamic responses for each specific component.

Challenge: Ensure ocean energy devices adapt to and mitigate the impacts of the continually moving ocean conditions they are deployed in, to reduce stress and fatigue on components and optimise power production performance.

Part A. Improve real time monitoring systems to assess and forecast the resource

Short to medium term real time monitoring and forecasting of the resource is necessary to determine the control strategies that will increase performance and operability of ocean energy projects.

Monitoring and forecasting the resource in real time requires:

- accurate resource measurement and short, medium and long term forecasting;
- real-time transmission;
- data analysis.

Existing monitoring systems used offshore for ocean science and meteorology usually provide a generalised overview of resource conditions. There is potential to increase the latter's resolution and improve

ocean energy device yield and the scheduling of O&M operations. The devices may, themselves, create disturbances that affect measurements which need to be accounted for. Whilst equipment to measure resource exists this may not have the long term stability and accuracy required for the ocean energy industry.

Develop better methods for real time transmission from device to shore and from shore to device

Real time monitoring of the ocean energy device and ocean conditions and transfer of the data to shore enables short and medium term forecasting: improving power production information for grid management and O&M planning.

However, communication systems used in other offshore activities are expensive and the strong loads on power cable conducts can damage fibre optic data cables that are housed within them. Experience has shown that reliability of these systems can be an issue and that bandwidth may be limited for wireless solutions.

Improve real-time data analysis methods

Placing sensors on ocean energy devices may affect data collection. This is particularly the case in wave energy converters, where the movement of the device may interfere with the measurement of wave amplitude and period.

Specific analysis tools with matrices to extract the resource's key parameters removing device interference, will improve resource data collection.

Part B. Improve control systems and dynamic response

Control system analyse the input signal against pre-determined requirements and use a system to control the output. A control system may, for instance, pitch tidal turbine blades or adjust the mooring lines in a floating ocean energy device to match sea level. If the sea conditions become too aggressive, the control system can put the device in 'survival mode' to limit its exposure to the waves or currents.

Determine the best conditions for device performance and mitigate the effects of loads

In ocean energy, the environment, the systems, components and sub-systems used differ greatly. Control systems need to monitor numerous parameters, not just wave height or current velocity. Through deployment and testing, the optimal performance conditions of each device and its components and systems can be determined.

By determining optimal operation environment and through real time monitoring of the device's environment, control systems can take actions to better manage and react to loads and reducing fatigue on materials and components. This will reduce the possibility of unexpected failures, unplanned maintenance and, therefore, increase the device's availability.

Triggering such dynamic responses can also be used to maximise a device's power output by continually positioning it in the most efficient way in respect to the resource.

Improved understanding of the effects of loads on ocean energy devices and their components will ease development of efficient control systems. Increased data on how devices react obtained in real sea conditions is necessary to improve modelling (also see chapter 2).

Optimise extreme conditions survival mode with real data to improve device availability and power output

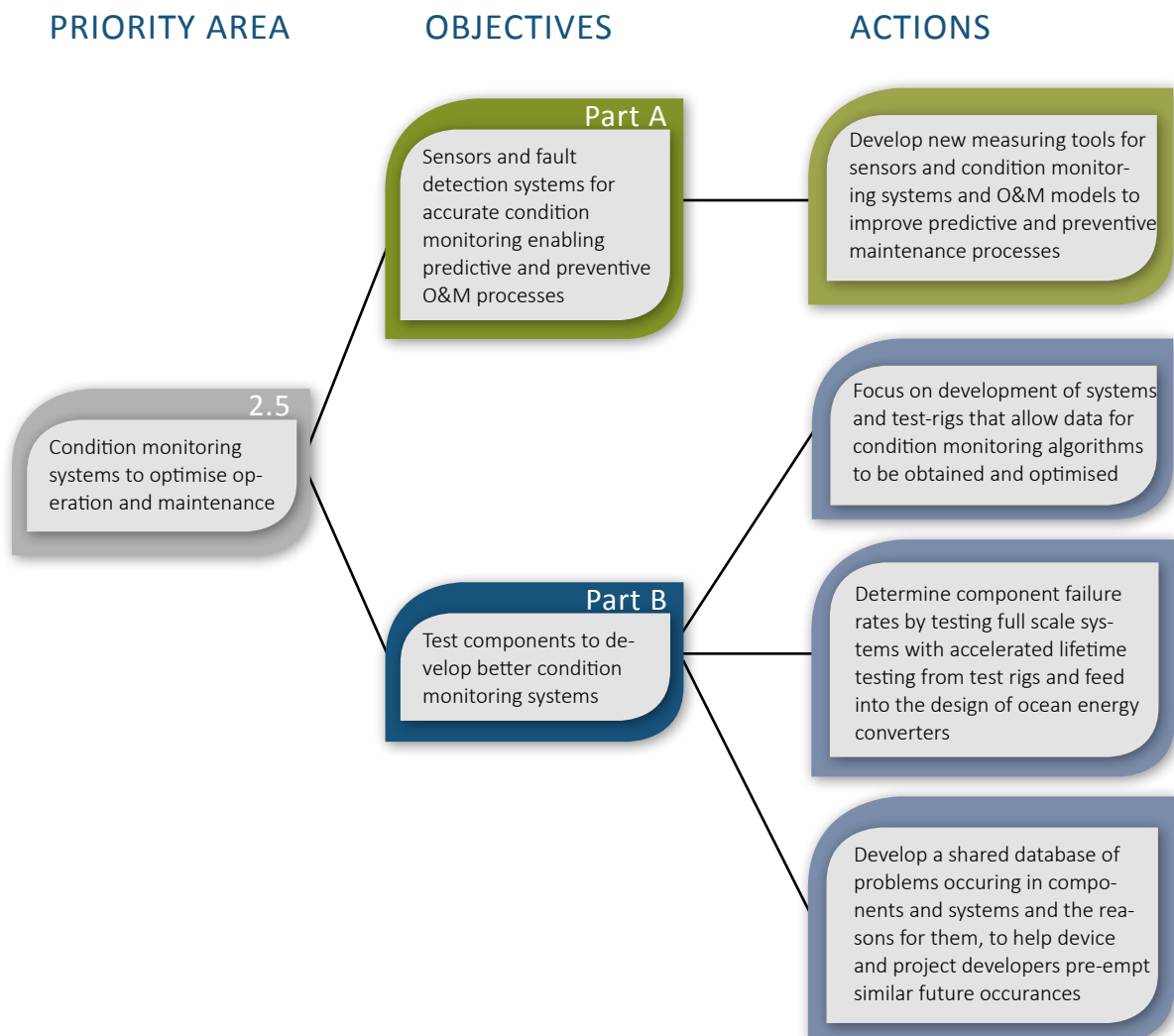
The use of control systems can prevent damage during extreme events, by operating the device in "survival mode". Each ocean energy device will have different resistance to aggressive resources before be turned to "survival mode" to protect the device from damage. In some cases, "survival mode" may decouple the PTO from the power electronics, or tidal device blades will be pitched to take less loads.

Due to the limited deployment of ocean energy devices to date, device developers may work overly-conservative assumptions about when to switch to survival mode. Improving the definition of how, when and under what conditions survival mode is required, a devices availability and power output can be increased.



AW Energy's Waveroller wave energy convertor being towed to deployment site in Peniche, Portugal

2.5 Condition monitoring systems to optimise operation and maintenance





Albatern's Squid wave energy convertor deployed off the Isle of Muck in Scotland

Ocean energy device operational performance can be improved through the development of new sensors, sensors integrated into components, and monitoring methods with relevant information and data transmitted to the O&M team to inform planned maintenance.

Condition monitoring systems and sensors are usually system specific. They are developed as part of each system design. For example, gearboxes often come with sensors to measure temperature, vibration, water ingress, metal particles in oil, etc. These sensors are designed for a specific gearbox. There is, therefore, a limit to the transferability of condition monitoring systems of each specific component. However a common understanding of these systems will help the sector increase reliability of ocean energy devices.

Condition monitoring systems play a critical role in informing maintenance and repair processes and can be used to set-up predictive or preventive maintenance; processes whereby certain maintenance operations are carried out at a given time reducing the risk of future component failure. The latter can improve the reliability and survivability of ocean energy devices.

- Preventive maintenance uses pre-defined criteria, such as number of operating hours and performance information against collected statistics on the

device to plan maintenance and prevent faults from occurring.

- Predictive maintenance is the application of the condition monitoring systems information with specific algorithms to analyse equipment health and performance and detect early defects that could lead to unplanned downtime or unnecessary expenditures.

Challenge: Designing reliable and accurate condition monitoring systems for ocean energy devices is key to streamline O&M and deliver a high level of reliability and survivability. Further sensor testing in relevant conditions for ocean energy converters is needed.

Part A. Sensors and fault detection systems for accurate condition monitoring enabling predictive and preventive O&M processes

Efficient condition monitoring has two main preconditions. Firstly, knowledge and understanding of the potential failures an ocean energy device is exposed to, secondly, the right tools to detect defects early on. Consequently, the appropriate sensors and fault detection techniques on components need to be developed to identify potential defects.

Develop new measuring tools for sensors and condition monitoring systems and O&M models to improve predictive and preventive maintenance processes

Sensors capable of measuring vibration, fatigue or damage on specific ocean energy device components and materials, such as on composite materials (used in tidal turbine blades), corrosion and structure integrity sensors need to be further developed, along with the appropriate monitoring algorithms to accurately report data in real time.

The sensors and their algorithms require tuning to the characteristics of the resource and how it interacts with the devices individually and the devices in an array to give accurate readings (see also ‘resource measurement’). Obtaining data on such complex resource interactions requires extensive testing. As the interaction between devices, devices in arrays and the resource is affected by numerous complex phenomena (such as vibrations, resonance, turbulence, wake effects...), on top of tank testing, testing and validation in real sea conditions is required.

The data and experience gathered by the sensors can be used to develop O&M models to inform preventive and predictive maintenance processes, reducing the need for unscheduled repairs and maintenance and, therefore, operating costs related to personnel mobilisation and vessels.

Part B. Test components to develop better condition monitoring systems

Advanced algorithms needed for condition monitoring, have to take into account the complexity of data on symptoms of incipient failures, the failures themselves and the resultant effects of failure on machinery.

Focus on the development of systems and test-rigs that allow data for condition monitoring algorithms to be obtained and optimised

Extensive test data is required to optimise condition monitoring algorithms to better inform predictive maintenance actions.

In addition to data gathered through demonstration and device deployment, test rigs can lead to an improved

understanding of failure mechanisms of components and sub-systems and are particularly suitable for accelerated lifetime tests. Algorithms can then be optimised to balance the cost of intervention and early maintenance against the impact of delaying the maintenance actions.

Determine component failure rates by testing full scale systems with accelerated lifetime testing from test rigs and feed into the design of ocean energy converters

A knowledge of the frequency with which a system or component fails, the failure rate, is needed to inform maintenance algorithms and determine the maintenance strategy.

Failures are caused by defect in design, process or quality of systems or components. A single component failure may cascade to other components or sub-systems. Equally systems may be designed in such a manner that a single failure does not cause a significant impact to the integrity of the whole system or its power production. This is called failure modes and effect analysis (FMEA).

A better understanding of the failure mode and effect will allow maintenance algorithms to correctly identify the criticality of certain components failing and help to reduce O&M costs.

Develop a shared database of problems occurring in components and systems and the reasons for them to help device and project developers pre-empt similar future occurrences

Information on component and systems failures may be difficult to obtain due to the commercial advantage gained in addressing these and the lack of incentive to share data among device developers and update a common database. This can be addressed, at least in part, by requiring data on component failures from public grant funded programmes.

The reasons for component and system failure are many and varied. Understanding the physics of failures and building a database of failure modes will improve understanding of the demands placed on components. This will then inform the development of appropriate validation methods and processes.

3



Atlantis Resources' AR1000 tidal turbine being lifted into position

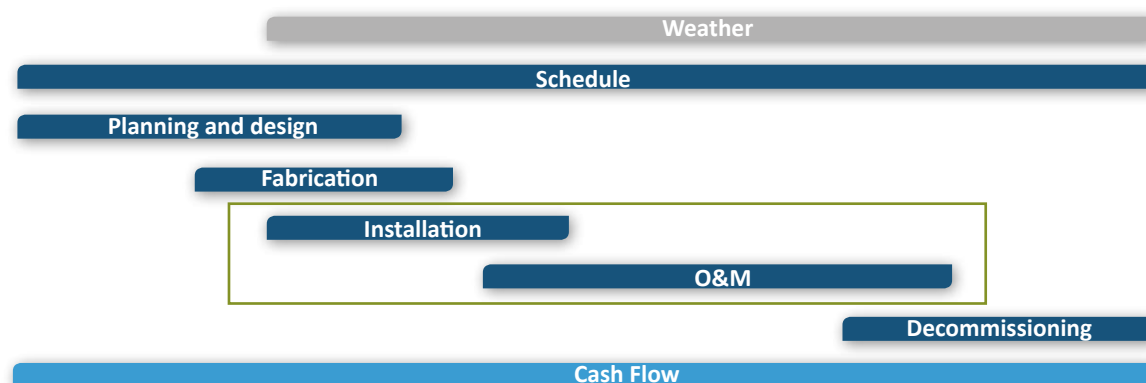
3. Installation, Logistics and Infrastructure

TABLE 3: COST REDUCTION POTENTIAL AND ESTIMATED RESEARCH & INNOVATION BUDGET: INSTALLATION, LOGISTICS AND INFRASTRUCTURES

CAPEX reduction potential	High
OPEX reduction potential	High
Estimated budget for 2018-2020	<p>Total € 85m</p> <ul style="list-style-type: none"> • Demonstration of marine technology access & logistics Est. Cost: € 70m • Establish consistent consenting, environmental and socio-economic assessment baseline frameworks Est. Cost: € 15m

Installation and operation and maintenance (O&M) activities can be a significant part of ocean energy project economics.

FIGURE 4: OFFSHORE PROJECT DEVELOPMENT VALUE CHAIN⁹



Due to the limited number of devices and projects deployed to date, ocean energy does not yet have a full, dedicated supply chain.

Vessels adapted from other marine or offshore activities may not be ideal for working in the challenging conditions where ocean energy devices are deployed.

This may result in the need to use expensive vessels or, otherwise, reduce the number of available weather windows in which installation and maintenance work can be carried out.

The development of optimised waterborne and underwater vehicles, components and processes designed and constructed to service the industry, therefore, will improve logistics and ocean energy economics. However, a fundamental pre-condition to its development is a

medium- to long-term visibility of potential volumes deployed. Failing this, companies with the potential to participate in the ocean energy supply chain will not make the necessary investments.

Ocean energy devices typically need to operate for a lifetime of at least 20 years, maintaining low operation and maintenance costs is a key factor in a project's economics and, therefore, the cost of electricity produced. Adapting existing marine value chains to the specific requirements of ocean energy and creating a bespoke supply chain will help reduce installation and operating costs.

Determining the state-of-the-art in other marine sectors will facilitate identification of possible synergies and, where possible, how to tailor them to the specificities of ocean energy.

⁹ TP Ocean Research. 2016

Research priorities for Materials, Components and Systems			
●●● High priority ●● Medium priority ● Low priority			
3.1	Access to ocean energy sites, design adapted processes and vessels	●●	2020
3.2	Reduce uncertainty, risk and cost of foundations, anchoring systems and cables	●●●	2018

CROSS TECHNOLOGY

Windows that allow work to be carried out on an offshore ocean energy farm or plant can be unpredictable. Planning tools, developed taking into account real data from deployed projects will be able to optimise offshore processes, reducing uncertainties and costs in O&M processes.

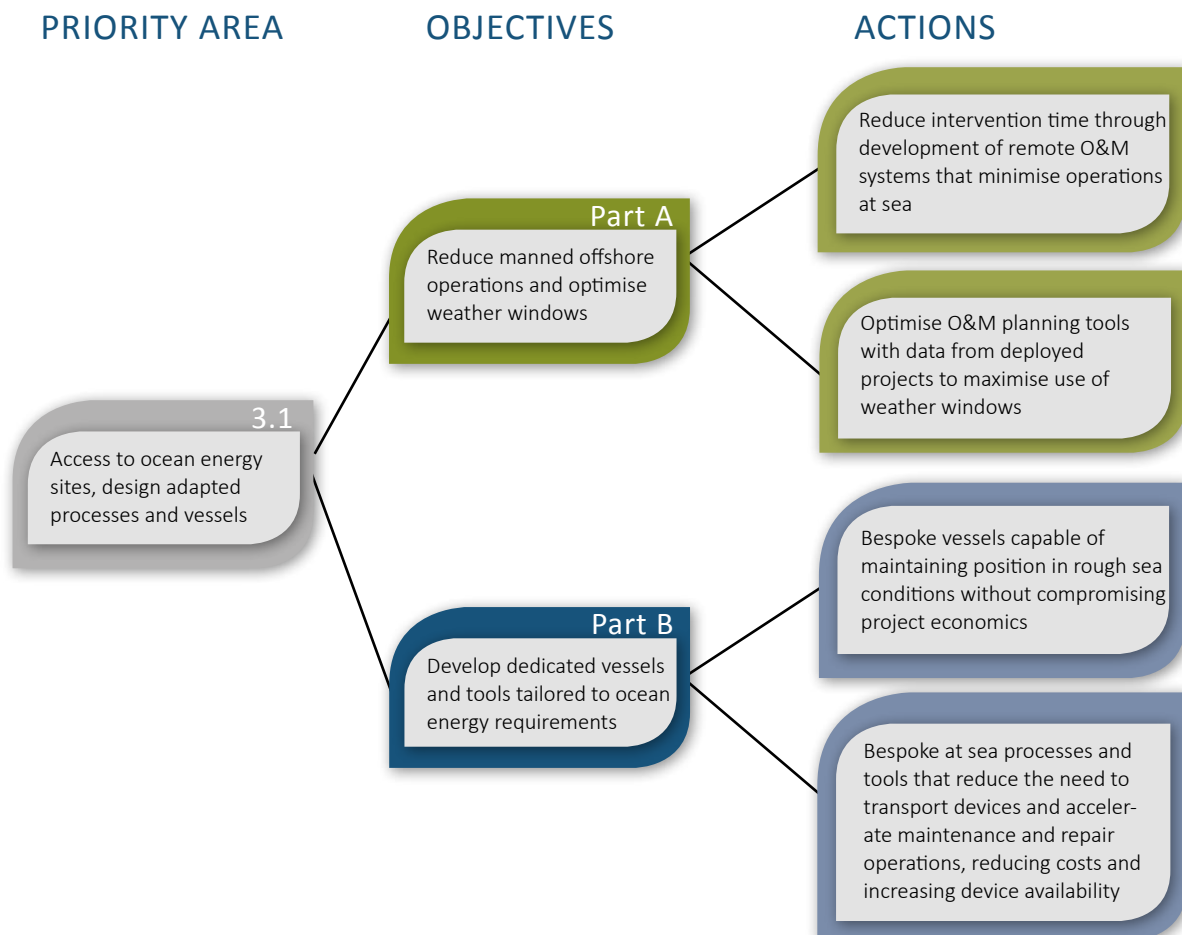
Ocean energy devices, whether floating or bottom fixed will require regular connection and disconnection from their foundations and moorings as well as connection and disconnection of their power cable to allow maintenance work to be undertaken out of the water. Improving rapid connection/disconnection systems for both foundations and cables will help reduce maintenance or replacement of connectors. The development of generic foundations and mooring systems could cost-effectively address this issue.

TIDAL STREAM AND WAVE

Sites where ocean wave and tidal devices are deployed are characterised by their strong currents or waves. To ensure precision installation or maintenance operations, sophisticated vessels that can maintain position with high degree of precision in rough sea condition are required. Existing vessels are not, necessarily, intended for ocean energy devices, but often for operations with significantly bigger or bulkier objects, making them costly to charter and operate. Vessels intended to work in high-energy sites with components and devices of the size and weight of the ocean energy sector will need to be developed to keep vessel costs from compromising project economics.

Sending technicians out to an offshore site to carry out installation or maintenance operations is both costly and increases health and safety risks. Improving technology for controlling remotely ocean energy devices will minimise the number of manned offshore operations required. Likewise, unnecessary transport costs can be cut by systems and processes allowing repairs can be carried out out of the water but at sea.

3.1 Access to ocean energy sites, design adapted processes and vessels



A dedicated installation and O&M supply chain for ocean energy will optimise processes and reduce project costs considerably. Sites for wave and tidal energy are more challenging to work in for marine operators as these energetic locations are usually in areas 'to be avoided' by conventional marine users.

Currently vessels from the offshore oil and gas industry, able to navigate in strong currents, high waves and able to maintain position during operation are used in ocean energy development. Such vessels have the required

technical specifications for ocean energy farm installation and O&M activities but, their cost can be prohibitive, particularly when used for single prototypes or small scale projects.

Specialist and dedicated vessels are required, but the early stage of the ocean energy market and lack of visibility on future volumes does not encourage investment in and development of bespoke vessels. New approaches to reduce installation and O&M costs should be developed.

At present, publicly available information on the operation of vessels in ocean energy sites is limited. Better dissemination of experience, successes and failures in this domain can foster innovation. The objective is to reduce costs of installation, intervention and O&M through the development of an appropriate supply chain consisting of versatile vessels and methods including partially or fully autonomous installation mechanisms.

Development may also draw on the experience of other sectors. For example, mobile deployable military logistics and engineering capability, accurate site intelligence, well-rehearsed and integrated workforce and rapid installation of pre-formed components to achieve fast set up and switch on.

Challenge: Installation and O&M can be time consuming and expensive. Weather windows for operating vessels and underwater Remotely Operated Vehicles (ROV) can be short due to the energetic sea conditions in which ocean energy devices are deployed. Furthermore, off-shore installation and maintenance can be a significant share of total project costs. Complexity in planning off-shore operations due to the short lead-time in determining weather windows adds to project uncertainties and increases costs.

Part A. Reduce manned offshore operations and optimise weather windows

As carrying out tasks at sea depends on the availability of – at times - short weather windows and involves high costs and increased safety risks, limiting offshore operations as far as possible when planning installation or O&M activities is fundamental.

Reduce intervention time through development of remote O&M systems that minimise operations at sea

It is possible to minimise operations at sea by developing systems that, whenever possible, remotely control the ocean energy device from shore, and design devices and arrays in such a way as to reduce O&M cost. Equally, when intervention is necessary systems may be designed in such a manner as to reduce the time spent offshore. This may involve rapid connection/disconnection systems or better access systems and methods to

maintain critical components. Research should be carried out in systems and methods that minimise intervention times.

Optimise O&M planning tools with data from deployed projects to maximise use of weather windows

O&M planning tools to optimise operations during weather windows can be designed. However, to improve their efficiency more data and experience from deployed projects is needed to correlate them to specific operations and vessel characteristics. Such planning tools need to be dynamic and fine-tuned as data on sea conditions increases and new vessels are designed. The objective of developing such tools is to maximise the use of weather windows.

Part B. Develop dedicated vessels and tools tailored to ocean energy requirements

Ocean energy device foundations need to be positioned precisely. Pin-piled foundations, monopile foundations and moorings are permanently fixed into place and cannot be moved or relocated once installation is complete. Devices using gravity foundations, on the other hand, may be repositioned, albeit at a cost.

Bespoke vessels capable of maintaining position in rough sea conditions without compromising project economics

Ocean energy array lay-outs are optimised to decrease interference between devices and increase power yield, ensuring each device is correctly positioned is crucial. Incorrectly placed devices could result in increased occurrence of device failure or decreased device performance. Consequently, installation vessels going out of position can result in damage to the ocean energy device or be detrimental to project yield, therefore, economics.

Vessels that can maintain position with a high degree of precision, whether man operated or controlled remotely, are a requirement of the sector. Vessels currently available on the market, apart from relatively expensive dynamic position vessels, are not necessarily optimised for the rough sea conditions in which many ocean energy devices are sited.

As the industry moves forward, ensuring position precision during installation and maintenance at a cost of vessels that does not overly impact project economics will require the development of bespoke high performance vessels and underwater remote operated vehicles. Innovation in this domain will benefit from vessel use in other sectors, such as oil and gas and offshore wind.

Bespoke at sea processes and tools that reduce the need to transport devices and accelerate maintenance and repair operations, reducing costs and increasing device availability

The ocean energy value chain for operation at sea is still in its infancy due to the relatively few deployed devices

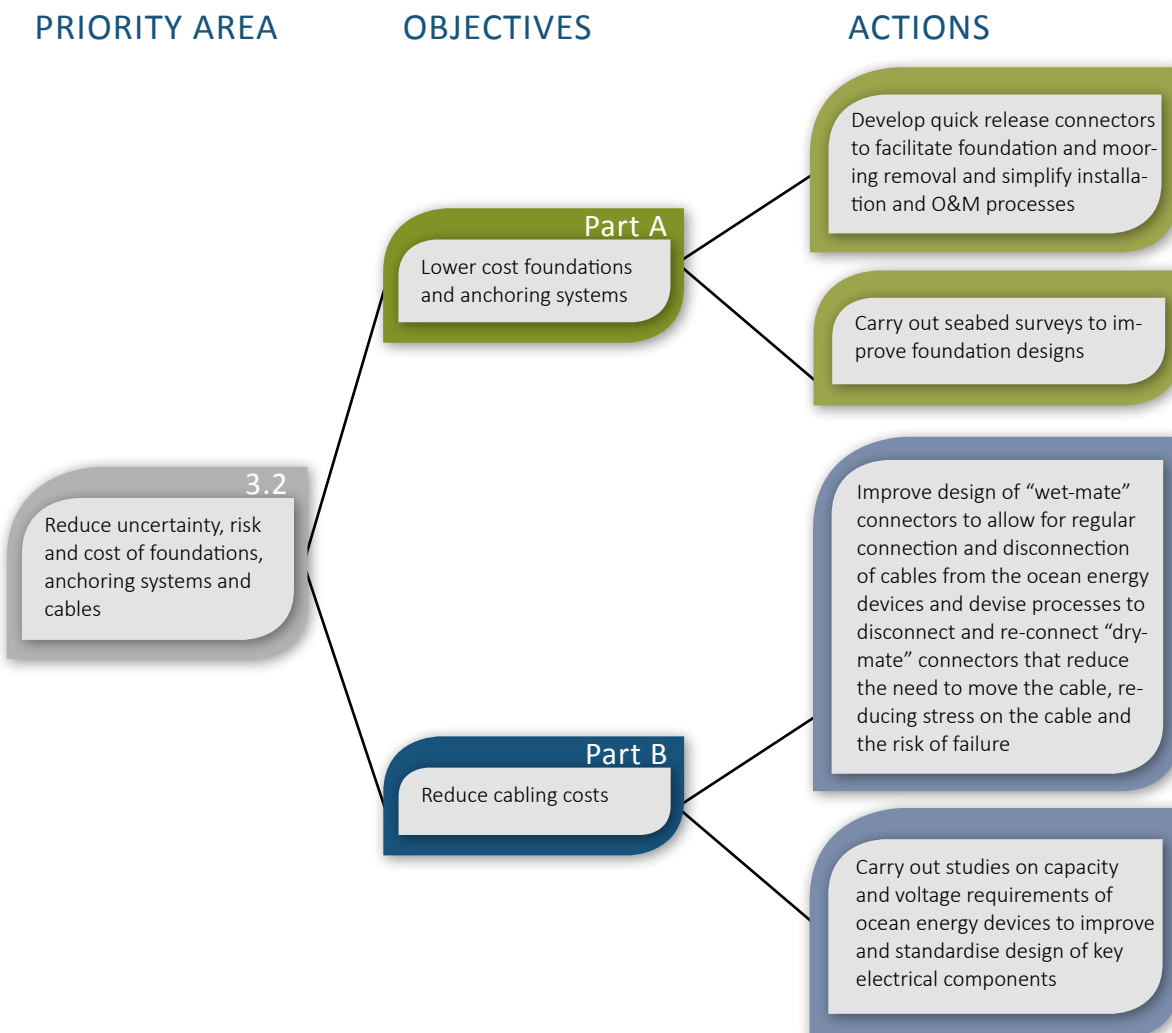
to date. As for vessels, there are not standardised or bespoke tools and procedures to carry out operation and maintenance of ocean energy devices at sea and each device and site may have particular requirements.

As for vessels, the lack of tailored solutions can increase the cost of carrying out operations at sea. The development of standard methods and tools for operations at sea is, therefore, fundamental to the long-term development of the ocean energy industry. Techniques that, for instance, allow retrieval of devices and carry out maintenance and repairs in situ will reduce unnecessary transport costs and time while improving device availability.



Power cable drum housing at the European Marine Energy Centre, Scotland

3.2 Reduce uncertainty, risk and cost of foundations, anchoring systems and cables



Foundations and moorings are the points of attachment between the ocean energy converter and the seabed. In some locations the seabed will consist of sand and clay, in other locations the seabed will consist of rock. Foundations and moorings can constitute a significant part of an ocean energy project's costs.

Moreover, foundation and mooring installation operations for ocean energy devices are necessarily carried out at sea. As for device maintenance, this increases costs and lead-times are highly dependent on weather windows. Scheduled and un-scheduled maintenance operations can, therefore, lead to extended device down-times.

Challenge: Optimise installation, maintenance and decommissioning processes for foundations and moorings to reduce operating lead-times at sea.

Part A. Lower cost foundations and anchoring systems

Foundations and moorings are located under the water, inevitably in harsh sea environments. The different types of seabed will require different foundation solutions and installation methods, along with their associated costs. Foundations and anchoring systems are tailored to the site and ocean energy device specifications.

Develop quick release connectors to facilitate foundation and mooring removal and simplify installation and O&M processes

To reduce installation and maintenance costs, foundations and anchoring systems can be optimised to:

- limit subsea operations;
- be easily deployed and recovered, ideally using small vessels;
- converge in design enabling the development of generic systems compatible with different technologies, devices and/or seabed;
- have a low environmental impact.

Bottom-fixed devices are generally brought to surface or towed back to shore to facilitate maintenance and limit underwater work. Developing “quick release connectors” that allow rapid connection and disconnection of ocean energy devices off the mooring lines or foundations can help reduce operation time at sea and underwater. This process will work in conjunction with electrical cables that also have to be disconnected from the machine or foundations (see quick release connectors in part B below).

Due to the important number of connections and disconnections expected over a 20 or more years operating period, these innovative systems need to be resilient.

Carry out seabed surveys to improve foundation designs

Better characterisation of ocean energy deployment sites can improve foundation design. Accurate understanding of interaction of the resource on the seabed such as the sedimentation coverage, current, turbulences, and so forth will facilitate improved foundation design, avoiding oversizing components which can increase manufacturing and installation costs.

Part B. Reduce cabling costs

Power cables and connectors are key assets for ocean energy devices and arrays to deliver electricity to shore. Power cable and connector robustness requires particular attention; the impact of loads due the strength of the ocean resource and the turbulent conditions ocean energy devices can be sited in increases beyond what is generally the case in cables used in other offshore sectors. As a result, power cables and connectors are subject to failures. These can be difficult to fix due to the power cable connections to the devices and, sometimes, power hubs being underwater. Repairs can, thus, provoke long down-times.

The development of connectors that ease coupling and decoupling from the ocean energy device, together with improved installation methods for power cables and specific systems for floating/tethering platforms will reduce lead-time for operations at sea.

Improve design of “wet-mate” connectors to allow for regular connection and disconnection of cables from the ocean energy devices and devise processes to disconnect and re-connect “dry-mate” connectors that reduce the need to move the cable, reducing stress on the cable and the risk of failure

Many ocean energy devices are partially or fully submerged. To reduce cable installation times and facilitate the recovery of the device for onshore repairs, power cables need to be readily and repetitively connected and disconnected.

“Wet-mate” connectors, that allow power cables to be connected and disconnected underwater, are used in other industries such as oil and gas. However, in the latter uses, the connector is not designed to be repeatedly connected and disconnected over the projects life-time as would be the case in ocean energy applications. Consequently, wet-mate systems designed for multiple connections and disconnections would improve the logistics of maintaining ocean energy devices and offer the potential for significant cost reductions in O&M.

Alternatively, ocean energy devices can be designed to keep the cable connector dry, allowing the use of

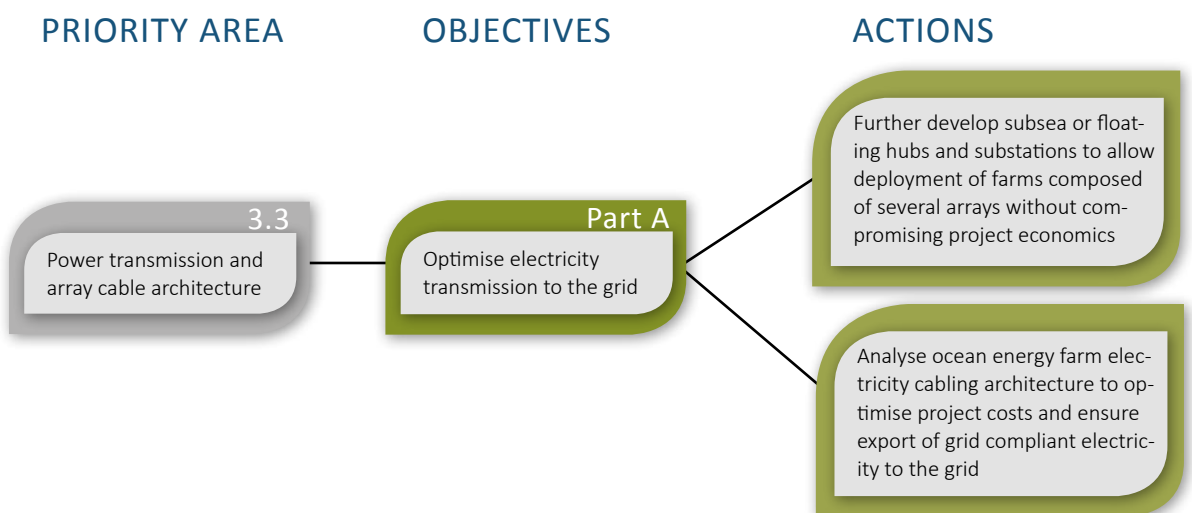
cheaper and more readily available “dry-mate” connectors. However, to carry out maintenance or repair operations and, therefore, disconnect the cable, the ocean energy device needs to be retrieved. This may require moving the power cable numerous times over the project’s lifetime which can cause stress and wear protections. Processes that simplify retrieval and disconnection of dry-mate connectors need to be perfected to reduce the risk of future cable failures.

Carry out studies on capacity and voltage requirements of ocean energy devices to improve and standardise design of key electrical components

Standardising rated power and voltage for electrical components within ocean energy devices will allow optimisation of their design and ultimately lead to off-the-shelf products, bringing down manufacturing costs.

To achieve this, power quality studies on ocean energy devices should be carried out aimed at understanding capacity and voltage requirements. A certain level of dissemination of PTO and operations data is needed would permit accurate designs for electrical characteristics and architecture of key components such as connectors.

3.3 Power transmission and array cable architecture





Fibre optic and power cable installation at the Galway Bay test site, Ireland

Part A. Optimise electricity transmission to the grid

Prototype and small pilot tidal and wave projects are mostly connected to onshore electricity grid through individual single cables to an onshore substation. As the sector evolves and increasingly large ocean energy farms are deployed on a commercial, individual cabling to shore may prove uneconomic.

The ocean energy sector will need to optimise how power cables are laid among the clusters of devices in a farm (inter-array cables), how the various cables are collected into a single sub-station or hub, and rationalise the amount of cables from the farm to shore (export cables).

Ultimately, the electricity delivered to the onshore grid needs to respond to the requirements of the grid operator (be grid compliant). An ocean energy farm's electricity infrastructure, therefore, needs to ensure cost-effective and grid compliant power delivery.

Challenge: Develop cost effective cabling solutions for arrays and farms of ocean energy devices, optimising electricity export to the onshore grid.

Analyse ocean energy farm electricity cabling architecture to optimise project costs and ensure export of grid compliant electricity to the grid

The layout of the offshore electrical network, both the inter-array and export cables, can impact the economics of an ocean energy project. The electricity configuration

and architecture of an ocean energy farm, therefore, needs to be optimised. Analysis of best network arrangements suitable for multiple ocean energy converters and ensuring compatibility with grid requirements should be carried out.

Further develop subsea or floating hubs and substations to allow deployment of farms composed of several arrays without compromising project economics

In offshore wind farms several turbines are typically connected together in an array. Several arrays will compose the farm and each array will collect the power produced from its turbines and connect to an offshore substation, above the water level, resting on a monopole or jacket. The substation will collect the cables from each array, condition the electricity produced and transmit it to shore through a large export cable.

A similar principle applies for ocean energy farms, but an identical solution, particularly as regards sub-station siting is unlikely to be workable. Subsea or floating hubs or substations may be needed where it is impractical to locate a bottom-fixed structure (due to depth, wave loading or cost).

Where devices are removed from sites for maintenance and repairs, there may also be particular switching needs to isolate the devices from live cables before removal. Considering the costs linked to subsea cabling solutions, tailored technologies and processes need development, taking full account of their impact on project economics.

4



Schottel Hydro SIT turbines loaded onto a Plat-o tidal platform

4. Non-Technological Issues

TABLE 5: COST REDUCTION POTENTIAL AND ESTIMATED RESEARCH & INNOVATION BUDGET: CROSS-CUTTING ISSUES

CAPEX reduction potential	High
OPEX reduction potential	High
Estimated budget for 2018-2020	<p>Total € 105m</p> <ul style="list-style-type: none"> • Pre-normative research for developing industry standards Est. Cost: € 5m; • Manufacturing & production advances/ supply chain Est. Cost: € 100m

Demand for a product is the fundamental pre-condition for an industry to develop, set up manufacturing units, attract investments and create jobs. In the energy sector, demand for new power generating capacity will be determined by an increase in energy consumption, a need to retire old power plants and replace them with new ones and a necessity or will to reduce consumption of one energy resource (such as fossil fuels) in favour of another (renewables).

Europe’s electricity system is, currently, characterised by overcapacity (too many power generating units) to cater for a stagnant electricity consumption. This situation, moreover, has brought power prices in the European markets to an all-time low, reducing appetite to invest in new generation capacity. Nevertheless, Europe’s power generating fleet is ageing, and investments in new generation capacity are necessary to replace power plants that need to be retired. Moreover, the EU is largely dependent on imported – mainly fossil - energy sources while committed to decarbonise its economy.

Consequently, whereas the market conditions are not conducive to significant investments in the energy system, these remain necessary if the EU is to meet its overall objectives with regards to energy production. Political leadership for the energy transition is, therefore, required with public support to push emerging technologies, such as ocean energy, to maturity. Without this political momentum, the emergence of an ocean energy industry and the development of significant ocean

energy capacity capable of meeting a large part of Europe’s power needs will not be possible.

It is, however, the very emergence of an industry with a significant manufacturing capacity, deploying numerous devices year-on-year, alongside continued R&D efforts, that will reduce risks for investors and drive down the cost of manufacturing and deploying ocean energy devices and, consequently, reduce the sector’s cost of energy.

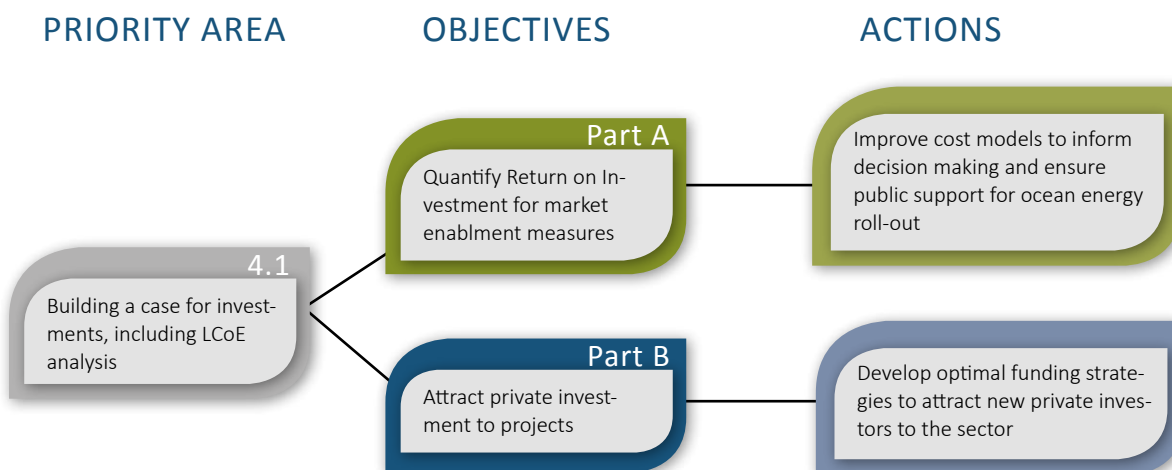
On its side, the ocean energy industry needs to design its devices and projects with replicability and manufacturability in mind, this will allow the sector to ramp up manufacturing and deployment to meet future demand for ocean energy generating capacity, while reducing costs.



Wello, Penguin wave energy converter

Non-technological research priorities			
●●● High priority ●● Medium priority ● Low priority			
4.1	Building a case for investment, including LCoE analysis	●●●	2018
4.2	Develop manufacturing expertise for ocean energy	●	2020
4.3	Standards, Health, Safety and Environment	●●	2019

4.1 Building a case for investments, including LCoE analysis



There are a number of issues that can adversely affect the economics of project in early development phases:

- a lack of economies of scale;
- a limited market deployment, resulting in limited benefits from ‘learning by doing’;
- conservative margins/contingencies applied to equipment and services due to higher perceived risks and limited experience.

A lack of economy of scale that increases the LCoE of small projects

A certain project size is needed to make economies of scale. When constructing or deploying a single unit the relatively fixed costs of:

- developing the project and obtaining environmental consents and permits;
- dedicated manufacturing and assembly facilities;

- an offshore O&M team and associated O&M base;
- spares;
- dedicated service vessel;
- infrastructure such as resource monitoring equipment, substation and cable, are all very high in comparison to the variable per machine costs. This will result in elevated LCoE for such projects. However for the same reason cost of energy will fall rapidly as more devices are deployed that can ‘share’ the fixed costs. The deployment of arrays will reduce costs, however before deploying multi-machine arrays, single devices and small arrays need to be demonstrated.

Limited market deployment to date, resulting in limited benefits from ‘learning by doing’

With operational experience of devices in real sea condition, reliability and performance will increase. This learning effect is present in all aspects developed in this document: demonstration and modelling, logistics and installation, reliability and survivability, power generation, materials and manufacturing.

Conservative margins/contingencies applied to equipment and services due to higher perceived risks and limited experience

A lack of real knowledge on how a device will react at sea is usually overcome by making overly conservative assumptions during design. Through deployment, more accurate data on device requirements will be gathered allowing future devices to be built using smaller engineering margins. Avoiding “over-engineering” devices will lead to reduced device manufacturing and deployment costs.

Part A. Quantify return on investment for market enablement measures

To gain political support for market enablement measures for ocean energy there needs to be a clear understanding of the investment costs, and the likely return on investment to the public purse. Work has already been undertaken illustrating that a relatively small but significant investment in market deployment could

result in ocean energy being cost competitive with other renewable generation options with relatively small market deployment.

Improve cost models to inform decision making and ensure public support for ocean energy roll-out

Improved cost models for ocean energy will inform the energy transition debate and allow public authorities to better perceive the short-term cost/long-term benefits of ocean energy deployment. This is important to stimulate political and public support for the roll-out of the sector and ensure fit-for-purpose support is maintained at national and EU level.

Part B. Attract private investment to projects

To finance a project, a financial model is required by investors, banks and financing bodies that defines the return on investment. Normally a risk analysis will be conducted to estimate the impact on the return or LCoE of different factors varying from expected values. The larger these are, the greater the perception of risk and, hence, the greater the return and associated LCoE. Nevertheless, it is the validation of the parameters with project data that will help reduce risk perception and encourage investment.

LCoE is the prime factor to demonstrate the economic potential of different sources of electricity generation. The LCoE is affected by all the costs during the lifetime of the project. In ocean energy, this is still difficult to model due to the uncertainty linked to the lack of operational experience.

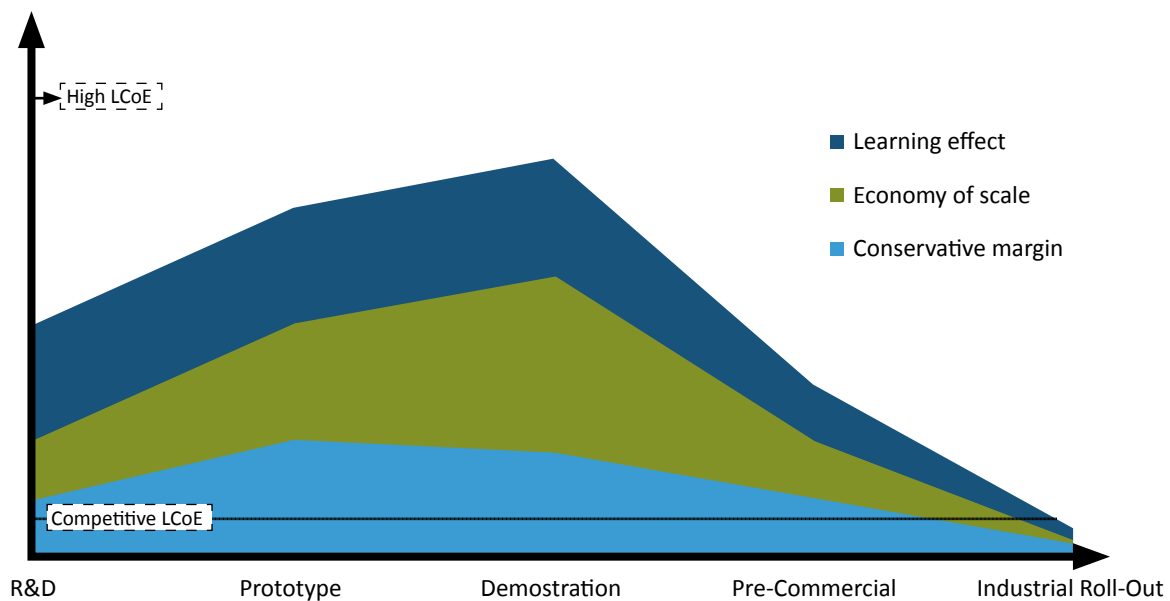
Due to novel technology and lack of experience in the sector ocean energy projects are currently unlikely to be able to secure commercial loans. This lack of ‘gearing’ means that projects require a higher LCoE to achieve the same return on equity investment. A higher risk profile further increases this, given the normal correlation between risk and return.

Enhanced ocean energy LCoE modelling, integrating a deeper understanding of the challenges and benefits of the sector, will demonstrate attractiveness.

Figure 5, below, shows how the costs of developing ocean energy, much like any new technologies, evolve as the sector moves further towards industrialisation. Early R&D is less capital intensive than the first demonstration arrays. It is after the first demonstration arrays

go into the water, that economies of scale and learnings will allow the sector to engage in a steep cost reduction path, bringing down the levelised cost of energy produced.

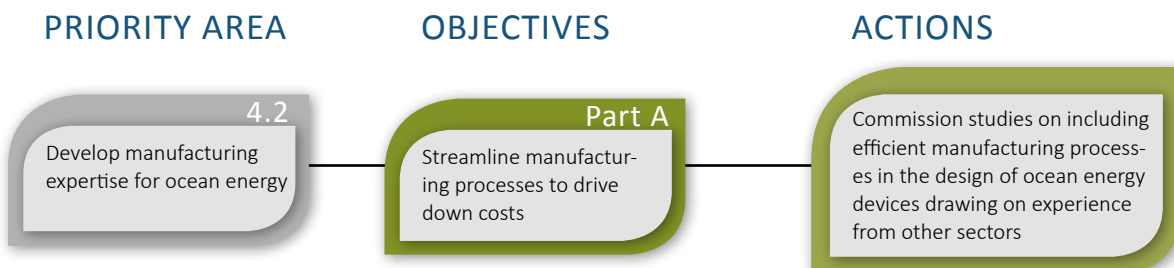
FIGURE 5: ECONOMY OF PROJECTS BY PHASES¹⁰



Develop optimal funding strategies to attract new private investors to the sector
Investor strategies linked to project scales, risk reduction processes and public support measures should be

developed to show how to balance risk and reward for different classes of investors. This will facilitate the entrance of new private investors into the sector.

4.2 Develop manufacturing expertise for ocean energy



¹⁰ TP Ocean Research. 2016

Part A. Streamline manufacturing processes to drive down costs

‘Manufacturability’ needs to be worked into the design and fabrication of ocean energy devices. Manufacturing Readiness Level (MRL) are commonly used to measure

progress in this sense and ultimately indicates the level of economic viability of the devices. Streamlined manufacturing is key to reducing costs, involving the supply chain in research and development and planning for future volumes.

TABLE 6: TABLE OF MANUFACTURING READINESS LEVEL¹¹

MRL	Definition
1	Basic manufacturing implications identified
2	Manufacturing concepts identified
3	Manufacturing proof of concept developed
4	Capability to produce the technology in a laboratory environment
5	Capability to produce prototype components in a production relevant environment
6	Capability to produce a prototype system or subsystem in a production relevant environment.
7	Capability to produce systems, subsystems or components in a production representative environment
8	Pilot line capability demonstrated. Ready to begin low rate production
9	Low Rate Production demonstrated. Capability in place to begin Full Rate Production
10	Full Rate Production demonstrated and lean production practices in place

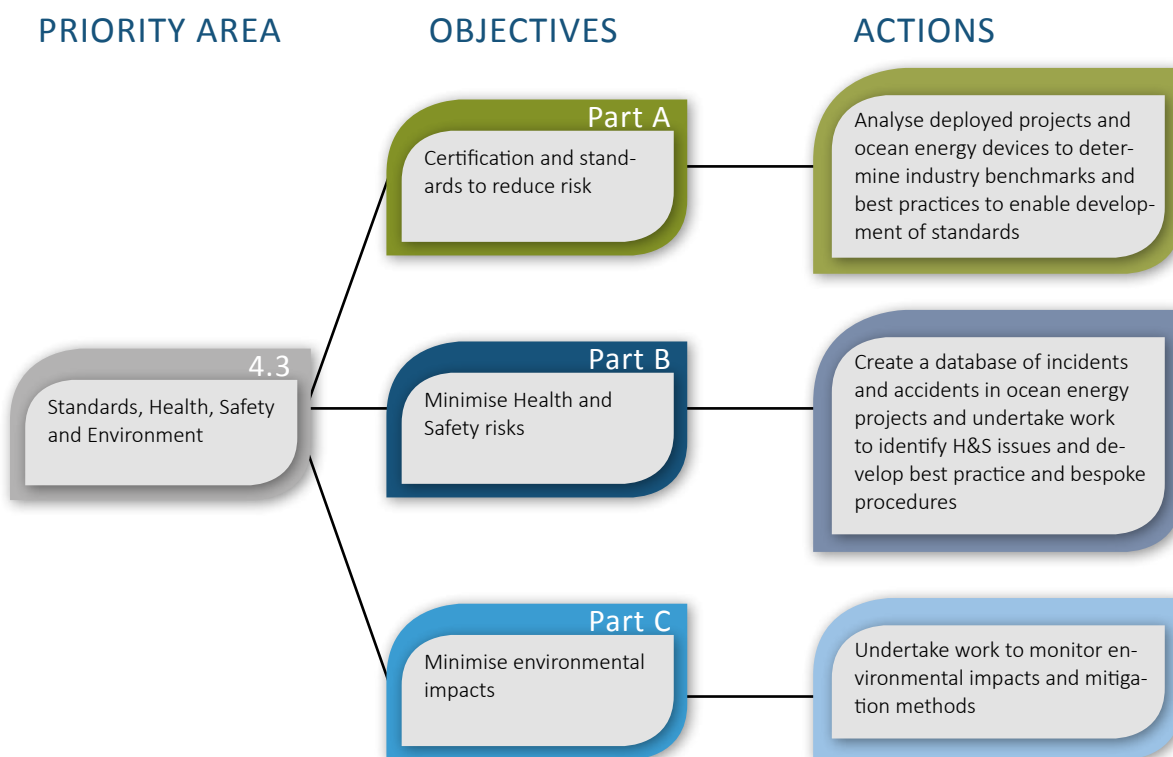
Commission studies on including efficient manufacturing processes in the design of ocean energy devices drawing on experience from other sectors

As the ocean energy industry develops and the number of devices built increases, their designs need to take into account manufacturing requirements to ensure the fabrication process is lean and cost-effective. Manufacturing tolerances, for instance, should be reduced where they are not critical and device design or its manufacturing processes should ensure easy accessibility during build. The supply chain should be involved in such work to ensure processes are efficient throughout.

Experience in other sectors that have moved from project-by-project production to serial production, whether it be in other renewable energy technologies or shipbuilding or the aeronautical sector, can be a useful indicator of best practice and help plan the manufacturing progression of ocean energy technologies. Studies on improving manufacturing processes could be carried out to ensure dissemination of best practice and identification of synergies with other sectors.

¹¹ United States Department of Defense

4.3 Standards, health, safety and environment



As ocean energy deployment takes off, project development and construction will be greatly facilitated by the development of device design standards, bespoke health and safety procedures and environmental impacts. The relatively limited experience in deploying ocean energy devices, means that few procedures, tailored to the industry, are in place and that permitting procedures and regulations are fit-for-purpose: ensuring high-levels of environmental protection without putting unnecessary burdens on the project developers.

The weight of unnecessary regulation and uncertainties created where regulation is not sufficient, are also a factor in a project’s cost and its investors’ perception of project risk. Consequently, creating bespoke procedures for ocean energy development will play a role in the cost of energy produced. This will be particularly the case in

early projects that tend to be smaller, but where permitting costs are similar to those of larger projects, increasing, therefore, the formers’ cost of energy.

Challenge: create frameworks for technological standards, health and safety and environmental permitting and monitoring that evolve as ocean energy farms are deployed and creating learnings. Frameworks need to ensure the best possible level of worker and environmental protection without compromising the economics of ocean energy projects.

Part A. Certification and standards to reduce risk

Standards are reference documents that establish procedures and methods to certify product performance

and service reliability. They help reduce risk for project investors by comparing technology performance and operating procedures to sector benchmarks.

Standards are fundamental to commercialise any product, whether it be a full device or a component or subsystem. All supply chain innovation, therefore, should be involved in the development of ocean energy industry standards to include critical enabling systems such as connectors or power electronics.

Analyse deployed projects and ocean energy devices to determine industry benchmarks and best practices to enable development of standards

The common cost drivers of ocean energy should be identified to prioritise which standards need to be developed and how components and processes should be certified. This will include things like resource characterisation, technology to transmit data shore, components and sub-systems, decommissioning and recycling.

An analysis of deployed projects and performance of the most advanced ocean energy devices should be carried to determine industry benchmarks and best practices to enable the development of standards.

Part B. Minimise health and safety risks

Working at sea presents a number of health and safety risks that are not present in onshore sites. All offshore industries, including energy industries such as wind and oil and gas have built a wide-knowledge base on health and safety risks and processes to mitigate them.

While many at sea health and safety risks are shared across all maritime industries, each sector will also have to assess specific risks connected to its devices, platforms and procedures. One characteristic, specific to the ocean energy sector, is the aggressive waves or tidal resources that projects are developed in. Whereas all marine sectors will have established “Man-Overboard” procedures, these may need to be revised and tailored to the specificities of wave or tidal deployment.

Create a database of incidents and accidents in ocean energy projects and undertake work to identify H&S issues and develop best practice and bespoke procedures

There is no complete collection of HSE data for ocean energy offshore activities and the relatively small amount of deployed machines means that there is still little experience of its specific health and safety risks.

A database collecting information on both accidents and near misses throughout the sector should be set-up. Analysis of the collected data should be used to push project developers to work together to define best practice (or practices to be avoided) to minimise health and safety risks.

Part C. Minimise environmental impacts

Currently, there is no comprehensive picture of the environmental impact of ocean energy devices. As any marine activity, ocean energy technologies have an effect on their surrounding environment and sea-side. A clear understanding of the environmental impacts of ocean energy devices will allow mitigation of any possible negative effects.

To achieve this, it is necessary to allow the first machines and farms into the water and monitor their environmental impacts. The data collected from these first projects will allow the sector and regulators to gain a better understanding of potential impacts and, improve mitigation requirements for further projects.

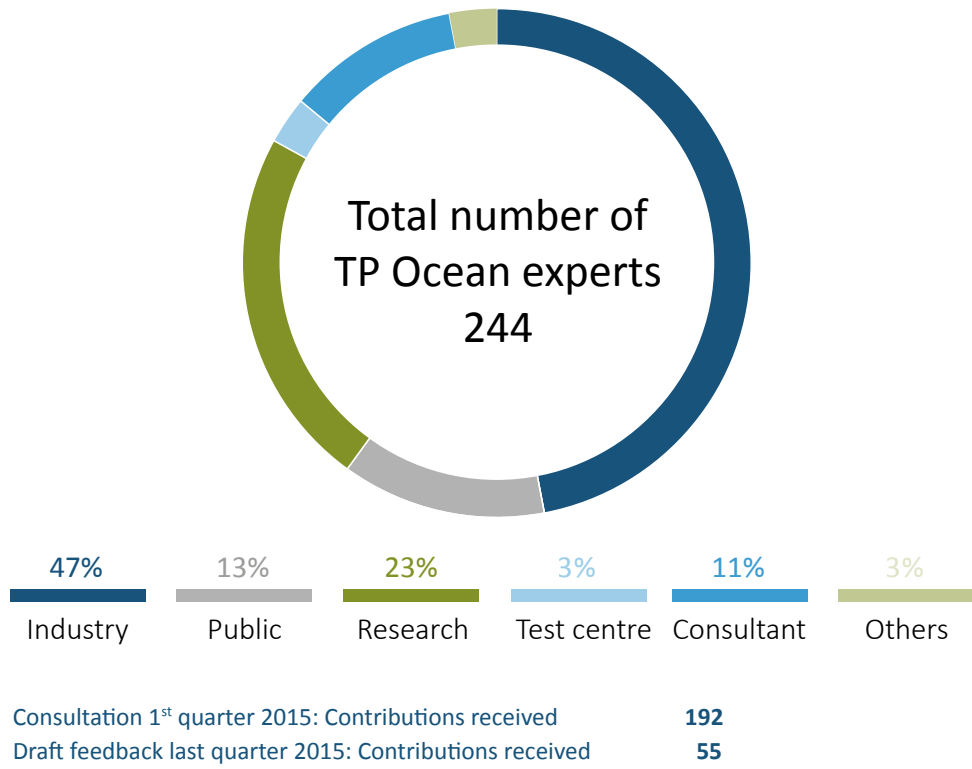
Undertake work to monitor environmental impacts and determine appropriate mitigation methods

Work should be undertaken to monitor environmental impacts and any mitigation methods from existing projects to inform future projects. As knowledge is developed, and providing results are positive, this should help to reduce project development timescales and ensure maximal environmental protection.

Depending upon this work further research on the environmental impact of a particular ocean energy converter may be needed to adapt components and processes.

Annexes

ANNEX 1: COMPOSITION OF TP OCEAN MEMBERSHIP AND PARTICIPATION IN SRA PREPARATION



ANNEX 2: GLOSSARY OF TERMS

3D	Three-dimensional
ADCP	Acoustic Doppler Current Profiler
Array	Series of 4 or more full-scale devices experiencing wake interactions
Availability	The percentage of time a device or farm is available to produce power
CAPEX	Capital Expenditure
CFD	Computational Fluid Dynamic
Controlled environment	Hydrodynamics facilities (like a wave, flume tank), waves, tides, salinity and any other parameters is determined in advanced and fully controlled
COTS	Commercial Off-The-Shelve
DP vessels	Dynamic Positioning vessels
Farm	Ocean energy power plant composed of two or more arrays
FMECA	Failure Mode Effect and Causality Analysis
H&S / HSEQ	Health and Safety / Health and Safety, Environment and Quality
IP	Intellectual Property
kW	Kilo Watts
LCoE	Levelised Cost of Electricity
MetOcean	Meteorology and Oceanography
MW	Mega Watts
MWh	Mega Watts per Hours are a product of power and time, not a rate of change of power with time. Power units measure the rate of energy per unit time
O&G	Oil and Gas
O&M	Operation and Maintenance
OEC	Ocean Energy Converter
OPEX	Operational Expenditure
OTEC	Offshore Thermal Energy Conversion
PCC	Power Control Centre
PTO	Power Take-Off

R&D	Research and development
Real sea condition	Deploy at sea, there is no control over the environment
Relevant environment	Deploy at sea, there is no control over the environment. Experiencing all the complex phenomena relevant to an ocean energy farm
Reliability	Measurable probability of devices/farms availability in a specific environment for a given time (life of the project around 25 years, or between planned O&M)
ROV	Remote Operated Vehicle
SHM	Structural Health Monitoring
Survivability	Measurable ability of a system (sub-system, components, etc.) to be available during/after disturbances (sea-states, corrosion, biofouling, loading, etc.)
SWAC	Sea Water Air Conditioning
TEC	Tidal Energy Converter
TP Ocean	The European Technology and Innovation Platform for Ocean energy
TRL	Technology Readiness Level
Supply Chain	Suppliers of components and subassemblies, services, etc to OEC providers and OE projects
WEC	Wave Energy Converter
Yield	Quantity of energy produced
Small-scale	Smaller size to that which would be used commercially, typically used for proving purposes
Full-scale	Similar size to that which would be used commercially
Scaling-effect	The relation between energy yield at smaller scale and full size
Numerical model	A computer based model used to try and replicate real world conditions

ANNEX 3: TECHNOLOGY READINESS LEVELS

HORIZON 2020 – WORK PROGRAMME 2014-2015 General Annexes Page 1 of 1 Extract from Part 19 - Commission Decision C(2014)4995 G. Technology readiness levels (TRL) Where a topic description refers to a TRL, the following definitions apply, unless otherwise specified:

TRL 1	basic principles observed
TRL 2	technology concept formulated
TRL 3	experimental proof of concept
TRL 4	technology validated in lab
TRL 5	technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 6	technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 7	system prototype demonstration in operational environment
TRL 8	system complete and qualified
TRL 9	actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

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