ICES Special Request Advice
Ecoregions in the Northeast Atlantic
Published 2 April 2019
Version 2: 4 April 2019

OSPAR request to advise on the current state and knowledge of studies into the deployment and environmental impacts of wet renewable technologies and marine energy storage systems

Advice summary

Current evidence suggest that, given responsible siting, significant changes (both near and far field) will only occur in the event either large numbers of devices or tidal barriers or tidal lagoons are deployed.

Notwithstanding the lack of model validation, ICES advises that large-scale developments should use regional hydrodynamic and morphodynamics models to predict environmental impacts, while ongoing monitoring of impacts should be continued during all phases of a development and at relevant spatial and temporal scales. However, for some receptors the predicted environmental effects from a relatively small number of devices are significant challenges when deploying wet renewable devices.

ICES advises both a move towards receptor-based assessments, and that targeted research and monitoring is needed to address key knowledge gaps for the different types of wet renewable devices as well as for the range of receptors and pressures acting both in isolation and in combination with each other. In addition, practical approaches and guidance, including worked examples on more ecosystem level cumulative effects assessments, are needed. Given the ongoing technological development and advancements in monitoring and assessment methodologies, such guidance will require regular review.

Clear and significant benefits would accrue from standardization in data collection, storage, and analyses, as well as improved access to all data and knowledge from all relevant sources.

Energy storage technologies are currently conceptual and their possible environmental impacts have not yet been fully described.

Request

In the past EIHA has developed Guidance on Environmental Considerations for Offshore Wind Farm Development, last updated in 2008, undertaken an Assessment of the Environmental Impact of Offshore Wind Farms and established an inventory of offshore wind farm developments. As the development of other types of marine renewables has been gathering pace in recent years, with more test devices for wave and tidal power and even commercial arrays in some cases, OSPAR has included these types of devices within its focus. In 2016 EIHA agreed to include other types of devices (wave (floating), wave (coastal infrastructure), tidal stream (turbines), tidal stream (hydrofoils), tidal stream (screws), tidal stream (kites), tidal flow (barrage), tidal flow (lagoon) and other)) in the renamed inventory of offshore renewable developments. However before considering the development of additional guidance on wet marine renewables EIHA would like advice on the current state and knowledge of studies into the deployment and environmental impacts of wet renewable technologies and marine energy storage systems, similar to that developed for wind farms. A draft outline for the advice is provided below. On the basis of this EIHA will then decide whether further guidance for Contracting Parties is required.

Elaboration on the advice

Introduction

There has been a significant interest in renewable energy devices in the marine realm to support efforts to combat the impacts of climate change, including increased temperatures, ocean acidification, and sea level rise, among others. In response to OSPAR's request, the supporting document annexed to this advice summarizes current knowledge on the effects of wet renewables on abiotic and biotic receptors.

Status of wet renewable development in the OSPAR region

Tides and waves can be used to generate electricity using a wide range of different technologies. Kinetic energy associated with tidal (marine) currents can be harnessed using various modular systems located at different heights in the water column. These include various types of turbines, oscillating hydrofoils, Archimedes screws, and tidal kites. The UK has the greatest level of deployment of tidal energy, at test centres in Scotland and Wales, and at commercial sites that are under development in Scotland. In France, in-stream tidal energy developments are also progressing, with the re-installation and grid connection of the Sabella D10 turbine at the Ushant Islands. Other European countries with operational and planned tidal devices include Belgium, the Netherlands, Norway, and Spain. The present trend in tidal devices appears to be moving away from heavy bottom-mounted devices and towards floating tidal devices and tidal kites.

The potential energy associated with tides can be harnessed by building a barrage across an estuary or by enclosing a tidal lagoon. Within the OSPAR area, tidal energy barrages have tended to exist as part of historical barrage developments, for example at la Rance in France (240 MW), and as part of flood protection infrastructure in the Netherlands (1.55 MW). While new tidal-energy specific barrages face serious challenges in the OSPAR region because of environmental impact concerns, tidal turbine installation in existing coastal infrastructure continues to be attractive. Tidal lagoon technology has not been progressed due to significant environmental and economic challenges. A total of 43 MW of tidal energy (stream and range) is now operational across the OSPAR area, with more than 320 MW either under construction, consented, or in planning phases.

Wave energy (or wave power) is the largest estimated global resource form of ocean energy. According to the World Energy Council (World Energy Council Netherlands, 2017), the economically exploitable resource ranges from 140 to 750 TWh yr^{-1} for current designs of devices when fully mature and could rise to levels as high as 2000 TWh yr^{-1} if all the potential improvements to existing devices are realized. Wave energy converters (WEC) have been developed to extract energy and can be deployed from the shoreline out to the deeper offshore waters. The Ocean Energy Systems Implementing Agreement (OES) identifies three main types of WEC: oscillating water column, oscillating bodies, and overtopping. A coastline infrastructure (fixed) wave energy plant is now exporting electricity to the Spanish grid. A wide range of offshore test devices are being trialed at the region’s many test centers. However, wave energy developments have not reached the same level of commercial deployment across the OSPAR region as has been achieved by tidal energy technologies. Excluding test centers, less than 1 MW of wave energy is currently operational across the OSPAR area, with circa 20 MW consented or in planning phases.

Energy production by marine renewables is dependent on the prevailing weather conditions, which fluctuate independent of electricity demand. In the event of future large-scale deployment of marine renewables, there will be a need to adapt the resultant stochastic power production to the actual power demand. This can be achieved through coupling the devices that generate power with energy storage systems. Today, two main concepts of storage technologies are being considered to manage the large electrical quantities produced offshore: Pumped Storage Systems (PSS) and Compressed Air Energy Storage (CAES). As these technologies are currently conceptual, their possible environmental impacts have yet not been fully assessed. The most likely and immediate storage of energy from wet renewables is the charging of large battery banks.

An alternative to local energy storage is the “power to molecules” pathway, where electrical power is converted to hydrogen gas using electrolysis. Since 2017, the European Marine Energy Centre (EMEC) has been producing hydrogen gas using electricity generated from tidal energy in Orkney. Hydrogen gas can be stored and transported. It can be used as fuel or combined with CO_2 and converted into methane or liquid fuels. Conversion of power to hydrogen gas can be done onshore or offshore. Offshore conversion could be done on retired oil and gas platforms.

What are some of the potential problems to the environment?

Hydrodynamics

Tidal and wave energy devices remove energy from the tidal current and wave fields, respectively, and this disturbance may alter the hydrodynamics, both near and far field. To date, the best insight into how tidal and wave developments will impact hydrodynamic processes and the physical marine environment has come from hydrodynamic modeling. Results indicate that significant changes will only occur with the deployment of very large numbers of devices, e.g. greater than 1.5 GW tidal developments, although large-scale impacts can result in far-field changes up to 100 km away. However, results from numerical modeling are indicative predictions and based on specific scenarios that are dependent on the array layout, position, bathymetry, and circulation. Large-scale developments should make use of the sophisticated regional hydrodynamic models that have been developed. However, as these model results are not validated due to the lack of development and data there is a level of uncertainty around their conclusions and therefore continued monitoring of environmental impacts is important.

Physical seabed and sediment transport

Physical seabed and sediment transport pathways (morphodynamics) could change as a result of wet renewable energy developments, leading to changes in the net deposition and erosion of coastlines and offshore sand banks, as well as larger-scale bathymetry and geomorphological changes. As with changes to hydrodynamics, substantial changes to morphodynamics are most likely to occur with larger developments and are dependent on regional sedimentology. Modeling results suggest that changes to seabed sediment would be a fraction of natural changes, but high energy extraction rates could lead to more substantial changes in the morphodynamics. Again it should be noted that modeling results are indicative for specific scenarios. Static components may also lead to scouring of bed sediments, due to the local increase in the hydrodynamic field around the structure, and seabed cables that are not buried could cause localized scouring of the seabed.

Benthos

Wet renewable energy devices affect marine benthos both directly and indirectly. A major direct effect is the colonization of epifauna, including non-indigenous species, on the devices. Indirect major effects are linked to changes in the physical environment (habitat loss/disturbance, changes in hydrodynamics, modification of the seabed), during the installation and/or exploitation phase, alterations of human activities during the exploitation phase, and changes in the biological components of the marine ecosystem. Based on the limited knowledge available on the effects of marine renewables, most of the major changes are considered local and site specific. Broader spatial effects on the benthos are mainly associated with tidal barriers and tidal lagoons as such devices can have large effects on the physical environment beyond the immediate vicinity of the device. Unwanted effects, especially in areas with protected habitats and/or habitats providing important ecosystem services, can be avoided through a careful marine spatial planning process guided by cumulative environmental impact assessments at the appropriate spatial and temporal scales.

The introduction of wet renewables can offer chances for the restoration of the marine benthic habitat. Exclusion of bottom fishing activities due to safety considerations removes an important source of disturbance to benthic habitats and could facilitate the recovery of the benthic environment. Further opportunities for habitat restoration are associated with (a) the design of the deployed infrastructure, provided they offer sufficient structural complexity needed for the establishment of healthy and diverse marine benthic communities, and (b) targeted species of conservation interest. Examples include the appropriate design of walls around tidal lagoons and the structures protecting cables.

Fish

Available information on the potential impacts of Wet Renewable Energy (WRE) devices on fish and fisheries focus on aggregation effects and the consequences for trophic foodwebs, collision risks either with fixed or with mobile elements, cable-induced effects, and on sound. Essential fish habitats such as nursery zones, spawning grounds, and migration routes should be avoided whenever possible as these functional areas are impacted by changes in seabed sediment and hydrodynamic conditions.

Fish aggregation may occur at WRE sites; however, impacts on trophic foodwebs need to be further documented, as the existing literature is mostly provided by Offshore Wind Farm (OWF) case studies. Collision with mobile parts of the WRE devices is a recognised risk for fish. Poor visibility is the main factor increasing the risk of collision, a risk that also increases with the diameter of the device and with larger fish size. Effects on fish conditions following collision need further research; to date, there is a focus on strike mortality with population value estimates of less than 1% in some studies. Effects of cables include ElectroMagnetic Field[1] (EMF), local temperature rise, and physical barriers in the case of dynamic cables suspended in the water column. Impacts of EMF include behavioural changes, which have been recorded for many species, from decapods to large elasmobranchs; benthic species are suspected to be more at risk than pelagic species, but further work is needed, especially as cables will be deployed (suspended) in the water column. Some considerations should also be given to the different life stages, as fish egg development can be impared by cable-induced changes in temperature.

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[1] Version 2: Acronym for EMF corrected.

Finally, in the case of commercial size arrays, research and monitoring is needed to explore the potential barrier effect of dynamical cables in the water column.

Response of fish to anthropogenic sound and associated impacts is species specific, and will differ depending on noise type and intensity. In recent studies the level of sound exposure is characterized in the context of environmental impact assessment (EIA), with an associated threshold level definition per species. Impacts range from avoidance behaviour to permanent injuries, with possibly lethal consequences. Further research is needed in this field and a precautionary approach applies.

Marine mammals

The primary concerns regarding marine mammals is the risk of collision with the moving parts of tidal energy converters; this is therefore the topic around which most research and monitoring effort has focused to date. Furthermore, wet renewable developments can either lead to displacement/attraction of marine mammals or act as a barrier to movement. The impact of displacement from individual devices is not likely to be highly significant as the relatively small footprint providing the location is not particularly critical for marine mammals. However, with a large number of devices the impact may become significant. Aggregation of fish could potentially lead to an attraction of marine mammals. The entanglement of marine mammals in mooring lines and cables has been raised as a potential concern, but there is very little evidence upon which to draw any conclusions. According to a review and risk assessment published by Scottish Natural Heritage, entanglement does not pose a significant threat to marine mammals. Large baleen whales were considered to be at a higher risk of entanglement, but this could be minimized by applying tension to keep cables taut.

Much effort has gone into developing and refining the quantitative predictive collision risk models used in the environmental impact assessment (EIA) phase for proposed projects to provide an estimate of the degree of risk posed by tidal energy devices. Monitoring of fine-scale interactions around tidal energy devices in order to better characterize and understand collision risk includes application of telemetry (tagging), camera technology, as well as active and passive acoustic monitoring. There has been some work on understanding consequences of collisions. More information on the behaviour of mammals in the presence of a turbine and on the physical consequences of a strike is required to fully understand the potential for death or injury.

An understanding of baseline functional habitat use is important to enable prediction of future risk, both from the perspective of collision risk but also to understand the potential consequences of any displacement. Recent investigations into fine-scale harbour porpoise density and use of the water column at a variety of tidal sites in Scotland have provided a substantial data set on porpoise depth distribution and underwater behaviour in tidal rapids that shows a large degree of variation between sites. Seal tagging studies have increased knowledge about the way that harbour and grey seals behave in tidal environments. However, the implication from these behavioural studies is that it is difficult to generalize between species and sites in relation to marine mammal usage of tidal sites. Therefore, some degree of site information will be required to characterize risk at sites of future development.

Underwater noise is also a concern, with the potential for noise generated during the construction and operation phases of marine energy projects to cause disturbance/displacement/barrier to movement. While such effects may be of no concern with small-scale single devices, it is of concern for future commercial scale arrays when several hundred devices may be deployed across a site. Empirical studies of responses have to date in some cases indicated small-scale, local avoidance to construction and operational noise; other studies have revealed a diminishing response over time. Some response to operating turbines may be good (to reduce collision risk), but over large areas, even small-scale responses could result in habitat exclusion, displacement, and/or barrier effects.

Birds

Little empirical data exists on the actual impacts of wet renewable developments and devices on birds, thus potential impacts are currently mostly inferred from knowledge of bird ecology and behaviour and from known impacts of other marine industries (e.g. offshore windfarms and shipping). The main potential impacts are due to collision with devices or displacement/attraction. Birds may be attracted to man-made structures at sea as artificial roosting sites, while artificial illumination at night and under low visibility conditions may also attract birds. Fish aggregating around devices could also attract foraging birds. Increased bird density around devices can increase the collision risk.

Underwater collision between diving birds and wet renewable devices may lead to direct mortality. However, based on limited data, no collision between a wave and tidal device and a seabird has been observed to date. The potential for collision mortality is assessed through collision risk modelling (CRM). For on- and offshore wind turbine generators CRMs are quite well developed and are widely applied in environmental assessments for proposed wind developments. For tidal current devices there is much greater uncertainty and no consensus on how collision risk should be quantified. Individual Based Modelling (IBM, also called Agent Based Modelling, ABM) approaches have a potential to become important CRM tools as they look to increase our mechanistic understanding of seabird collisions with tidal current devices, thus potentially providing a more realistic collision risk assessment.

The vulnerability of marine birds to acoustic disturbance is poorly understood. Noise may arise from vessel traffic, installation, operation, and decommissioning activities . Existing measurements of operational noise levels from both wave and tidal devices suggest that operational noise levels are unlikely to cause injury or significant behavioural effects to birds.

Sensitivity scores have been produced for species occurring in Scottish waters for both tidal stream turbine devices and wave energy convertors (WECs). Species classified with a high vulnerability score for tidal turbines in Scotland were black guillemot, razorbill, shag, common guillemot, and great cormorant. Great northern diver, red-throated diver, Atlantic puffin, black-throated diver, and little auk were classified with a moderate vulnerability score to tidal turbines. Only three species were classified with a high vulnerability score for wave energy devices in Scotland. Sensitivity scores for birds have not been calculated for tidal lagoons and barrages; however, the species likely to be affected have been reviewed. Wader species and waterfowl were considered to be at risk due to habitat change, i.e. changes in intertidal areas and salt marshes.

The level of impact is likely to increase with the scale of development: an array of multiple devices will generally pose a higher risk to a population than a single device or small-scale development. It is important that robust monitoring programmes are set up when developments are constructed, reducing uncertainty when later considering permits for expansions or new developments. Pre-construction surveys for wet renewables should classify to what extent a proposed development site is used by birds (i.e. bird densities) and more fine-scale associations of activity of birds in relation to the type of development proposed.

Seascape/public perception

Public perception and attitudes towards offshore energy projects are strongly influenced by the concept of an individual’s attachment of place, which can provoke opposition to developments. Impacts on seascape or visual disturbance are often cited as a potential public concern regarding wave and tidal devices. However, the visibility of devices will be scheme specific and is dependent on their distance from shore and the height from which they are viewed by the preceptor, e.g. they may be more visible from a cliff than a beach. Therefore, though the sea footprint of wave devices mentioned above may be low, the use of signaling lights and buoys to delineate exclusion zones around devices can disrupt an individual’s perception of a place. Visual impact mitigation measures that do not compromise safe navigation requirements such as micro-siting (relocation of devices on site), screening, or paint schemes that can reduce the visibility of devices and structures could be applied. Visual impacts may also occur from onshore infrastructure such as substations, and from activities during the installation and decommissioning process – although these will have a limited duration. Additional public concerns beyond visual impacts include: environmental impacts – with a particular concern for marine mammals and seabirds; marine space use conflict – particularly for fishing activity; reduced wave resources for leisure activities; and effects on tourism. Engagement of key stakeholders at an early stage of development will be an important strategy for mitigating public concerns.

Cumulative impacts

A range of conceptual frameworks are available to undertake cumulative impact assessments for marine renewable energy (MRE). However, there have been only limited practical applications of these frameworks. This is due to knowledge gaps and uncertainties concerning potential effects from individual and multiple devices, limited availability of data (device parameters or estimated effects) from MRE projects, lack of clarity over how the uncertainty associated with the estimated effects should be best combined, and a need to identify the appropriate reference populations or temporal/spatial scales against which effects should be assessed.

The focus to date has been on assessing pressures on individual receptors, with only limited attention paid to interactions between receptors. This is partly due to the difficulties in quantifying effects on individual receptors, let alone those that may result from potential interactions between multiple receptors.

There is a clear need for targeted research and monitoring that addresses key knowledge gaps for individual receptors and interactions between them, and for development of practical approaches and guidance that allow appropriate cumulative impact assessment to be undertaken.

Others

Turtles are of high conservation value and many populations are exhibiting substantial declines. However, to date the assumption is that they are likely to be of relatively low concern in relation to MRE due to their slow swimming speeds and limited potential impact mechanisms.

What are some of the potential benefits to the environment?

Exclusion, for navigational safety, of all vessels (including fishing vessels) around deployed devices would mean less disturbance on the seabed. The artificial reef effect and artificial roosts for seabirds provided by devices could also be considered as positive effects. These changes would increase species diversity and local density, which would initially be beneficial. However, the increase in fish density and thereby attraction of predators (e.g. seabirds and marine mammals) could lead to a potential increase in overall collision risk.

What can we do next? Lessons learnt, including data gaps and sharing information

A number of key activities were identified as next steps.

Strategic research and monitoring should be undertaken to better understand wet renewable effects on key receptors. This would also provide the benefit of shared resource burden across multiple parties. Research should be undertaken to facilitate a more ecosystem level approach to cumulative impact assessments. Both of these activities would benefit from standardization in methods for data collection, storage, and analyses, as well as improved access to and sharing of data.

Guidance and worked examples of cumulative impact assessment approaches should be developed and tested against a range of receptors and pressures, acting both in isolation and in combination with each other. The adoption of standardized approaches to cumulative impact assessments would increase the consistency and transparency of process and outcomes.

There are a wide range of emerging MRE technologies, not all of which could be captured in this document. For those that do not fall within the existing categories used in this report it may be necessary to review potential impact mechanisms and associated pressures to ensure that potential effects are not overlooked in the future.

To date, and for understandable reasons, little attention has been paid to potential effects of decommissioning. There have been a number of calls for the application of a multi-criteria decision analysis to provide the best solution after considering all options and their environmental, social, and economic impacts, which again should be based on the best scientific evidence possible and take into account the provisioning of multiple ecosystem services to society. Such an analysis and review of decommissioning options should be undertaken.

Conclusions

Although the bulk of the renewable energy generated by marine devices is produced by offshore wind farms, it is clear that wet renewables will be increasingly installed in the marine environment in the near future. The installation of wet renewable devices will lead to changes in both the abiotic and biotic components of the marine ecosystem, though the scales and significance of these changes are currently not clear.

To date, the key receptors constraining the deployment of MREs have been marine mammals, seabirds, and fish. However, the evidence base available to quantify actual effects on these receptors is limited. This is due to the difficulties encountered in collecting relevant data, and in some cases the lack of clearly defined post-installation monitoring. Strategic approaches to deliver effective research and monitoring to address these key knowledge gaps is therefore recommended.

Hitherto the focus for cumulative impact assessments has been on individual receptors and pressures as these have been identified as key constraints for developments; however, there is a clear need to understand how the interactions between receptors and pressures may influence the conclusions of cumulative impact assessments. This need will only increase as the number of MRE and other marine activities increases.

The suggested way forward is to move towards receptor-based assessments that consider both the ecological links between the abiotic and biotic components of the marine ecosystem and the feedback links between the different biotic components. This should be achieved by hypothesis-driven research, taking into account the link between structural components and the functioning of marine ecosystems, as this ultimately determines the provisioning of marine ecosystem services to society. This calls for cross-border coordination and cooperation in setting standards for data collection, sharing information, and setting research agendas.

Basis of the advice

The advice is based on a supporting document "Current state and knowledge of studies into the deployment and environmental impacts of wet renewable technologies and energy storage systems", attached to this advice as an annex. The supporting document in an adapted version of a report developed by experts from ICES working groups on marine benthal renewable energy developments (WGMBRED) and marine renewable energy (WGMRE) and by experts from the Marine Scotland Science. The reports from the external reviewers are added as an annex to the report (ICES, 2019).

Sources and references

ICES. 2019. Working Group on Marine Benthal Renewable Developments (WGMBRED). ICES Scientific Reports. 1:6. 95 pp. http://doi.org/10.17895/ices.pub.4914

Please see References (section 7) in Annex background document

Recommended citation: ICES. 2019. OSPAR request to advise on the current state and knowledge of studies into the deployment and environmental impacts of wet renewable technologies and marine energy storage systems. *In* Report of the ICES Advisory Committee, 2019. ICES Advice 2019, sr.2019.05, https://doi.org/10.17895/ices.advice.4894

Annex

Background document supporting the ICES advice to OSPAR on: "*Current state and knowledge of studies into the deployment and environmental impacts of wet renewable technologies and energy storage systems*".

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Executive summary

This report provides an overview of the state of affairs (1) with regards to the deployment of wet renewables and (2) marine energy storage systems; (3) how they affect abiotic and biotic components of the marine ecosystem and (4) developments and concepts on cumulative impact assessments related to marine renewable energy devices and (5) future perspectives.

This report provides the scientific basis to address the OSPAR request for advice on the current state and knowledge of studies into the deployment and environmental impacts of the following wet renewable energies and marine energy storage (floating, coastal infrastructure), tidal stream (screws, kites), tidal flow (barrage, lagoon) and others. Advice should cover the status of wet renewable developments in the OSPAR region, future prospects, potential environmental problems (sea bed habitat loss/disturbance, fish, marine mammals, birds, seascape/ public perception, and cumulative impacts), potential benefits, next steps and conclusions". The request was directed towards the ICES Working Group on Marine Benthal and Renewable Energy Developments (WGMBRED (WGMBRED) and the Working Group on Marine Renewable Energy (WGMRE).

A pre-meeting chaired by Jan Vanaverbeke, Belgium (WKWET, 15-16 January 2019) at ICES Headquarters, was attended by 11 participants from 4 countries, including members of WGMBRED and WGMRE and additional experts. The group analysed the OSPAR request, agreed on a structure for the report, and certain experts volunteered to conduct a literature review and provide the necessary knowledge base for the report.

WGMBRED met from 12-15 February 2019 in Brussels (Belgium). The input from WKWET participants was compiled, quality checked and adapted where needed; when relevant expertise was represented in the group. WKWET experts, not present at WGMBRED, accommodated texts where needed and a first version of this report was delivered to WGMRE.

WGMRE met in Oostende (Belgium) from 26-28 February 2019. Participants reviewed the WKWET report following input from WGBRED, quality checked, and adapted where necessary. Relevant experts contributed additional text and data to tables on MRE developments in ICES areas, and provided text on public perceptions and future prospects of MRE.

This report presents an overview of the currently known "wet renewables" (all marine renewable energy devices, excluding offshore wind devices) and how their deployment will likely change in the future. It further provides an overview of the concepts and techniques related to marine energy storage devices. Given the conceptual and experimental stage of marine energy storage devices, and the absence of data on how these devices affect the marine environment, the report is limited to a description of these marine energy storage devices.

This report provides a receptor-based summary of how the wet renewables can affect the marine environment. Receptors are either abiotic (hydrodynamics, physical seabed and sediment transport) or biotic (benthos, fish, marine mammals, birds, sea turtles, otters and polar bears). To avoid repetition, effects on these receptors were grouped according to pressure-inducing components (static component of the device, dynamic component of the device, cables) of wet renewables or consequences of their presence.

The report further discusses the developments on cumulative impacts assessments associated with wet renewables deployment in addition to many other human activities, and the need to move away from "data rich – information poor" monitoring of structural aspects of the marine ecosystem to hypothesis-driven functional research at the relevant spatial and temporal scales. This will require cross-border coordination in data collection and analysis, data storage and exchange and the development of a joint research agenda.

1. Introduction

It is now generally accepted that the Earth's climate is changing, resulting in increased temperatures, ocean acidification and sea level rise, among others. This global warming is related to the increased emissions of CO_2 to the atmosphere due to the burning of fossil fuels, deforestation and cement production use (Sabine, Feely, Gruber, Key, Lee, Bullister, Wanninkhof, Wong, Wallace, Tilbrook, Millero, Peng, Kozyr, Ono & Rios 2004). This triggered an increased need to reduce the CO_2 emissions to the atmosphere, a goal that partly can be achieved by increasing the share of renewable energy in the global energy demand. In 2014, the European Council adopted 'The 2030 climate and energy framework', thereby committing to reduce greenhouse gas emissions by 40% compared to the 1990 levels and to set a renewable energy target of at least 27% of the European energy consumption (Com 2014, 15 final/2).

To increase the use of renewable energy, there has been a significant interest in renewable energy devices in the marine realm (Marine Renewable Energy Devices, MREDs). A lot of effort was dedicated to the installation of offshore wind farms: there are currently 4149 offshore wind turbines installed, with 92 wind farms connected to the grid in 11 European countries, making a cumulative total of 15780 MW (Offshore Wind in Europe - Key trends and statistics 2017 2018). In addition to these offshore wind farms, so called 'wet renewables' are installed as well. For this report, we use the 'wet renewables' to refer to various types of tidal barrages, tidal stream and wave energy schemes. These type of marine renewable energy devices make use of more predictable sources of marine renewable energy such as tidal energy related to change in water level, tidal currents or waves (Frid *et al*. 2012) and are increasingly installed in the marine environment. However, there is a lack of clear understanding of how these devices affect the marine ecosystem (both abiotic and biotic) as the available information is scattered and fragmented. Frid *et al*. (2012) provided an overview of the environmental impact of tidal barrages and fences, tidal stream farms and wave energy devices, largely based on best available scientific knowledge from analogous activities. Copping *et al*. (2016) provided a valuable update, based on a limited number of case studies and found that the bulk of information concerned possible collision risk of fish and marine mammals with the wet renewables.

In order to advance the understanding of the possible effects of wet renewables on the marine environment, this report summarizes the knowledge on the effects of wet renewables on a set of abiotic and biotic receptors. Abiotic receptors include hydrodynamic regimes, underwater sound, marine dynamics, landscape, the physical sea bed and sediment transport. Biotic receptors include benthos, fish, marine mammals, birds, otters and turtles. In order to structure the possible reasons for change in any of these receptors, possible stress originating from wet renewables was allocated to several categories: the physical presence of the device, the dynamic component of the device, physical presence of moorings, mooring lines, cables and supporting structures, acoustic effects, electromagnetic fields generated and contaminants..

This report further deals with marine energy storage devices and cumulative impact assessments. Marine energy storage devices are currently highly conceptual and/or experimental and not regularly deployed. As such, information on how these marine energy storage devices affect the abiotic and biotic parts of the marine environments is not available. Therefore, the section on marine renewable energy devices is limited to a description of the current state of affairs of available technology. We further provide a summary of the current insights on cumulative impact assessment with focus on MREDs. Given the fact that MRED (wet renewables and offshore wind) are emerging technologies, there is still considerable debate on how to assess the effects of multiple MREDS in combination with other human activities. This report therefore summarizes the main issues related to cumulative impact assessment involving MREDs. When specific information is available on cumulative effects on certain receptors, the information is provided in the relevant section of the report.

ICES considers ecosystem-based management (EBM) as the primary way of managing human activities affecting marine ecosystems which emphasizes a management regime that maintains the health of the ecosystem while allowing appropriate human uses of the environment for the benefit of current and future generations. The ecosystem and fisheries overviews prepared by ICES use methods to identify and focus on the top five priority human activities and resulting pressures that can be locally managed within each ecoregion. ICES recommends that the current advice be read in conjunction with the relevant ecosystem and fisheries overviews available (Overview link).

2. Overview of wet renewable devices and Marine Energy Storage Systems

2.1 Tidal Energy

2.1.1 Energy resource and location

A major study by the European Commission evaluating the tidal current resource for 106 locations around Europe, with predefined characteristics making them suitable for tidal stream energy exploitation, estimated an exploitable resource from those sites of 48 TWh a year (European Commission, 1996) (RICORE project - http://ricore-project.eu/) .The aggregate capacity of this selection of sites amounted to an installed capacity of marine current turbines of more than 12,000 MW. A more recent study by Black & Veatch (Black & Veatch for Carbon Trust, 2005) suggests an estimated UK extractable resource of 22 TWh for tidal stream, using a modified and more accurate methodology. Other countries with an exceptionally high resource include Ireland, Italy, the Philippines and Japan. Figure 1 shows Europe's tidal stream potential selected locations along the European coastline.

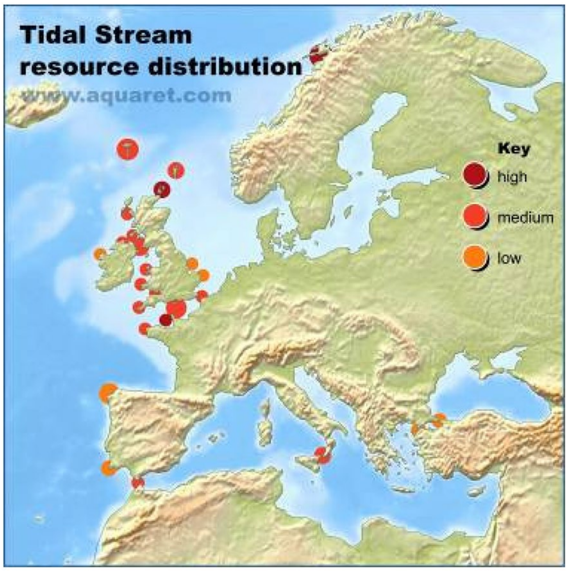

Figure 1. Tidal stream resource distribution in Europe evaluating the tidal current resource for selected locations around Europe, with predefined characteristics making them suitable for tidal stream energy exploitation. Source: www.aquaret.com.

2.1.2 Tidal devices[2]

Tidal energy is driven by the gravitational pull of the moon and sun, exploiting the natural ebb and flow of coastal tidal waters. Tidal forces are periodic occurrences which makes them predictable and reliable. Tidal energy which is a form of hydropower can be extracted from areas where there are fast sea currents, and these are often magnified by topographical features, such as headlands, inlets and straits, or by the shape of the seabed when water is forced through narrow channels. The tidal stream devices, which utilize these currents, are broadly similar to submerged wind turbines where they exploit the kinetic energy in tidal currents and turn into useful forms of power, mainly electrical. Due to the higher density of water, this means that the blades can be smaller and turn more slowly, but they still deliver a significant amount of power. To increase the flow and power output from the turbine, concentrators (or shrouds) may be used around the blades to streamline and concentrate the flow towards the rotors.

Horizontal axis tidal turbine

Horizontal axis turbines extract energy from moving water in much the same way as wind turbines extract energy from moving air. The tidal stream causes the dynamic rotors to rotate around the horizontal axis and generate power as seen in Figure 2. This type of Tidal Energy Converter (TEC) is pile mounted where rotors are mounted on a vertical static pole or shaft which penetrates the seabed.

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[2] Descriptions of tidal devices adapted from http://www.aquaret.com/

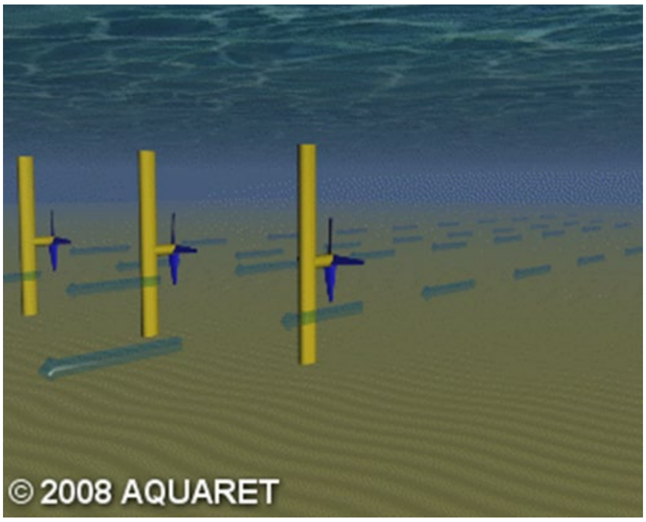

Figure 2. Horizontal Axis Turbine TEC. Source: http://www.aquaret.com/

Vertical axis tidal turbine

Vertical axis turbines extract energy from the tides in a similar manner to the Horizontal axis turbines, however the turbine is mounted on a vertical axis. The tidal stream causes the dynamic rotors to rotate around the vertical axis and generate power, as shown in Figure 3.

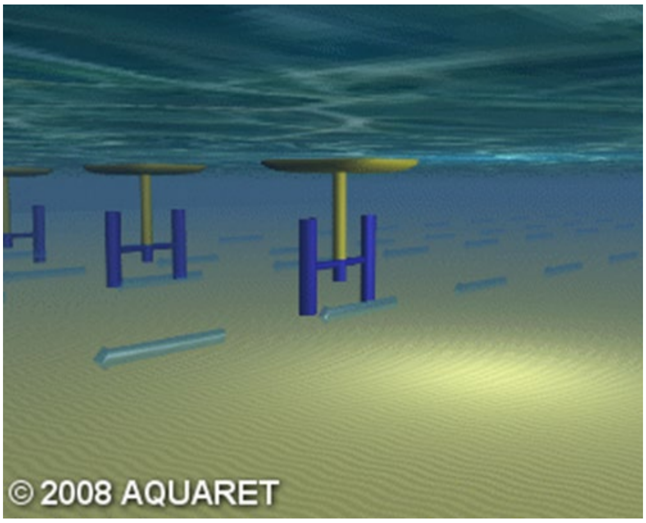

Figure 3. Vertical axis TEC. Source: http://www.aquaret.com/

Oscillating hydrofoil

A hydrofoil is attached to an oscillating arm (Figure 4). The tidal current flowing either side of a wing results induces hydrodynamic lift and drag forces due to a pressure difference on the foil section. These forces induce a resultant tangential force to the fixing arm which then drives fluid in a hydraulic system to be converted into electricity. The device is situated on the seabed by means of a fixed static base. An extension from the hydrofoil principle has been developed by the Eel Energy company who created a biomimetic undulating membrane (Drevet, 2015); the device was tested in the bay of Brest in spring 2018 with promising results (Figure 5). There are currently no plans to deploy commercial oscillating hydrofoils in the OSPAR region.

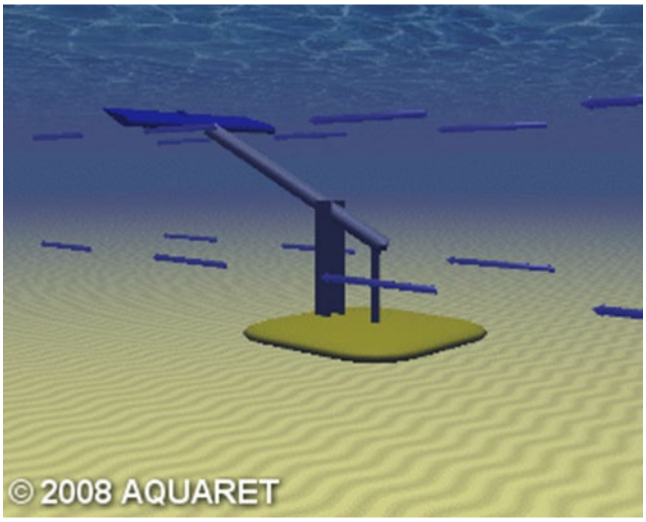

Figure 4. Oscillating hydrofoil TEC. Source: http://www.aquaret.com/

Figure 5. The Eel Energy prototype of biomimetic undulating membrane for tidal energy production (scale 1/6 for a device of 2,5 by 3 m) (source: IFREMER, Eel Energy)

Ducted or shrouded tidal turbines

Ducted turbines are turbines located inside of a large funnel-like structure which sits submerged in the tidal current, see Figure 6. As the flow passes from the inlet to the duct throat, its velocity is increased inversely proportional to the decrease in area, assuming mass flow is conserved. Since power generated is proportional to the cube of the flow velocity, the duct increases the energy that can be captured by a rotor of a given diameter (Shields, 2008). The flow of water can drive a turbine directly or the induced pressure differential in the system can drive an air-turbine. The device is situated on a fixed static base with dynamic moving parts being within the duct.

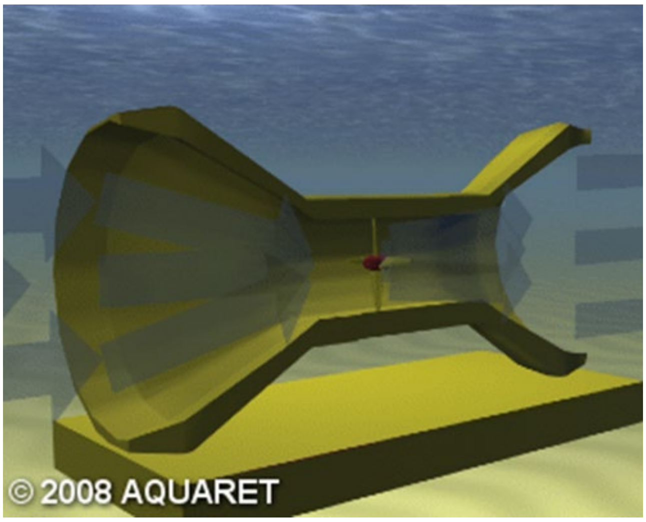

Figure 6. Enclosed tips (Venturi) TEC. Source: http://www.aquaret.com/

Archimedes screw

The Archimedes Screw is a helical corkscrew-shaped device (a helical surface surrounding a central cylindrical shaft) (Figure 7). The device draws power from the tidal stream as the water moves up/through the spiral turning the turbines. The device is fixed to the seabed by a static base.

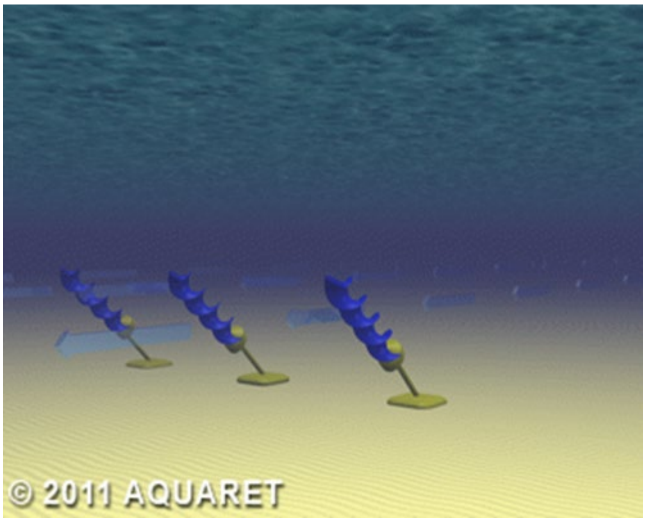

Figure 7. Archimedes screw. Source: http://www.aquaret.com/

Tidal Kite

A tidal kite is tethered to the sea bed and carries a turbine below the wing (Figure 8). The kite ‘flies’ in the tidal stream, swooping in a figure-of-eight shape to increase the speed of the water flowing through the turbine.

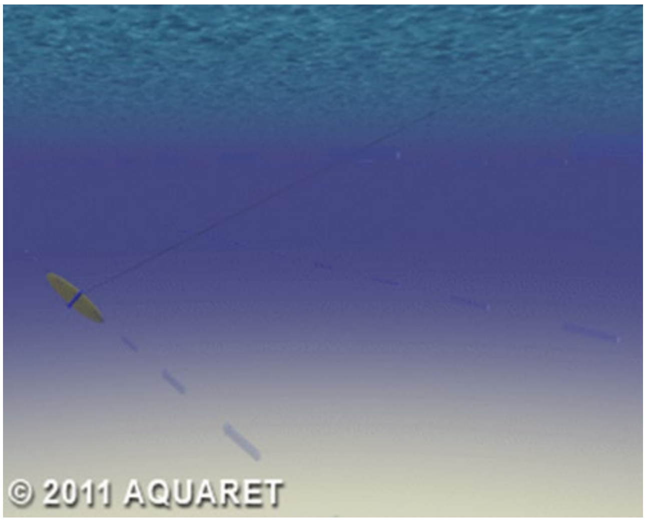

Figure 8. Tidal kite. Source: http://www.aquaret.com/

The dynamic flying motion and the length of the tether means that all parts will be constantly moving and covering a large area range with the device moving at speeds up to ten times that of the tidal flow (Zambrano, 2016). A recent example of where this technology is being tested is the concept of Deep Green, Minesto's tidal kite shown in Figure 9. Deep Green has been undergoing testing as a scale model for a number of years and the project to manufacture and commission the first commercial scale device is underway[3].

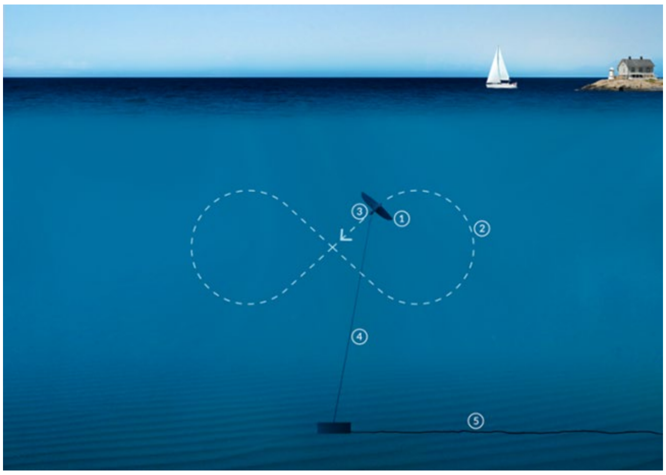

Figure 9. Diagram showing the eight-shape trajectory flown by Minesto's Deep Green tidal kite (Minesto, 2019).

There are several methods to fix the TEC to the seabed including:

i) Seabed mounted/gravity base

This is physically attached to the seabed or is fixed by virtue of its massive weight. In some cases, there may be additional fixing to the seabed.

ii) Pile mounted

This principle is analogous to that used to mount most large wind turbines, whereby the device is attached to a pole penetrating the ocean floor. Horizontal axis devices will often be able to yaw about this structure. This may also allow the turbine to be raised above the water level for maintenance.

iii) Floating (with three sub-divisions)

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[3] https://minesto.com/our-technology (Accessed February 2019)

- Flexible mooring: The device is tethered via at least one cable/chain to the seabed allowing considerable freedom of movement. This allows a device to swing as the tidal current direction changes with the tide.
- Rigid mooring: The device is secured into position using a fixed mooring system, allowing minimal leeway.
- Floating structure: This allows several turbines to be mounted to a single platform, which can move in relation to changes in sea level.

iv) Hydrofoil inducing downforce

This device uses a number of hydrofoils mounted on a frame to induce a downforce from the tidal current flow. Provided that the ratio of surface areas is such that the downforce generated exceeds the overturning moment, then the device will remain in position.

Tidal barrage

Tidal barrage systems are a tidal power generation method that work similar to hydropower and have sluices that control the tidal flow to drive turbines and generate electricity. One example is the Rance Barrage (La Rance Barrage) - located in Brittany, France. It is the world's first tidal power station - and also has one of the highest capacities with a peak rating of 240 MW. There are two main methods of producing electricity by tidal barrage: ebb and two-way generation. Ebb generation uses gates that allow the water to fill a basin to the normal level, these gates are then closed at full tide. The water is then held back for a few hours while the tide recedes, the gates are then opened and the water flows through turbines for several hours generating electricity through to low tide. Two-way generation uses turbines to generate power during both flood and ebb tide. All the water flows through the turbines and, unlike ebb generation, the water is not held back but allowed to flow freely and constantly turn the turbines. The energy produced is usually less than ebb generation but electricity is produced over a longer period of time.

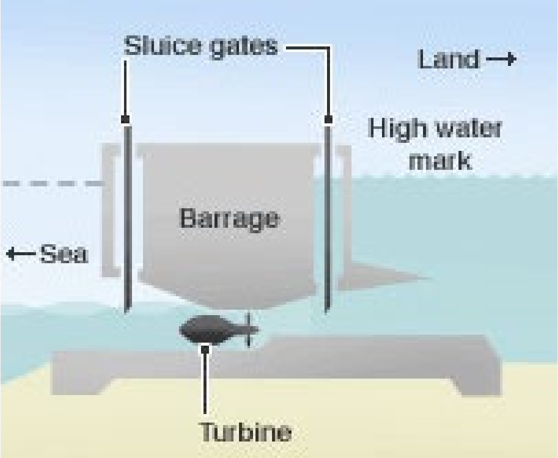

Figure 10. Diagram of an ebb generation tidal barrage (Source: Strathclyde University /Energy Authority of New South Wales)

Tidal lagoon

Tidal lagoons work in a similar way to tidal barrages by capturing a large volume of water behind a man-made structure, which is then released to drive turbines and generate electricity. Unlike a barrage, where the structure spans an entire river estuary in a straight line, a tidal lagoon encloses an area of coastline with a high tidal range behind a breakwater. Currently, the Swansea Bay project is the only tidal lagoon being considered in the ICES area although, as the UK government has declined to fund the project its future is wholly dependent on finding private investors.

Table 1 and 2 summarize the current (early 2019) status of tidal devices (stream and range) in the OSPAR countries. These tables are based on the knowledge available through ICES experts working groups. OSPAR contracting parties not present in the table have no developments of tidal devices at this time. Looking at these tables it becomes clear that the licensed and planned projects, especially in the UK, exceed currently operational projects by several orders of magnitude. Maps of tidal energy developments at European and worldwide scale can be found respectively at the Emodnet (http://www.emodnet.eu/map-week-%E2%80%93-ocean-energy-project-locations/) and Ocean Energy Systems websites (https://www.ocean-energy-systems.org/ocean-energy-in-the-world/gis-map/).

Table 1: Status of tidal stream devices-in those OSPAR countries that have either operational, under construction, licensed, and/or planned projects. Empty cells indicate absence such devices in the OSPAR country concerned.

		Turbines				**screws**				**kites**			
	Parameter	operational	Under construction	Licensed	Planned	operational	Under construction	Licensed	Planned	operational	Under construction	Licensed	Planned
Spain	No. of devices	1											
	Areal extent (km²)	0.0002											
	Capacity (MW)	0.002											
Belgium	No. of devices						3						
	Areal extent (km²)						> 0.1						
	Capacity (MW)						1.2-1.4						
Norway	No. of devices		1	1	5				1		1	1	
	Areal extent (km²)		2	10	TBD[4]				1		2	2	
	Capacity (MW)		4	1	12				1		1	1	
The Netherlands	No. of devices	2											
	Areal extent (km²)	<0.1											

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[4] TBD: To Be Determined at a later stage

	Capacity (MW)	~0.5											
UK	No. of devices	7		85	200+					1			20
	Areal extent (km²)	3.35		24.8	TBD					0.075			TBD
	Capacity (MW)	6.3		160.28	300+					0.5			10
France	No. of devices	1											
	Areal extent (km²)	<0.1											
	Capacity (MW)	1											

Table 2: Status of tidal range devices-in those OSPAR countries that have either operational, under construction, licensed, and/or planned projects. Empty cells indicate absence such devices in the OSPAR country concerned.

		barrage				**lagoon**			
	Parameter	operational	Under construction	licensed	Planned*	operational	Under construction	licensed	Planned*
The Netherlands	No. of devices	8			18				
	Areal extent (km²)	> 0.1			> 0.1				
	Capacity (MW)	1.55			3				
UK	No. of devices								16**
	Areal extent (km²)								11.5
	Capacity (MW)								320
France	No. of devices	24							
	Areal extent (km²)	>0.1							
	Capacity	240							

*planned is assumed to mean that the project has formally entered the planning process and submitted documentation to the relevant regulatory authority

**Swansea Tidal Lagoon – currently seeking funding

2.2 Wave energy

2.2.1. Energy resource and location

The worldwide theoretical potential of wave power has been calculated as 29,500 TWh·yr-1 (Mork *et al*., 2010). According to WEC (World Energy Council), the economically exploitable resource ranges from 140-750 TWh·yr-1 for current designs of devices when fully mature and could rise as high as 2,000 TWh·yr-1, if all the potential improvements to existing devices are realized.

Depending on the coastline's orientation towards the open ocean and the latitude, certain countries are well suited for ocean wave energy conversion, while others almost have no potential in the initial phase (Figure 11). Countries best suited for ocean wave energy conversion are the UK, Ireland, Norway, New Zealand, Southern Australia and Chile, followed by Northern Spain, France, Portugal, North American and South American coasts and South Africa.

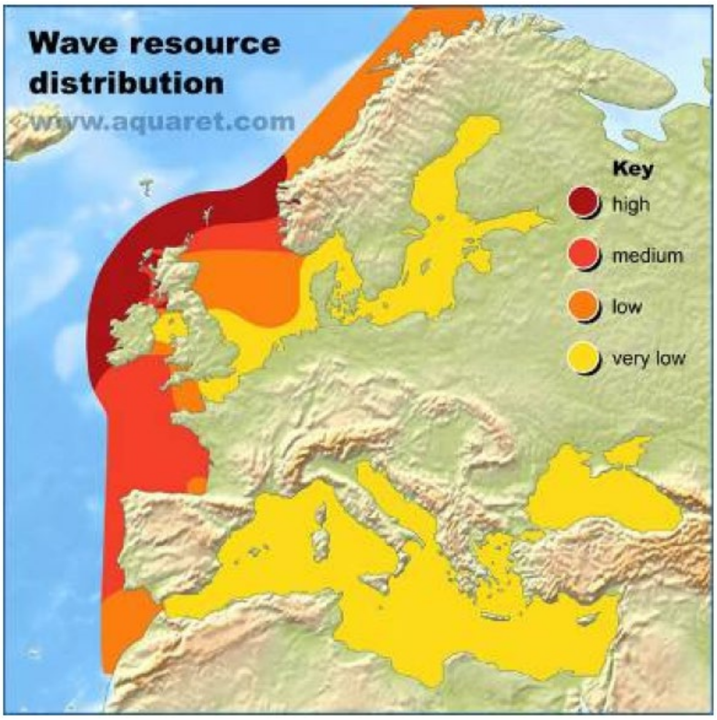

Figure 11. Wave resource distribution in Europe. Source: www.aquaret.com.

2.2.2. Wave Devices[5]

Wave power is the capture of energy from waves, and waves are produced by wind action and are therefore an indirect form of solar energy. This energy can be captured and converted into electricity by wave energy converter (WEC) machines. These WECs have been developed to extract energy from shoreline out to the deeper waters offshore. The Ocean Energy Systems Implementing Agreement (OES) identifies three main types of WEC (Figure 12): oscillating water column, oscillating bodies and overtopping.

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[5] Descriptions of wave devices largely adapted from http://www.aquaret.com/

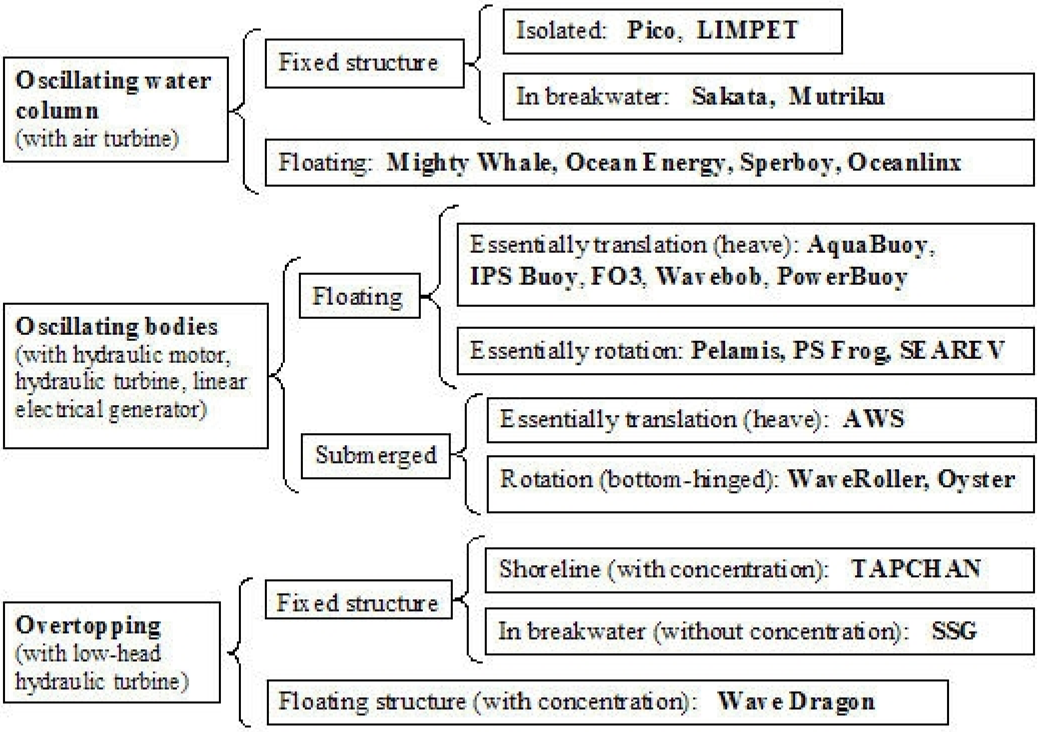

Figure 12. Wave energy technologies. Source: www.ocean-energy-systems.org

Oscillating water column (OWC)

An oscillating water column is a partially submerged, hollow structure (Figure 14). It is open to the sea below the water line, enclosing a column of air on top of a column of water. Waves cause the water column to rise and fall, which in turn compresses and decompresses the air column. This trapped air can, for example be forced through a bi-directional turbine which rotates to generate electricity. The device can either be fixed to a static base on the seabed (example: Limpet) or floating (example: Mighty Whale).

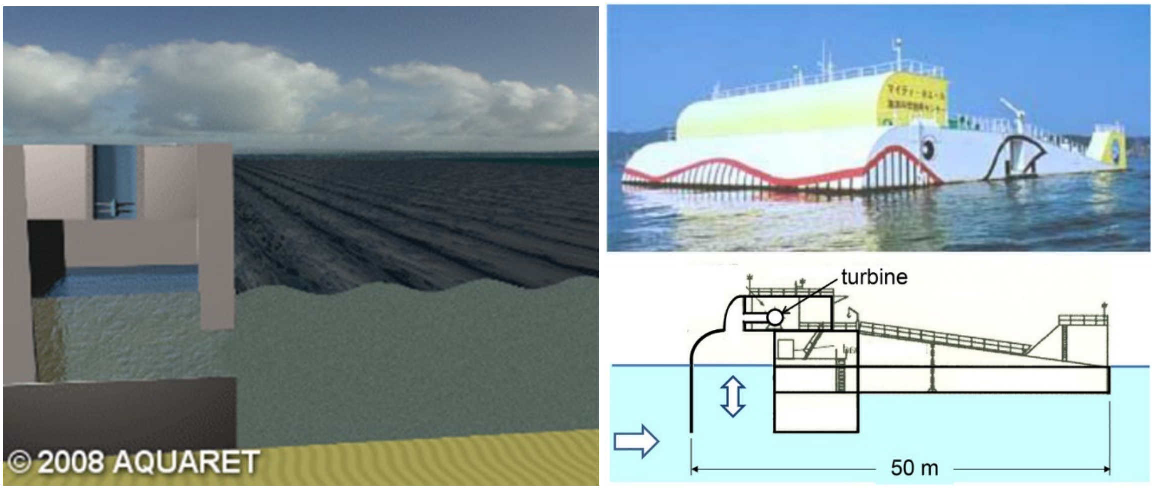

Figure 14. Oscillating Water Column. Left static base Source: http://www.aquaret.com/. Right floating (Mighty whale – Falcao & Hernriques, 2016)

The Mutriku wave energy plant in Spain is currently the only commercial, grid-connected wave energy plant within the OSPAR region. It was connected to the grid in 2011, and is owned by Ente Vasco de la Energia (the Basque energy agency). The Mutriku plant has a 300 kW generating capacity and consists of 16 turbines housed in a breakwater at the port of Mutriku.

A previous 250 kW coastal oscillating water column plant on the Island of Islay, Scotland, was decommissioned between 2012 and 2018.

Oscillating bodies - floating

Example 1 – Linear attenuator

An attenuator is a floating device which operates parallel to the wave direction and effectively rides the waves (Figure 8). The device is composed of segments and the joints separating the segments generate energy by compressing hydraulic oil by means of two pistons driving a hydraulic motor and eventually an electric generator. An example of an attenuating device is Pelamis which was manufactured by Pelamis Wave Power[6]. The wave device was tested at EMEC's wave test site at Billia Croo off Orkney (see Figure 11) but the company has since gone into administration.

Figure 11. Left Panel: schematic of wave attenuator. Right Panel: the Pelamis wave device at EMEC, Orkney (EMEC 2014)

Example 2 - Bulge wave

Bulge wave technology consists of a rubber tube filled with water, moored to the seabed heading into the waves. As the wave comes, the tube flexes with it in the same motion, rather like a snake (Figure 17). The water enters through the stern and the passing wave causes pressure variations along the length of the tube, creating a 'bulge'. As the bulge travels through the tube it grows, gathering energy which can be used to drive a standard low-head turbine located at the bow, where the water then returns to the sea. The Anaconda wave device, developed by Bulge Wave Power is an example of this type of device.

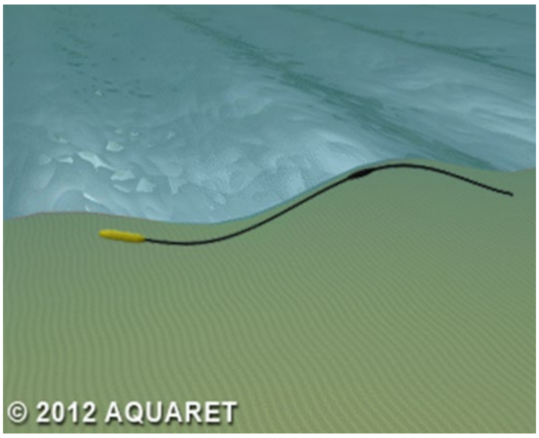

Figure 17. Bulge wave device. Source: http://www.aquaret.com/

Example 3 - Point absorber

A point absorber is a floating structure which absorbs energy from all directions through its movements at/near the water surface (Figure 12). It converts the motion of the buoyant top relative to the base into electrical power. The power take-off system may take a number of forms, depending on the configuration of displacers/reactors.

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[6] http://www.emec.org.uk/about-us/wave-clients/pelamis-wave-power/ (Accessed February 2019)

The device can either be mounted on a static base on the seabed and the dynamic part moves up and down on the water surface or connected to a number of subsurface components.

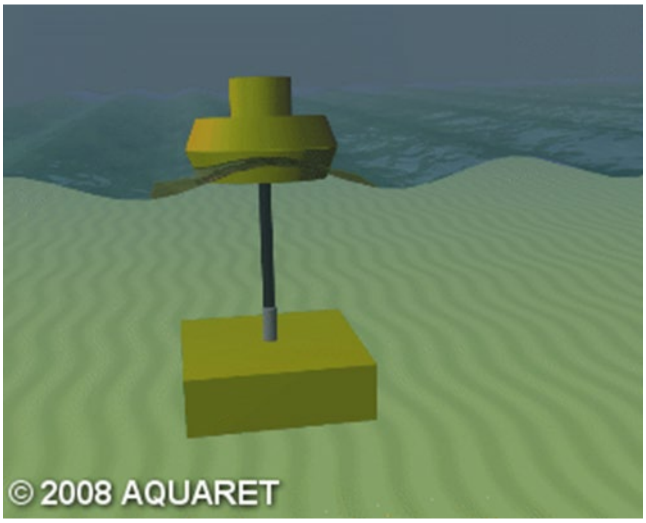

Figure 12. Point absorber. Source: http://www.aquaret.com/

Example 4 - Rotating mass

Two forms of rotation are used to capture energy by the movement of the device heaving and swaying in the waves. This motion drives either an eccentric weight or a gyroscope and the movement is attached to an electric generator inside the device, creating mechanical energy. Figure 18 shows a cross section of the device floating on the water surface and moving with the motion of the waves. The dynamic rotor is fully enclosed within the inside of the device. The Penguin by Wello is an example of this type of device.

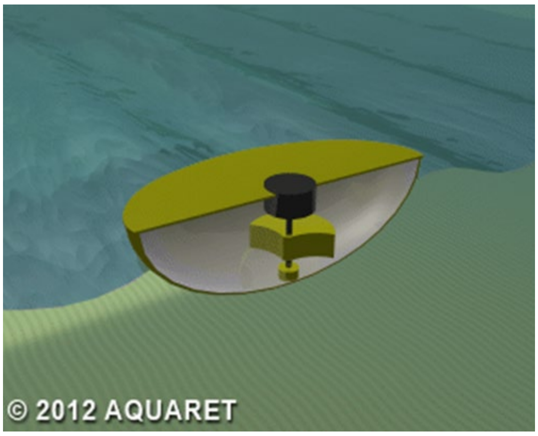

Figure 18. Rotating mass device. Source: http://www.aquaret.com/

Oscillating bodies - submerged

Example 1: Wave Surge Converter

A wave surge converter is essentially a paddle, which rotates around a fixed static seabed mount (Figure 13). The paddle oscillates as a pendulum mounted on a pivoted joint in response to the movement of water in the waves. Energy is extracted from wave surges and the movement of water particles within them. The most commercially available Oscillating Wave Surge Converter is the Oyster device, which is manufactured by Aquamarine Power (Talpur, 2016).

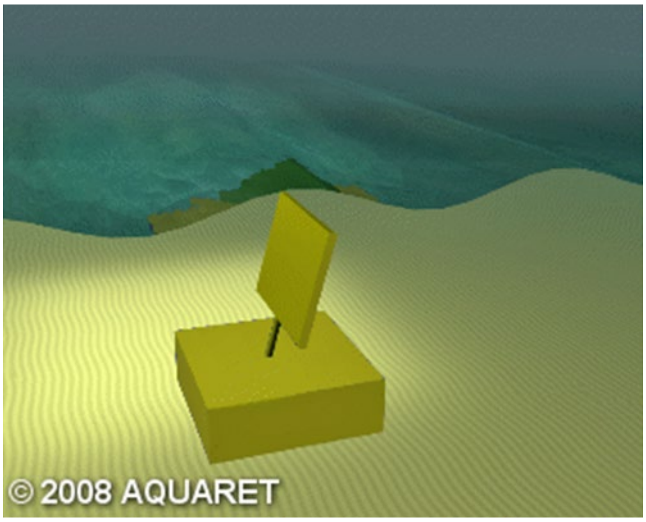

Figure 13. Oscillating wave surge convertor. Source: http://www.aquaret.com/

Example 2: Submerged pressure differential

Submerged pressure differential devices are typically located near shore and attached to the seabed via a static base (Figure 16). The motion of the waves causes the sea level to rise and fall above the device, inducing a pressure differential in the device. The dynamic motion is therefore the device moving upwards and downwards just below the water surface. The alternating pressure pumps fluid through a system to generate electricity. Archimedes Wave Swing, developed by AWS Ocean Energy is an example of this type of device.

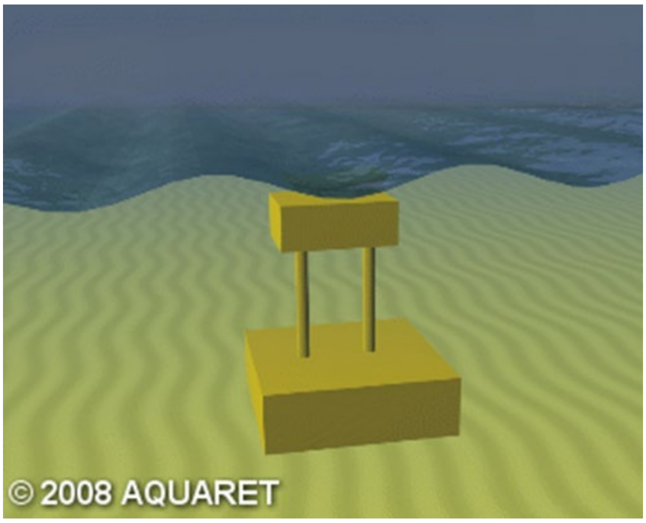

Figure 16. Submerged pressure differential device. Source: http://www.aquaret.com/

Overtopping device

Overtopping devices capture water as waves break into a storage reservoir (Figure 15). The water is then returned to the sea passing through a conventional low-head turbine which generates power. An overtopping device may use 'collectors' to concentrate the wave energy. An example of a floating overtopping device is the Wave Dragon by Wave Dragon.

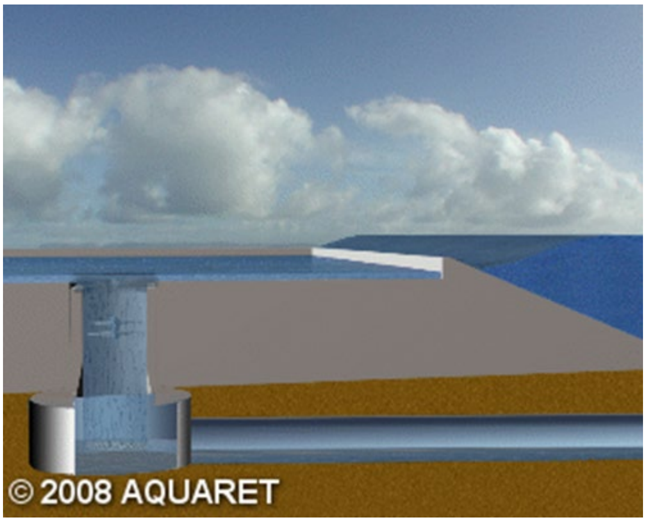

Figure 15. Overtopping/terminator device. Source: http://www.aquaret.com/

Table 3 summarizes the current (early 2019) status of wave devices in the OSPAR countries. This table is based on the knowledge available to the members of the ICES working groups MBRED and MRE, OSPAR contracting parties not present in the table have no developments of wave devices at this time. This table illustrates that there are relatively few licensed and planned projects foreseen for the near future. Maps of wave energy developments at European and worldwide scale can be found respectively at the Emodnet (http://www.emodnet.eu/map-week-%E2%80%93-ocean-energy-project-locations/) and Ocean Energy Systems websites (https://www.ocean-energy-systems.org/ocean-energy-in-the-world/gis-map/).

Table 3: Status of wave devices in the OSPAR region:

		Wave: offshore				Wave: coastal infrastructure			
	Parameter	operational	Under construction	licensed	Planned	operational	Under construction	licensed	planned
Belgium	No. of devices		1	7-160[7]					
	Areal extent (km²)		0.0004	16.3					
	Capacity (MW)		0.005	5					
Norway	No. of devices	1-2	2	1	2				
	Areal extent (km²)	2	2	2	TBD[8]				
	Capacity (MW)	<0.5	0.5	0.2	0.2				
Spain	No. of devices	1				1			
	Areal extent (km²)	0,001				1.4			
	Capacity (MW)	0.03				0.3			
UK – test centres only	No. of devices	Variable[9]			Variable[10]				
	Areal extent (km²)	112 km²			0				
	Capacity (MW)	Variable			TBD				

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[7] The number of devices will depend on the type chosen (Wavestar C6, Poseidon P60, Weptos 350 kW, FlanSea 80 kW Wave Pioneer or Seabased were among those initially considered)

[8] TBD: To Be Determined at a later stage

[9] Includes test sites with variable number of operational devices

[10] Depending on the type of devices selected

Ireland	No. of devices				6				
	Areal extent (km²)				TBD				
	Capacity (MW)				5				
Portugal	No. of devices		1	2	1	1	1	2	1
	Areal extent (km²)	-	0,4	0,52	1,3	0.4	0,0009	0,0028	0,5
	Capacity (MW)	-	0,35	1,05	5,6	0.35	0,35	1,05	5,6

‘planned’ is assumed to mean that the project has formally enterd the planning process and submitted documentation to the relevant regulatory author

2.3 Energy Storage Systems

The need to store renewable energy generated at sea is currently mainly associated with offshore wind farms (OWF). Energy production by these OWFs is dependent on the prevailing weather conditions, which are fluctuating daily. Hence, there is a need to adapt the stochastic power production from OWFs to the actual power demand. This can be achieved through coupling the devices generating power with energy storage systems. Today, two large types of storage technologies are suitable to manage the large electrical quantities produced from OWFs (Katsaprakakis 2016): Pumped Storage Systems (PSS) and Compresses Air Energy Systems (CAES). Below, we describe the general principles behind these technologies, and provide some examples of marine applications of these technologies. Examples of these technologies coupled with the wet renewable devices described above are not available now. As these technologies are currently conceptual, their possible environmental impacts will not be discussed in detail in this document. Currently, the most likely and immediate storage of energy from wet renewables is the charging of large battery banks.

Pumped Storage Systems

PSS are technically the most mature and economically most competitive energy storage systems for large power plants and are largely used on land (Katsaprakakis 2016). The operating principle is based on connecting two water reservoirs situated at different altitudes in nearby locations (Katsaprakakis 2016). When there is a surplus of energy, it is used to pump water from the lower reservoir to the reservoir at the higher location. By doing so, the energy surplus is stored as gravitational energy. When there is a demand for power, water is released from the upper reservoir to the lower reservoir, while passing through a hydro power plant, producing the necessary energy (Figure 19).

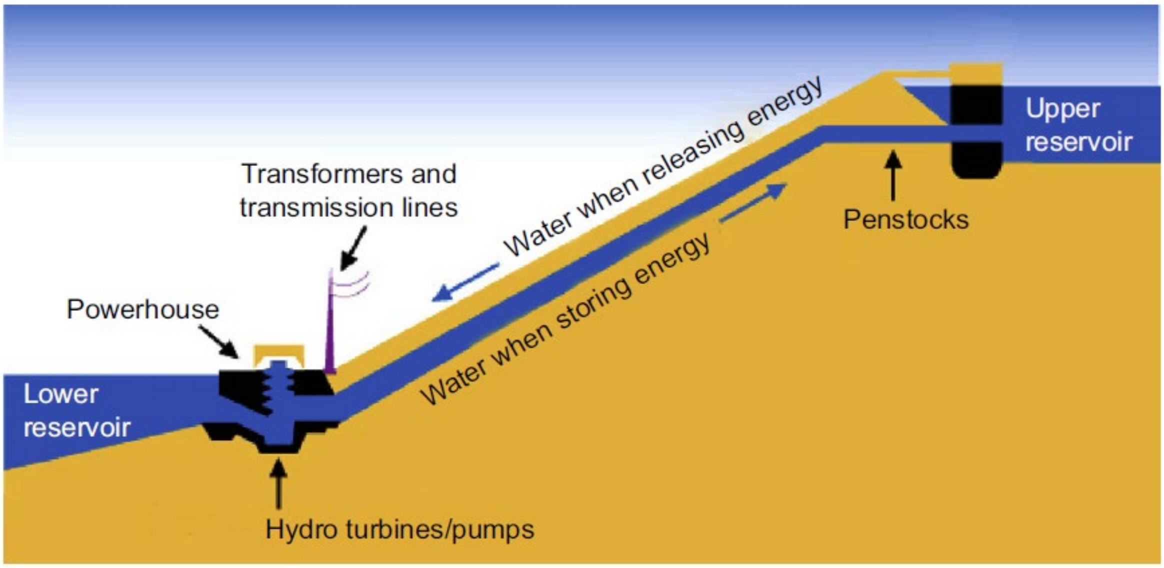

Figure 19. Basic structure of a pumped energy storage system. Source: http://www.nepalenergyforum.com

Seawater-pumped storage systems

Seawater-pumped storage systems makes use of seawater in the lower reservoir. This seawater is pumped to a reservoir at a higher location. At that higher location, the risk of leaking seawater into the environment should be minimised. An examples of a seawater-pumped energy storage system is in place in the Greek island Ikaria, where the energy to pump the water to the higher reservoir is derived from land-based wind farms (Papaefthymiou, Karamanou, Papathanassiou & Papadopoulos 2010). However, as these seawater-pumped systems need to be located close to the coast, coupling with offshore renewable energy devices would be a possibility (Katsaprakakis 2016); the developments of such innovations are expected within the period 2020-2050 (EIA 2012). To the best of our knowledge, a seawater-pumped storage system connected with offshore renewable energy devices is not in place yet. Other seawater-pumped storage systems include the so-called ‘energy atolls’ or ‘energy islands’ (Figure 20).

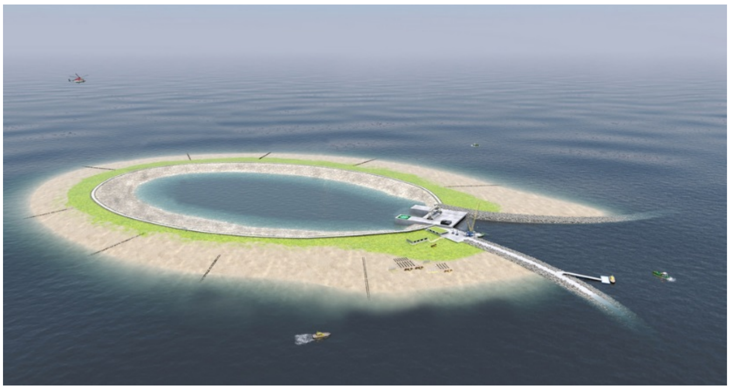

Figure 20. Render of an energy island (https://www.iland-energystorage.be)

When there is an energy surplus, the energy can be used to pump the seawater out of the central area of the artificial island to lower the water level there below the level of the surrounding sea. When the energy demand exceeds energy production, seawater can enter the central area while passing through a hydropower installation (EIA 2012). A request for a license for such an energy island off the Belgian coast was submitted in 2014 and the first Belgian Marine Spatial Plan (2014-2020) included a location for this project. Due to local opposition the application was withdrawn in 2015.

Derived concepts

Buoyant Energy is another offshore energy storage solution, which is largely based on the principles of the seawater-pumped energy storage systems (Klar, Steidl, Sant, Aufleger & Farrugia 2017). In contrast to the earlier described seawater-pumped energy storage systems, buoyant energy makes use of a smaller reservoir (the inside space of a floating structure) inside a larger reservoir (the surrounding sea) (Figure 21).

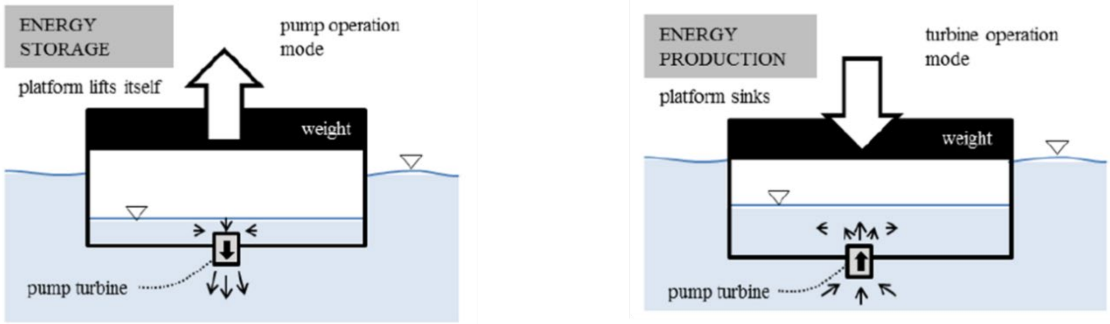

Figure 21. Basic concept of buoyance energy storage system. Left panel: energy storage. Right panel: energy production (Klar *et al*. 2017*)*.

A pump is installed in the lower part of the floating structure and used to pump water from the central space to the surrounding ocean. The surplus on energy is used for this process. As the volume of water inside the structure decreases, it will become more buoyant and it will move up. When power generation is needed, the surrounding seawater is allowed to enter the structure and drives a power generating turbine that is integrated in the lower part of the structure as well. Klar *et al*. (2017) suggest that these structures can be located in between offshore wind turbines or integrated in the design of floating wind farms. To date, there is no information about buoyant energy storage systems being in place in the marine environment.

Building on the concept of buoyance energy storage systems, (Klar, Steidl & Aufleger 2018) introduced the concept of the “light” buoyance energy storage systems. They are largely similar to the buoyance energy storage systems but constructed out of light construction material (waterproof fabric), which can result in reduced investment costs. In contrast to the buoyancy energy storage device, the water level inside the floating structure is above the level of the surrounding sea (Fig. 19).

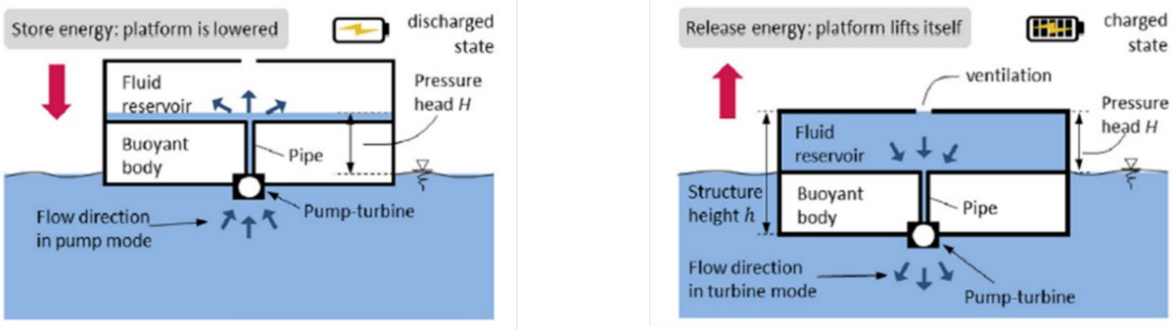

Figure 22. "Light" buoyancy energy storage system. Left panel: energy storage. Right panel: energy production (Klar *et al*. 2018).

To store energy, water is actively pumped into the central device, thereby increasing its weight and lowering the platform into the water. In this way, electric energy needed for pumping is converted to potential energy. To generate electricity, the water is allowed to flow back to the surrounding sea through a turbine integrated in the lower part of the structure. Thereby, the stored potential energy can be converted back to electric energy. As clearly stated in Klar *et al*. (2018), the design is still conceptional and has never been tested in realistic scenarios. (Slocum, Fennell, Dundar, Hodder, Meredith & Sager 2013).

The Ocean Renewable Energy System (ORES) builds on similar principle, but is located on the seabed or could act as mooring systems for floating wind farms or can be connect to any type of renewable energy device (Slocum *et al.* 2013). In short, spheres are mounted on the seafloor, excess power is used to pump water out of the spheres. As the spheres are located at the seafloor, the hydrostatic pressure can be used to allow the water to flow back in through a turbine to generate electricity (Figure 23). According to Slocum *et al*. (2013), deployment depth should be >200m which limits the application of these devices to deep-water marine renewable energy devices.

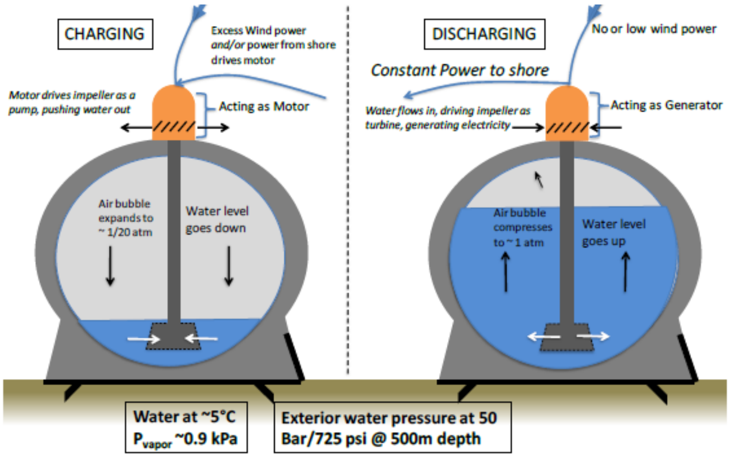

Figure 23. Internal view of the bottom-mounted ORES concept (Slocum *et al*. 2013)

Compressed Air Energy Storage Systems

Compressed Air Energy Storage Systems (CAESs) are based upon compression of air to high pressures using surplus energy, expansion of the compressed air flowing over the turbine generates electricity when needed (Katsaprakakis 2016). Underwater CAESs takes the advantage of the hydrostatic pressure associated with water depth. Two categories of underwater storage vessels have been considered to date: rigid vessels (e.g. submerged caissons anchored to the seabed), and cable-reinforced fabric bags anchored to the seabed, known as Energy Bags (Figure 23, Pimm *et al*. 2014). For both device types, there is the need to have a connection with a land-based or floating facility to connect with compression and expansion machinery. Proposals for deployment and testing of rigid vessels have been put forward in California. Energy bags have been tested both in the lab and offshore at the 25m deep European Marine Energy Centre (EMEC) off the coast of Orkney and are currently being tested in Lake Ontario. In addition, a modeling study (Sheng *et al*. 2017) investigates the use of underwater CAESs to store energy generated by a tidal turbine farm to support an isolated island, disconnected from a main grid. However, there is no evidence that underwater CAESSs are active at the moment in the marine environment.

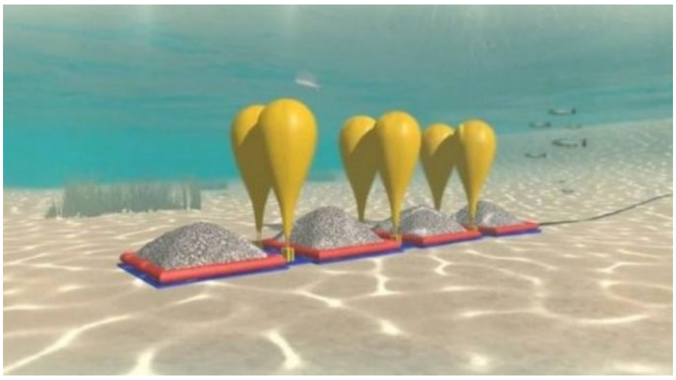

Figure 23. Visualisation of Energy Bag type of underwater CAESs (source: Greentech Media)

Apart from storing energy, there is increasing interest in the 'power to molecules' pathway where electrical power is converted to hydrogen gas using electrolysis (World Energy Council Netherlands 2017). Since 2017, the European Marine Energy Centre (EMEC) has produced hydrogen gas using electricity generated from tidal energy in Orkney. Hydrogen gas can be stored and transported. It can be used as fuel or combined with CO_2 and converted into methane or liquid fuels. Conversion of power to hydrogen gas can be done onshore or offshore. Offshore conversion can be done on retired oil and gas platforms, but on the long term it is expected that this conversion will take place at large "artificial islands". In that case, cables will always be needed to transport electricity to the users on the main land.

3. The future prospects

3.1 Tidal Devices

Across the OSPAR region tidal energy development is again moving forward following recent industry setbacks relating to withdrawal of investment and dissolution of tidal energy companies. A total of 43 MW of tidal energy (stream and flow) is now operational across the OSPAR area, with more than 320 MW under construction, consented or in planning phases (see Tables 1, 2). The present trend in tidal devices seems to be moving away from heavy bottom mounted devices and towards floating tidal as these devices have considerable advantages: deployment and maintenance is much easier and enormously cheaper than bottom mounted devices; the mid water column location of the devices taps into faster tidal flows; and the amount of steel and concrete used is much less (and therefore less expensive) than for bottom-mounted devices (A. Copping, pers. comm.).

3.1.1 In-Stream Tidal Energy

The UK has the greatest level of deployment of tidal energy, at test centres in Scotland (EMEC), and Wales, and at commercial sites are under development in Scotland (Meygen + Nova). At EMEC, Orbital Marine's (formerly ScotPowerRenewables) SR2000 generated 3 GWh in 2018, while Spanish company Magallanes Renovables tested their 2MW floating tidal energy platform. Two commercial arrays have also been deployed at different scales: the Nova Innovations array at Bluemull Sound Shetland, aimed at community-scale energy generation; and the SIMEC Atlantic Meygen Array (4 MW) in the Pentland Firth, aimed at national-grid scale generation. Both schemes are undertaking work to extend their capacity in 2019 and 2020.

In France, in-stream tidal energy developments are also progressing, where the Sabella D10 turbine (1MW) was re-installed and grid-connected at the Ushant Islands in 2018 for a further three years.

Belgian developments focus predominantly on lower energy environments..

3.1.2 Tidal energy barrages and lagoons

Within the OSPAR area, tidal energy barrages have tended to exist as part of historical barrage developments, for example at la Rance in France (240 MW), and as part of flood protection infrastructure in the Netherlands (1.55 MW). While new tidal-energy specific barrages face serious challenges in the OSPAR region because of environmental impact concerns, tidal turbine installation in existing infrastructure continues to be attractive.

Tidal lagoon technology has not been progressed following the UK Government announcement that the submitted proposals in Wales (including the Swansea Bay tidal lagoon) did not represent value for money so it would not be investing public funds[1]. Whilst there are significant environmental and economic challenges interest in developing the technology remain.

[1] https://www.gov.uk/government/speeches/proposed-swansea-bay-tidal-lagoon

3.2 Wave devices

Wave energy developments have not reached the same level of commercial deployment across the OSPAR region as has been achieved by tidal energy technologies. The majority of offshore technologies are test devices being trialed at the region's many test centres, although coastline infrastructure (fixed) wave energy plants are now exporting electricity to the Spanish grid.

3.2.2 Nearshore fixed and floating wave energy devices

To date, there are no operational commercial-scale nearshore fixed and floating wave energy developments within the OSPAR region. Two projects which were given consent to deploy approximately 90 wave energy devices along the west coast of the Scottish Outer Hebrides have now been cancelled, following the collapse of device developers Pelamis and Aquamarine power. The intellectual property from these commercial scale devices has now been taken up by Wave Energy Scotland, a publicly funded organization designed to support the commercialization of wave energy technology.

In Sweden, 36 wave energy devices (50 kW) were installed at the Sotenäs Wave Energy Park by Seabased, however the company took the decision not to pursue further development in 2017, and no buoys are currently attached to the installed foundations.

3.2.3 Test sites

Test sites are an essential element of any emerging technology developments. Companies from across the OSPAR region continue to test their wave energy technologies at the European Marine Energy Centre (EMEC). Finnish company Wello Oy has deployed their 500 kW Penguin device at EMEC since 2011, and is set to deploy a second device as part of the European Horizon 2020 funded CEFOW project. Other wave energy developers with devices deployed at or soon to be deployed at EMEC include the Swedish CorPower Ocean and Belgian company Laminaria.

The Spanish marine energy test site BiMEP (Biscay Marine Energy Platform) has also added new facilities to support the development of commercially viable technologies. These include the Marine Corrosion Test Site "El Bocal", a new offshore facility to test materials called HARSHLAB, and off-grid wave buoy testing at PLOCAN and Punta Langosteira Test Site (a new test site at the Galician coast). BIMEP hosts the MARMOK-A-5 device, the first floating wave energy device connected to the grid in Spain. The Basque company Oceantec Energías Marinas, promoted by TECNALIA and Iberdrola, has recently deployed its first Wave Energy Converter (WEC) at BiMEP, and ARRECIFE plans to test its first AT-0 1:2 scale prototype in BiMEP during the summer of 2019 (Figure 24a,b)

The Oceanic Platform of the Canary Islands (PLOCAN), located on the island of Gran Canaria is a marine test site for ocean energy converters prototypes, with an initial site capacity of 15 MW, planned to be extended to 50 MW by 2020. The installation of two submarine cables (5 MW/13,2 kV) started in 2017 and were commissioned during 2018. There are expected to be grid connected in 2019.

Figure 24a. MARMOK-A-5 device deployed by IDOM at BIMEP after refitting with OPERA innovations.

Figure 24b. HarshLab deployed by TECNALIA at BIMEP during an inspection

In France, the SEM-REV test site is located off the mouth of the Loire river on the Atlantic coast, it is part of the research infrastructure THeoREM (Ifremer and Centrale Nantes). It is hosting a prototype of autonomous powering platform, the WAVEGEM© developed by GEPS TECHNO (Figure 25); the testing started at the beginning of 2019 for an 18-month period. The platform is powered by a wave energy converter with a maximum capacity of 1MW. The SEM-REV is also hosting a number of environmental monitoring buoys looking at wind and waves, and at biological compartments, as well as the first French floating wind turbine. In the Mediterranean area, the new MISTRAL test site is located off the industrial harbour of Fos-sur-mer. While no wave energy devices have been deployed there, research programs for environmental monitoring of MRE are ongoing since 2018.

Figure 25: the WAVEGEM© prototype at its transfer from Saint Nazaire harbour to SEM-REV test site (source: https://www.geps-techno.com/wavegem/)

In the Nordic countries, Swedish company Waves4Power has deployed their device as part of the WavEL project at Runde, Norway.

Other wave energy test sites in the OSPAR Region include the Atlantic Marine Energy Test Site in Ireland (AMETS, currently no device deployments); Wave Hub (currently no device deployments) in Falmouth and Pembrokeshore, UK; FabTest (currently no device deployments) in Falmouth, UK.

3.4 Outlook

The large number of developments in planning stages across ICES countries reported suggests that there is a strong industry-led potential for increasing developments into the future. However, it should be noted that a large number of applications have been withdrawn due to financial or logistical limitations, so the potential is likely not being met.

Opportunities for future developments:

- New developments in Marine Spatial Planning Decision Support Tools (MSP DSTs)
- Projects dealing with the environmental impact of marine renewables will reduce the uncertainty about these impacts or at least increase the knowledge about them.
- EU renewable energy targets
- Non-grid connected systems for offshore energy provision to multi-use systems, for example offshore aquaculture or metocean buoys
- Microgrid supply in remote and/or developing regions

Barriers:

There are still several barriers to overcome. Ocean energy needs to demonstrate the ability to improve on survivability and reliability to be considered as an attractive investment and a potential contributor to the future energy mix supply. Similarly, there is a need for a stable legal framework and proactive policy to push forward the development of the sector. Further barriers include:

- Uncertainties about environmental impacts of marine renewables.
- Inconsistent consenting processes.
- Site selection and places for new developments.
- Investment conditions & finance

4. Potential changes to the environment

The potential changes to the receptors (biotic and abiotic) are described below.

4.1 Hydrodynamics

Hydrodynamics relates to waves and currents, how they interact together and how they interact with the bathymetry and structures in the marine environment. Tidal and wave energy each directly remove energy from the tidal current and wave fields, respectively. Any disturbance to the hydrodynamics within a region may alter the levels of mixing and could have an effect on the local density structure including the levels of stratification. The two predominant hydrodynamic processes reviewed here are tides and surface waves. Tidal processes include the range, speed and phase of the tide and it is likely that tidal energy developments will impact these processes to some extent, as tidal energy is being directly removed. Surface waves will be altered to an extent by any offshore structure with a near surface presence through wave breaking, shoaling, reflection, refraction, and/or diffraction. Wave energy converters are likely to have a large near-field effect on the wave field as energy will be removed from the wave field.

It is important to consider how hydrodynamic processes may change as a result of wet renewables because (i) they include the underlying renewable energy resource, and (ii) they control a whole range of physical and ecological processes and therefore can act as pathways of wider ecological change.

There are a variety of ways to measure hydrodynamic processes in the marine environment, from in situ instrumentation on moorings or vessels, to remote sensing from land or space. However, small scale developments are only likely to lead to very small localized changes to the hydrodynamics. Large scale developments are more likely to lead to far field changes, and since there are no large developments it is impossible to measure the magnitude to change. For this reason, numerical modelling of the hydrodynamics is an extremely useful tool for understanding the impact of larger scale developments, as detailed below.

The static component of a wet marine renewable energy development refers to the foundation structures in most cases. For this reason, there is a lot of overlap with literature on the foundations of offshore wind farms. When a foundation is placed on the seabed, the hydrodynamic field will experience local accelerations around the structure (Whitehouse *et al*. 2011) as well as decelerations downstream and immediately in front of the structure (Rivier *et al*. 2017). Such changes to the hydrodynamics can lead to scour of the marine sediments (Whitehouse *et al*. 2011). The dynamic components of a horizontal axis tidal turbine are the turbine blades which extract energy from the flow. This leads to a downstream wake where the flow speed is significantly reduced.

4.1.1 Energy Removal

Tidal energy developments directly remove energy from the tide and will therefore alter tidal processes to some extent. Qualitatively, tidal currents will be slowed down by tidal stream devices and there may be some acceleration in the flow around devices/arrays. A head drop in tidal water level may also be experienced across tidal stream devices and arrays.

The tides within a tidal barrage scheme will be disrupted leading to changes to the timings and range of the tide, and this could result in reductions in the area of the intertidal habitat within the barraged region (Wolf *et al*. 2009). Tidal lagoons will change the tide in a similar manner to tidal barrages but developments are potentially orders of magnitude smaller in size and power output. Lagoons therefore have the potential to have far less impact on hydrodynamics and tides than tidal barrages. However, a large number of lagoons within a region could have a significant cumulative impact on the tides, and impacts will also be dependent on placement within a region.

Wolf *et al*. (2009) modelled potential barrage schemes in the eastern Irish Sea and predicted that the introduction of five large-scale schemes could lead to an increase in tidal amplitude along some parts of the Irish coastline, potentially increasing local flood risk. They also found that the Bristol Channel bed shear stress would be reduced, and that the intertidal area behind a barrage is significantly reduced. From five barrage or lagoon schemes considered for the Severn Tidal Power development, one scheme had far-field impacts which reached the Irish coastline and could increase high tide levels by up to 10 cm (DECC, 2010). Predicted far-field impacts for all of the other four schemes considered for the Severn estuary were below 10 cm.

Initial studies of tidal processes in tidal sites focused on quantifying the available tidal resource, both tidal range (e.g. Burrows *et al*. 2009) and tidal stream (Black & Veatch 2005, e.g. Blunden & Bahaj 2007, Bryden *et al*. 2007). Much early work on tidal stream energy focused on the simplistic scenario of an idealized channel modelled using one-dimensional analytical models (Garrett & Cummins 2005, Bryden & Couch 2007). This work showed that tidal channels typically have limited available resource. Whilst the extractable power at first increases with the number of free stream turbines, it eventually plateaus out and decreases once the maximum extractable power for the channel has been reached. Tidal stream turbines in idealised channels have also been modelled using more sophisticated hydrodynamic models, modelling the flow in either two or three dimensions (e.g. Walkington & Burrows 2009, Yang *et al*. 2013). Such idealised models predict a redistribution of flow speeds within the channel, which decreases in the immediate vicinity of the tidal turbines and increases around the turbines.

Since these early resource and impact assessments, more sophisticated regional hydrodynamic models have been developed for many sites of particular interest, such as the Pentland Firth and Orkney Waters, Scotland (e.g. Easton *et al*. 2012, Adcock *et al*. 2013, O'Hara Murray & Gallego 2017). These models can resolve in detail the complex hydrodynamic conditions around many tidal stream sites, enabling much more realistic resource assessments to be conducted. These models can now represent the energy extraction of tidal stream turbines and other feedbacks of such devices on the tidal flow (e.g. Yang *et al*. 2013, Roc *et al*. 2013). This not only improves the resource assessment and array design, but also allows the impact of tidal stream developments on the tidal stream, and potentially other physical processes, to be investigated. Due to the lack of development and the challenges of making measurements in and around tidal stream sites, hydrodynamic modelling has to date provided the most insight into how large (commercial) scale tidal developments could change the physical marine environment. Shapiro (2011) modelled a large tidal stream farm in the eastern Celtic Sea and found there to be large scale changes in current speed. The highest magnitude changes were confined to around 20 km from the tidal farm, but there were changes to the residual circulation observed up to 100 km away. O'Hara Murray and Gallego (2017) examined how large developments in the Pentland Firth could impact tidal processes and sediment transport in the region. It was found that developments totaling around 1 GW mean extracted power are unlikely to lead to significant changes in the physical marine environment, whereas larger developments, > 1.5 GW mean extracted power, could change the sediment transport by 10 % or more. It was also found that the amount of change, and where it occurs, is dependent on array layout including the vertical positioning of tidal stream turbines, as well as the bathymetry and circulation in the region. De Dominicis *et al*. (2017) modelled a large tidal stream farm in the Pentland Firth (1.64 GW) and investigated the far-field physical impacts. Far field changes to the tidal range and currents were predicted, with changes of around 1 cm in range and 0.25 cm/s in current speed down the east coast of the UK. Far field changes in stratification were also predicted, meaning that some tidal mixing fronts in the North Sea may be shifted.

Spectral wave models have been used to explore the impact of wave energy converters (WEC) and arrays on the wave field. Early studies represented arrays as partially transmitting barriers. Millar *et al*. (2007) modelled the Wave Hub site 20 km off the Cornish coast in the UK, with the wave farm represented as a 90% transmitting barrier. They found that the significant wave height at the shoreline was reduced by an average of 1 cm (< 1%). Later studies developed more sophisticated ways of representing WECs in spectral wave models, by making the transmission coefficient wave frequency dependent (e.g. Smith *et al*. 2012). This is more realistic as WECs are likely to remove more energy from specific frequencies than others. Rusu *et al*. (2013) modelled Pelamis wave attenuator devices approximately 15 km off the Portuguese coastline using a spectral wave model. They explored two scenarios with a total of 5 and 10 devices in 1 and 2 rows, respectively. Immediately down wave of the devices, the two scenarios produced decreases of around 10% and 20%, respectively, and the shadow zone for the second scenario (10 devices) was larger than the first. At the shoreline, the two scenarios decreased the significant wave height by around 2-3% and 5%, respectively. It was also found that the shape of the nearshore waves was modified, as well as the wave induced longshore currents. These studies showed that small arrays of WECs, 15 – 20 km offshore, are likely to only lead to a shoreline change of a few percent. More recently, Venugopal at al. (2017) modelled much larger arrays of wave attenuators and wave surge converters off the west coast of Orkney, northern Scotland, in order to investigate the cumulative impact on the wave climate. The changes to the wave field were significant in some cases, with up to 1 m change in significant wave height. This change did reduce with distance from the array, as diffracted wave energy propagated into the lee of the arrays.

4.2 Physical seabed and sediment transport

Physical seabed and sediment transport pathways could change as a result of wet renewable energy developments, leading to changes in the net deposition and erosion of coastlines and offshore sand banks, as well as larger scale bathymetry and geomorphological changes. Sediment transport occurs via a variety of mechanisms but can be broadly split into bedload and suspended load. Changes to shear stress at the bed may result in changes to net (bedload) migration of sediment at the bed, but also to the amount of sediment re-suspended. Wet renewable energy developments in sediment rich areas are most likely to have some impact on the near-field sediment dynamics, such as scour around foundation structures. However, large tidal stream and tidal range developments are likely to cause far-field changes to the flow field and bed shear stresses, which could influence far-field sediment transport pathways. The bed shear stress has a quadratic dependence on the flow speed so even a small change in slow speeds could lead to a significant change in net erosion and sediment transport.

The surficial seabed sediments present on the European continental shelf vary spatially in character and thickness. Much of the sediment on the UK continental shelf is the product of erosion during the last glacial maximum. The transport of these sediments is controlled by currents and waves, and the initial mobilization of sediment into the water column is controlled by the local level of shear stress imposed on the seabed by these hydrodynamic forces. Once sediment is mobilized, it can be transported, and tends to be deposited where the local water velocity reduces, meaning the shear stress at the bed is no longer sufficient to pick-up sediment of that grain size. This way, sediment, in time, can become sorted into a dynamic state of equilibrium where smaller grain sizes are found in areas of low energy, and larger grain sizes are found in areas of high energy.

Static components, such as foundation structures, moorings and anchors, may lead to the scouring of bed sediments, due to the local increase in the hydrodynamic field around the structure which can result in flow separation and the generation of turbulent vortices. Scour around marine structures has been well studied as it can lead to important engineering issues. Often scour protection is used, by placing objects such as rocks around foundation structures. Such interventions, whilst solving the engineering issue, can lead to secondary scour around the scour protection (CEFAS 2006).

The change in hydrodynamics (ref Yang) resulting from the dynamic component of a tidal stream turbine could alter the erosion and deposition of sediment in the proximity of devices. Tidal turbines are likely to increase turbulence close to the bed, and also increase flow speeds around the device(s), leading to enhanced bed shear stresses and sediment entrainment. However, the decrease in speeds within the wake of turbines could create a region that favors the deposition of sediment and could lead to long term accumulation of coarse sediments within tidal stream farms (Martin-Short *et al*. 2015). Most tidal stream sites are likely to be extremely dynamic and when bed sediments are present there is likely to be significant natural sediment entrainment during the tidal cycle. For this reason, the far-field impacts on sediments due to the removal of tidal stream energy are likely to have more of an impact on regional sediment transport. Model results from Yang *et al*. (2014) found that high numbers of turbines are required to significantly alter the tidal system.

Seabed cables are most likely to be buried but if they do have a seabed presence localized scour of bed sediments could occur (Taormina *et al*., 2018). Strong tidal stream sites may have little or no seabed sediments, and in these cases, cables are often run along natural features in the bedrock in order to offer them some protection.

4.2.1 Energy Removal

The Pentland Firth, northern Scotland, is an area of high tidal currents and has received a lot of attention as a prospective site for significant tidal stream development. Whilst it is classified as a sediment starved region (Shields *et al*. 2009), mainly comprised of bedrock, there are some areas of coarse sand and gravel, and these sediment patches have been studied by several authors (Martin-Short *et al*. 2015, Fairley *et al*. 2015, Chatzirodou *et al*. 2016, Mcilvenny *et al*. 2016). The flow patterns in the region have most likely sorted the available sediment into these two areas (Chatzirodou *et al*. 2016, Mcilvenny *et al*. 2016), and the complex hydrodynamics maintain them in a state of equilibrium over long periods of time. Any changes to this flow structure will therefore most likely result in a change to the sandbanks. Fairley *et al*. (2015) modelled the morphodynamic impact of four arrays of tidal stream turbines in the Pentland Firth, UK, using a three-dimensional numerical model. The bed level of the mobile sediment patch changed by less than 0.2 m over the month that was simulated. Fairely *et al*. argued that this was insignificant compared to natural bed level changes of over 5 m, but noted that the arrays simulated only extract a fraction of the total tidal stream resource and that higher energy extraction rates could lead to more substantial changes in the morphodynamics in the region. Martin-Short *et al*. (2015) modelled an array of tidal turbines in the Inner Sound of Stroma, an Island close to the southern shore of the Pentland Firth, and concluded that tidal arrays larger than 85 MW within the Inner Sound would most likely effect natural patterns of sediment transport.

4.4. Benthos

4.4.1 Static Component

4.4.1.1 Changes in seabed habitat

The introduction of artificial structures can affect the seabed in multiple ways, and therefore the organisms associated with the seabed. The installation of piled devices will lead to a local loss of seabed habitat, proportionally to the size of the device and the number of devices installed. Gravity based structures have large heavily weighted foundations made from concrete or similar materials, placed directly on the seabed. The seabed habitat directly underneath a gravity base will be lost. Pin-piling, which involves piling several steel pipes into the seabed, results in a smaller area of total loss of habitat. Seabed impacts associated with anchored foundations, on the other hand, will depend on the size and type of anchor. Movement of anchor chains can scour the seabed and cause substantial damage to benthic habitat around an anchor point. As an example, the habitat loss from a single wave energy converter (WEC) can be relatively small (between 8 and 40 m^2), but the footprint can be much larger when seabed levelling is involved (up to 1 km^2) or when scaled up to a 10 MW wave power farm (> 2 km^2) (MacLeod 2014). Impacts of large-scale deployment of devices on the seabed are unknown and require both long-term studies and modelling (Langhamer 2010). Loss of habitat may be considered critical when it is protected and is valued for its ecosystem services. Shore-based WECs, which require modification of the shoreline or creation of a breakwater, are particularly concerning due to the direct loss of subtidal habitats, and irreversible changes to hydrodynamic conditions. Where WECs are in shallow water (10 to 30 m), short-term habitat damage or loss may occur from activities such as site preparation, deployment of infrastructure and mono-piling. Resuspension of sediments as a result of the construction phase can i.e. indirectly impact kelp beds (Annex I habitats in the Council Directive 92/43/EEC) by hindering reproduction, recruitment and photosynthesis and favour establishment of less diverse seaweed communities (Roleda 2011; MacLeod 2014)

4.4.1.2 Reduced pressure to seabed habitat - Fisheries Exclusion

Fisheries exclusion zones are often put into place around marine renewable energy devices to prevent fishing vessel collisions or gear entanglement with infrastructure thus reducing pressure on the seabed. (Inger *et al*. 2009). Exclusion of bottom fishing activity, and particularly trawling gear, will remove an important source of disturbance to benthic habitats (Kaiser *et al*. 2006), and could enable seabed habitats damaged by trawling to recover (Tillin *et al*. 2006) as observed at the Swedish test site of Lysekil (Langhamer 2010). However, 'fishing the line', or fishing activity targeting the edge of exclusion zones in order to exploit spill over (the export of juvenile and adult fish to the unprotected waters; Kellner 2007), remains a threat to benthic habitats. It is worth noting, however, that these effects are much more likely to be associated with wave energy developments rather than tidal energy developments, where high current flow rates may preclude trawl fisheries.

4.4.1.3 Changes in hydrological regime

Changes in hydrology affect distribution of sediments, patterns of sedimentation and seabed bathymetry, all of which directly influence benthic fauna. Hydrological changes influenced by wave and tidal devices are discussed under 'energy removal' but tidal barrage and tidal stream are considered here.

.The ideal location for a tidal barrage is where tidal range exceeds 6 m (Kirby and Retière 2009). However, tidal barriers that were originally constructed for the purposes of coastal protection may subsequently be modified to include a turbine, such as those in the Netherlands at Oosterscheldekering (Leopold & Scholl, 2018). A tidal barrage causes gross changes to the hydrological regime of the water body and a cascade of interactions which impact bathymetry, tidal current regime and seabed sediment distribution and therefore the benthos. In La Rance (France), only the most tolerant organisms (the blue mussel *Mytilus edulis* and the ragworm *Hediste diversicolor)* survived the construction of the tidal barrage. After reopening the barrage, the carrying capacity of the intertidal zone increased and became more diverse (Kirby & Retière 2009). The vast changes experienced by the construction of the tidal barrage at La Rance have been used to predict environmental consequences of other proposed schemes such as a tidal barrage across the River Severn in southern England.

Tidal lagoons are under review in the U.K. Due to their scale, tidal lagoons could significantly alter tidal current regimes. Given that tidal flow rates have been demonstrated to have a strong effect on benthic assemblage composition (Clarke, 2006), these developments may have a substantial impact on nearby benthic assemblages. Designs could, however, include opportunities for ecosystem restoration. For example, developers of tidal lagoon areas in Swansea Bay have suggested that the development would create new sheltered environments with low wave action and high-water clarity, which would be suitable for the development of seagrass meadows. Seagrass meadows provide a valuable ecosystem service through nutrient cycling, fisheries production and provision of biodiversity (Calloway 2017) and are recognised as Annex I habitats under the EU Habitats Directive.

4.4.1.4 Biofouling and artificial reefs

Introduction of a hard substrate to an environment with a soft seabed creates new niches for species that would not otherwise occupy that environment. Infrastructure associated with wet renewable energy developments is typically constructed from steel and/or concrete, providing newly available surface area for colonisation by marine organisms (fouling fauna). Organisms that have been recorded on man-made structures include oysters and mussels, anemones, barnacles, macroalgae, sponges and soft corals , and can occur in large densities (De Mesel *et al*. 2015. This can attract other organisms such as mobile invertebrates (Krone *et al*. 2017), fish (Reubens *et al*. 2014), marine mammals and seabirds. In this way, renewable energy structures could be considered to be artificial reefs, associated with a greater density and biomass of fish when compared to surrounding soft bottom areas (Wilhelmsson & Malm 2008). In cases where nearby natural reefs exist in proximity to wave or tidal energy developments, biofouling communities on artificial structures may facilitate recruitment of reef-associated species into the area, boosting local populations. However, these structures may alternatively attract mobile adult organisms away from other habitats and act as aggregating devices rather than enhancing biomass production (Grossman *et al*. 1997). Current wave and tidal energy structures have not been designed to act as artificial reefs with specific conservation or ecological outcomes in mind. Present designs are unlikely to offer sufficient structural complexity to provide the diversity of ecological niches associated with natural reefs, and are unlikely to harbour as much biodiversity as more complex natural and purpose-built artificial reefs (Menge 1976).

Tidal lagoon developments represent a special case of infrastructure development where walls constructed around lagoons could provide new intertidal and subtidal habitat, attracting reef-associated species. It was suggested that the wall constructed around a proposed tidal lagoon in Swansea Bay could provide habitat for numerous hard-substrate species, and may eventually act as artificial reefs. The honeycomb worm, *Sabellaria alveolata*, is a species which forms biogenic reefs and has been reported in association with other coastal defence structures in the vicinity, and may also colonise the tidal lagoon walls. The lagoon will also offer opportunities to restore oyster beds to the area by constructing spatting ponds which promote settlement of oysters, a focus of nature conservation in the U.K. (Firth *et al*. 2013; Calloway 2017) and other OSPAR countries (Kerckhof *et al*. 2018; Christianen *et al*. 2018).

4.4.1.5 Non-native species (NNS)

The arrival of NNS is a threat to biodiversity and ecosystem functions and can have considerable socio-economic impacts (OSPAR 2017, Pederson *et al*. 2017). A new structure provides an opportunity for colonisation without existing competition from the indigenous population (Tyrrell & Byers 2007). Within the OSPAR region, the potential vectors for dispersal of NNS are through deliberate release of organisms for cultivation purposes (Pederson *et al*. 2017); discharge of water, sediment and biofilm from ships' ballast-water tanks (Drake *et al*. 2007); colonising the hulls of recreational and commercial boats (Ashton *et al*. 2006) or by 'rafting' on floating items over the sea surface to areas where they might not otherwise reach (Thiel & Gutow 2005; Coolen *et al*. 2016). On wave and tidal energy devices, it is possible that NNS may make up a substantial component of the biofouling community (De Mesel 2015), although studies on wind turbines in the north sea have shown that NNS are not as prevalent on artificial structures as predicted. Once settled on these structures, they can source propagules to other areas or simply migrate to nearby natural habitats (Adams *et al*. 2014). The installation of marine renewable devices together with other forms of development, such as aquaculture or offshore wind, may have created networks of artificial structures which act like 'stepping stones' for the establishment of new populations of non-native species (De Mesel 2015; Nall *et al*. 2015)..

The type of devices, their spacing and position on a structure influence the type and abundance of species which settle (Adams *et al*. 2014; Kerckhof *et al*. 2018). A tidal device, for example, provides a habitat from the seabed upwards to part way through the water column while a floating wave device mainly provides substrate at the surface of the water column, in addition to its anchor. At the site of a Dutch windfarm, many NNS were reported found on the intertidal surfaces but only one was found sub-tidally (Kerckhof *et al*. 2018). High levels of shipping traffic, as is often experienced during the construction and maintenance phase of a development, could facilitate further introduction and spread of NNS (Nall *et al*. 2015)

Once established, it is very difficult to eradicate NNS them. Therefore, the best mechanism for prevention of NNS is to instigate measures on the likely dispersal vectors, such as the International Convention for the Control and Management of Ships' Ballast Water and Sediments. Mitigation measures for reducing the risk of NNS should be considered by the industry and its regulators. Lists of NNS have been compiled by many countries (e.g. Nall *et al*. 2015; Bos *et al*. 2016) and organisations such as ICES (Pederson *et al*. 2017), which should be used as a baseline dataset for monitoring spread of existing NNS and future invasions.

4.4.2 Dynamic components

4.4.2.1 Biofouling and artificial reefs

Components of marine renewable devices are rapidly colonized by fouling fauna. This is largely discussed under 'static components' but an example specific to tidal is described here. Tidal devices require areas containing strong currents which are often characterised by tide-swept rock. A tidal device at the Falls of Warness tidal race site in the Orkney Isles acted as a localised artificial reef structure although there was evidence of temporal effects. It contained a higher biodiversity and species composition than a control site, which was related to the provisioning of shelter from fishing and natural predators (Broadhurst & Orme 2014). [will require cleaning of fouling]

In contrast to most tidal energy sites, wave energy sites are usually set in a greater diversity of environments, ranging from highly energetic sites along the west coast of Scotland to the more benign environment at Lysekil in Sweden. At Lysekil (Sweden), wave energy devices were characterised by an inceasing abundance and diversity as a consequence of an abundant and diverse fouling fauna, and the presence of hard bottom species. For other wave energy developments, the type of community present on the device is likely to depend on the environment in which the device is deployed (Macleod *et al*. 2016, Miller *et al*. 2013)

4.4.2.2 Hydrological changes

Presence of a moving structure in the water or on the seabed will serve to affect current patterns (discussed under 'static components'). Wave and tidal devices are designed to extract energy from the water column (discussed under 'energy removal').

4.4.2.3 Non-native species

Any hard substrates in the marine environment, whether dynamic or static, are colonised by epifauna including NNS (see 'static components').

4.4.3 Cables

Installation of cables to transport electricity back to the shore may have multiple but local impacts, depending on the length of cable and the substrates traversed. The installation will result in local habitat loss (limited with along the length of the cable) in the subtidal and intertidal, create noise and cause sediment resuspension. Once operational the cables will generate electromagnetic fields (EMF), noise and potentially heat. Cables exposed to the surface may attract biofouling including NNS (discussed under 'static components'). Overall, ecological impacts associated with power cables in the marine environment can be considered weak or moderate, although many uncertainties remain, particularly concerning electromagnetic effects (reviewed in Taormina *et al*. 2018). The environmental effects from wet renwables cables on seabed are not different from any other power cables. Cables suspended in the water column will be comparable to floating offshore wind devices.

4.4.3.1 Cable installation

The route of a cable back to shore may cover a variety of seabed substrates and habitats and require different methods to install it appropriately. Cables are usually buried under the seabed using techniques such as trenching with a cutting wheel in rocky sediments and ploughing or water jetting in soft sediments. Cables may require protection from fishing gear, anchors or wave action. If trenching is not possible, cables may be covered using methods such as rock-mattresses, ducting, or rock dumping. Such methods may cause a loss of benthic habitats. Back-filling the trench with a similar material may enable habitat recovery to some extent, but back-filling using a different material, such as rock dump on soft sediment, may result in development of an alternate community. A trenching plough varies in size between 2 and 8 m. In the intertidal zone, the use of mechanical excavators can disturb an area in the order of tens of metres. Alternatively, horizontal directional drilling (HDD) runs the cable 10 m below the surface and can be used for distances of between 70 and 1000 m. The disturbance is only limited to a few square metres at the exit points of the cable. Maintenance and decommissioning are expected to have similar effects as the installation (Taormina *et al*. 2018).

4.4.3.2 Resuspension of sediment

The disturbance of soft substrate, such as when using a trenching plough to install a cable, can lead to remobilisation of sediments (referred to as siltation or sedimentation) and accumulation of sediments on the seabed. Duration of sedimentation and turbidity in the water column are dependent on hydrological conditions, particle size and type and duration of deployment. Impacts of sediment resuspension are lower in coarser grained areas because these sediments usually sink out of suspension quickly. Dispersal models of calcareous sediment, suggest relatively short-term (60 hours) and localised effects (0.09% of an offshore wind farm area) (Didrikas and Wijkmark 2019).

Accumulation of sediment on the seabed can smother benthic organisms. Often communities of benthic infauna can recover on soft sediments, such as seagrass beds, where there is frequent natural variability in sedimentation (Vermaat, NSR., MD., JS, CM, N, S. & van Vierssen 1997) but recovery on hard substrates, such as kelp beds may be less likely (MacLeod 2014). Efficiency of filter-feeding in invertebrates such as *Pecten maximus* (king scallop) may be impaired (Szostek *et al*. 2013). Further research into effects of sedimentation specific to impacts of wet renewable devices are required together with thresholds that impacted species can tolerate.

4.4.3.3 Reef effects

The extent of biofouling and development of reef is dependent on the materials used to trench a cable, whether it has been left exposed on the surface and the neighbouring ecological communities. On hard substrates, reef effects are expected to be limited, but reef effects may be evident when a cable in a soft-sediment environment is protected by concrete mattresses or rock dump.). Communities typical of hard substrate have been reported on oil and gas pipelines in the northern North Sea (Harrald *et al*. 2018), and species richness increased with the habitat complexity by the material.

4.4.3.4 Electro Magnetic Fields (EMF)

Studies have demonstrated that there are behavioural and physiological effects on benthic organisms but further studies are required to assess the thresholds of priority species at important life stages in a given area. There are few studies on the sensitivity of benthic organisms and there have been no confirmed reports of changes in community composition or species assemblage changes as a result of EMF, noting this is difficult to determine given the other factors that lead to community dynamics. Examples include physiological and behavioural studies, reporting on the effect of EMF associated with cables, showing changes in the shape of immunocytes in the Mediterranean mussel (Ottaviani *et al*. 2002), a delay in the embryonic development of the purple sea urchin (Zimmerman *et al*, 1990) and subtle behavioural response in the American lobster, *Homarus americanus*, which stayed closer to the seabed and changed its direction of travel in response to EMF from the cable (Hutchison *et al*. 2018). Hutchinson *et al*. (2018) found a stronger response in the Little skate, *Leucoraja erinacea* as the skates travelled further, turned more often and were also closer to the seabed, which suggested greater exploratory behaviour. On the other hand, Bergström *et al*. 2012 concluded that the local increase in crustaceans and fish around artificial structures was more likely due to a reef effect rather than any potential known impact from electromagnetic fields. In order to evaluate the effects of EMFs on specific organisms, it is therefore desirable to measure and model EMFs and put into the context of Earth's natural magnetic fields and other EMFs in the area

Shielding of cables can aid enclosure of the direct electric field of the cable; however, the magnetic field component is still present and therefore can result in the generation of an induced electric field in the surrounding environment. Even small magnetic fields (in the microTesla range) can be detected by some organisms. Some elasmobranchs use electroreceptors to detect their prey and for orientation purposes (Hutchinson *et al*. 2018) and thus an EMF from a cable may be detected and result in a change in behaviour. Burial of cables increases the distance from the source to the organism in question, thereby reducing the peak intensity but this will not mask the EMF completely (Gill *et al*. 2014). In addition to burial depth, several other factors affect levels of EMF. These include cable materials (e.g. insulation, permittivity), number of conductors, cable configuration distance between cables, current flow and cable orientation relative to Earth's magnetic field. Ultimately, these factors are project and site-specific with relation to both the magnitude of the EMF emitted and the ecology of the area affected.

Species-specific effects have also been reported in benthic invertebrates such as crustaceans, bivalve molluscs, urchins and some benthic fish (Normadeaux *et al*. 2011, Hutchison *et al*., 2018). Few ecological studies on the consequences of EMFs exist and reports of ecological effects are mixed.

4.4.3.5 Heat emission

When a cable transports electricity, some of the energy is lost as heat which leads to an increase in temperature at the cable surface and its immediate environment. Water flow around the cable dissipates the heat but thermal radiation does emit heat to surrounding sediments even 10s of cms away. Heat emission is dependent on the physical characteristics and the electrical tension of the cable, the burial depth and the seabed type. For example, cohesive sediments will emit more heat than coarser sediments at an equal level of transmission and AC cables will emit more heat than DC cables (Taormina *et al*. 2018). Shielding the cable and cable burial will reduce the amount of heat reaching the surface sediments significantly. At the offshore wind array of Nysted, in an area of medium sand and a burial depth of 1 m, one 33 kV AC cable and another 132 kV AC cable resulted in a maximal temperature increase of 2.5 ^{0}C at a depth of 50 cm beneath the cable (Meißner 2006). It should be noted that MRE export cables are unlikely to be as large as those for offshore wind farms, and therefore heat emission will be smaller. However, such temperature changes near the surface sediments can modify chemical and physical properties of the substratum (Emeana *et al*, 2016), the oxygen concentration profile and the development of communities of microbes and bacteria. This may impact the physiology of benthic organisms living in the surface sediments (Taormina *et al*. 2018). Very few studies exist on the impact of thermal emission from cables on the benthic communities. Further experimental studies combined with modelling of thermal radiation are urgently required to fill this knowledge gap.

4.4.4 Sound

There has not been any report on the effect of sound related to the installation and exploitation of wet renewables in benthos. However, notable effects of sound on some benthic invertebrates have been reported. The physiology and behaviour of *Carcinus maenus* (the shore crab/ European green crab) was affected by the experimental playback of ship noise whichresulted in crabs being distracted from food, taking longer to shelter from predators and consuming more oxygen indicating potentially higher levels of stress. The effect was greater in larger crabs and they did not exhibit habituation to repeated levels of exposure(Wale 2013a,b). Changes in predator evasion behaviour were reported in the Caribbean hermit crab (*Coenobita clypeatus*) in response to boat motor noise (Chan *et al* ., 2010). This was related to noise distraction and preventing the crab from responding to a threat. Changes in feeding behaviour were also observed in American lobster (*Homarus americanus*) as a result of exposure to high levels of seismic sound (Payne *et al*., 2007). These studies suggest that high levels of anthropogenic sounds may put invertebrates such as these at risk of elevated predation and greater oxygen consumption potentially leading to risk of starvation. Further studies are required on invertebrates in response to sound intensities and frequencies at levels experienced during the operation and construction phases of wet renewable devices to correctly assess the .

4.4.5 Energy removal

4.4.5.1 Wave energy removal

WECs remove energy from waves and thus lower the impact of waves on the intertidal zone, which may result in a change in ecological communities. In areas off the coast of Scotland, which coincide with kelp forests, the clearing of kelp beds in order to facilitate the installation of WECs, may have the opposite effect. In Norwegian waters, forests of *L. hyperborea* reduce wave heights by up to 60% (Mork 1996). This loss in a coastline's ability to buffer waves may result in greater coastal erosion on shore, although the effect may be dampened by a reduction in wave energy from the WEC (MacLeod 2014). Installation of many wave energy devices may reduce the wave height of long waves thereby reducing stress on the seabed (Shields 2011). These changes in wave action may result in a shift away from *Laminaria hyperborea*, which prefers exposed areas to other species of seaweed, such as *Saccharina latissima* and *Saccorhiza polyschides*, which support a lower diversity (Burrows 2012).

Presence of a structure in the environment can change the physical processes operating around it and directly influence substrate type and composition of the ecological communities. Both tidal energy extractors and WECs are designed to extract energy from the sea and thus reduce current or wave energy respectively to the surrounding seas and shorelines. The effect of a single tidal energy extractor may be minimal but to make a significant amount of energy, an array of 10s to 100s may be required (Kregting *et al*. 2016) and collectively, these may cause a significant reduction in current velocity or wave energy on the environment. Several studies have investigated the effect of current reduction from tidal energy extractors but have found minimal ecological effects on the benthos (Kregting *et al*. 2016, Kregting *et al*. 2018,O'Carroll *et al*. 2017)

4.4.6 Contamination

As with many human activities, risks on contamination due to the introduction of wet renewables can be caused by accidents (ship collisions, spill of pollutants) related to the installation and exploitation of the devices. More specifically, additional risk is in the mobilisation of historic contaminants fromthe sediment (Matthiessen & Law 2002; Gill 2005; Cada, Ahlgrimm, Bahleda, Bigford, Stavrakas, Hall, Moursund & Sale 2007; Bonar, Bryden & Borthwick 2015) during installation, leaching of toxins from anti-fouling paint, and zinc contamination from sacrificial anodes (Matthiessen, Reed & Johnson 1999) being used to prevent renewable energy devices from corrosion (Momber 2011; Titah-Benbouzid & Benbouzid 2017). The sheath of cables may be made of heavy metals such as copper and lead that are potential sources of contaminants particularly if old cables are not removed. Heavy metals may dissolve and spread into the sediment and present a risk to sediment communities (Taormina *et al*. 2018).

4.5 Fish

4.5.1 Introduction

Immersed WECs may affect ocean and tidal currents, swell and sediment dynamics (di Milano *et al*., 2015), which may in turn alter fish habitat, create artificial reefs and act as fish aggregation devices.

Fish populations rely on essential habitats to carry out their life cycle. These are nursery areas, spawning grounds, and migratory roads that link these habitats together. Whenever possible, these essential fish habitats need to be avoided, spatially and/or temporally, when planning the deployment of WREs. Nursery zones exhibit higher concentration of juvenile fish than surrounding areas; they are defined by large food availability, high temperature and calm hydrodynamic conditions, which benefit growth of juvenile fish, and by shallow depth that provide shelter from predators and increases survival (Beck *et al*. 2001). Due to their coastal characteristics nursery habitats worldwide have already lost in quality and in quantity, directly affecting fish populations' abundance (Rochette *et al*., 2010; Sundbald *et al*., 2012). Likewise, spawning grounds are characterized by adult fish aggregation during the mating period although not all species exhibit such aggregation behaviour. The identification of spawning grounds rely on habitat modelling (Petitgas *et al*., 1998); they are therefore unequally identified for different species, with commercially valuable ones being better known than others (Gonzalez-Irusta et Wright, 2016a, 2016b). Both nursery and spawning grounds will be affected by changes in sediment properties of the seabed, nurseries are especially sensitive to hydrodynamic conditions (Overzee *et al*., 2015; Rochette *et al*. 2010). Depending on the species considered, migration routes between different fish habitats may cover an area the width of the English Channel (*e.g.* for sole *Solea solea*, Burt and Millner, 2008) or of the Atlantic Ocean (*e.g.* for bulefin tuna *Thunnus thynnus*, Galuardi *et al*. 2010). They are therefore difficult to delineate and to protect from anthropogenic pressure. At the scale of a WRE site development, little is known on the potential effects of EMF emissions and/or of physical obstruction to fish migratory routes.

4.5.2 Static Component

4.5.1.2 Aggregation – reef like effects

The 2008 OSPAR assessment of aggregation resulting from OWFs highlighted available evidence to suggest that some fish are likely to aggregate within an OWF array, although with a local redistribution of fish rather than an increase fish numbers (OSPAR, 2008), therefore this is of local interest but of low ecological significance. Possible implications for localised population structure are changes in foraging efficiency (the capture of prey by a predator), which controls both adult and juvenile survival and condition (Hutchinson, 1978). This may be of particular importance when considering species that show a degree of site fidelity such as Atlantic cod and pouting which have been found to aggregate around offshore wind turbine foundations (Reubens *et al*., 2013, Reubens*,* 2013b, Reubens*,* 2011). with large aggregations of juvenile Atlantic cod at the foundations of wind turbines during summer and autumn, during which they exhibited crepuscular movements relating to feeding activity, and pouting which were found to show a dietary preference for prey species that lived on the turbines. However to date, empirical evidence are lacking to infer on this type of effect of WECs.

Foraging opportunities appear to be the main attractor to marine megafauna, likely driven by an enhanced prey abundance, vulnerability and diversity (Benjamins *et al.*, 2015) with potential for MREIs to have a significant anthropogenic influence on marine ecosystems, and the positive and negative effects are likely to interact in complex and unpredictable ways with potential for trophic cascade effects (Witt *et al*., 2012). A modelling study carried out in the eastern Channel suggested that such trophic effect from OWF implementation would be of moderate impact for fish populations dominated by demersal species (Raoux *et al*. 2018).

Large fish that swim close to the surface (e.g. basking sharks) may also be at risk of collision or entanglement with underwater elements of WECs (Wilson *et al*., 2007) particularly where there are predator prey interactions. Our understanding of fish behaviour, which may contribute to these risks, around wave and tidal installations is limited - although studies such as those utilising DiDSON cameras (Viehman and Zydlewski, 2017), Echosounder (Williamson *et al*., 2017, Fraser., 2018) and video footage with ADCP survey techniques (Broadhurst *et al*., 2014) have provided an insight to fish behaviour around these technologies, further work is still required. It is therefore important that consideration be given to both fish aggregation and behaviour around wave and tidal renewables devices when undertaking environmental impact assessments, not only with regard to fish populations, but also with regard the effects that this may have on the ecosystem.

4.5.1.3 Fisheries

The Horizon 2020 MUSES project report (Kafas *et al.*,2018) considers fishing within offshore wind farms in the North Sea, providing multi-use perspectives from Scotland and Germany. This study utilises up to date information and publications and finds that establishing offshore wind farms in carefully selected areas can contribute to fisheries management initiatives (e.g. reduction of fleet segment in certain areas; promotion of sustainable fishing practices). Here consideration is given to factors that affect the commercial fishing sector, including both positive effects from the introduction of offshore wind farms (e.g. areas inaccessible to fishing which may increase the available biomass in the immediate surroundings with positive knock-on effect for fishing; offering opportunity for alternative gears such as creels to proliferate due to spatial restrictions to competing fleet segments (e.g. mobile gears) and negative effects (e.g. increase in safety risk from unburied / exposed sections of power cables, ; and various potential negative impacts on target species, such as those from underwater noise or electromagnetic fields). It is likely that many of these will be similar for wave and tidal developments, although there may be further impacts on the ability to utilise certain fishing gears, given the nature of moving components or to anchoring methods.

4.5.2 Dynamic component

4.5.2.1 Fish strike

Fish collision with MRE devices has been identified as an actual risk in the context of their commercial development. Existing knowledge is based on devices monitoring at test-sites facilities, modelling studies and on laboratory experiments.

A review of environmental effects of tidal energy development (Polagye *et al.*, 2011b) reported that the presence of singular or multiple tidal turbines in the marine environment will create the potential for a number of physical interactions with the water, seabed, and species or habitats in the surrounding area. Flume and field experimental data show high survival rates for fish passing through rivers or flumes with tidal turbines (Copping *et al.*, 2014). There are currently no large scale arrays of wave or tidal technology that would allow *in situ* field observations of blade strike on fish, indeed a number of investigators have cautioned that migratory fish passing through an entire hydrokinetic power project with large numbers of closely spaced turbines may not be able to completely avoid turbine interactions (Amaral *et al*., 2015), this may be either actively or passively. Bevelhimer *et al.* (2015) found some evidence that the presence of an operating turbine affected the swimming trajectories of fish, for the most part there was little evidence that individual fish made drastic changes in direction, location, or swimming speed in response to an operating turbine.

The findings of Hammar *et al.* (2014) indicate low risk for small sized fish. However, at large turbines (≥5 m), bigger fish seem to have high probability of collision, mostly because rotor detection and avoidance is difficult in low visibility. Risks can therefore be substantial for vulnerable populations of large-sized fish, which thrive in strong currents. This is supported by Amaral *et al*. (2015) whereby strike mortality has been shown to increase with the ratio of fish length to blade thickness with conventional turbines (i.e., for a given blade thickness, larger fish will have a higher probability of mortality) when strike speeds are sufficiently high to cause lethal injuries.

Recently, Copping *et al*. (2016) provided a thorough review of knowledge on the risk posed to fish from direct interactions with wet MRE devices, including blade strike. Gathered information originates from both computational models (Romero-Gomez and Richemont, 2014) and from laboratory trials (Amaral *et al*., 2015; Hammar *et al*., 2015). First of all, the literature review highlights the importance of visual capability in the avoidance of the structure, with failure to avoid rising from 0,1 in daylight to 0,75 in low light conditions. Collision risks for fish will also increase with turbine diameter and current speed, and is greater for larger fish due to lower agility ; Finally, a field case study recorded a loss of 0,65% of the fish population due to blade collision.

Therefore, the potential effects of blade strike should be considered in the case of commercial deployment of wet MRE devices, particularly for larger fish species that reside within the local area, or that migrate through the area. Further work is required on the potential effects of blade strike, including long term effects of injury.

4.5.3 Cables

4.5.3.1 Electromagnetic fields

The previous assessment on offshore wind, as provided in 2008, highlighted available evidence suggesting that the only impacts from electromagnetic fields of concern are changes to behaviour of electro-sensitive species and species sensitive to magnetic fields, and noted that the significance of such behavioural changes were unknown but potentially high.

Since 2008, there have been a number of reviews and studies undertaken that consider these impacts on decapods (e.g. *Homarus americanus* (Hutchison *et al*., 2018), *Cancer pagurus* (Scott *et al*., 2018)), elasmobranchs (e.g. *Leucorjaj erinacea* (Hutchison *et al*., 2018), Catsharks (Kimber *et al*., 2011), teleost fish (e.g. *Oncorhynchus tshawytscha* (Wymen *et al*., 2018), *Anguilla anguilla* (Kropp, 2013, Orpwood, 2015), Chinook salmon (Kavet *et al*, 2016) Atlantic salmon (Armstrong, 2015)) that have improved our understanding of the effects of EMF on those species, but there still remain many knowledge gaps.

It has been suggested that EMF from subsea cables could serve as an impediment to migration or movement for fishes moving near the seafloor (Claisse *et al*., 2015). Baring-Gould (2016) report that since the source of EMFs is the cable on the sea floor, benthic and demersal species, which are closer to the source, are considered more likely to be exposed to higher field strengths than pelagic species. However, the nature and the variety of wet renewable technologies means that some will have cables suspended in the mid-water column, potentially creating larger EMF emissions than devices that have buried cables (Freeman *et al*., 2013), which may interact with pelagic species or species that move between the demersal and pelagic environment. It should be noted that whilst cable burial is often referred to as a mitigation and has been used as such by offshore developers to reduce potential impacts this is not supported by any current studies as it assumes that the peak EMF needs mitigated. In general, the magnetic field passes through the seabed and the water column in the same way hence burial does not reduce it. What burial does is reduce the physical distance between the surface of the cable and the receptor organism on the seabed. Therefore the receptor will not encounter the maximum field but will encounter a field within the range of detection and within the range of potential effects (whether behavioural, physiological or other). For some receptors the EMF will come within the range of attraction, hence burial will not act as any mitigation, furthermore receptors that bury in the seabed will experience a different intensity. It is a complicated scenario which requires targeted studies to address the key potential effects. Note that some fish species such as plaice (*Pleuronectes platessa*) and flapper skate (*Dipturus* cf *intermedia*) have shown vertical movements within the water column (Fox *et al*., 2017) and may therefore also be affected.

4.5.3.2 Temperature

Electrical cables induce a temperature rise in the surrounding seabed substratum (Emeana *et al*., 2016; Meißner & Sordyl, 2006). Its impacts are considered negligible for fish due to their ability to move. However, fish eggs laid on the seabed may experience changes in hatching duration with detrimental consequences on larvae survival rates (Wood and McDonald, 1997).

4.5.3.2 Physical barrier

At a commercial-sized MRE site, dynamic cables in the water column create arrays that may act as a physical barrier to fish either passing or migrating through the area.

4.5.4 Sound

Pile-driving noise during construction is of particular concern as the very high particle motion levels (and for some species very high sound pressure) could potentially cause permanent or temporary hearing damage, prevent fish from reaching breeding or spawning sites, finding food, and acoustically locating mates (Mueller-Blenkle *et al*., 2010). It should be noted that whilst the installation of many tidal stream device designs will not require pile driving, drilling of anchor points and armouring of cables using concrete mats or rock-dumping are also potentially noisy activities (Nedwell *et al*., 2007) and that noise during the operational phase of wave farms is likely to have a less acute effect (Witt *et al*., 2012). In a review of environmental impacts for marine and hydrokinetic projects to inform regulators, Baring-Gould *et al.* (2016) report that although full-frequency sound propagation and animal receptor sensitivity is a complicated relationship, the likely impacts of measured radiated sound from single marine hydrokinetic devices are small and confined to limited areas near devices. Thus far, observed radiated sound levels are below those that are considered likely to cause physiological damage.

Effects of noise may depend upon the fish species with physiology, life stage or life event potentially affecting the impacts that underwater noise may have. There remain many key knowledge gaps on the topic, often requiring a precautionary approach to assessments or mitigation. There are however some interesting studies that provide some information on key areas of concern.

Highlighting the need to consider each species individually, Schramm *et al.* (2017) evaluated changes in fish position relative to different intensities of turbine sound as well as trends in location over time. Results varied depending on species with redhorse suckers (*Moxostoma* spp.) responding to sustained turbine sound by increasing distance from the sound source, Freshwater drum (*Aplondinotus grunniens)* showing a mixed response and largemouth bass (*Micropterus salmoides)* and rainbow trout (*Oncorhynchus mykiss)* not indicating any likely response. The importance of future research to utilize accurate localisation systems, different species, validated sound transmission distances and to consider different types of behavioural responses to different turbine designs is highlighted.

Mueller-Blenkle *et al*. (2010) undertook studies involving playback of offshore wind pile-driving noise to cod *(Gadus morhua)* and sole *(Solea solea)* held in large pens, movements of fish were analysed and sound pressure and particle motion were measured. It was found that there was a significant movement response to the pile-driving stimulus in both species at relatively low received sound pressure levels, for sole: 144 – 156 dB re 1µPa Peak; and cod: 140 – 161 dB re 1 µPaPeak and particle motion between 6.51x10-3 and 8.62x10-4 m/s2 peak. The results indicate that a range of received sound pressure and particle motion levels associated with pile-driving will trigger behavioural responses in sole and cod. It is noted that the exact nature and extent of the behavioural response needs to be investigated further and that future studies should investigate the response at critical times (e.g. spawning and mating) and the effects of pile driving on communication behaviour.

Popper *et al.* (2014) report few publications consider the effects of sound or vibration on fish eggs and larvae with two produced since the 2008 assessment for offshore wind. These focus on the effects of pile-driving noise on fish larvae, including common sole (*Solea solea*), herring (*Clupea herengus*), and plaice (*Pleuronectes platessa*) (Bolle 2012, 2014). The results of the larval studies showed no significant differences in mortality between the control group and the exposure groups for any of the species or larval stages. These studies did not, however, consider potential long-term effects.

Whilst the number of studies on the effects of noise on fish is limited, consideration of underwater noise within offshore renewables EIA has focused on sound pressure, although the need to consider particle motion has been raised. Nedelec *et al*., 2016 report that because the majority of aquatic animals' sense sound using particle motion, this component of the sound field must be addressed if acoustic habitats are to be managed effectively. Indeed, Popper and Hawkins (2018) find that currently, sound exposure criteria for fish and invertebrates have been derived from often poorly designed and controlled studies that have not taken account of the sensitivity of these animals to particle motion. It is also found that there have been very few measurements made of different fishes and invertebrates to particle motion (e.g. hearing thresholds at different frequencies, including infrasound) which makes assessment of the potential effects of particle motion difficult. In Scotland, applicants for offshore energy developments have recently been advised that consideration to particle motion should be given. This has resulted in desk-based reviews that generally find that particle motion propagation mapping in relation to offshore developments remains unfeasible and direct measurement is the only method of accurately determining particle motion at a given location (ICOL particle discussion document, 2017[11])

Sound pressure has, until recently been considered in accordance with the dBht (Species) metric proposed by Nedwell *et al.* (2007) that expresses the level of perceived sound pressure weighted by a filter that reflects the frequency-dependent sensitivity of hearing for the species of interest. Popper *et al.* (2014) considers the use of this metric and find that whilst the general concept may have some value in the context of behavioural responses by fish, its application and adoption requires far more scientific validation and the inclusion of those species that primarily respond to particle motion. They report that the application of weighting requires reliable measures of hearing sensitivity versus frequency (audiograms), but these are only available for a few fish species and that confidence in the validity of audiograms for many species is limited because of poor acoustic conditions surrounding the experiments, uncertainties as to whether particle motion or

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[11] https://www2.gov.scot/Resource/0052/00528521.pdf

* - dBht (Species) metric proposed by Nedwell *et al.* (2007) that expresses the level of perceived sound pressure weighted by a filter that reflects the frequency-dependent sensitivity of hearing for the species of interest

pressure is the relevant sound dimension, and the methodologies applied to determine thresholds. They suggest that it may be more appropriate to apply generalised weighting functions for defined functional hearing categories[12].

Particularly given the lack of species-specific audiograms, the guidance provided by Popper *et al.* (2014), that provides the categories and exposure criteria to assess impacts by, has recently been adopted for use within EIA for offshore renewables. Used in conjunction with updated sound propagation models, as considered by Farcas *et al.* (2016) that take into account bathymetry, sediment and water column data to provide better predictions of noise exposure, this provides the most up to date consideration of the potential effects of sound pressure on fish species. It should be noted however that propagation models are only as good as the input data. Indeed, Farcas *et al.* (2016) report that the most important factor to reduce uncertainty in noise exposure predictions is the sound level of the noise source with Frid *et al*. (2012) finding that many sources of underwater noise are yet to be well described by measurements, particularly novel sources such as wave and tidal energy devices. Lepper *et al*. (2011) has undertaken operational noise assessment on the Pelamis P2 system at the EMEC wave site but further studies will be required to take into account the varied technologies associated with the wave and tidal renewable energy industry.

As found by Baring-Gould *et al.* (2016), the biological implications of sound and particle motion remain highly uncertain; even though thresholds have been established for harassment for certain species, the biological response and behavioural context for sound emissions are still unknown. Identifying any direct biological responses to radiated noise from marine hydrokinetic devices continues to be difficult and a precautionary approach should be taken until key knowledge gaps are addressed.

4.6 Marine Mammals

4.6.1 Introduction

In general, there has been more concern about the effects of tidal energy developments on marine mammals than the effects of wave energy. This is primarily due to concerns about the potential for collisions between marine mammals and the moving parts of tidal energy converters. Most wave energy devices have not been considered to pose the same risks of injury or mortality, although there have been concerns raised about the potential for entanglement with mooring lines, including the effects of 'ghost fishing' where loose fishing gear can get tangled in mooring lines and pose a risk of snagging and drowning marine mammals. Most research on the effects of wet renewables on marine mammals has focused on the effects of tidal stream, horizontal axis rotor type turbines but the summary of impacts below will provide details about device type wherever possible. The Annex IV 'State of the Science Report' provides a useful summary of knowledge of the impacts of marine renewable energy devices on a number of receptors, including marine mammals (Copping *et al*. 2016). This section provides an update of information published since the publication of the Annex IV report.

Marine mammals are covered by a large degree of legal protection and all cetaceans are listed on Annex IV of the EU Habitats Directive as European Protected Species and as such are afforded protection from killing, injury and significant disturbance. A number of European marine mammal species are also listed on Annex II which requires the designation of protected sites for their protection.

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[12] *Popper et al. (2014)* categories

Fishes with no swim bladder or other gas chamber (e.g., dab and other flatfish). These species are less susceptible to barotrauma and only detect particle motion, not sound pressure. However, some barotrauma may result from exposure to sound pressure.

Fishes with swim bladders in which hearing does not involve the swim bladder or other gas volume (e.g., Atlantic salmon). These species are susceptible to barotrauma although hearing only involves particle motion, not sound pressure.

Fishes in which hearing involves a swim bladder or other gas volume (e.g., Atlantic cod, herring and relatives, Otophysi). These species are susceptible to barotrauma and detect sound pressure as well as particle motion.

4.6.2 Static component

Static components of wet renewable developments may lead to displacement of marine mammals or act as a barrier to movement. The impact of individual devices is not likely to be highly significant due to a relatively small footprint if the location is not particularly critical for marine mammals. However, at large number of devices the impact might become significant.

Aggregation of fish (see chapter above) could potentially lead to an attraction of marine mammals.

The evidence for either displacement or attraction is currently limited and any responses are likely to be device, location and species specific (Sparling *et al* 2013).

4.6.2 Dynamic component

4.6.2.1 Collision Risk

The risk of collision with the moving parts of MRE structures has been the primary environmental concern in relation to renewable devices and marine mammals, and as such, is the topic around which most research and monitoring effort has focused to date.

Much effort has gone into developing and refining quantitative predictive collision risk models which can be used in the environmental impact assessment (EIA) phase for proposed projects to provide an estimate of the degree of risk posed by tidal energy devices. Examples of these models developed specifically for marine animals include Wilson *et al*. (2014), Scottish Natural Heritage (2016) and Band *et al*. (2016). These efforts have largely focused on horizontal axis turbines although a number of bespoke collision risk models have been developed for other types of turbine. For example, both Booth *et al*. (2015) and Schmitt *et al*. (2017) have used 4D simulation approaches (3D model over time) to model the risk of a marine mammal colliding with the 'flying kite' Deep Green Minesto turbine. As part of the site wide environmental appraisal for the EMEC site in Orkney, Scotland, EMEC (2014) adapted an existing collision risk model to account for two additional device types: 1) An annular device with an open core through which animals could pass without collision, and 2) a device with contra-rotating rotors – i.e. two blades operating in reverse rotational directions.

Where marine mammals and a device occur in the same place, the probability of a strike will depend on the physical characteristics of the device (blade shape, size and speed), the characteristics of the animals (swimming behaviour, body size, approach angles), and the ability of animals to take evasive action to avoid a strike. Appraisal of modelling efforts (e.g. Band *et al*. 2016, Joy *et al*. 2018) have demonstrated that the predictions of these models are most sensitive to assumptions about the density of animals at a site, turnover, degree of avoidance/evasion and the consequence of collisions. In particular, this body of work highlights the degree to which animals can detect and avoid the moving parts of turbines remains uncertain, despite being one of the most important parameters required for more accurately estimating collision risk (e.g. Band *et al*., 2016, Joy *et al*., 2018).

For tidal lagoons/barrages where turbines are not situated in open water, and instead are enclosed in structures, the assumptions of random distribution and passage that most collision risk models rely upon are unlikely to hold and therefore these quantitative models may be less useful. Lagoon projects have additional concerns with entrapment and the enclosed nature of bulb[13] turbines in this setting mean that close-range evasion may be less likely. Bulb turbines are commonly used in conventional river hydro projects and have also been used in tidal range projects (e.g. the Sihwa Project in South Korea).

A number of efforts worldwide in recent years have been developing technology to provide new tools to monitor fine scale interactions around tidal energy devices in order to better characterise and understand collision risk. This includes application of telemetry (tagging), camera technology as well as active and passive acoustic monitoring (Hastie 2012, Hastie *et al*. 2014, Joslin *et al*. 2014, Polagye *et al*. 2014, Cotter *et al*. 2015, Sparling *et al*. 2016, Williamson *et al*. 2016, Williamson *et al*. 2017). So far there are only a limited number of studies where these technologies have been deployed at active tidal sites where data have been published (Sparling *et al*. 2017, Williamson *et al*. 2017, Malinka *et al*. 2018). A number of other devices including Nova Innovation turbines in Bluemull Sound, Shetland, various devices at the Scottish test centre EMEC as well as an OpenHydro turbine at FORCE, have had monitoring conducted around them using a variety of methods including multibeam sonar, underwater cameras and hydrophones, but so far little of the resulting data or information has made it into the public domain (Copping *et al*. 2016). An exception to this is Malinka *et al*. (2017) which reports on passive acoustic monitoring around an operational tidal turbine in Ramsey Sound in Wales. The period of turbine operation was relatively short so low sample size limited any analysis with respect to changes in porpoise behaviour or occurrence in relation to turbine operation. The study did reveal that the monitoring system successfully detected and localised porpoise

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[13] http://www.tidallagoonpower.com/tidal-technology/turbine-technology/

and dolphin vocalisations and that analysis of tracks suggested that individuals of both species were capable of detecting the structure and responding to it.

There has been some work on understanding consequences of collisions. Carlson *et al*. (2012), Copping *et al*. 2017) used a finite mesh modelling approach to predict the consequences of a killer whale being struck by an Open Hydro device as part of the assessment of the SnoPud project in Snohomish, Washington, US. The study concluded that a strike from the proposed Open Hydro device would not result in significant injury to a killer whale. Researchers at the Sea Mammal Research Unit in Scotland have carried out a series of collision trials, using a vessel-mounted turbine blade and seal and porpoise carcasses to mimic blade strikes. MRI scans of carcasses after the trials demonstrated that significant skeletal damage occurs at speeds above 6m/s (Onoufriou *et al*. in press). Below these speeds there was no evidence of skeletal trauma or obvious indicators of extensive soft tissue damage, although due to the difficulties in assessing soft-tissue damage such as bruising and tissue oedema in previously frozen carcasses, these soft-tissue assessments were not considered reliable indicators. Grear *et al* (2017) tested two mechanical properties of harbour seal tissues to better understand the ability of the skin and blubber to resist blunt force trauma. They found significant differences in response between test speeds and age of the animal, but not the orientation of the tissue relative to the strike. Tissues were either frozen or fresh, where in the case of the former, they found an increase in stiffness and strength of the skin, but there was no conclusive trend in blubber material properties. They concluded that frozen tissue, especially skin, cannot serve as an accurate replacement for testing fresh material. The other caveat to note, regarding these approaches outlined in Onoufriou *et al* (in press) and Grear *et al* (2017) is that there remains no reliable assessment of concussion as a result of blunt force trauma, which has the potential to be fatal (i.e. the animal loses consciousness and drowns). Copping *et al* (2017) combined the results of these tissue experiments with 1) estimates of the force that a tidal turbine blade might exert as a result of a strike and 2) simple estimates of the probability of encounters between seals and tidal turbines to attempt to quantify the level of overall risk to harbour seals. As with previous modelling exercises with little empirical basis, the authors concluded that more information on the behaviour of seals in the presence of a turbine and on the physical consequences of a strike were required to fully understand the potential for death or injury.

As well as monitoring around tidal energy projects and research to better understand the consequences of collision, there has been a focus on understanding baseline marine mammal use of tidal environments. An understanding of baseline functional habitat use is important to enable prediction of future risk, both from the perspective of collision risk but also to understand the potential consequences of any displacement. Until recently, studies of marine mammals in tidal environments were relatively sparse. A number of studies have been carried out using a variety of techniques; telemetry, passive acoustic monitoring (PAM) and visual surveys, to document the patterns of marine mammal usage in tidal environments.

Recent investigations into fine-scale porpoise density and use of the water column at a variety of tidal sites in Scotland have provided a substantial data set on porpoise depth distribution and underwater behaviour in tidal rapids that shows a large degree of variation between sites. These data and the methodological and analytical developments associated with them are summarized by Macaulay *et al*. (2015) and Macaulay *et al*. (2017). This study showed that the depth distribution of harbour porpoise was typically bimodal with maxima between 0–5 m and at 22-24 m, which was similar across sites regardless of differences in seabed depth, thereby providing insight into the potential separation of the porpoise from the depth of a tidal turbine blade. At the only site where measurements were taken at night (Kyle Rhea), porpoises were generally located near the sea surface, highlighting the importance of understanding diurnal variation in depth distribution for accurate prediction of collision risk (Macaulay *et al*. 2015). Complicating our ability to predict risk, Benjamins *et al*. (2017) demonstrated that the distribution of harbour porpoise can vary in tidal habitats at very small spatial and temporal scales.

Seal tagging studies have increased knowledge about the way that harbour and grey seals behave in tidal environments. In the narrow, tidal channel of Kyle Rhea on the west of Scotland, harbour seals are present between April and August and haul out during the ebb tide, then spend a high proportion of their time during the flood tide period actively foraging in the high current areas (Hastie *et al*. 2016). In this study between 50% and 100% of the seals' dives were to the seabed. Another telemetry study (Joy *et al*. 2018) revealed that in the tidal currents of Strangford Narrows in Northern Ireland, harbour seals predominately swam against the prevailing current during both ebb and flood tides. Similarly, as reported in Band *et al* (2016), harbour seals in the Pentland Firth also apparently predominately travelled against the current, where slow speed movement in the opposite direction of the current demonstrated that they were either swimming against the current or taking advantage of local scale tidal features and eddies to maintain station against the flow. Similar to the seals at Kyle Rhea, not all dives were to the seabed and there was a proportion of mid-water diving. This behaviour is in contrast to previous studies where most diving was thought to be to the seabed. In contrast to the behaviour of Kyle Rhea harbour seals, Lieber *et al*. (2018) reported that harbour and grey seals in the Strangford Narrows were more likely to be distributed on the periphery of high current areas where there is the highest vertical shear (i.e. the largest difference between fast moving surface and slower near-seabed flows). However, this was based on a limited sample of observations from a vessel conducting repeat line transect surveys over two days (one on a Spring and one on a Neap tide). As at-surface sightings without any correction for differences in sighting probability with respect to flow rates provide limited reliable evidence for preference or habitat use below the surface, it makes inference on the potential for collision risk with sub-sea devices difficult.

In the Netherlands, the Oosterscheldekering, a storm surge barrier that has five integrated tidal turbines, is sited in an area where harbour porpoise, grey seals and harbour seals occur (Leopold & Scholl, 2018). Prior to installation of the turbines (December 2015), the surge barrier was already in place (from 1986). Pre-installation of the tidal turbines, a telemetry tagging study of a small number of seals did show that individuals were passing through the storm surge barrier, suggesting that it was not acting as a physical barrier to movement; however, it is not known how they passed through the storm surge (e.g. at the surface, near the bottom, at slow or fast tides or during which phase of the tide). Counts from aerial surveys pre- and post-installation suggest that there is no significant deviation from the baseline trends in seals, but the authors acknowledge that there is a lack of statistical power, and that to detect a change, it would have had to be quite severe. Post-mortem studies of seals post-installation were undertaken on seven carcases; cause of death could not be determined for two, and for the other five, potential collision with the turbines was not the causal factor in their death. With respect to porpoise, population estimates and strandings records suggested that it was a stable population in the area. There were some indications of collision with objects in two stranded porpoises, which may have been the turbine, but other objects could include vessels or the storm surge wall. The initial work post-installation suggests that the impact of these tidal devices is minimal; however, caution should be exercised due to small sample sizes and low statistical power.

The implication of most of these studies is that it is difficult to generalise between species and sites in relation to marine mammal usage of tidal sites. Therefore, it is likely that some degree of site information will be required to characterise risk at sites of future development. Other aspects for consideration are, as devices start to become more viable in lower flow environments, could this potentially increase the risk of collision between marine mammals and operating MRE devices, whereby, in lower flow environments, fish could potentially aggregate around the device and therefore attract marine mammals (see below for more discussion of potential fish aggregation).

Despite these knowledge gaps regarding collision risk, particularly with respect to scaling demonstration sites to arrays, consideration is being given to the development of potential mitigation of collision risk. For example, the UK NERC funded MANTIS project is investigating sound propagation of acoustic deterrent devices (ADDs) in tidal environments to inform the potential for the future use of ADDs around tidal energy devices, should collision risk require mitigation.

4.6.3 Sound: Underwater noise

Underwater noise is also a concern, with the potential for noise generated during the construction and operation phases of marine energy projects to cause disturbance/displacement/barrier to movement. While small scale single devices may not be a concern due to the scale over such effects would operate, this is a concern for future commercial scale arrays where several hundred devices may be deployed across a site. Noise during construction (vessels, noise associated with installation procedures e.g. drilling, piling, cable laying) and the noise associated with turbine operation can be of concern, the latter because of the long-term nature of the operational phase. A growing number of devices have been characterised acoustically, reviewed in Robinson and Lepper (2013), as well as Schmitt *et al*. (2018) and Lossent *et al*. (2017), more recently. Listening Space Reduction (LSR) has been quantified for two devices, based on in-situ recordings of the quarter-scale Minesto Deep Green sea kite and the full-scale SCHOTTEL IST horizontal axis turbine, for harbour seal and harbour porpoise (Pine *et al*. 2019). Pine *et al* (2019) define LSR as the listening space decay that occurs around the tidal turbines, and uses the audiograms of the species of interest to assess the LSR; these are presented as distances at which a percentage of LSR occurs. Their findings demonstrated that the LSR was influenced by type of turbine, species and season. As might be expected, for both species, LSRs were highest during winter, which was characterised by low ambient noise conditions. In the summer, higher levels of ambient noise effectively ‘masked’ the noise from the device.

Malinka *et al* (2018) reported on passive acoustic monitoring at a tidal turbine in Wales. This study revealed that the device would have been clearly audible to marine mammals in the vicinity, largely as a result of regular, loud ‘clanging’ noises from metal flaps designed to reduce the flow of silt into the turbine frame. Another distinctive and clearly audible mechanical source of noise came from the hydraulic pumps used to rotate the turbine into the current. In contrast, other studies (Ben Wilson *et al*, EU MaRVEN project) recorded very quiet levels. Quiet enough to suggest that there is a potential risk of mammals not being able to detect a potential hazard.

Empirical studies of responses to date have indicated small scale, local avoidance in some cases to construction and operational noise (Savidge *et al*. 2014, Hastie *et al*. 2017, Joy *et al*. 2017, Joy *et al*. 2018) with other studies revealing a diminishing response over time (Robertson *et al*. 2018). In the case of the latter, Robertson *et al*. (2018) reported a response in harbour porpoise to playbacks of turbine sound that decreased over time: porpoises were initially observed responding at ~300 m from the playback location during trial 1, which decreased to 100 m during trial 2 and disappeared in trial 3. Unfortunately, during this study, a vessel was only present during playbacks and not during control periods so the observed responses could be due to the playbacks, the vessel presence or a combination of both. Differences between studies and species is likely related to the level and nature of the sound and the hearing ability of species. Some response to operating turbines may be good (to reduce collision risk) but over large areas, even small-scale responses could result in habitat exclusion, displacement and/or barrier effects. There has been no pile driving involved in the installation/construction of wave or tidal MRE devices to date, but its future use cannot be ruled out, particularly if the use of gravity bases reduces due to cost reduction measures. This would pose a more significant concern, particularly at the scale of large commercial arrays.

4.6.5 Cables

4.6.5.1 Electromagnetic fields

The potential impacts from electromagnetic fields are changes to the behaviour of electro-sensitive species and species sensitive to magnetic fields. Marine mammals are generally thought to be relatively insensitive to electric fields but are likely to be sensitive to magnetic fields, particularly species that undergo large scale migrations (Fisher *et al*, (2010). However, the occurrence and nature of any effects of EMF from MRE cables are unknown for marine mammals. If large scale behavioural changes were to occur, the significance of such changes may be potentially high. However, given the current scale of deployment, and the highly mobile nature of marine mammals, this has not been a big concern, particularly in the context of the potential for more direct impacts through collision. However, if they did respond to cables then mammals would more likely detect EMFs from DC cables than from AC cables, because the former characteristically have static B-fields (similar to the geomagnetic field) and they are of higher intensity than the latter. The likelihood of exposure will also be a function of the depth of the water above the cable and the depth of swimming because field strength dissipates with distance (Copping *et al* 2016).

4.6.5.2 Mooring lines and Cables: Entanglement

The entanglement of marine mammals in mooring lines and cables has been raised as a potential concern, but there is very little evidence upon which to draw any conclusions. According to a review and risk assessment published by Scottish Natural Heritage (Benjamins *et al*. 2014), entanglement does not pose a significant threat to marine mammals. Large baleen whales were considered to be at a higher risk of entanglement but this could be minimised by ensuring tension is applied to make sure cables are taut. There was a further concern that if derelict fishing gear becomes entangled in moorings, this would pose a risk for a wide range of species (including fish and diving seabirds). Benjamins *et al* (2014) called for a more in-depth assessment of the snagging risk and subsequent presence of derelict gears amongst moorings. However, no such further review has been carried out.

4.6.5.3 Aggregation of fish leading to indirect effects

Indirect effects mediated through effects on prey – e.g. if significantly affecting fish behaviour, may influence marine mammals indirectly. For example, see the section above on potential for fish aggregation as a result of the static component. In this respect, the key issue for marine mammals is that any fish aggregation may result in attraction to the structure for marine mammals, but evidence so far suggests that these effects are mainly seen at slack tides, which may mean risk to marine mammals is not increased, in this instance.

4.6.6 Eurasian Otters

The impact of MRE on Eurasian otters (*Lutra lutra*) has not been well studied. When assessing the environmental impact of proposed MRE projects, if likely to be present in the vicinity, otters will be included in the assessment, typically under the 'terrestrial and intertidal ecology heading'. Like cetaceans, otters are European Protected Species (listed on Annex IV) so are afforded strict protection. The potential for impact is likely to be restricted to disturbance and habitat loss from onshore and intertidal construction and O&M activities, although if devices were deployed near to shore, there is the potential for collision related impacts, given that coastal otters are assumed to forage up to 100 m from the shore, diving to depths exceeding 10 m (Conroy & Jenkins, 1986, McCafferty, 2004).

4.7 Seascape/public perception

There is limited research on the how WEC or TEC might affect seascapes or how public perception might impact their deployment (Devine-Wright, 2011; Bailey *et al*, 2011; Dreyer *et al*., 2017), with the vast majority of studies investigating public acceptance of offshore wind energy (Wiersma & Devine-Write, 2014). However recent work has set out how a research agenda for understanding public perceptions of tidal energy might be set out (Jenkins *et al*., 2018).

Public acceptance is recognised as an important issue in the implementation of renewable energy technologies and in meeting energy policy goals (Devine-Wright, 2007). A recurring theme considered to be a conditioning factor in the public's perception and attitude towards offshore energy projects is the power they have to provoke oppositions by strongly affecting the concept of place attachment of individuals. This complex and emotive relationship between the public and marine areas may pose some challenges to MRE in general, and to wave energy in particular (Bailey *et al*., 2011). The attachment relationship of communities to the ocean is also argued by Arnold (2004) who concluded that people tend to associate the sea to familiar shorelines and care less about offshore areas due to limitations of personal interactions and lack of deeper sea knowledge. It would be expected that the distance and visual impact reduction factors (inspired by the expression “out of sight, out of mind”) associated with ocean energy projects would increase the social acceptance of this type of energy source compared to wind power projects and other sources. However, concerns do not diminish, and existing research is not yet sufficient to establish the effects of the “out of sight, out of mind” concept on individuals' perceptions. As wave and tidal devices are likely to be offshore and do not project far above the sea surface, they are unlikely to be seen from the shore and thus visual impacts are usually considered less significant when compared to those of offshore wind energy. However, the visibility of devices will be dependent on their distance from shore and the height from which they are viewed by the preceptor, e.g. they may be more visible from a cliff than a beach. Visual impacts of tidal barrages and tidal lagoons can be large, with often strong negative perception from these developments. The visual impact of wave power technologies should also not be overlooked. One of the concerns raised is the signalling light and buoys used to delineate exclusion zones around the sites, which may disrupt the place attachment of the local people (Devine-Wright, 2009).

Onshore infrastructure such as sub-stations can also have effects that endure throughout the lifetime of the wave or tidal projects. These can occur from shore to sea and vice versa and may be linked to different phases of the project. Visual impacts from installation or decommissioning may have an effect on heritage assets, though it will only be of limited duration. During operation where the device itself is submerged but is supported by structures that remain visible, or when the device is present at the surface during operation, visual effects on the existing environment have been recommended to be assessed (Firth, 2013).

The degree to which a WEC or TEC scheme has visual impacts on the existing environment is strongly related to the appearance of the proposed devices and supporting structures. At sea, steps have to be taken to ensure that devices and structures are visible to other sea users for safety of navigation and to enable legitimate activities to carry on. Visual impact mitigation measures that do no compromise safe navigation requirements such as micro-siting (relocation of devices on site), screening or paint schemes that can reduce the visibility of devices and structures might be applied (Firth, 2013).

Apart from visual impact concerns WEC and TEC public acceptance focuses mainly on the following areas:

1. Marine space use conflicts: concerns over displacement of fishing activity, loss of fishing income and compression of fishing effort into areas outside of the developments (West *et al*., 2009; Simas *et al*., 2012) have been raised at multiple developments. Fishers in Ireland expressed similar concerns, however, they also felt the MRE and fishing could co-exist provided development was managed appropriately (Reilly, O’Hagan & Dalton 2014).
2. Environmental impacts: potential adverse effects on marine flora, fauna and habitats are some of the top concerns listed by stakeholders. Marine mammals and seabirds are the most relevant species mentioned to be affected (Simas *et al*., 2012);
3. Reduction in access to or availability of wave resources typically for leisure activities such as surf. At Wave Hub, stakeholder interviews revealed that initial concerns by local surfers (e.g. Stokes, Beaumont, Russell & Greaves (2014)) were calmed by the report from Millar *et al* (2007) stating there would be no impact on surf waves, however, concerns still existed by surfers from outside of the area (West, Bailey & Whithead 2009). Local surfers suggested potential benefits from WEC schemes could include better wave data to improve local surf forecasts;
4. Effects on tourism: test centres are located in peripheral coastal regions, so offer the prospect of diversification of employment from low-skill and low-wage traditional industries, such as tourism, agriculture and fishing (Bailey *et al*., 2011). In most cases, however, there is the important proviso, especially among local business representatives, that existing interests would not be adversely affected (Simas *et al*., 2012);

Research in UK island communities found generally positive attitudes to MRE, but these were strongly shaped by place-related values including seascape, and conflicts with these values was often a major reason for concerns about MRE (de Groot, 2016).

In general, it can be concluded that stakeholders expressed support for the concept of ocean energy. The main reasons for this are reducing fossil-fuel dependence, tackling climate change and reducing dependence on energy imports, which is an evident opinion from stakeholders surveyed in southern European wave energy test centres. The main concerns identified for all test centres, meanwhile, were conflicts in shared-use sea areas, visual impacts and the potential adverse environmental effects of wave-energy projects (Simas *et al*., 2012, Dreyer *et al*, 2017). Engagement of key stakeholders at an early stage has been identified as an important strategy for mitigating concerns (Johnson *et al*., 2015).

4.8 Birds

4.8.1 Introduction

A bird will be exposed to a potential pressure if there is an overlap between its foraging, resting, or breeding areas and the area where a wet renewable energy development is constructed. Spatial and temporal overlap can be quantified at different scales, from whether birds are present in the general region of a development, to whether birds forage at a development site. For underwater devices (e.g. tidal stream devices) potential exposure to a pressure requires quantification of diving parameters, e.g. whether birds spend time at the depths where a tidal stream turbine operates (see e.g. Madsen *et al*. 2013).

Several reports and papers have reviewed the potential impacts of wet renewable developments on birds (*inter alia* Clark *et al*. 2006, Furness *et al*. 2012, Grecian *et al*. 2010, Langton *et al*. 2011, Copping *et al*. 2016), most of these focussed on tidal turbines and wave energy convertors (WECs), including a relatively recent international report (Copping *et al*. 2016). However, very little empirical data exists on the actual impacts of wet renewable developments and devices on birds, thus potential impacts are currently mostly inferred from knowledge of bird ecology and behaviour and from known impacts of other marine industries (e.g. offshore windfarms and shipping).

The risk of negative impacts on birds from wet renewable developments can be quantified from the probability of an interaction between a bird and a wet renewable device occurring in combination with the severity of any negative consequence of such an interaction (ranging from direct mortality to a temporary increase in energy expenditure) (Furness *et al*. 2012, Copping *et al*. 2016). It is important to distinguish between actual risk, i.e. where a risk is quantifiable from empirical observation and/or empirically tested models, and perceived risk, i.e. where uncertainty and lack of empirical data mean that risk cannot be accurately assessed. For wet renewables many risks currently fall into this latter category owing to a lack of sufficient empirical data to quantify risks, with additional data some risks may be possible to 'retire' if found to be biologically insignificant (Copping *et al*. 2016).

For wave and tidal stream devices it is primarily diving bird species that are at risk from negative impacts, while for tidal range developments a broader range of species could be impacted (inter alia waders, gulls, and waterfowl). Further, species may be impacted indirectly through ecosystem changes (e.g. in prey species abundance and distribution) or directly by devices including elements above the sea surface. A wider range of species may be disturbed by vessel traffic and general activity throughout a development cycle from construction, to operation and maintenance, and to eventual decommissioning.

The likelihood of marine birds to be significantly impacted by offshore renewable developments has been classified using sensitivity scoring approaches which predict the risk of a species being negatively affected by a development by using a combination of an understanding of a species ecology and behaviour (Furness *et al*. 2012, Wade *et al*. 2016). As the potential impact pathways differ between development types a single sensitivity score for a species cannot be used. Furness *et al*. (2012) produced sensitivity scores for species occurring in Scottish waters separately for tidal stream turbine devices and wave energy convertors (WECs). Species classified with a high vulnerability score for tidal turbines in Scotland was black guillemot, razorbill, shag, common guillemot and great cormorant. Great northern diver red-throated diver, Atlantic puffin, black-throated diver and little auk was classified with a moderate vulnerability score to tidal turbines. Only three species were classified with a high vulnerability score for wave energy devices in Scotland (Furness *et al*. 2012). Similar approaches have been applied for sensitivity to offshore wind farms in both German and Scottish waters (Garthe & Hüppop 2004, Furness *et al*. 2013) and such approaches could be applied in other areas for new development types in future. Sensitivity scores for birds have not been calculated for tidal lagoons and barrages, however the species likely to be affected has been reviewed (Clark 2006). Wader species and waterfowl were considered to be at risk due to habitat change, changes in intertidal areas and saltmarshes.

Pressures can lead to lethal effects (e.g. collision mortality) or sub-lethal effects (e.g. displacement from foraging areas and disturbance). Pressures may also act indirectly through changes to physical processes affecting prey species thus affecting foraging birds. Some pressures may act independently while others may interact, e.g. diving birds could forage more in a development area if prey abundance increased (e.g. through a reef effect) but this could increase exposure to other possible pressures (e.g. collision with tidal turbines).

The level of impact is likely to increase the larger the scale of development, an array of multiple devices will generally pose a higher risk to a population than a single device or small-scale development (Copping *et al*. 2016). For instance, displacement effects are expected to be minor for a single WEC device but may become significant for larger scale arrays. How risk scales up from developments with a single or a few devices to large scale commercial arrays is unclear, this is especially case for dynamic devices (Copping *et al*. 2016).

While there is a good general understanding of the range of potential risks, there remains large uncertainty on the likelihood of impacts and of the potential severity of impacts. As such, it is important that robust monitoring programmes are setup when developments are constructed, such that uncertainty can be reduced to inform the permitting of later developments. This model is applied in Scotland through the policy of 'Survey, Deploy and Monitor' (Scottish Government 2016), where consents for developments include conditions for post-construction monitoring in addition to pre-construction pre-consent site surveys to collect baseline data on how birds use an area.

Pre-construction surveys for wet renewables should ideally both classify to what extent a proposed development site is used by birds (i.e. bird densities) and more fine-scale associations of activity of birds in relation to the type of development proposed. For tidal stream developments understanding fine scale habitat associations (tens-hundreds of metres) may allow fine-scale siting of devices to avoid tidal current features used by diving birds, such as high turbulence and downward vertical current features used by several pursuit-diving seabird species (Wagitt *et al*. 2016). Similar principles may be relevant to other wet renewables, such as WECs, though this remains to be explored.

As sites for wet renewable developments are often inshore, shore-based observations may be chosen to determine baseline distributions of birds, however such surveys may produce biased estimates of bird distributions (Copping *et al*. 2016, Wade 2015, Waggitt *et al*. 2014), especially for sites with fast tidal currents (Waggitt *et al*. 2014). As such it is advised that if shore-based observations are made, viewsheds should not exceed 1.5 km (Wade 2015). Alternatively, boat or aerial surveys may be used to provide observations that are not biased against birds more distant from shore.

Monitoring of interactions between birds and wet renewables is increasingly possible with underwater platforms developed incorporating detection systems including acoustic sensors and cameras (Williamson *et al*. 2016, 2017, Polagye *et al*. 2014). While biologging devices including GPS tracking and dive loggers are improving our understanding of the foraging behaviour of birds including during dives, which can help inform on e.g. collision risk (Masden *et al*. 2013).

There are other possible stressors but these are unlikely to lead to significant bird population-level impacts for bird species: EMF, Energy Removal, and chemical discharge or leaching (Copping *et al*. 2016).

4.8.2 Overview of possible impacts of wet renewables on birds

4.8.2.1 Static Component

Wet renewable developments may lead to displacement of birds. Some species will avoid the structures, while for others attraction may occur. Birds may be attracted to manmade structures at sea as artificial roosting sites (Dierschke *et al*. 2016, Tasker *et al*. 1986), while at night and under low visibility condition artificial illumination may also attract birds (Montevecchi 2006). Attraction could increase the likelihood of other stressors impacting birds by increasing the density of birds in an area or increasing foraging activity. At a demonstration WEC device an autonomous camera system recorded several species roosting on the device, including black guillemot (Jackson 2014), a pursuit diving species potentially vulnerable to underwater collision.

For devices including parts above the water surface birds could also collide during flight (Grecian *et al*. 2010). Collision between flying birds and rotor blades of offshore wind turbine generators has been a major concern for offshore wind development (e.g. Masden & Cook 2016), however it is likely to be a significantly lower risk for wet renewables as parts above the surface will likely be stationary or moving at much slower speeds than the rotors of wind turbine generators.

4.8.2.2 Dynamic Component – collision risk

Underwater collision between diving birds and wet renewable devices may lead to direct mortality. However, to date no collision between a wave and tidal device and a seabird has been observed (Copping *et al*. 2016). Unlike marine mammals, birds will generally only dive when foraging (flightless species such as penguin being absent in the OSPAR area), thus collision is only likely to occur where wet renewable developments overlap with areas where seabirds forage or undertaking evasive behaviour. Devices that have parts moving at speed underwater are most likely to lead to mortality in diving birds, thus tidal stream devices (both kites and turbines) are the main types of wet renewable developments considered to pose a collision risk to birds.

The potential for collision mortality is assessed through collision risk modelling (CRM), for on- and offshore wind turbine generators CRMs are quite well developed and are widely applied in environmental assessments for proposed wind developments, though uncertainty remains on likely levels of collision mortality owing to uncertainty in avoidance rates, flight heights, and flight speeds (Masden & Cook 2016, Johnston *et al*. 2014, Masden *et al*. 2015). For tidal current devices there is much greater uncertainty and no consensus on likely levels of mortality nor of how collision risk should be quantified.

For tidal current devices a variety of CRMs have been developed with three main approaches: Band adapted (Davies & Thompson 2011), SRSL encounter model (Wilson *et al*. 2007), and exposure time population modelling approach (Grant *et al*. 2014). Collision risk arises from a combination of tidal device parameters (e.g. turbine swept area), site usage by diving birds, bird diving behaviour, and bird biometry. Alternative CRM modelling approaches use different sub-sets of these parameters to quantify collision risk.

Tidal stream devices usually rely on strong tidal currents, so are likely to be sited at relatively inshore sites often proximate to headlands and islands. The probability of a species interacting with tidal stream devices is dependent on an overlap in habitat use with tidal stream device development sites. However, general overlap between bird distribution and development sites may be insufficient to suggest risk as to have a risk of collision with tidal turbines, birds must be diving at the location of turbines and to the depths where these operate, i.e. sharing the same microhabitat (Waggitt & Scott 2014, Waggitt *et al*. 2016). For the MeyGen tidal turbine development (Orkney, Scotland, UK) several species of seabird were observed in the development area (MeyGen 2012), yet more detailed observations suggest that only a subset of these species were regularly diving in the area (Wade 2015).

Collision risk models usually include a flux component, that is the number of birds moving through an area over a given time period. For flying birds this may be a realistic simplifying assumption, but for diving birds this may be less applicable as these dives are usually performed in a repeat sequence as the birds have to surface to breath and/or handle prey captured. Some species may use a strategy termed ‘tidal conveyor’, diving into a current and drifting downstream with the current, then flying up current before diving again (observed by Roger 2014 cited by Copping *et al*. 2016), such behaviour has the potential to increase probability of interactions with sub-surface wet renewables for individual birds foraging in a development area.

Traditional CRM models attempt to predict the potential number of birds colliding with devices, and ultimately mortality, which is often based on a set of assumption which are not very flexible. Individual Based Modelling, IBMs (also called Agent Based Modelling, ABM) modelling approaches have a potential to become important CRM tools as they look to increase our mechanistic understanding of seabird collisions with tidal current devices. Chimienti *et al*. (2014) modelled how diving behaviour may vary depending on prey distribution, the seascape, and the presence of underwater devices. Such approaches may allow CRMs to be refined to incorporate more realistic models of diving behaviour. These modelling approaches, when informed by empirical studies of diving behaviour (e.g. Chimienti *et al*. 2016, Masden *et al*. 2013), may reduce uncertainty in CRM parameter values and quantify variation around parameter means. Such information could allow for underwater CRMs to provide collision estimates with a measure of uncertainty in a similar way to recently developed stochastic CRMs for aerial collision of seabirds in flight with offshore wind turbine generators (Masden 2015, McGregor *et al*. 2018).

4.8.2.3 Sound

Noise may arise from vessel traffic, installation, operation, and decommissioning activities (Copping *et al*. 2014). Other than operational noise most noises will be short in duration, though may be significant, e.g. if piling is required for device foundations. Existing measures of operational noise levels from both wave and tidal devices suggest that operational noise levels are unlikely to cause injury or significant behavioural effects (Copping *et al*. 2016). As diving birds operate both above and below water these species are exposed to both underwater and aerial noise.

The vulnerability of marine birds to acoustic disturbance is poorly understood. Experimental work suggests some diving bird species may have relatively good underwater hearing (Johansen *et al*. 2016) though to what extent hearing is used by diving birds during foraging is not well understood. African penguin (*Spheniscus demersus*) were recently found to change their foraging areas during periods of intense underwater noise (seismic surveys) (Pichegru *et al*. 2017), which suggests that other pursuit diving seabird species could potentially be vulnerable. Similar to marine mammals, there are two main potential impacts for sound, damage to hearing either temporary or permanent (temporary or permanent threshold shift respectively) and changes in behaviour, e.g. displacement from an area, or avoidance/escape flights, as well as potential indirect impacts such as changes in the distribution of prey in response to noise. Acoustic disturbance is expected to be more detrimental when birds have limited mobility, e.g. if flightless during moult or for adults accompanying flightless young (i.e. they cannot fly to escape). Operational noise also has the potential to be a positive effect by providing an audible cue that may lead to birds increasing avoidance of a development, and thus reducing the probability of interacting with a device (Inger *et al*. 2009).

Research priorities in regards to birds and wet renewables could therefore be:

- Collection of data on collisions and behavior around wet renewables
- Improved collision risk modelling based on individual based/agent based modelling
- Effect of noise on bird behavior

4.9 Others

4.9.1 Turtles

Five species of sea turtle are known to occur within the OSPAR Regions: loggerhead (*Caretta caretta*), green (*Chelonia mydas*), hawksbill (*Eretmochelys imbricata*), Kemp's Ridley (*Lepidochelys kempii*), and leatherback (*Dermochelys coriacea*). The two species of main concern within the OSPAR Regions are C. *caretta* (OSPAR Commission 2009b) and *D. coriacea* (OSPAR Commission 2009a). There are no turtle nesting sites along the Western European margin.

C. caretta are found in high numbers around the Azores (Region V) but are also occasional storm-blown vagrants to the Celtic Seas (Region III) and the Bay of Biscay/Iberian Coast (Region IV). This restricted distribution of *C. caretta* may limit the impacts on this population to those which are likely to result from installations developed in those waters.

The occurrence of *D. coriacea*, however, is more widespread within the North Atlantic, and thus all waters of the OSPAR Maritime Area are considered part of their natural foraging range, with the offshore waters of Region IV suggested as an area of high use within the NE Atlantic (Eckert 2006; Doyle, Houghton, O'Súilleabháin, Hobson, Marnell, Davenport & Hays 2008).

4.9.1.1 Static Component

There is limited evidence of risk of animals colliding with static components of MRE (Copping, Sather, Hannah, Whiting, Zydlewski, Staines, Gill, Hutchinson, A, Simas, Bald, Sparling, Wood & Masden 2016). This should hold true for sea turtles, due to their slow swimming speed and apparent ability to easily avoid static structures. Dense arrays of MRE devices may result in the avoidance of areas previously utilised by sea turtles, excluding them from habitats used for foraging or causing displacement along migratory routes (Copping *et al.* 2016). Static components of MRE devices, such as foundations, may promote the growth of reef habitat. This could increase foraging opportunities for turtles such as *C. caretta* and *D. coriacea* (Duarte, Pitt, Lucas, Purcell, Uye, Robinson, Brotz, Decker, Sutherland, Malej, Madin, Mianzan, Gili, Fuentes, Atienza, Pagés, Breitburg, Malek, Graham & Condon 2013; Makabe, Furukawa, Takao & Uye 2014; Barnette 2017). In addition, arrays of MRE devices may create de-facto marine protected areas, thereby reducing the pressure on sea turtles from fisheries bycatch (Copping *et al.* 2016). Overall, there is a lack of knowledge on how turtles specifically may be impacted by static components of individual or arrays of MRE devices.

4.9.1.2 Dynamic Component

There is some risk of collision with the moving parts of MRE devices. It is possible sea turtles could become trapped, maimed, or otherwise harmed in the dynamic components of a tidal device, e.g. the blades of a submerged turbine (Copping *et al.* 2016), which may lead to mortality. According to Copping *et al*. (2016), there has been a general lack of concern expressed regarding the potential for harm from the dynamic components of a WEC device. However, it is possible that those devices with a large surface expression and oscillating parts could pose a collision risk to sea turtles.

4.9.1.3 Cables

Sea turtles have been shown to use the Earth's magnetic field in navigation (Lohmann, Putman & Lohmann 2012; Brothers & Lohmann 2015). Cables carrying electric current (and which thus emit an electromagnetic field (EMF)) may have the potential to disorientate sea turtles, particularly hatchlings (Copping *et al.* 2016). This may be of greater relevance for floating MRE devices, which may have electric cables hanging down through the water column. However, there is very little research published on the impacts of EMF on turtles, and thus the level of impact is uncertain.

The physical presence of mooring lines, anchor lines, or power cables may all act to directly entangle or entrap sea turtles within an MRE device array (Copping *et al.* 2016). Furthermore, the possibility of “ghost” fishing gear becoming caught on cables could result in the indirect trapping and subsequent drowning of sea turtles. However, there is a general paucity of literature on interactions between sea turtles with wave and tidal energy devices, and limited knowledge of such interactions with offshore wind farms (Copping *et al.* 2016).

4.9.1.4 Sound

Piniak *et al*. (2012) demonstrated that the hearing sensitivity of *D. coriacea* overlaps with the frequency and source levels of many anthropogenic noise sources, including seismic airgun arrays, drilling, low-frequency sonar, shipping, pile driving, and operating wind turbines, with the greatest sensitivity shown to be between 100 – 400 Hz in water and 50 – 400 HZ in air. Martin *et al*. (2012) found a very similar degree of sensitivity in *C. caretta*, with the greatest sensitivity also recorded at 100 – 400 Hz. This finding was supported by Lavender *et al*. (2014).

While little to no research has yet been carried out to determine the physiological and behavioural responses of sea turtles to noise pollution (Popper, Hawkins, Fay, Mann, Bartol, Carlson, Coombs, Ellison, Gentry, Halvorsen, Løkkeborg, Rogers, Southall, Zeddies & Tavolga 2014), it has been suggested that turtles may be impacted by the masking of auditory cues (Copping *et al.* 2016). Sea turtles have been observed exhibiting an escape/startle response when in the vicinity of active airgun arrays (Deruiter & Larbi Doukara 2012). In their review of publication patterns on the impacts of anthropogenic noise on marine life, Williams *et al*. (2015) noted that sea turtles remain understudied, with “only two abstracts solely mentioning them”.

4.9.1.5 Energy removal

The removal of kinetic energy on a large scale has the potential to impact a diverse range of physical processes. Any change to the flow of water may result in changes to primary production, with cumulative effects on higher trophic levels. Of significance for sea turtles would be any change in the occurrence, density, and abundance of species upon which they predate, e.g. various jellyfish species. This may act to alter the behaviour of turtles, possibly causing them to be attracted or to avoid MRE device arrays (Copping *et al.* 2016). Doyle *et al*. (2008) described contrasting the recorded movements of two *D. coriacea*, tagged off the south west of Ireland: T1 immediately travelled south to feeding grounds west of Africa via Madeira and the Canaries; T2 travelled south to the Bay of Biscay, where it remained for 66 days. The movement of the latter coincided with a mesoscale eddy feature (evident from satellite imagery), which may have proven to be a rich feeding area. Thus, it is not unlikely that leatherback turtles could be attracted to areas where jellyfish (their main prey) begin to occur more regularly, in denser numbers.

4.9.1.6 Contaminants

Again, a lack of turtle specific information exists within the literature. It possible that bioaccumulation of toxins could occur for turtles which prey on species of jellyfish. This could be of particular relevance for near shore tidal devices which may use stronger biocides or antifouling paint), and those toxins could then be absorbed by organisms upon which jellyfish predate. It is also possible that leakage of lubricants, fuels, hydraulic fluids or other liquid hydrocarbons could cause acute damage to turtles (suffocation, poisoning) on a local scale (Copping *et al.* 2016). These threats are extrapolated from those which may exist for marine mammals and fish.

4.10 Cumulative impacts

For the purposes of this section, cumulative effects are all effects resulting from human activities in the marine environment that have the potential to impact the key receptor groups included in this report.

From the sections above, it is clear that there is an emerging knowledge base that helps to inform assessment of the potential effect of the deployment of marine energy devices on many receptors. This may relate to the effects from a single MRE development or the cumulative effects from a number of similar developments. However, marine renewable energy devices are likely to be installed in marine areas where a range of other activities (fishing, aggregate extraction, oil and gas exploration, navigational dredging, building of artificial hard structures for coastal defence, harbour walls) are already in place. Hence, receptors may be subjected to cumulative impacts from stressors originating from all ongoing activities.

Cumulative Effect Assessment (also: Cumulative Impact Assessment) – holistic evaluations of the combined effects of human activities and natural processes on the environment (Stelzenmüller, Coll, Mazaris, Giakoumi, Katsanevakis, Portman, Degen, Mackelworth, Gimpel, Albano, Almpanidou, Claudet, Essl, Evagelopoulos, Heymans, Genov, Kark, Micheli, Grazia, Rilov & Rumes 2018) – theoretically offer a tool to investigate the integrated effect of multiple human activities on the ecosystem. However, Cumulative Effect Assessment (CEA) is currently an umbrella term for a broad range of methodologies, driven by multiple drivers (Willsteed, Gill, Birchenough & Jude 2017), suffering from in inconsistent terminology (Stelzenmüller *et al.* 2018). Rather than discussing the problems and solutions in the entire scientific field of CEA methodologies, this section focuses on CEA in relation to renewable marine energy devices. Currently, most of these devices are offshore wind farms, but the principles and guidelines are assumed to be similar to CEAs associated with the wet renewables described in the current report.

Willsteed *et al*. ((Willsteed *et al.* 2017), in an attempt to establish common ground for CEAs of marine energy developments, listed 6 considerations to be taken into account when conducting CEAs: (1) temporal accumulation of cumulative effects; (2) spatial accumulation of cumulative effects; (3) endogenic and exogenic sources of pressures; (4) ecological connectivity; (5) receptors at the centre of assessments and (6) purpose and context of the CEA. In a review of 9 CEAs conducted for 9 offshore wind farms in the UK, (Willsteed, Jude, Gill & Birchenough 2018) found that the spatial aspect of activities and pressures was dealt with more comprehensively then the temporal aspect. Applied spatial boundaries were straightforward to understand and applicable to the receptors identified for the assessment. Temporal boundaries scored less well, as they followed the assumption that temporal pressures exist for the duration of the activity and did not consider the temporal aspects of pressures relative to the receptors.

Endogenic pressures are those created within the system that can be managed, while exogenic pressures are emanated outside the system or operate at scales beyond the system (Elliott 2011). Climate change is such an exogenic pressure, and should to be taken into account within CEA, as it can interact with endogenic pressures, given the time scales of MRED lifecycles. However, it is currently unclear how potential impacts of climate change can meaningfully be included in CEA.

Ecological connectivity refers to the fact that ecosystem components are interacting (i.e. changes in prey abundance can affect food-web properties). This requires a shift in CEA, where currently the effect of stressors is assessed to unlinked receptors in the environment. The road forward is to move away from assessing effects on individual species and take a broader perspective considering the existing connections between ecosystem components and how they affect the functioning of the marine environment. Establishing clear cause-effect relationships, cascading through different components of the ecosystem can be a way forward (Dannheim *et al*. 2019).

There is currently a need to place receptors at the core of assessments due to the widely acknowledged potential risk posed to them by MRE developments, either in isolation or cumulatively. Generally, CEAs follow a stressor-led approach, assessing how a single stressor from one development and the same stressor associated with another activity in a proximal development would affect a receptor (Duinker, Burbidge, Boardley & Greig 2012). However, it should be acknowledged that receptors experience a wide range of stressors, originating from a single or multiple activity. Hence, CEAs should investigate the combined effect of these stressors on the receptor, which in turn can lead to improved consistency between CEAs as it will enable the development of unified metrics that can be applied to a receptor or an ecological function (Segner, Schmitt-Jansen & Sabater 2014).

Recent CEAs (Inch Cape, 2018) relating to the potential effects of offshore windfarms in the UK on seabirds have estimated the collision mortality for each individual wind farm across all seasons, apportioned these estimated collisions to appropriate reference populations e.g. breeding Special Protection Areas or regional populations (Furness, 2015), and assessed the population-level consequences of those cumulative effects using Population Viability Analyses (NNGOffshoreWind, 2018). Population level consequences have also been estimated based on effects derived fromindividual based models (Warwick-Evans *et al* 2018). Similar approaches to estimating cumulative effects could be used for other receptors e.g. marine mammals, pressures e.g. disturbance due to underwater noise or displacement, and marine activities e.g. fisheries bycatch.

However, the focus on individual receptors and stressors runs the risk that interactions between them may be ignored, and potentially significant cumulative effects overlooked. This risk increases as the number of MRE developments and other marine activities increases, as may the relevance of larger scale processes such as hydrodynamics and habitat 'stepping stones' for NNS. To mitigate against such risks, CEA approaches should be developed that allow multiple receptors, stressors and marine activities to be included, and allow more integrated, ecosystem level assessments to be undertaken. Such integration is being considered across receptors under the reporting of indicators of Good Environmental Status under the Marine Strategy Framework Directive. It will also facilitate integrated management to achieve sustainable use of the marine environment (Elliott 2011).

Taking into account the considerations listed by Willsteed *et al.* 2017 to produce an ecosystem level CEA is not straightforward. First of all, the marine ecosystem needs to be characterised on four dimensions to describe the connectivity between geographically separated areas exhibited by highly mobile marine species and by marine species with large dispersal distances of eggs and larvae (Barbut, Grego, Delerue-Ricard, Vandamme, Volckaert & Lacroix 2019).

Secondly, despite a large body of research there is still a lack of clear understanding on the link between ecosystem structure and functioning in the marine realm (Daam, Teixeira, Lillebø & Nogueira 2019), but recently MRED related cause-effect relationships resulting in altered ecosystem functioning have been mapped (Dannheim *et al*. in press). However, the interactions between ecosystem components and multiple (exogenic) effects can be complex, (additive, synergistic or antagonistic (Crain, Kroeker & Halpern 2008)) and non-linear, requiring deeper consideration (Stelzenmüller *et al.* 2018). Both Stelzenmüller *et al*. (2018) and Willsteed *et al*. (2017) suggest making use of trait-based information on receptor organisms to identify and predict multiple stressor effects. Public databases collecting and sharing trait information (i.e. Biotic – www.marlinac.uk/biotic, WoRMS – www.marinespecies.org) are considered crucial for the development of such trait-based approach in CEAs (Stelzenmüller *et al.* 2018).

As a consequence of the lack of data, CEAs suffer from uncertainty (Stelzenmüller *et al.* 2018). Regarding CEA for MRED developments, uncertainty is often considered as the uncertainty about the likelihood of other future activities and whether them to include or exclude in the CEA (Willsteed *et al.* 2018). However, other sources of uncertainty include a lack of (good-quality) data and knowledge, low predictive ability of ecosystem behaviour, natural variability and changing policies (see (Stelzenmüller *et al.* 2018). Taking them into account using standardised methodology (Stelzenmüller, Vega Fernández, Cronin, Röckmann, Pantazi, Vanaverbeke, Stamford, Hostens, Pecceu, Degraer, Buhl-Mortensen, Carlström, Galparsoro, Johnson, Piwowarczyk, Vassilopoulou, Jak, Louise Pace & van Hoof 2015) would support decision-makers in making determinations of environmental risk associated with the developments of MRED (Masden, McCluskie, Owen & Langston 2015) There is also the risk that CEAs may incorporate precaution at multiple steps within individual project assessments, and that combining this precaution (‘precaution stacking’) within a CEA may result in unrealistically high cumulative effects being estimated. A method for appropriately accounting for uncertainty is therefore required to provide informative CEAs. There is also the risk that CEAs may incorporate precaution at multiple steps within individual project assessments, and that combining this precaution (‘precaution stacking’) within a CEA may result in unrealistically high cumulative effects being estimated. A method for appropriately accounting for uncertainty is therefore required to provide informative CEAs.

5. What can we do next?

It seems clear that wet renewable energy devices will be installed at increasing speed. While these devices will reduce CO_2 emissions associated with energy production, they also have the potential to affect multiple components of the marine environment. These effects may be association with installation, operation or decommissioning , while emerging technologies will create new challenges in understanding and mitigating against their potential negative effects.. These challenges will require question-driven monitoring, pro-active research, and science-based marine spatial planning to enable the installation of wet renewables in an environmentally sustainable manner.. Below, a number of emerging topics for the future are discussed.

5.1 Strategic monitoring to understand wet renewable effects.

The potential effects of MRE upon a small number of receptors are currently key constraints to the development of the sector. As discussed in the previous sections, to date marine mammals, seabirds and fish have been identified as critical issues across a number of geographic locations.

Gathering data that are able to address the key knowledge gaps that exist for theses receptor are however, extremely challenging. This is due to the difficulties in accessing study sites, the conditions that may be encountered at the sites, the still evolving monitoring technologies required, the level of expertise required to gather or analyze the data, the high degree of spatial and temporal variation in distribution and abundance of highly mobile marine species, and the very low occurrence of some events of interest e.g. avoidance behaviour or collision events.

Data collection for the purpose of assessing the effect of deployed MRED (and other human activities) can suffer from having poorly defined questions and data collection protocols, and can be poorly resourced. As such, they may provide little useful information in relation to both effects upon individual receptors and ecosystem-scale related changes, and are therefore considered ‘Data Rich, Information Poor – DRIP’ (Wilding, Gill, Boon, Sheehan, Dauvin, Pezy, O’Beirn, Janas, Rostin & De Mesel 2017). Data collection must be question driven, focus on the key metrics of relevance, and should be at the relevant spatial scales (often beyond the local scale of the MRED) (Wilding *et al.* 2017). It should be driven by established cause-effect hypotheses (Dannheim *et al*. in press) and should be fit for contribution to quantitative models mapping the vulnerability of ecosystem components to specific pressures (Stelzenmüller *et al.* 2018).

The challenges identified above would be best addressed via strategic research and monitoring activities that are focused where the opportunities to address the issues are greatest. This would also provide the benefit of shared resource burden across multiple parties.

5.1 Towards assessing the effects of wet renewables using the ecosystem approach

The ecosystem approach is based on the application of appropriate scientific methodologies focused on levels of biological organization which encompass the essential processes, functions and interactions among organisms and their environment. This approach differs from most of the current studies investigating the effect of wet renewables, as they are generally targeted towards investigating the effect of the device on a single receptor of interest. However, interactions between renewable energy devices and ecosystem components can cause changes that are of a sufficient scale to change ecosystem services provision, particularly in terms of fisheries and biodiversity and, change the distribution of fish, birds and mammals through changes in the trophic linkages (Wilding *et al.* 2017).

To our knowledge, there is no evidence yet on how wet renewables affect the provisioning of ecosystem services to society. Pioneering work on the effect of offshore wind farms on the provisioning of marine ecosystem services showed that these offshore wind farms have mixed impacts across ecosystem services, with negative effects on the sea-scape and the spread of non-native species and positive impacts on commercial fish and shellfish (Hooper, Beaumont & Hattam 2017). However, the same authors stressed the need for a better understanding of long-term and population effects of offshore wind farms on species and habitats, and how these are placed in the context of other pressures in the environment. Such increased understanding will not be achieved through the execution of standard monitoring programmes, designed for assessing change in selected receptors after the installation of the renewable energy devices. Many monitoring programmes lack clarity and rigour, may be at inappropriate temporal or spatial scales, and therefore do not contribute to an increased understanding of the interactions between marine renewable energy devices and the marine ecosystem at relevant scales (Wilding *et al*. 2017).

Most monitoring programmes focus on assessing structural aspects (density, diversity, occurrence, etc) of selected component of the marine ecosystem and no not focus on how the structural changes can affect important ecosystem processes underpinning the provisioning of ecosystem services (Duncan, Thompson & Pettorelli 2015). An increased understanding of the effect of marine energy renewable devices on the provisioning of ecosystem services will require the mapping of the multiple direct and indirect effects on ecosystem processes, and how these processes relate to the delivery of ecosystem services (Figure 26, Causon & Gill 2018)

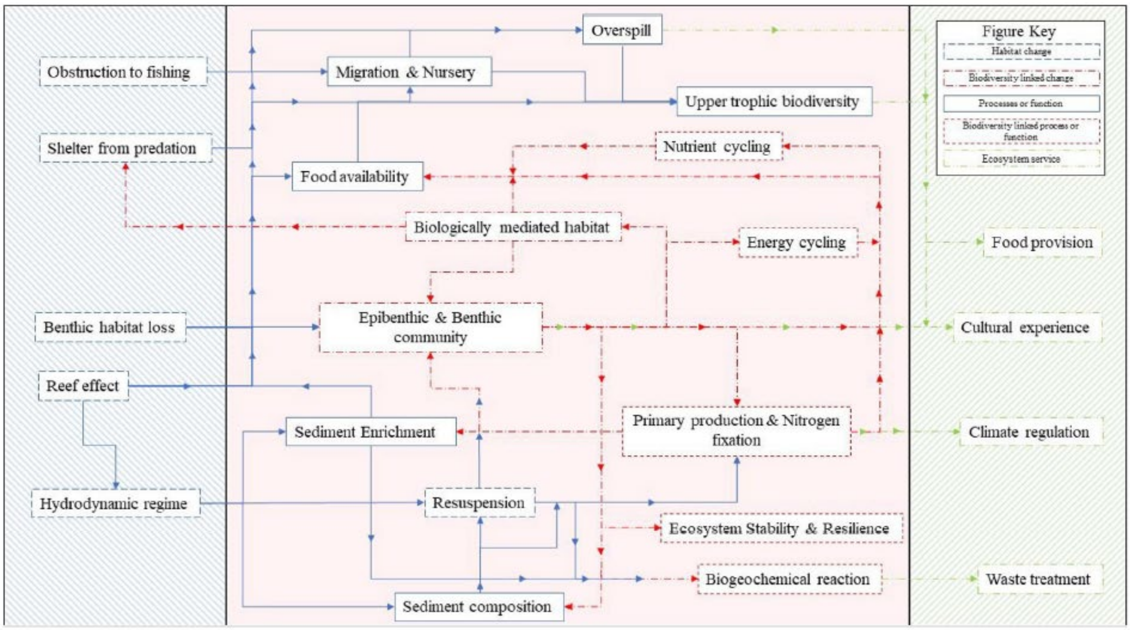

Figure 26 Biodiversity mediated linkages between habitat modification, ecosystem processes and functions, and the provision of ecosystem services in relation to offshore wind farm structures. Zones represent direct changes (blue hatching – left), secondary changes effecting processes and functions (red – centre), and linked ecosystem services (green hatching – right) (Causon & Gill 2018)

Based on such mapping, cause effect relationships can be formulated (Dannheim *et al*. in press) that can serve as the basis for hypothesis-driven research (versus monitoring), at relevant temporal and spatial scales and yield useful data to assess relevant ecosystem-level change (Wilding *et al*. 2017), which will at the same time help overcome the current problems (uncertainty due to lack of relevant data) faced in the Cumulative Effect Assessment procedures (see above).

Such data, reflecting changes in the biotic and abiotic components of the ecosystem can be used to further develop or fine-tune ecological and oceanographic models to allow a sound estimation of the effects of multiple wet renewables (and future technologies, see below), in combination with other human uses, on the health of the marine ecosystem, and it's capacity to deliver ecosystem services.

In order to progress, harmonized (response variables, methodologies,) data collection, data storage and exchange procedures should be established, and a coordinated research agenda developed. Setting up regional databases where relevant information (generated by both academia and industry) is compiled and made accessible to researchers, policy levels and industry would be a major step forward (Wilsteed *et al*. 2017). Similarly, a coordinated cross-border and multidisciplinary research agenda should be established .

5.3 Data availability

In order to facilitate research that addresses the key knowledge gaps and the undertaking of CEAs, data should be made freely available through easily accessible interfaces, including web portals (e.g. Emodnet, www.emodnet.eu).

5.2 Decommisioning

Regardless of the technique applied, all offshore renewable energy installations in the OSPAR region will need to be removed during decommissioning at the end of their productive life (Smyth *et al*. 2015, Fowler *et al*. 2018). The impact of this removal has not been included in the review performed here. The activities performed during decommissioning and removal, will result in changes to the environment. For example, vessel traffic will increase temporarily, seabeds will be disturbed when objects are removed from the sediment and artificial habitats will change back to natural habitats. To date, only a few renewable energy farms have been decommissioned (Gourvenec 2018) and little consideration has been given to the best environmental options for decommissioning of offshore renewables (Smyth *et al*. 2015). A recent study showed that, although aiming to restore pre-existing conditions via removal, full removal is not considered the best option in all situations by many scientists (Fowler *et al*. 2018). Alternatives include toppling of structures, leaving parts of the foundation *in situ*, as well as relocation to a central location (Smyth *et al*. 2015, Fowler *et al*. 2018).

There have been a number of calls for the application of a multi-criteria decision analysis to provide the best solution after considering all options and their environmental, social and economic impacts (Fowler *et al*. 2015, Gourvenec 2018), which again should be based on the best scientific evidence possible and taking into account the provisioning of multiple ecosystem services to society. Such an analysis and review of decommissioning options should be undertaken.

5.3 Emerging technologies

In addition to the wet renewable technologies included in this report, technologies are emerging that might in the future be applied offshore in the OSPAR region. These technologies are are at various readiness levels, with some still in the proof-of-concept phase or laboratory validation while others will be tested with offshore pilots in the near future. They include floating offshore solar farms, in which existing solar technology is developed for projects on lakes and for protected sea sites such as lagoons and harbors. The first offshore floating solar pilot for the OSPAR region is currently being prepared for the North Sea in The Netherlands (Bellini 2018). Energy production is expected to be 10-15% higher than land-based solar systems due to the reflection and cooling effect of the seawater (Grech *et al*. 2016, Sahu *et al*. 2016). Additional technologies include salinity gradient power generation, at locations where a gradient between saline and fresh water is present. Electricity is generated using membrane-based techniques such as pressure-retarded osmosis and reverse electro-dialysis (Jia *et al*. 2014). Applications of the technique have been limited to only a few projects outside controlled environments (REDstack 2019). Ocean Thermal Energy Conversion (OTEC) relies upon temperature gradients to generate electricity (Vega, 2002). Combinations of techniques, such as wave energy combined with energy storage systems, is expected to arise in the future. The Ocean Grazer, for example, combines wave energy converter technology with on-site energy storage, around wind turbines. The intention is to increase energy production while storing excess energy from both the turbine and wave system as liquefied hydrogen (Ocean Grazer B.V. 2019).

For many emerging technologies it would be premature to develop guidance at this stage. Instead a watching brief should be maintained and guidance provided as and when required.

6. Conclusions

Although the bulk of the renewable energy generated by marine devices is produced by offshore wind farms, it is clear that wet renewables will be increasingly installed in the marine environment in the near future. The installation of wet renewable devices will lead to changes in both the abiotic and biotic components of the marine ecosystem, though the scales and significance of these changes are currently not clear.

To date, the key receptors constraining the deployment of MREs have been marine mammals, seabirds and fish. However, the evidence base available to quantify actual effects on these receptors is limited. This is due to the difficulties encountered in collecting relevant data, and in some cases the lack of clearly defined post- installation monitoring. Strategic approaches to deliver effective research and monitoring to address these key knowledge gaps is therefore recommended.

Whilst the focus for CEAs has been on individual receptors and pressures as these have been identified as key constraints for developments, there is a clear need to understand the how the interactions between receptors and pressures may influence the conclusions of CEAs. This need will only increase as the number of MRE and other marine activities increases.

The suggested way forward is to move towards receptor-based assessments that consider both the ecological links between the abiotic and biotic components of the marine ecosystem and the feedback links between the different biotic components. This should be achieved by hypothesis-driven research, taking into account the link between structural components and the functioning of marine ecosystems, as this ultimately determines the provisioning of marine ecosystem services to society. This calls for cross-border coordination and cooperation in setting standards on data collection, sharing and setting research agendas.

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