Future Science Brief

Nº 9 April 2023

European offshore renewable energy

Towards a sustainable future

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This Future Science Brief is a result of the work of the European Marine Board Expert Working Group on Offshore Renewable Energy. See Annex 1 for the list and affiliations of the Working Group members.

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Foreword

As I write this foreword, the 27th Conference of the Parties (COP27) is coming to an end in Sharm el-Sheikh (Egypt), with unfortunately no progress on how greenhouse gas emissions will be reduced, although the dedicated fund to repair the loss and damage already suffered by the countries of the South is a good start. As confirmed by the Secretary-General of the United Nations, Antonio Guterres, in his final address to COP negotiators: *"Clearly, this fund is not enough, but it is an essential political signal to rebuild the broken trust"*.

Indeed, people are starting to understand that the climate crisis is real, and science is urging action to achieve the Paris Agreement to limit global warming to well below 2°C above pre-industrial levels and the more ambitious target to limit temperature increase to below 1.5°C. In December 2019, to respond to this challenge, the European Union launched its Green Deal aiming to transition to a fairer, healthier, and more prosperous society, whilst guaranteeing a healthy planet for future generations. According to the 2019 EU Climate Law, the EU aims to reduce its emissions by 2030 and become climate neutral by 2050, with significant ambition for the expansion of offshore renewable energy. The solutions outlined in the EU Green Deal can only succeed if people, communities, and organisations are all involved and take action. There is an urgent and immediate need to significantly reduce carbon emissions and move towards a carbon neutral society. Renewable energy can potentially supply the energy needed to support an ever-growing population and increasing industrialisation. There are many different offshore renewable energy resources including wind, waves, currents, tides, and thermal (the temperature gradient between warm surface waters and cold waters at depth). The extraction of these resources is at different levels of development, ranging from the research stage to that of commercial exploitation, particularly for offshore wind.

While offshore renewable energy resource extraction is less mature than that on land, it is an attractive area for growth. To achieve the EU Green Deal vision, European offshore renewable energy capacity must increase 30-fold. However, there is a lot of competition for maritime space, and offshore renewable energy development must be conducted in line with EU nature conservation and restoration requirements. It is therefore imperative that the development of the European offshore renewable energy sector is conducted in a responsible, equitable and sustainable manner, and in collaboration with relevant parties.

In 2010 the Marine Board – ESF published a Vision Document on Marine Renewable Energy that made recommendations for the development of marine renewable energy in Europe. In 2020 the European Marine Board felt it was timely to revisit the topic, and a new EMB Working Group on Offshore Renewable Energy kicked off in June 2021 and have worked with efficiency and enthusiasm to deliver this informative Future Science Brief.

On behalf of the Members of the EMB, I would like to thank the Chairs and Members of the Working Group (Annex 1) for their hard work and dedication in producing this Future Science Brief. I would also like to thank the external reviewers for their valuable input. I thank the EMB Secretariat for supporting the Working Group and coordinating the production of this document, namely Paula Kellett, Britt Alexander, Ángel Muñiz Piniella, Ana Rodriguez, Sheila Heymans, and Jana Van Elslander.

Gilles Lericolais
Chair, European Marine Board
April 2023

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Executive summary

Considering the Ocean environment as a potential source of energy is not new. Renewable energy research and technological development have been looking at the Ocean for some time. The first offshore wind farm in Europe was installed by Denmark in 1991 in the Baltic Sea and decommissioned in 2017[1].

The 2010 EMB Vision Document 2 on Marine Renewable Energy (Le Boulluec *et al.,* 2010) presented the research challenges and opportunities for a new energy era in Europe. It offered an overview of how renewable energy from the Ocean can provide innovative solutions to tackle future energy challenges and to fully contribute to the EU 2020 vision[2]. It provided a baseline of information representing progress in marine renewable energy development at that time.

The signing of the Paris Agreement[3] in 2015 brought significant public and political attention to the wider issues of climate change, and solutions such as offshore renewable energy that could support the achievement of the Paris Agreement.

In 2019 the European Green Deal[4] outlined Europe's vision to become the first climate-neutral continent with no net emissions of greenhouse gases by 2050. There is also an interim aim to *"reduce net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels"*. The related 2020 'EU Strategy to harness the potential of offshore renewable energy for a climate neutral future' presented the key role for offshore renewable energy in achieving this vision.

The global economic and geopolitical situations in 2022, including the recovery from the COVID-19 pandemic, increasing fuel prices, and the war in Ukraine leading to questions of energy security, have further increased the impetus on governments to accelerate the move away from a reliance on oil and gas as energy sources. Offshore renewable energy sources should play a key role in that move.

In light of these geo-political, economic, and environmental drivers, this Future Science Brief outlines the state-of-the-art in knowledge on offshore renewable energy (ORE). It also highlights key research needs to help us fully understand the implications of such an energy transition.

The main recommendations are to:

- Address misalignment in policy, and the approaches and practices used in different EU Member States that hinder efficient and sustainable ORE development and deployment;
- Support measures to increase the availability of open and high-resolution data, to understand ORE resource availability, environmental impact, and the impact of climate change;
- Further develop the research capability to holistically investigate the ecological and socioeconomic benefits and impacts of ORE;
- Conduct further research into the technical, environmental and socioeconomic aspects of ORE devices and their full lifetime from design to operation through to decommissioning, to improve sustainability and viability;
- Ensure that offers for training and skills development match industry requirements.

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[1] https://www.power-technology.com/features/full-circle-decommissioning-first-ever-offshore-windfarm/

[2] http://ec.europa.eu/europe2020/index_en.htm

[3] https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

[4] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

This Future Science Brief and its recommendations support the UN Decade of Ocean Science for Sustainable Development (Ocean Decade) in a number of ways.

The Future Science Brief highlights knowledge to indirectly support Societal Outcome 1 *(A clean Ocean where sources of pollution are identified and reduced or removed)* and Challenge 1 *(Understand and map land and sea-based sources of pollutants and contaminants and their potential impacts on human health and Ocean ecosystems and develop solutions to remove or mitigate them)*, presenting a state-of-the-art on cleaner energy production approaches, which would support the removal of fossil fuel-related pollutants. It also provides knowledge to support Societal Outcome 3 *(A productive Ocean supporting sustainable food supply and a sustainable Ocean economy)* and Challenge 4 *(Generate knowledge, support innovation, and develop solutions for equitable and sustainable development of the Ocean economy under changing environmental, social and climate conditions)*, by providing recommendations on the further development of offshore renewable energy as a key component of a sustainable Ocean economy, and discussing how the development of renewable energy can consider environmental, social and climate factors. Finally, it supports Challenge 5 *(Enhance understanding of the Ocean-climate nexus and generate knowledge and solutions to mitigate, adapt and build resilience to the effects of climate change across all geographies and at all scales, and to improve services including predictions for the Ocean, climate, and weather)* by providing recommendations for the development of renewable energy as direct mitigation to climate change.

This Future Science Brief and its recommendations support the EU Mission: Restore our Ocean and Waters and its objectives and enablers in several ways.

It addresses Objective 2 *(Prevent and eliminate pollution of our Ocean, seas, and waters)* by providing recommendations on how renewable energy can be sustainably developed, as a direct measure for reducing fossil fuel-related pollutants. It also addresses Objective 3 *(Make the sustainable blue economy carbon-neutral and circular)* by making recommendations on how to develop the renewable energy sector to not only support Europe's climate-neutral vision, but to also consider its own circularity.


Credit: Dzintra Grinbergs

Wavy conditions on the north coast of Madeira, Portugal.

EMB acknowledges that while the Working Group members writing this document and its recommendations represent some diversity in terms of European geographical location (see Annex 1), professional background, and career level, their views do not represent ideas from all forms of diversity. This document has a European focus, but its messages and recommendations are relevant to offshore renewable energy stakeholders globally.

1 Climate change: The need for clean energy

The world has changed profoundly in recent years with a global recognition that we are in a climate emergency and must rapidly reduce our use of fossil fuels. Therefore, it is imperative to fully understand the role that offshore renewable energy will play in meeting the world's energy needs (European Commission, 2020b). There needs to be a clear understanding of the positive and negative environmental and social implications of large-scale development of 100s to 1000s of gigawatts of offshore renewable energy worldwide in the next few decades (IRENA, 2019).

This chapter highlights the urgent need to switch to using our Ocean for large-scale energy extraction in the fight against climate change and outlines how the use of offshore renewable energy can help to reduce fossil fuel reliance and harmful emissions. It also outlines the aspects of climate change that can directly influence the production of offshore renewable energy.

Terminology used in this document

There are a number of terms that are used when discussing marine-related energy extraction.

The term **offshore energy** refers to all sources of energy that can be extracted from the Ocean, including both fossil-based (e.g. oil and gas) and renewable sources.

The term **offshore renewable energy**[5] refers to all sources of renewable energy that can be extracted from the Ocean, including wind, wave, tidal, Ocean/marine current, thermal and salinity gradient, floating solar and algae-based biofuels.

The term **marine renewable energy** refers to a subset of offshore renewable energies including waves, tides and Ocean currents, thermal and salinity gradient, floating solar and algae-based biofuels.

The term **Ocean energy** refers to a different subset of offshore renewable energies, specifically waves and tides (range and current), Ocean circulation currents, and thermal and salinity gradients[6].

Throughout this document and in line with terminology used by the European Commission, we will use the all-encompassing term **offshore renewable energy**, abbreviated to **ORE**, unless a distinction is appropriate.

1.1 How bad is climate change for the Ocean?

We are all aware that the planet is warming, but not everyone is aware of the role our Ocean plays in counteracting this. The Ocean has greatly slowed the rate of climate change by taking up more than 90% of the extra heat stored on the planet. This extra heat has arisen from increased greenhouse gas (GHG) emissions, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), water vapour and fluorinated gases. The Ocean is taking up around 25% of the excess carbon emitted by human activities (IPCC, 2019).

But this comes at a cost. The Ocean has warmed at all depths, with the greatest increases occurring in surface and shallow coastal waters (IPCC, 2019). The Ocean is also acidifying as increased CO_2 uptake decreases seawater pH. This acidifying effect reduces the future ability of the Ocean to take up more carbon (Goodwin *et al.*, 2009), and affects the physiology of many marine species. The global Ocean has lost around 2% of its dissolved oxygen in the past 50 years, caused directly by lower solubility in warmer water

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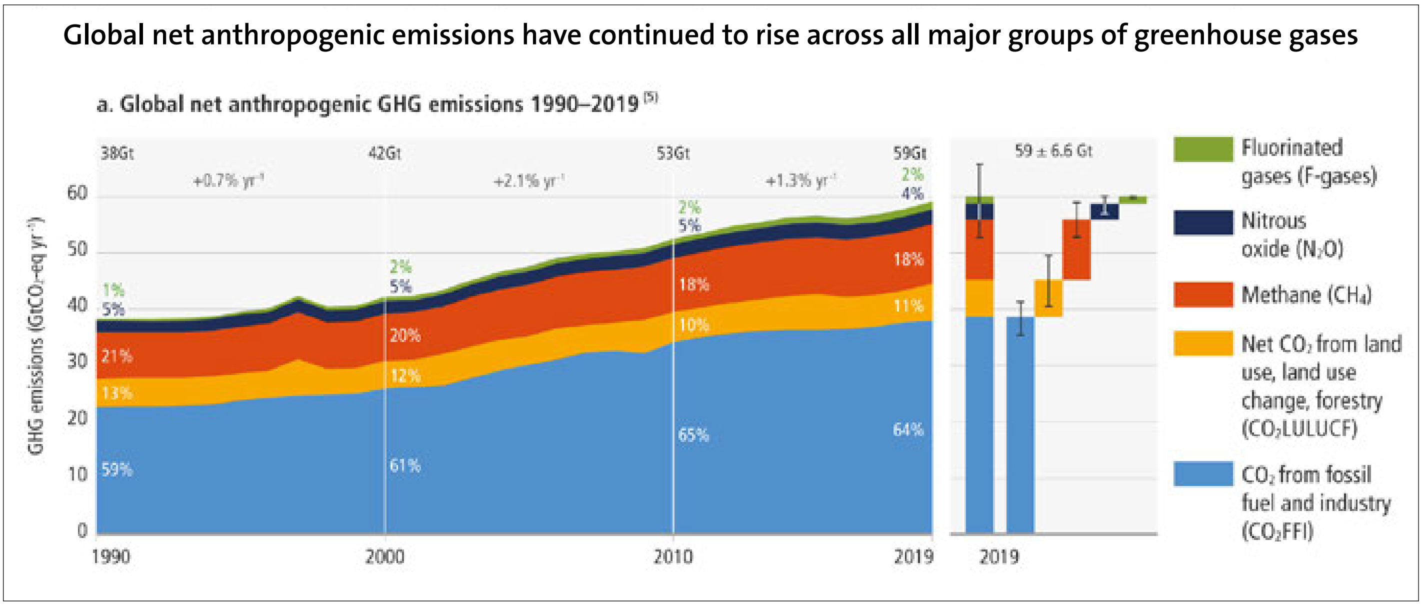
[5] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2020:741:FIN&qid=1605792629666

[6] https://research-and-innovation.ec.europa.eu/research-area/energy/ocean-energy_en

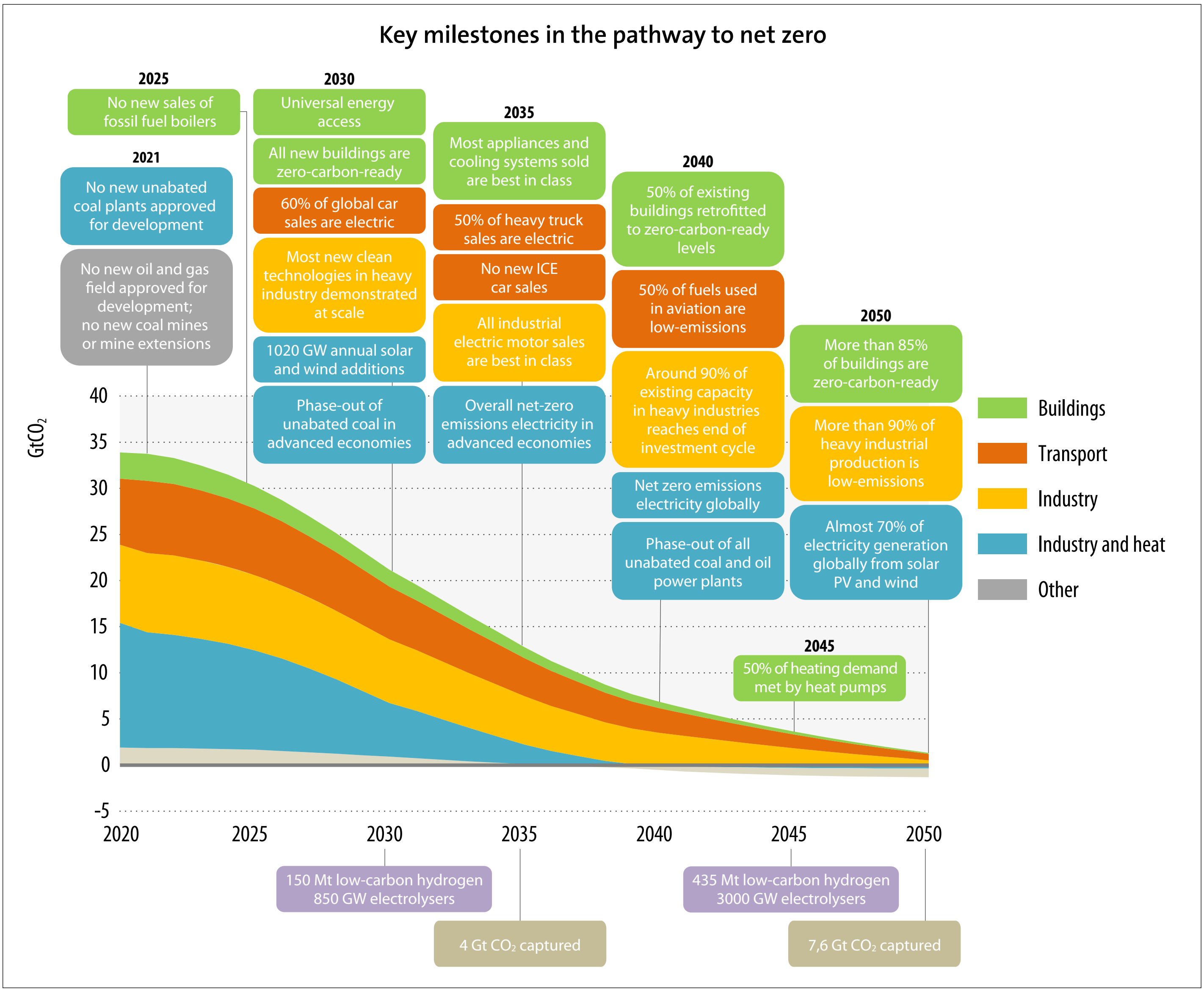


Global net anthropogenic emissions have continued to rise across all major groups of greenhouse gases

a. Global net anthropogenic GHG emissions 1990–2019 [5]

Credit: Figure SPM.1 in (IPCC, 2022b)

Figure 1.1 Global net anthropogenic greenhouse gas emissions 1990-2019.



Key milestones in the pathway to net zero

Credit: (IEA, 2021a), Net Zero by 2050: A Roadmap for the Global Energy Sector, https://www.iea.org/reports/net-zero-by-2050, CC-BY-4.0

Figure 1.2 Key milestones in the pathway to net zero.

and indirectly via reduced mixing between surface layers and deeper waters (Stramma & Schmidtko, 2019). There is emerging evidence for climate change impacting the strength and direction of Ocean currents (Halo & Raj, 2020), which could impact heat exchange in the Ocean and lead to the shutdown of the Atlantic Meridional Overturning Circulation (AMOC), a key part of the global Ocean circulation system (MetOffice, 2019). Many fish stocks depend on Ocean currents for transport between spawning and feeding areas. This could eventually affect commercial fish stock recruitment success (Pörtner & Peck, 2010). Finally, global sea levels are rising and will continue to rise due to melting land-ice and the thermal expansion of water with rising temperatures (Oppenheimer *et al.,* 2019).

1.2 What is the role of offshore renewable energy in addressing climate change?

Renewable energy is an important climate mitigation and adaptation measure. Given the continuous rise in anthropogenic GHG emissions (see Figure 1.1), it is imperative to increase the pace of renewable energy penetration in countries' energy mix. According to the International Energy Agency's[7] (IEA) scenario for Net Zero GHG emissions by 2050 (IEA, 2021a, Table 2.6), the anticipated required capacity additions of renewable energy from onshore and offshore solar and wind by 2030 is 1,020 Gigawatts (GW) per year, which is significant given that in 2022, Europe's total installed wind capacity was 236GW[8].

By 2050, it is foreseen by the International Energy Agency (IEA) that 70% of electricity production globally should come from solar and wind energy (see Figure 1.2). The most recent Intergovernmental Panel on Climate Change (IPCC) report also foresees a high potential for wind and solar energy to support emission reductions by 2050 (IPCC, 2022, Figure SPM 7).

The International Renewable Energy Agency[9] (IRENA) estimates that to keep global temperature rise at 1.5°C, 25% of the emissions reductions must be provided using renewable energy (IRENA, 2022). Offshore renewable energy (ORE) still produces GHG emissions, but these are much lower than those of fossil fuels, as is shown for the example of wind and solar energy in Table 1.1. Hoegh-Guldberg *et al.,* (2019) suggest that ORE can mitigate the production of up to 5.4 gigatons (Gt) of CO_2 equivalent per year by 2050, representing approximately 10% of global efforts to keep temperature increase under 1.5°C.

From an economic perspective, the global climate value[10] of offshore wind energy only (considering the value from reduced emissions and on reductions in the cost of abatement) is estimated to be $ US 100 in a scenario with no climate policy, $ US 120 where a limit is set on permissible carbon emissions (carbon caps), and $ US 450 billion with significant carbon taxes respectively (Cranmer & Baker, 2020). This is the case even with the highest offshore wind energy cost assumptions and lowest damage severity of climate change factors used.

Electricity generation approach	Equivalent grams of CO_2 emitted per kWh
Fossil fuel	360 – 1259
Onshore wind energy	14.5 – 28.5
Offshore wind energy	11
Solar energy from solar panels / photovoltaics	8 – 83

Table 1.1 Comparison of GHG emissions for different electricity generation approaches over their lifetime.

Credit: Based on (Barthelmie & Pryor, 2021; UNECE, 2021)

1.3 What are the main effects of climate change on offshore renewable energy?

ORE systems are sensitive to structural risk from weather and climate variability, which can reduce the efficiency of their energy production. The impact of climate change on the available offshore energy resources is uncertain and is the subject of a growing body of scientific research. The magnitude and direction of the predicted changes depends on the region and climate change scenario considered. Reviews summarising the existing (and often contradictory) literature on this subject are presented by Solaun & Cerdá (2019) and more recently by Gernaat *et al.,* (2021). The expected climate change impacts vary by region however Weiss *et al.,* (2020) suggest that the areas expected to be most suitable for ORE deployment are not likely to be significantly affected by climate change. Climate change also affects meteorological and oceanographic parameters such as wind speed, wave height and period, Ocean current speed and sea level. These meteorological and oceanographic variables and their extremes impact the design of offshore and coastal structures and operations, and their ability to withstand environmental loads. A more detailed discussion on the future needs regarding understanding the effects of climate change on ORE is presented in Section 6.1.

1.4 What are the interactions between climate change and offshore renewable energy?

Large-scale energy extraction from offshore renewable resources will lower the likelihood of marine ecosystems experiencing the more extreme effects of climate change. However, the effects of these installations and of extracting energy can have impacts that are synergistic with climate change and have similar consequences (de Dominicis *et al.,* 2018; Sadykova *et al.,* 2020). Large-scale offshore energy extraction is not the 'free energy' proclaimed in some economic evaluations, and the cost of its effects must also be considered (Dasgupta, 2021). The extracted

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[7] https://www.iea.org/

[8] https://windeurope.org/intelligence-platform/product/wind-energy-in-europe-2021-statistics-and-the-outlook-for-2022-2026/

[9] https://www.irena.org/

[10] Global climate value is a valuation of the financial return considering climate-related risks and opportunities.

energy would otherwise have served another purpose within the Ocean ecosystem e.g. by providing heat to marine surface waters (Dorrell *et al.,* 2022). The ecological effects of ORE are covered in Chapter 4 and in published reviews (e.g. Copping & Hemery, 2020) but they should be understood in the context of climate change rather than against a non-shifting current baseline (Wolf *et al.,* 2021). We need to understand the compromises we are making between the positive impacts of using ORE to reduce the impacts of climate change on the environment and humanity, against potential negative impacts of installing offshore renewable energy extraction devices in maritime space. For example, as discussed in more detail in Section 6.2.3, deep-sea mining for energy transition minerals used in components of turbines and batteries is critical for the creation of renewable energy devices but causes irreversible impacts to deep-sea ecosystems. According to the IEA (2021b), by 2040, the demand for minerals needed for clean energy technologies will be four times the present demand, increasing by up to six-fold by 2050. This issue is not limited to ORE but could also have serious implications for its development.


Credit: European Marine Board

Oil rigs in waters off Santa Cruz, Tenerife, Spain.

2 State of global offshore renewable energy

The marine environment contains abundant renewable energy, arising from wind, waves, tides, the sun, and thermal and salinity differences. Technologies and devices to extract these energies efficiently and sufficiently, either by converting them into electricity or energy storage media for future use, are being, and need to be, further developed.

This chapter provides brief reviews of the characterisation and global distribution of offshore renewable energy resources, and of existing and emerging offshore renewable energy technologies up to 200km from the shore.

In the context presented in this document, the basic unit of power, a watt (W), is a measure of the rate of energy transfer, e.g. from an offshore renewable energy source to electricity. A watt-hour (Wh) is a unit of energy which describes the amount of power generated in an hour. Annex 3 presents a comparison of the different units of power.

2.1 Offshore renewable energy resource review

This section outlines the estimated global energy resources of different offshore renewable energy (ORE) sources. It is important to note that the use of theoretical power is debatable because not all theoretically estimated power can be extracted due to technical and economic efficiencies encountered when installing devices offshore, the efficiency of the extraction method, and natural factors such as variations in wind and wave direction (see e.g. Guo & Ringwood, 2021). Chapter 3 provides more detail on the availability of ORE resources in European waters, and its implications.

2.1.1 Wind

Compared to onshore wind, offshore wind is stronger and less turbulent, and thus more energetic and stable. The estimated global energy demand in 2019 was 65,000 Terawatt Hours (TWh), while onshore and offshore wind energy could, in an ideal/theoretical situation, provide 900,000TWh per year[11].

Due to the technological maturity of wind turbines and the expertise of onshore developers, offshore wind energy is the most advanced offshore renewable energy option. Energy extraction from wind depends on wind speed and density of the air and is usually quantified in terms of either wind power density or the amount of power available per year at a given location. Wind speed varies in time and space, and therefore the mean wind speed at a certain height (e.g. 100m above sea level which approximately corresponds to the wind turbine hub height) is often used to characterise offshore wind energy resources. Figure 2.1 shows the global distribution of mean wind speed (top) and available power density (bottom) at sites up to 200km offshore, taken from the Global Wind Atlas[12]. This figure clearly shows a significant difference in mean wind speed and wind power resource in different areas, with the most notable difference being about twice the wind speed (and therefore eight times the wind power) towards the North or South Poles compared to the Equator.

The global offshore wind resource is mainly assessed by combining satellite remote sensing data with hindcast datasets generated using numerical atmospheric models (Bosch *et al.,* 2018; Karagali *et al.,* 2013). Atmospheric models provide estimates of wind speed every one to three hours at different heights above the ground (or sea level), and at different geospatial locations. The models provide estimates of wind speed and direction (at different heights above a ground datum or mean sea level). To get wind speed estimates closer to the turbine hub height, the European Centre for Medium-Range Weather Forecasts[13] (ECMWF) also provides estimates of wind speed and direction at 10m and 100m above sea level. However, since the tips of the blades of the wind turbine are at different heights as they rotate, the rotor (i.e. the rotating part of the turbine comprising of the hub and blades) equivalent wind speed (instead of the wind speed at the hub height) is used for the estimation of the annual energy production. In addition, the rotor diameters of modern offshore wind turbines have increased from 112m (in 2010) to 157m (in 2019) (IRENA, 2021).

Long-term (three to five years or more) atmospheric data based on simulations from hindcast models and satellite observations are used for resource assessment, i.e. these data are used to

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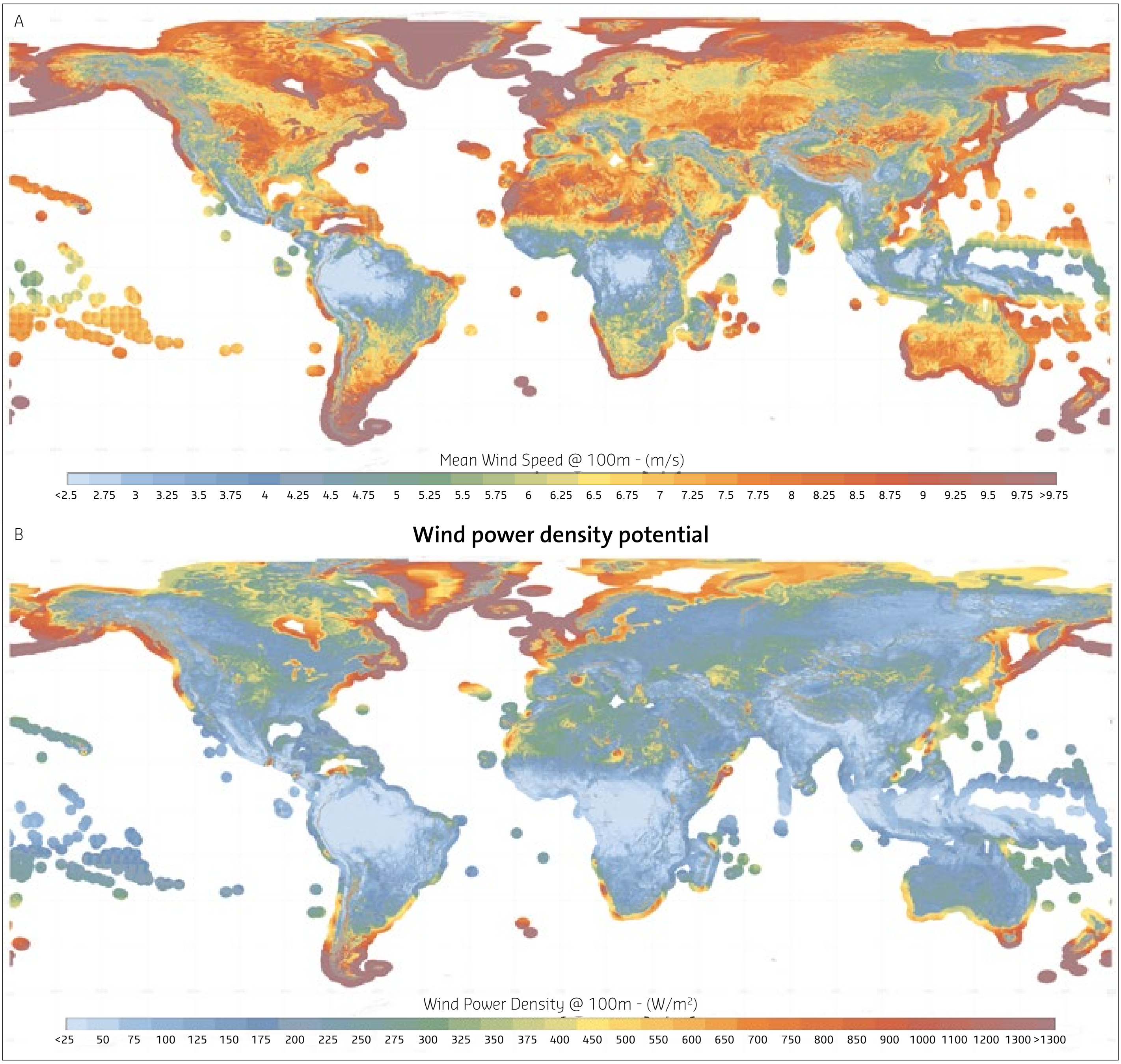
[11] https://carbontracker.org/solar-and-wind-can-meet-world-energy-demand-100-times-over-renewables/

[12] https://globalwindatlas.info/

[13] https://www.ecmwf.int/



Credit: Global Wind Altas, CC BY 4.0

Figure 2.1 A. Global distribution of mean wind speed, and **B.** wind power density potential at a reference height of 100m for offshore areas up to 200km offshore. Source: Maps obtained from the Global Wind Atlas 3.0, a free, web-based application developed, owned, and operated by the Technical University of Denmark (DTU). The Global Wind Atlas 3.0 is released in partnership with the World Bank Group, utilising data provided by Vortex, using funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information: https://globalwindatlas.info.

plan where offshore wind farms should be situated. Numerical atmospheric models have multiple types of uncertainties (such as uncertainties in initial conditions, uncertainties caused by errors in the model formulation/parameterisation schemes or numerical integration methods), thus measurements are very important to evaluate and validate their results (Olafsson & Bao, 2020). Moreover, the available spatial resolution of these models is not currently fine enough to assess wind variability (instability, eddies and turbulence) at the scale of a single turbine. This is needed to support the design and dynamic analysis of offshore wind turbines. To make an accurate assessment of the flow at this scale additional long-term datasets combining *in situ* monitoring with high sampling frequency (e.g. a sample taken every second), fine recording period (e.g. a recording duration of ten minutes), and short recording interval (e.g. one hour between ten-minute recordings) and very fine resolution atmospheric models or, usually, computational fluid dynamics techniques[14], are necessary. New monitoring solutions that can provide vertical wind profiles are also necessary, such as floating LIDAR (Light Detection and Ranging). Such technology still needs further development.

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[14] Computational fluid dynamics techniques use continuity and momentum equations, within software packages, to predict how gases and liquids flow and interact with different objects.

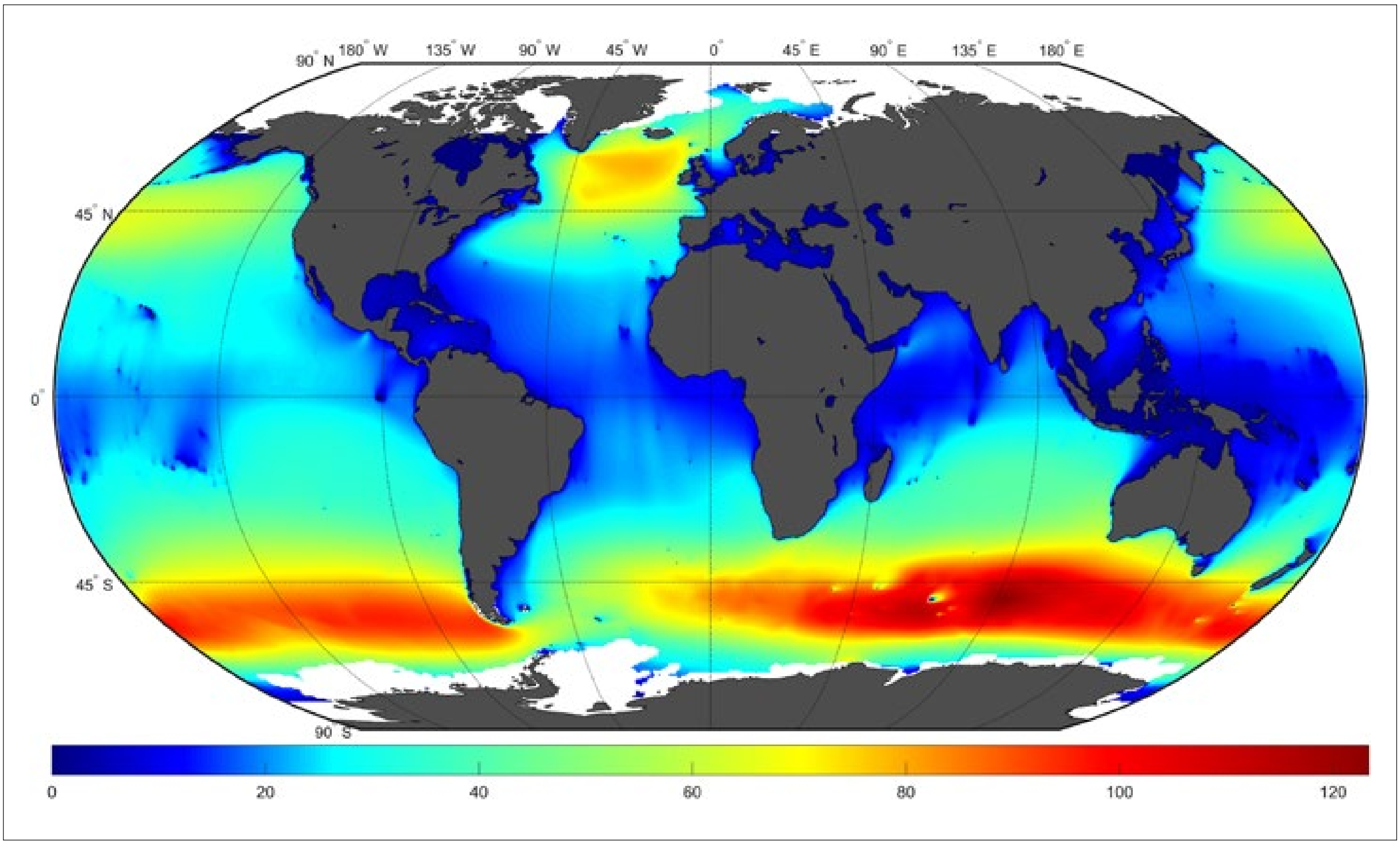

Figure 2.2 Global mean value of wave power, P (kW/m).

Credit: (Martinez *et al.*, 2020, Figure 3) CC BY 4.0

2.1.2 Waves

Wave energy has great potential as an offshore renewable energy resource. It is unevenly distributed globally, and is most available between 40°- 60° N, e.g. in the North Atlantic, and 40°- 60° S. Wave power is a function of wave height, wave period (i.e. the time between two consecutive wave peaks passing a given point) and seawater density. Figure 2.2 shows the global mean offshore wave power. Wave power density is highest in the open Ocean, while in more sheltered, coastal areas, where it is more realistic to deploy Wave Energy Converters (WECs), it is typically around a quarter to half of the wave power density of the open Ocean.

Similar to wind, wave energy is highly variable seasonally and inter-annually, and location dependent. Closer to the Equator the mean wave power is lowest, however there is permanent and relatively constant wave action. In the higher latitudes where the mean wave power is high, the operation of a WEC requires high installation and maintenance costs to survive those conditions. Consequently, areas of highest wave energy resource are not necessarily optimal for energy extraction (Portilla *et al.,* 2013). The theoretical potential annual global wave energy production is estimated to be 29,500TWh[15].

Sea state data (i.e. wave height, wave period, wave direction) used to estimate the available wave resource in a given area are obtained by *in situ* monitoring, numerical spectral wave models[16], and remote sensing techniques. For coastal areas where WECs are usually deployed, high spatio-temporal resolution wave models combined with *in situ* wave measurements are required to evaluate and calibrate numerical model results. The directional distribution of wave energy is also important as this plays a major role in some WEC technologies (Soukissian & Karathanasi, 2021).

2.1.3 Tides and currents

Energy can be extracted from tidal currents (the horizontal movement of water), tidal range (the vertical change in water level) and Ocean circulation currents (such as the Gulf Stream). Flow speed is a key factor in assessment of the available energy: median current speeds greater than 1.1m/s (3.96km/h) are economically favourable for energy extraction (Khare *et al.,* 2019).

Since tides are very predictable (at locations where long-term tidal gauge measurements are available), tidal range is often used to characterise the global distribution of tidal energy, as shown in Figure 2.3 (IRENA, 2014a). Tidal range is often enhanced in coastal areas or channels and displays considerable variation around the globe. The funnelling effects of bays, estuaries and inlets, or areas where flow is constrained by the presence of islands or headlands, can provide a viable tidal energy resource (Vila-Concejo *et al.,* 2020). The morphology of some bays may also create large tidal ranges at the head of the bay and consequently strong tidal currents. Locations such as the Bay of Fundy in Canada[17], Cook Strait in New Zealand (Walters *et al.,* 2010), and the Pentland Firth in the UK (Coles *et al.,* 2021) are good examples that have been targeted for development. Tidal energy was harnessed in early commercial ventures through the construction of barrages, such as the 240MW La Rance tidal energy station in France and the 254MW Sihwa Lake Tidal Power Station in the Republic of Korea (Neill *et al.,* 2021).

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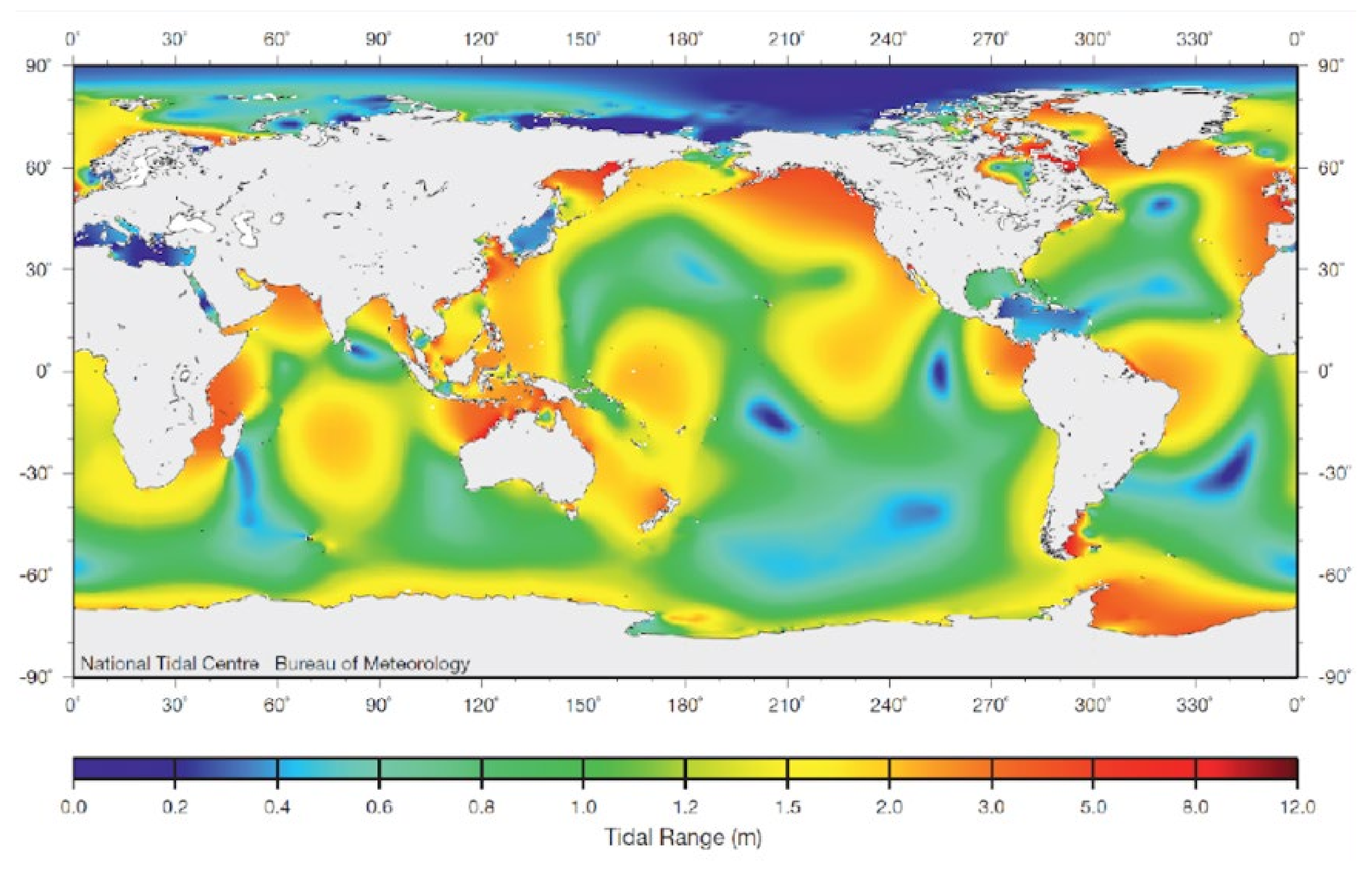
[15] https://www.oceanenergy-europe.eu/ocean-energy/wave-energy/

[16] Numerical spectral wave models mathematically provide a description of how a wave energy field changes over time and in coastal areas can be used for forecasting.

[17] https://www.oceanenergy-europe.eu/industry-news/sustainable-marine-powers-up-tidal-energy-in-nova-scotia/



Credit: (IRENA, 2014a)

Figure 2.3 Global tidal range distribution.

The estimated global tidal energy available for extraction per year ranges between 150 and 800TWh[18], with potential estimates up to 1200TWh (IRENA, 2020a).

Data on tidal energy properties such as current speed and direction and tidal range are obtained from *in situ* measurements, drifters, and numerical oceanographic models. *In situ* measurements are obtained from oceanographic buoys, or Acoustic Doppler Current Profilers (ADCP) that are deployed on the sea bottom or placed on the bottom of ships. Tidal ranges are usually measured at coastal locations, harbours, bays, ports, etc. through tidal gauges. Free floating devices called drifters can submerge and measure marine current characteristics at different depths. It is noted that sea level rise due to global warming should also be included in all projections for tidal resources (Sobey, 2005).

The number of coastal locations with strong enough tidal currents or high enough tidal ranges to make energy extraction economically viable is limited (Figure 2.3, highlighted in red). In highly energetic sites where current velocities can regularly reach values higher than 2.5m/s (or 9km/h) the flow is invariably turbulent, which creates high resource variability in space and time. The characterisation of this variability is necessary to properly access the potential of the resource. Further development and design of high-resolution *in situ* monitoring devices, tools and procedures are necessary to quantify the current profiles and turbulence. Ocean circulation currents are generated by factors including Earth's rotation, wind, gravity, temperature and salinity in the Ocean, and their location, width, depth, and flow are determined by the shape of the Ocean basin in question and the Coriolis Force (caused by Earth's rotation acting on both air and water). Their flow is typically considered to be continuous and almost unidirectional, and they are characterised by low variability and high predictability. However, early indications of weakening and instability of these currents due to climate change are being observed (Boers, 2021). It is also not clear from the literature how much potential energy could be extracted from Ocean currents, although the US Department of the Interior (2006) estimate global power in Ocean currents to be around 5000GW. Energy extraction from Ocean currents is at present only considered for the Gulf Stream in the Atlantic Ocean, and the Kuroshio Current in the Pacific Ocean, and no commercial installations have yet been deployed. This energy resource will not be considered further in this document.

2.1.4 Solar

Solar energy is created by the power from the sun as electromagnetic radiation, called solar irradiance. The intensity of solar irradiance is variable and depends on latitude, season, time of day, weather conditions, solar cycle, etc. In the Ocean, solar energy could be extracted using solar panels (photovoltaic (PV) systems) fitted to dedicated floating platforms or to existing offshore structures. Data on solar irradiance in the Ocean are mainly obtained using dedicated sensors called pyranometers (mounted on buoys or on-board ships), numerical atmospheric models and satellite imagery (Trolliet *et al.,* 2018).

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[18] https://ec.europa.eu/research-and-innovation/en/projects/success-stories/all/tidal-flows-generate-huge-potential-clean-electricity

2.1.5 Other resources

In addition to the more mature and/or well-known ORE technologies presented above, there are also several other resources under consideration. These are not the focus of this document but are briefly introduced here. It is also noted that the process of sea water air conditioning (or geo-exchange of heat and cooling), where the temperate of sea water is used directly in installations rather than being converted to energy, is outside the scope of this document.

Thermal Gradient

Ocean Thermal Energy Conversion (OTEC) uses the thermal gradient between deeper cold seawater and warmer surface water to generate electricity using a heat engine. Areas of largest temperature gradient between deep and surface water (above 20°C, which is the lower threshold for OTEC applications) occur in a belt around the Equator, especially in the western part of the Pacific Ocean. This energy is continuously available and offers a significant resource potential, and a very high capacity to produce energy. This capacity factor is the ratio of the actual electrical energy produced for a specific time-period compared to the theoretical maximum electrical energy produced in the same period. The data needed to calculate OTEC include seawater temperature at different depths, which are obtained using buoys, oceanographic model results, CTD casts (which measure Conductivity (or salinity), Temperature, and Depth) from research vessels, and more recently, by autonomous underwater vehicles and the ARGO profiling floats[19].

Many possible configurations for OTEC plants have been proposed, ranging from floating to land-based plants. There have been some relevant international OTEC developments in recent years:

- In Japan, a 100 kilowatt (kW) OTEC demonstration facility was established by Okinawa Prefecture in 2013, with technical assistance from Saga University[20];
- An OTEC plant set up by the Natural Energy Laboratory of Hawaii Authority in the 1970s and taken over by Makai Ocean Engineering[21] in August 2015;
- The Korea Research Institute of Ships and Ocean Engineering (KRISO) developed a 1 Megawatt (MW) OTEC plant in 2019, and recently transported it for installation as an onshore OTEC facility in South Tarawa, Republic of Kiribati, in the South Pacific Ocean[22]. Completion of the installation was expected in 2022.
- In 2022, São Tomé and Príncipe, in cooperation with the Global OTEC company and the Small Island Developing States (SIDS) Sustainable Energy and Climate Resilience Organisation, signed a Memorandum of Understanding for the development of a 1.5MW floating Ocean OTEC platform offshore São Tomé Island. The deployment of the platform is anticipated for 2024[23].

A map with potential future OTEC developments is provided by OES (2021c) and a review of OTEC has recently been provided by Herrera *et al.,* (2021).

Even though European waters are in mid- and high- latitudes (i.e. areas that are not favourable for thermal gradient energy exploitation because the temperature differences are not large enough) some European countries still support the development of OTEC R&D programmes for application in their overseas territories as well as in tropical Small Island Developing States (SIDS). Apart from electricity generation, OTEC power can be also used for desalination and freshwater production that is of utmost importance in tropical areas. In 2022, a consortium called PLOTEC[24] from Austria, Italy, Portugal, Spain, and the UK received funding in the context of the Horizon Europe Framework Programme for the design and simulation of an OTEC platform capable of withstanding the extreme conditions associated with tropical weather. A scaled demonstrator model will be tested at the Oceanic Platform of the Canary Islands (PLOCAN) facility in Gran Canaria in 2024. The consortium will engage with SIDS leaders and policymakers for future capacity-building. These advances should help to overcome technical and economic challenges and achieve a multi-MW full-scale demonstration plant which would make a significant step towards commercialisation.

Salinity gradient

Salinity gradient energy (SGE) can be produced from the salinity difference between seawater and fresh-water. This energy is typically generated using either: a) pressure-retarded osmosis (PRO), where salt- and fresh-water are separated by a membrane and mixed via osmosis, with the energy of the physical flow being extracted, or b) Reverse Electro Dialysis (RED), where salt ions are transported through membranes to generate a charge (Han *et al.,* 2021).

Plants can be located either at naturally occurring gradient sites such as where rivers flow into the sea, or alongside other infrastructure such as desalination plants. A comprehensive review of SGE is provided by Cipollina & Micale (2016). SGE is both highly available and predictable, and salinity data is obtained by the same means as seawater temperature, although salinity data at depth is not as critical given that salinity plants are located in shallow coastal and nearshore waters or estuaries.

Reasons that the use of salinity gradient energy extraction is not more mature include a lack of research on the environmental and legal implications of these installations, the high cost of components, especially the membranes, and a lack of realistic operative cost estimates and real-world experience with these devices which act as a barrier for policymakers and investors (IRENA, 2014b).

Biomass

Marine biomass in the form of algae is a renewable resource for biofuel production. The algae (which are usually cultivated) can be

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[19] https://argo.ucsd.edu/

[20] http://otecokinawa.com/en/

[21] https://www.makai.com/ocean-thermal-energy-conversion/

[22] http://www.ocean-thermal.org/mw-scale-otec-for-kiribati/

[23] https://www.ccreee.org/news/2022-un-oceans-conference-prime-minister-of-tonga-oversees-historic-signing-of-development-of-worlds-first-ocean-energy-power-purchase-agreement-for-sao-tome-and-principe/

[24] https://plotec.eu/

converted into biofuel by extracting their fatty acids (called lipids). Biofuels can be produced from both macroalgae (e.g. seaweeds) and microalgae (e.g. phytoplankton), and have the advantage that agricultural land is not taken up displacing other biofuel crops (e.g. corn, soy, grasses). However, it is important to note that while macroalgae can be cultivated at sea (either open sea or shallower coastal waters), microalgae can only be cultivated in controlled systems on land (in artificial ponds or tanks, or in closed bioreactors). Supported by EU funding, an expert working group of Eklipse[25] recently reported on the *"State of knowledge regarding the potential of macroalgae cultivation in providing climate-related and other ecosystem service"* (Bermejo *et al.,* 2022). A review of progress and further needs towards a biorefinery for microalgae is presented by Wood *et al.,* (2022).

Biofuels are particularly useful in the transport and heating sectors. Algae have the potential to yield significantly more energy than current biofuels, are able to produce the longer-chain lipids needed for e.g. aviation fuel, and, in biodiesel form, they also emit lower levels of greenhouse gases than conventional diesel fuel.

The sustainability and costs associated with biofuel generation from algae are variable and are strongly linked to the way they are cultivated and extracted (Darda *et al.,* 2019). A technological challenge for large-scale development is that currently more energy is required to extract the lipids than gained back from the resulting biofuel, and so more efficient extraction methods are being explored (Sarwer *et al.,* 2022).

Power-to-X and hydrogen

The 'Power-to-X' concept is defined as conversion of surplus electricity produced by ORE sources into hydrogen or other products for energy storage purposes, offering a means to address imbalances between resource availability and demand, especially for intermittent ORE sources such as wind (see Section 6.2.2. for more discussion). It is not intended as a replacement for renewable energy.

Hydrogen can be generated using the process of electrolysis, where an electric current is used to split water into its components, hydrogen and oxygen. Where the required electricity for the electrolyser is supplied by renewable energy sources, the hydrogen is sometimes called 'green hydrogen'.

Power-to-X systems offer direct ways to decarbonise various industrial processes and to provide an energy source for transportation (e.g. shipping, aviation) because the ORE-generated hydrogen can be used as a fuel instead of fossil fuels. Power-to-X systems also allow stored energy to be transported. Hydrogen is therefore considered *"essential to support the EU's commitment to reach carbon neutrality by 2050"* (European Commission, 2020a). The possibility of using wind power for hydrogen production and avoiding the need for grid infrastructure upgrades to manage resource variability is very relevant for the ORE sector. A further advantage is that the cost of hydrogen production can potentially be cut by 60% - 80% (IEA, 2021a; Wilson, 2020). An example of this is the community-led 'Surf 'N' Turf' project[27] in Orkney, UK, where excess wind and tidal current power generated on the island is used to produce hydrogen,


Credit: Jose Gayo Pelaez

A team of researchers at Swansea University are using food and farm waste to cultivate microalgae as part of the Interreg North-West Europe project ALG-AD[26].

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[25] https://eklipse.eu/request-macroalgae/

[26] https://www.nweurope.eu/projects/project-search/alg-ad-creating-value-from-waste-nutrients-by-integrating-algal-and-anaerobic-digestion-technology/%C2%A0%C2%A0

[27] https://www.surfnturf.org.uk/index.php

which is then used to power harbour and local ferry operations in Orkney's capital, Kirkwall. The generated hydrogen can also be used in other applications, such as the production of methane or ammonia for use in natural gas systems or in fertiliser (Power-to-gas) and methanol for use in fuel cells (Power-to-liquid). The hydrogen can also be used to power fuel cells, converting the stored power back to electricity (Power-to-Power).

Given that not all industries (e.g. mining, aviation) will be easy to electrify, there will be an increasing role for ORE in the generation of green hydrogen and other green fuels to support further decarbonisation.

2.1.6 Comparing different offshore renewable energy resources

Wave and tidal power have a much larger power density than wind and solar power, i.e. they have larger power availability per unit volume. However, the utilisation of ORE also depends on the efficiency, maturity and cost-effectiveness of the corresponding technologies. At present, offshore wind energy systems are much more mature than other ORE technologies.

If a certain technology, such as a wind turbine, wave energy converter (WEC), tidal turbine, or solar PV, is used, the actual energy converted to electricity also depends on the device, which typically varies for different environmental conditions. The average energy a device can produce is a function of the efficiency of the device and the long-term distribution of the energy resource (i.e. wind speed distribution or joint distribution of wave parameters), which varies with time. Table 2.1 below shows a general comparison in capacity factor, energy production and cost between the different resources for which information is readily available in the literature. There is significant variation in the estimations provided in different sources, therefore this information should be taken as indicative only. These values are also estimated global values that vary depending on geographic, technological and economic variables. As offshore wind has already been commercialised, one could expect that other technologies would be much more costly.

2.2 Offshore renewable energy technology review

This section reviews different ORE technologies and their maturity in terms of commercial development, with a focus on offshore wind, wave, tidal current and range and solar energy technologies. The European Commission defines the maturity of a technology in terms of Technology Readiness Level (TRL), where TRL 1 has basic principles outlined, and TRL 9 represents an actual system proven to work in an operational environment and therefore ready for commercialisation[30]. For each of these stages, the Strategic Research & Innovation Agenda (SRIA) published within the scope of the ETIPOcean[31] platform (ETIPOcean, 2020) has identified technological challenges and priority topics for the next four to five years that will increase the reliability, availability, maintainability and survivability of ORE devices (see Section 3.1.5).

ENERGY TYPE	CAPACITY FACTOR	ESTIMATED ANNUAL ENERGY PRODUCTION TECHNICAL POTENTIAL	ESTIMATED LEVELISED COST OF ELECTRICITY
	(The average absorbed power (or electricity) divided by the maximum power (or electricity) that a device can produce)	(TWh/year)	(Average cost of generating electricity over the generation lifetime, $ US/kWh)
Offshore wind	0.3-0.6	4,000-37,000	0.08
Wave energy	0.25-0.32	5,560	0.33-0.44
Tidal current	0.5-0.7	150-1,200	0.28-0.29
Floating solar	0.1-0.3	9,000[28]	0.06-0.11[29]
Thermal gradient	0.9-0.95	83,400	0.03-0.38
Salinity gradient	0.8-0.84	1,650	0.11-2.37

Table 2.1 Indicative comparison of different ORE resources. Sources: (Bhuiyan *et al.*, 2022; IPCC, 2011; IRENA, 2020a; Langer *et al.*, 2020; Newby *et al.*, 2021; Oliveria-Pinto & Stokkermans, 2020; Ocean Energy Europe; Yang *et al.*, 2022)

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[28] Based on the ideas presented here, where 14,000GW would equate to around 18,000TWh depending on location, and the assumption of 50% of overall global solar energy production taking place at sea (rather than on land): https://www.bloomberg.com/news/articles/2022-04-20/solar-energy-may-generate-half-of-world-s-power-by-2050?leadSource=uverify%20wall. The authors are not aware of an equivalent estimate in the published literature.

[29] Estimate based on examples in sheltered waters only, as no commercial-scale applications exist in open seas.

[30] https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf

[31] https://www.etipocean.eu/

ORE technologies have reached different stages in their development:

- Offshore wind energy is mature and in commercial operation (TRL 9), with floating wind in a pre-commercial phase (TRL 8);
- Wave energy is at full-scale prototype phase (TRL 7);
- Tidal current energy is in the demonstration phase with pilot projects (TRL 6);
- Tidal range energy is mature and in commercial operation (TRL 9);
- Offshore or floating solar energy is in early demonstration phase (TRL 5).

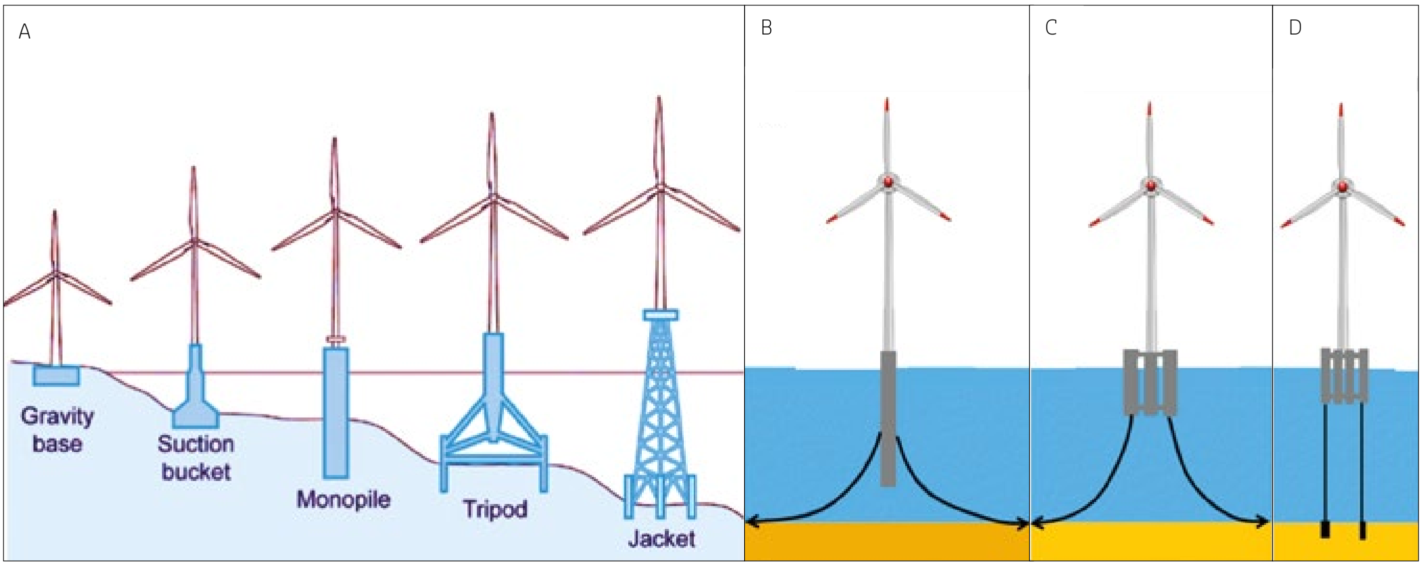
2.2.1 Offshore wind turbines

Wind turbines convert wind energy to kinetic energy via a rotating turbine, and then to electricity directly or via a drivetrain (i.e. the components that transfer the power from the moving blades to the generator) and a generator. Offshore wind development has significantly benefitted from the experience gained from onshore wind turbine technologies and operations. In particular, the standardisation of commercial systems towards a design with three-bladed horizontal axis turbines which face the wind (upwind) that can change the angle of the blade to the wind (pitch-controlled) and operate at different rotation speeds (variable-speed) has been an important offshore wind development during the past 20 years. Wind turbines are designed to operate in different wind speeds, such that maximum power efficiency is achieved by adjusting the rotation speed for wind speeds lower than predicted average speed. A controlled power output is obtained by pitching the blades for wind speeds higher than the rated value, i.e. the wind speeds at which it is designed to operate. Turbine technology is very mature, and modern turbines feature aerodynamically efficient blades, cost-effective blade and tower structural designs and robust turbine control systems.

Traditionally offshore wind turbines and electrical blades are made of composite materials (e.g. fibreglass and polyester, or fibreglass and carbon), whereas bottom-fixed and floating support structures, towers, moorings, and anchors are made of metal (steel, aluminium) or concrete. Drivetrains, generators, and power cable components also include critical minerals and rare earth metals.

Moving from land to offshore shallow water areas (with water depth of 0-20m), then into intermediate water depths (20-60m), and finally towards deep water areas (with water depth greater than 60m), has required the development of different foundations to support the wind turbines. As shown in Figure 2.4, foundations for shallow or intermediate waters are typically bottom-fixed, and include designs such as monopiles, tripods, jackets, foundations with suction buckets and gravity-based structures. Such technologies are mature and have been widely developed, especially monopile foundations, which are the most used foundations in current offshore wind farms because they are simple to design and install. Factors such as water depth, seabed type and possible environmental impacts influence the choice of foundation.

Gravity base foundations are used for depths up to 10m, monopiles are economic for water depths of 20–40m, and jacket foundations are considered competitive for water depths up to 70m. For deeper offshore areas, bottom-fixed foundations become too large and expensive (Jiang, 2021), and floating wind turbines become more economically feasible. These floating turbines are anchored to the seabed via mooring lines and have spar, semi-submersible or tension leg platform designs, as shown in Figure 2.4. In recent years, floating wind turbines have gained significant interest not only from a research perspective, but also in pre-commercial development. Pilot demonstrators of spar and semi-submersible floating wind turbines already deployed at sea include Hywind Scotland[32] and WindFloat[33] as shown in Figure 2.5. However, no tension leg platform floating wind turbine prototypes have yet been tested at sea, because of the complexity and the high cost for transport and installation. A list of existing and planned prototypes of floating wind turbines can be found in the Carbon Trust Joint Industry Project report (Strivens *et al.,* 2021).



Credit: Left: (Puruncajas *et al.*, 2020), CC BY 4.0; Right: (Manzano-Agugliaro *et al.*, 2020) CC BY 4.0.

Figure 2.4 Left A: Illustrations of bottom-fixed foundations for offshore wind turbines. **Right B-D:** Floating foundations for offshore wind turbines, **B:** Spar; **C:** Semi-submersible; **D:** Tension leg Platform.

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[32] https://www.equinor.com/energy/hywind-scotland

[33] https://www.principlepower.com/windfloat

Both bottom-fixed and floating structures have been extensively deployed at commercial scale by the oil and gas sector, leading to the availability of relevant experience and expertise. However, offshore wind turbine foundation and support structure designs have different requirements to those of oil and gas installations, and therefore new skills need to be developed. Moreover, design analysis methodologies for offshore oil and gas installations may not translate directly to ORE. In the recent 'Scotwind'[34] offshore wind leasing process, 60% of the 24GW of projects for which bids were submitted related to floating as opposed to fixed offshore wind. Floating offshore wind is expected to account for between 100-150GW of the targeted 450GW offshore wind capacity for 2050 (WindEurope, 2020).

Although most wind turbines in commercial offshore wind farms today are Horizontal Axis Wind Turbines, proposals have also been made for Vertical Axis Wind Turbines (VAWTs) (Arredondo-Galeana & Brennan, 2021) (Figure 2.6). VAWTs can lower the centre of gravity of the turbine, which is beneficial for the stability of floating wind turbines. Two contra-rotating VAWTs are currently under investigation at the IFREMER test site (Matoug *et al.*, 2020). However, further development of VAWT designs to maximise efficiency and address issues with reliability is needed before they can be commercialised.

According to IRENA (2020a), the global offshore wind sector received $ US 25.7 billion in investment in 2018 (i.e. 20% of the total for wind energy). In the same year, China led the way with offshore projects worth $ US 11.4 billion, with European projects valued at $ US 3.3 billion.

Cost reduction is the major driver for the further development of the offshore wind industry and is particularly sensitive to the choice of foundations for a given water depth. Recently power delivery by offshore turbines have been scaled up through improvements in design, efficiency and adaptation to the available resource. Typical modern turbines have a power rating of eight to ten MW, up to 14MW.

Offshore development facilitates the deployment of increasingly larger turbines because of the feasibility to transport such turbines by ship (as opposed to road for onshore development). However, the operation and maintenance (O&M) costs for offshore wind installations are much higher than on land: 23% of total investment cost over the project lifetime vs 5% on land (Ren *et al.*, 2021). One of the bottlenecks for future development lies in the design and manufacture of cost-effective ultra-large turbines (rated power exceeding 20MW): further research and development are needed on new blade materials and design optimisation.

2.2.2 Wave energy converters

A wave energy converter (WEC) is a device that converts energy from surface waves to electricity. As shown in Figure 2.7, there are three basic WEC types (Falcão, 2010) which can be sub-classified into:

- Oscillating water column (OWC) devices which utilise the air pressure difference caused by the wave-induced water surface 'up-down' movement. The advantage of this type of device is that the air turbine is located above sea level, which reduces damage from corrosion and fouling. However, these devices need to be able to operate in two directions to account for the up-down movement, making them less efficient than one-directional devices;
- Overtopping devices which collect the water that spills into a device as the waves pass and then passes in through a turbine to generate energy; and
- Oscillating bodies which utilise the relative motions between a floating structure and a reference body to drive a generator and produce energy.

Credit: A: Equinor; B: Photo courtesy of Principle Power

Figure 2.5 A: Hywind Scotland spar floating wind turbine; **B:** WindFloat Atlantic semi-submersible floating wind turbine.

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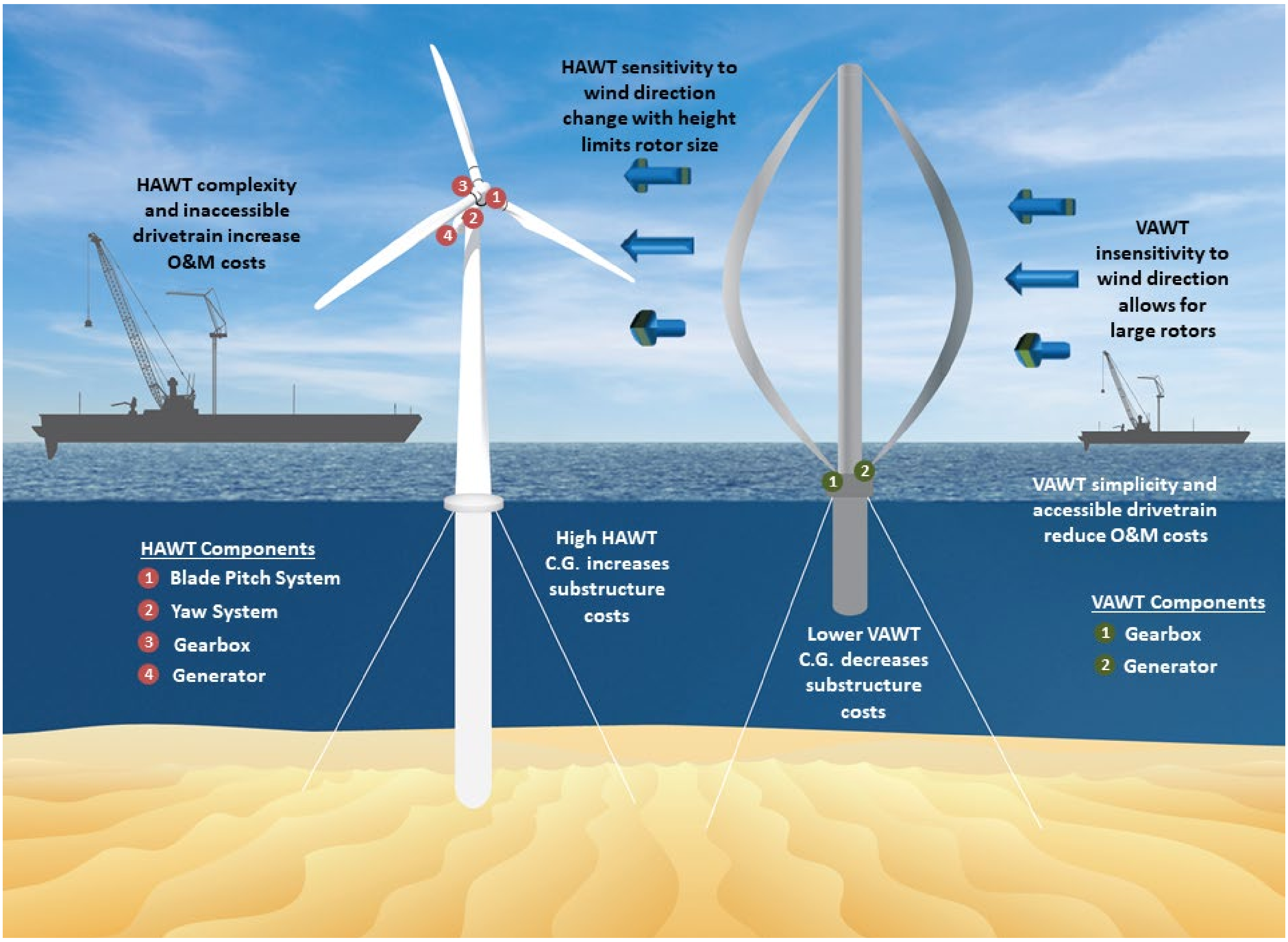
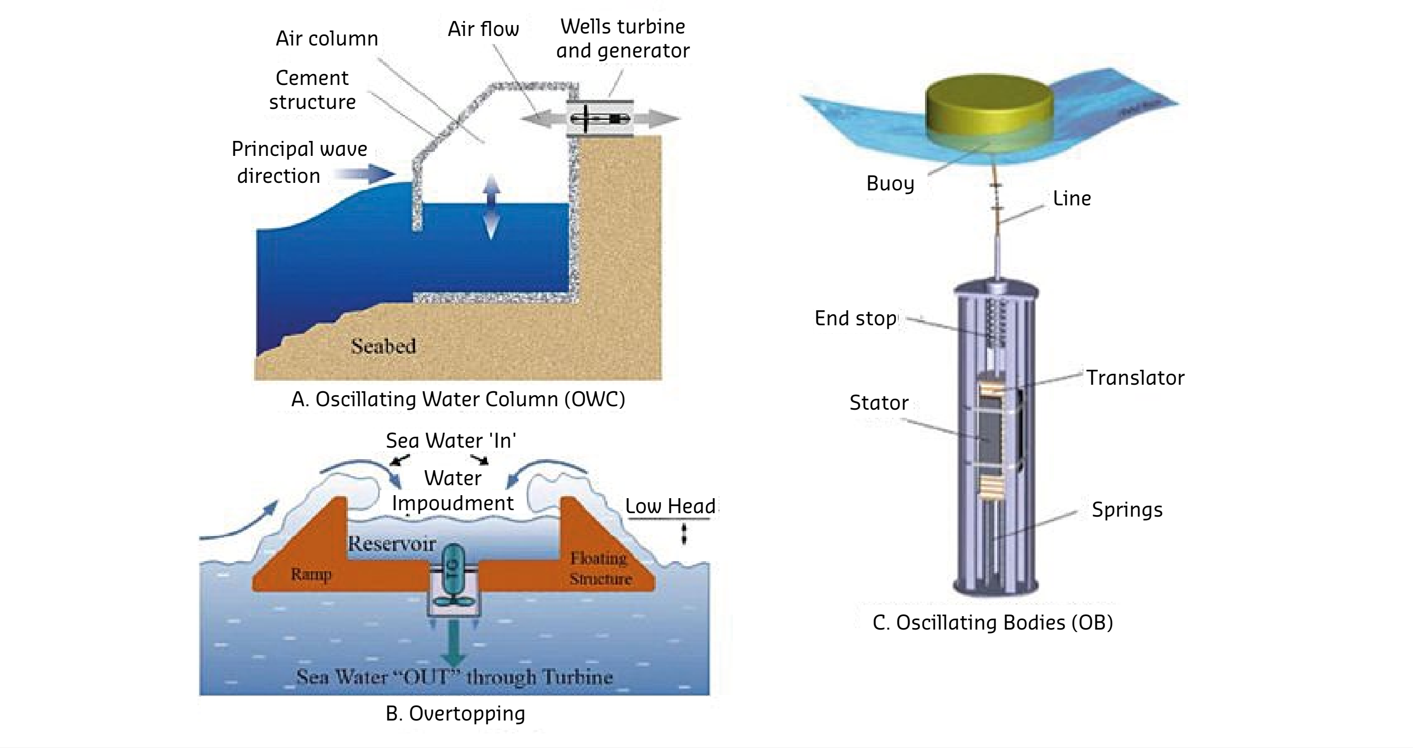
[34] https://www.crownestatescotland.com/our-projects/scotwind



Credit: Sandia National Laboratories

Figure 2.6 Comparing horizontal- and vertical-axis wind turbines.



A. Oscillating Water Column (OWC)

B. Overtopping

C. Oscillating Bodies (OB)

Credit: (Syarif Arief *et al.*, 2020) CC BY 4.0

Figure 2.7 Types of wave energy converters.

Since the 1980s, there have been many different types of WEC concepts that have been studied theoretically, numerically and experimentally at model and even prototype scale. WECs have not yet been developed at commercial farm scale, although there are ongoing developments of several concepts towards commercialisation, notably the oscillating body CorPower device[35] (see Figure 2.8) and Oscilla Power's Triton-C wave energy system[36]. Unlike the wind energy industry, which has converged on a small number of turbine designs, the wave energy industry is still exploring a wider range of approaches to both absorb the energy from the waves and transform this energy into electricity. Theories, numerical methods/models, and model-scale experimental studies to quantify the hydrodynamics, power efficiency and to some extent the survivability of proposed WECs have been very well developed for conceptual studies. However, up to 2017, most of the WEC prototypes had short testing periods or failed due to survivability issues (European Commission, 2017a). The challenge to develop pre-commercial prototypes is not unique to wave energy and is faced by all other types of ORE development, except offshore wind. The industry is aware of this barrier, and is developing technology for high efficiency energy capture, reliability and survivability in extreme weather conditions and advanced control technologies.

In recent years, large-scale WEC prototypes of 100-500kW have been developed and tested at sea (OES, 2021b). Experiences from testing these prototypes are invaluable to better understand power performance (helping to validate simulations), fabrication, operation, technological optimisation and potential areas for cost reduction. As noted by ETIPOcean (2020), it is important to extensively test these devices, their foundations and moorings, in real sea conditions to learn more and eventually advance their TRL.

Some representative examples are listed below and shown in Figure 2.8:

- In 2020, China's Guangzhou Institute of Energy Conversion (GIEC) installed a 500kW WEC, a variant of the oscillating body type, called Sharp Eagle, which consists of a semi-submersible floater and a hinged double floating body[37];
- In 2019, Finland's AW-Energy Ltd installed the 350kW WaveRoller, a bottom-hinged surface-piercing flap-type WEC and a variant of the oscillating body type, in Portugal[38];
- In 2021, Wave Swell Energy installed a 200kW WEC oscillating water column device, the UniWave200, in Tasmania, Australia[39];
- In 2021, Mocean Energy installed a 10kW prototype WEC (Blue X) at the European Marine Energy Centre (EMEC) test site in Orkney, UK[40];
- In 2021, Oscilla Power tested the 100kW Triton-C point absorber WEC, at the US Navy Wave Energy Test Site in Hawaii[41];
- In 2022, Sweden's CorPower Ocean began testing a full-scale 300kW oscillating body type WEC C4 point absorber device, which has a unique wave spring design that allows the WEC to be more efficient in different wave frequencies[42]; and
- In 2022, the Waveswing WEC, a 16kW submerged wave power buoy using a direct-drive generator, was deployed at the EMEC test site. The trials will be repeated in early 2023[43].

Figure 2.8 Wave energy converter prototypes. **A:** AW-Energy's WaveRoller; **B:** Wave Swell Energy's UniWave device; **C:** An artist's impression of a CorPower C4 wave farm.

Credit: A: AW-Energy; B: Wave Swell Energy; C: CorPower Ocean

[35] https://corpowerocean.com/

[36] https://www.oscillapower.com/post/oscilla-power-to-deploy-triton-c-wave-energy-system-in-hawaii

[37] https://english.cas.cn/newsroom/news/202007/t20200703_240149.shtml

[38] http://aw-energy.com/waveroller/#technology

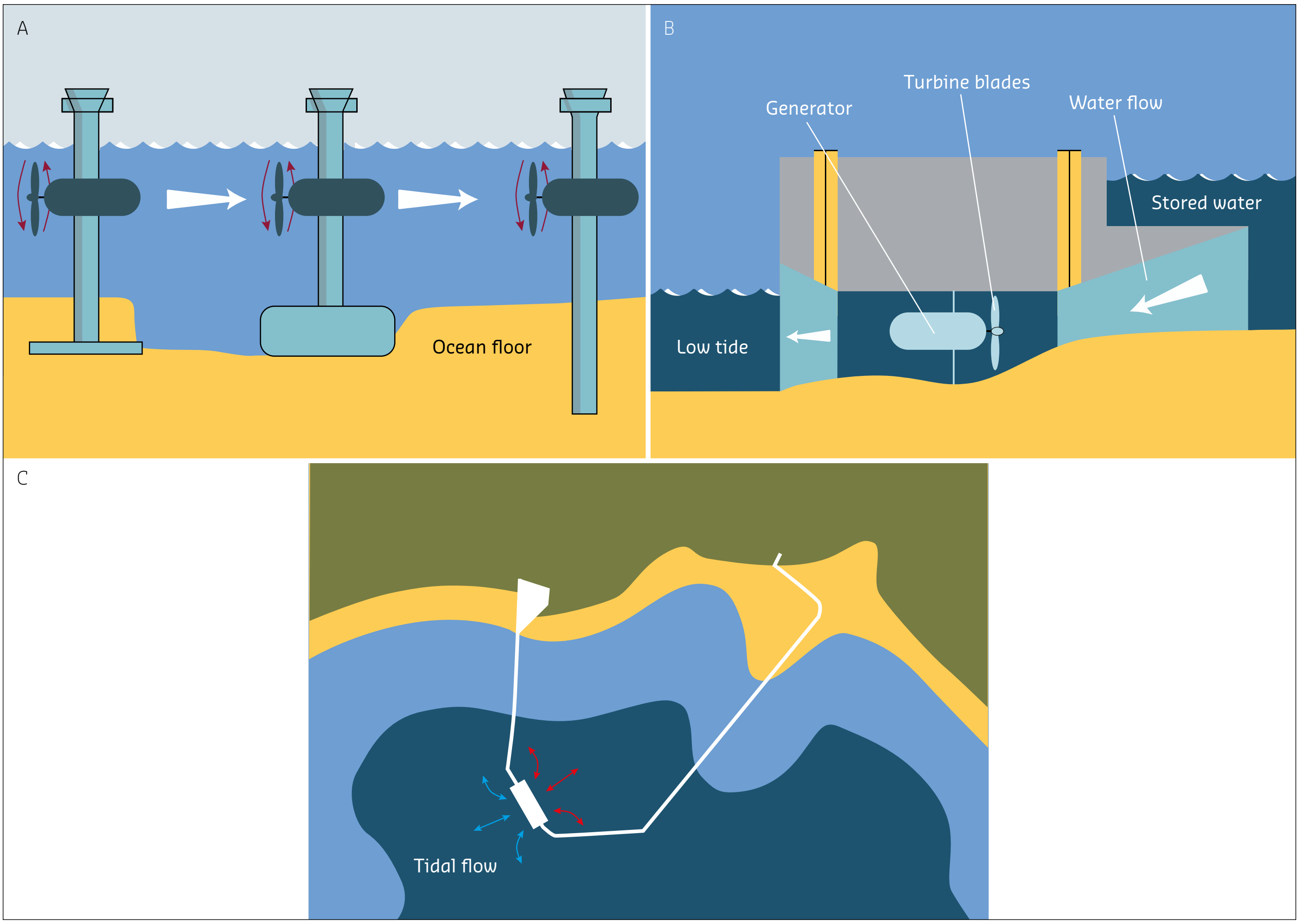
[39] https://www.waveswell.com/

[40] https://www.mocean.energy/blue-x-device-removal/

[41] https://www.oscillapower.com/post/oscilla-power-to-deploy-triton-c-wave-energy-system-in-hawaii

[42] https://www.corpowerocean.com/technology/

[43] https://awsocean.com/archimedes-waveswing/



Credit: Zoeck, based on original by The Asean Post

Figure 2.9 Methods for generating electricity from the tides: **A:** tidal current, **B:** tidal barrage, **C:** tidal lagoon.

2.2.3 Marine turbines

Marine turbines are devices that are used to extract energy from tidal currents (tidal current turbines) and tidal ranges (where turbines form part of the system with a tidal barrage or tidal lagoon) as shown in Figure 2.9. Marine turbines are completely submerged in seawater, giving rise to challenges in material selection and design of blades, corrosion, installation and O&M. These challenges arise due to the large current speeds, as well as the waves in these locations and the large forces that these will exert on the turbines, low visibility underwater affecting maintenance, the inherently damaging nature of salt water and biofouling effects (Stringer & Polagye, 2020).

Tidal current turbines operate in seawater but have similarities to wind turbines in that they possess blades, drivetrains and support structures. Marine turbines require far smaller rotor diameters than wind turbines to achieve the same power output, as seawater is much denser than air. Different configurations and prototypes of tidal turbine designs have been developed and MW-size turbines have been tested at sea recently (OES, 2021a), representing a significant step towards commercialisation.

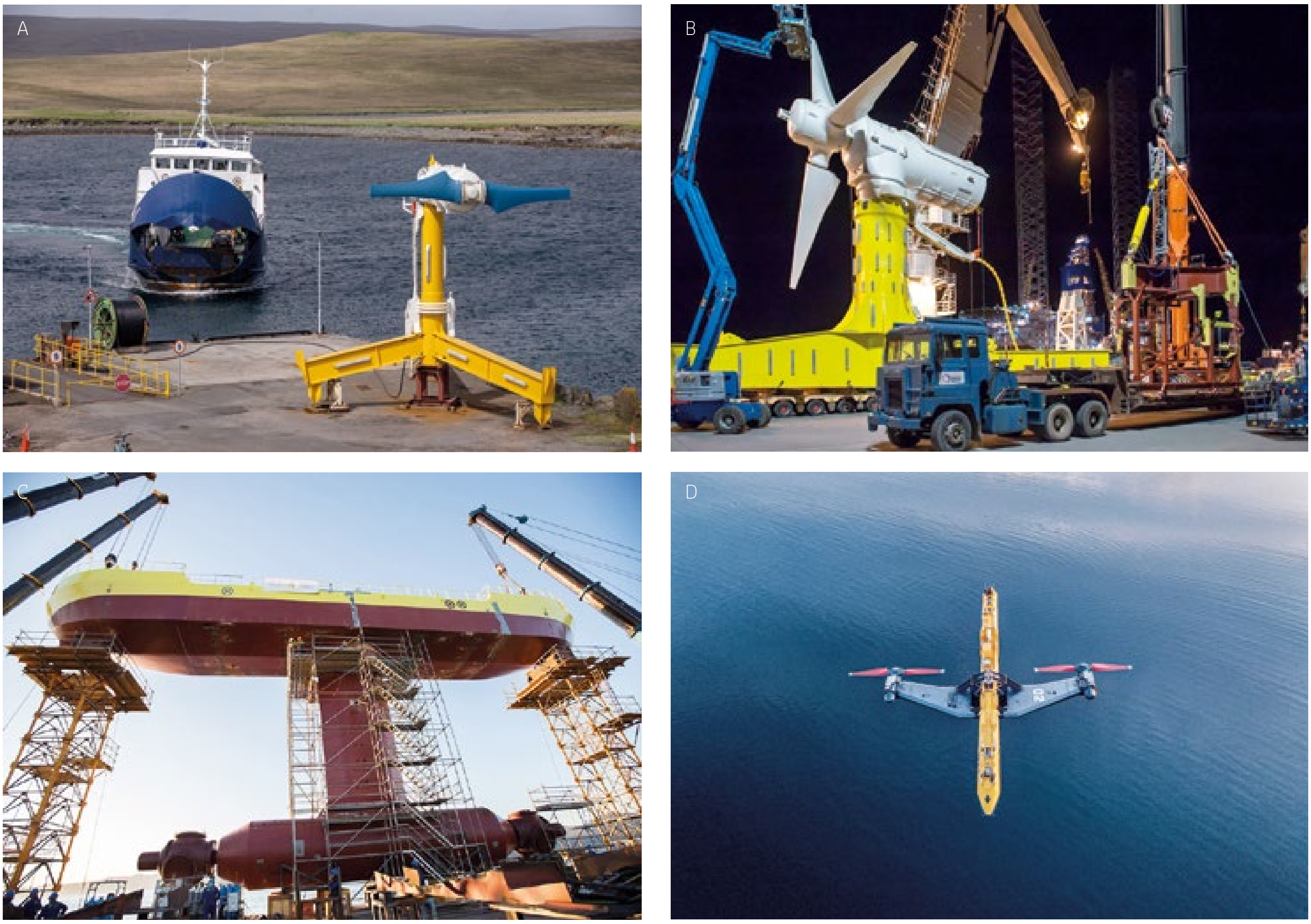


Figure 2.10 MW-size tidal turbine prototypes. **A:** Shetland Tidal Array device; **B:** MeyGen Array device; **C:** Assembling the main structure of the Magallanes Renovables device; **D:** Orbital Marine Power device.

Credit: A: Nova Innovation; B: SIMEC Atlantis Energy; C: Magallanes Revovables; D: Orbital Marine Power

Several examples of devices are listed below and shown in Figure 2.10:

- In 2016, Nova Innovation installed the world's first offshore tidal energy array, the Shetland Tidal Array, at Bluemull Sound in Shetland (see Section 3.1.1);
- In 2018, SIMEC Atlantis Energy[44] developed and installed four 1.5MW three-blade bottom-mounted tidal turbines in the MeyGen array in Pentland Firth, UK. This is the largest planned multi-phase tidal current project in the world, and the only commercial multi-turbine array currently in construction;
- In 2019, HydroQuest[45] installed a 1MW tidal current turbine with a dual vertical contra-rotating axis in France, which was in operation for testing for two years until October 2021;
- In 2019, Magallanes Renovables[46] tested a 45m long floating platform equipped with two 1.5MW rotors at the European Marine Energy Centre (EMEC) in Orkney, UK;
- In 2021, Orbital Marine Power[47] installed and tested a 72m long floating tidal turbine platform with two 1MW turbines at the same site in Orkney;
- In 2022, Sustainable Marine tested the grid-connected 420kW PLAT-I 6.40, equipped with six 70kW instream turbines at the Grand Passage/Bay of Fundy, Canada[48]; and
- In 2022, Sabella installed and connected its D10 turbine to the Ushant Island grid in Brittany, France. The turbine has been providing electricity since then. Assessment of the production over the first eight months showed that the turbine has a capacity to cover up to 49% of the island's electricity consumption[49].

[44] https://simecatlantis.com/

[45] https://www.hydroquest.fr/en/tidal-turbines-services/

[46] https://www.magallanesrenovables.com/

[47] https://www.orbitalmarine.com/

[48] https://www.sustainablemarine.com/press-releases/sustainable-marine-delivers-first-floating-tidal-power-to-nova-scotia-grid

[49] https://www.sabella.bzh/sites/default/files/upload/communiquePresse/20221201_-_pr_d10_power_curve_certified_en.pdf

A detailed review of energy storage solutions suitable for tidal currents is given by Zhou *et al.,* (2013).

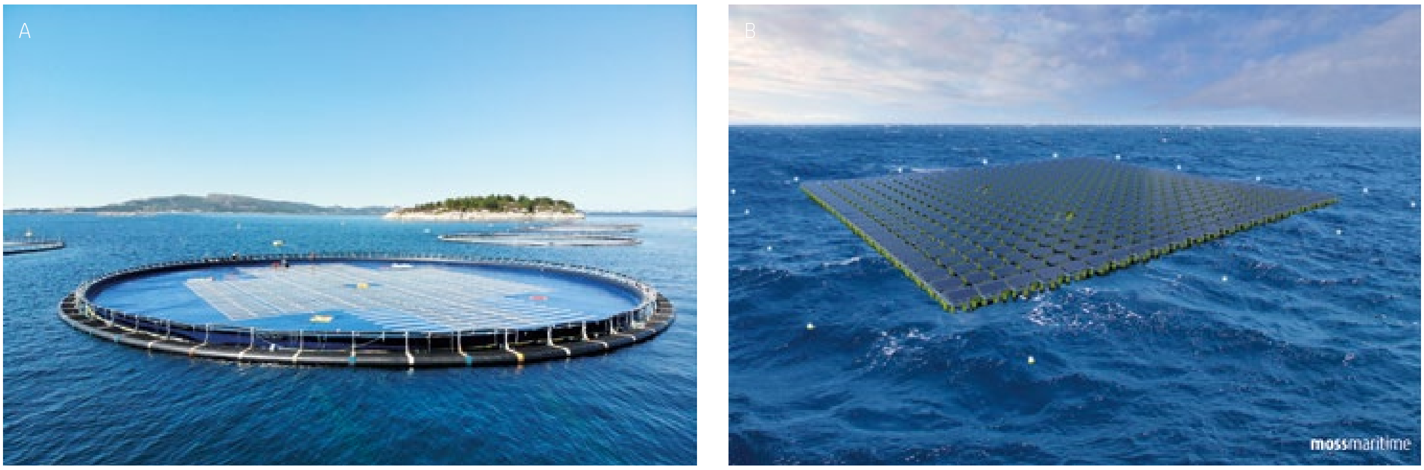
Tidal barrages are dam-like structures that are built across the mouth of a bay or river. However, unlike a dam, they allow water to flow in and out through the structure. The water flows into the bay or river at high tide, via turbines located within the barrage structure, and flows back out at low tide, again via the turbines, generating electricity in both directions. Tidal barrages are still the most powerful ORE systems, with notable examples being the La Rance tidal plant[50] in France (240MW) and the Sihwa Lake tidal plant[51] in Korea (254MW). Some smaller multi-MW tidal plants also exist in China and Russia, and smaller systems are also being considered for local needs in Small Island Developing States (SIDS) (OES, 2020). However, the construction of tidal barrages can have significant environmental impacts in the wider area on benthic habitats, fish and mammal passage and migration, phytoplankton dynamics and bird communities (Frid *et al.,* 2012; Retiere, 1994). Due to the variable nature of the water height during a tidal cycle, there are different configurations of the turbine at the various stages. Also, energy must be extracted from flows in both directions. Both of these factors drastically decreases the efficiency (or increases the cost) of the turbine and overall system.

Tidal lagoons are an alternative means of extracting energy from tidal ranges. Tidal lagoons are complete enclosures within highly tidal areas and are artificially created (rather than a straight structure across an existing bay or river). As with tidal barrages, they use a dam-like structure, a small section of which contains turbines, and extract energy both while the tide is rising and falling. An example is the proposed Swansea Bay Tidal Lagoon in the UK (Petley & Aggidis, 2016)[52], which has yet to be permitted because of concerns regarding its potential environmental impacts (Elliott *et al.,* 2018).

2.2.4 Floating solar energy platforms

Soler energy is extracted using solar panels, or photovoltaics (PV). Onshore solar energy is one of the cheapest renewable energy resources. Floating solar PV have been implemented on lakes and reservoirs, where wave action is very limited. In such applications, plastic floating structures are connected to steel frames that support the solar PV panels. An example is the world's first floating solar PV farm in Singapore, developed by Sembcorp Tengeh[53] (see Figure 2.11). Other concepts have been proposed and prototypes developed for deployment in sheltered coastal areas with a mild wave climate, such as OceanSun[54] developed in Norway.

In seas with relatively high waves, the previously mentioned systems struggle with survivability due to their flexibility and the large forces exerted by waves. More solid floating platforms, made of steel or concrete, are needed to support the PV panel deck, such as the concept developed by Equinor and Moss Maritime for sea trials in 2022[55]. However, to make these systems commercially viable, a very large Ocean surface area needs to be covered with solar panels to produce sufficient power, which presents considerable design and spatial planning challenges. Moreover, there is limited experience in other offshore sectors of designing, mooring, and operating such large floating structures, and doing so in a cost-effective way. These challenges, along with technological challenges linked to e.g. clouds and other coverage issues, the cost of movable panels (for permanent optimal orientation), and the deterioration of the materials in the marine environment, will need to be overcome to develop floating coastal and offshore solar PV commercially. A review of projects related to onshore and offshore solar energy up to 2013 is provided by Trapani & Santafé (2014), with more recent overviews of offshore solar installations presented by Vo *et al.,* (2021) and Yousuf *et al.,* (2020).



Credit A: Ocean Sun Floating PV, patented; B: moss maritime

Figure 2.11 Floating solar PVs. **A:** OceanSun floating solar PV; **B:** Offshore floating solar concept by Equinor and moss maritime.

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[50] https://tethys.pnnl.gov/project-sites/la-rance-tidal-barrage

[51] https://tethys.pnnl.gov/project-sites/sihwa-tidal-power-plant

[52] http://www.tidallagoonpower.com/projects/swansea-bay/

[53] https://www.sembcorpenergy.com.sg/business/energy-solutions/solar/floating-solar/

[54] https://oceansun.no/

[55] https://www.equinor.com/en/news/20210114-test-offshore-solar.html

2.3 Integrated use of offshore renewable energy

Most ORE devices will require a large Ocean area for commercial development and therefore it is natural to investigate the synergy of different devices, co-located at the same site, in terms of efficient Ocean space and infrastructure use and complimentary power production. Combined systems are typically divided into two main types: co-located and hybrid. Co-location consists of deploying independent systems (e.g. separate wind and wave devices, or floating wind and solar devices) at the same site, while hybrid systems combine different ORE technologies on the same platform. Different combinations of ORE technologies have been proposed and designed: wind-wave, wind-solar, wind-tidal, wave-solar as well as wind-solar-tidal-wave.

An analysis by Soukissian *et al.,* (2021) regarding the hybrid exploitation of offshore wind and solar energy in the Mediterranean Sea identified the Aegean and Alboran Seas as areas with high potential and low variability for both resources, with the Gulfs of Lion, Gabes and Sidra, the Aegean Sea, and Northern Cyprus also appearing feasible. Overall, the hybrid exploitation of offshore wind and solar energy in the Mediterranean Sea seems promising.

There are also investigations looking at placing electrolysers for hydrogen production *in situ* with the different ORE devices, as it may be more efficient to transport hydrogen back to land than electricity. However, no commercial concepts have been developed for any of these systems yet.

Hybrid platforms are only as mature as their least mature components (e.g. those with the lowest TRL), which poses a challenge in terms of the viability of the systems, meaning that extensive prototyping and demonstration at sea is required to increase TRL. There are limited examples of hybrid platform developments. Pelagic Power in Norway[56] developed the W2Power hybrid wind-wave energy system as a semi-submersible platform, combining two wind turbines and multiple oscillating body WECs. The platform has so far achieved TRL 6 through deployment in open sea[58]. The company Floating Power Plant[58] developed the Poseidon Wave and Wind system, and a 37m scale model (called P37, see Figure 2.12) equipped with ten 3kW oscillating body and oscillating water column WECs and three 11kW wind turbines. It was tested off the Danish coast between 2008 – 2013, and using findings from the tests, work is now ongoing to develop and deploy an improved commercial level (TRL 7) design[59]. The company also expects to launch a platform combining wind and wave energy with hydrogen storage in 2025.

The EU-SCORES project[60], funded under Horizon 2020, will consider co-located devices, and present the benefits of continuous energy production with small space requirements via complementary energy sources (wind, sun and waves). The project will organise two demonstrations in Europe: An offshore PV system co-located with a bottom-fixed wind farm in Belgium, and a wave energy array co-located with a floating wind farm in Portugal. The project runs from 2021-2025.

Credit: Floating Power Plant A/S

Figure 2.12 Hybrid wind-wave energy system, Floating Power Plant P37 system.

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[56] https://www.pelagicpower.no/

[57] https://www.innovationnewsnetwork.com/w2power-offshore-wind-deployment-worldwide/25183/

[58] https://www.floatingpowerplant.com/

[59] https://webgate.ec.europa.eu/maritimeforum/en/node/5472

[60] https://euscores.eu/

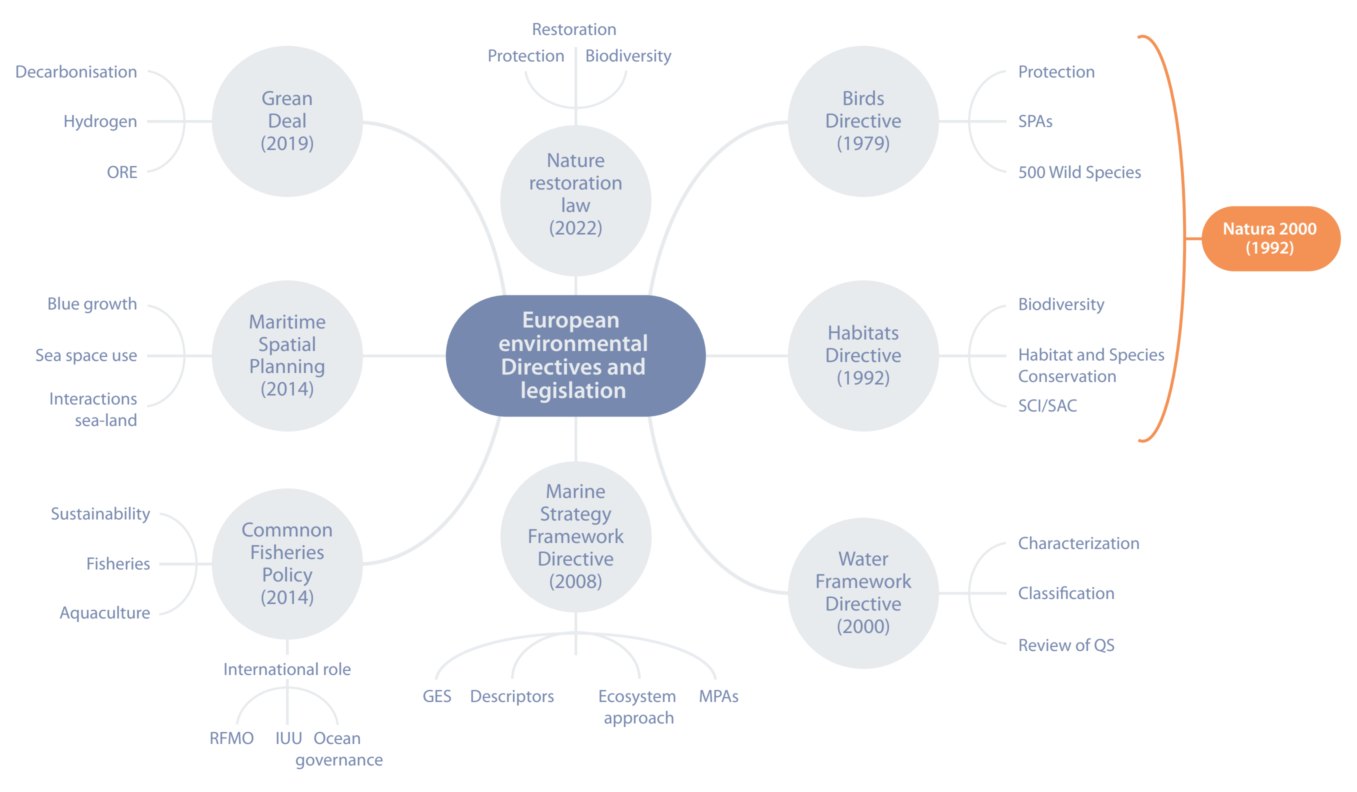
3 Review of European offshore renewable energy status

In recent years, Europe has maintained its pledge to become a world leader in renewable energy, through policy instruments and by promoting technology development, especially in light of the 2015 Paris Agreement.

This chapter presents the European Union's vision regarding offshore renewable energy, as well as the current and planned status of different offshore renewable energy installations in European waters.

3.1 European policies and aims

Policy for offshore renewable technology in the European Union is driven by the European Green Deal and its objective to reach carbon neutrality by 2050. Non-EU countries, such as Norway[61], the UK[62] and Switzerland[63], have different approaches on the extent to which they abide by the requirements and/or sentiments of the Green Deal. However, to ensure sustainable development, the development of the sector will need to be in accordance with both carbon and biodiversity targets, and will also be influenced and shaped by policies which manage maritime spatial planning, grid connectivity and other sectors. The European Union has several policy instruments that specifically concern the impact of human activities on the state of coastal and marine environments. Relevant EU Directives and legislation for offshore renewable energy (ORE) are presented in Figure 3.1. A full list of EU policy instruments that relate to ORE are presented in Annex 2.



Credit: Updated from (Benedetti-Cecchi *et al.*, 2018)

Figure 3.1 Key EU Directives regarding the seas and Ocean, where GES = Good Environmental Status, MPAs = Marine Protected Areas, QS = Quality Status, RFMO = Regional Fisheries Management Organisation, IUU = Illegal, Unreported and Unregulated fishing, SPAs = Special Protection Areas, SAC = Special Areas of Conservation, SCI = Sites of Community Importance.

[61] https://www.regjeringen.no/contentassets/38453d5f5f5d42779aaa3059b200a25f/a-european-green-deal-norwegian-perspectives-and-contributions-20.04.2021.pdf

[62] https://www.chathamhouse.org/2020/02/what-european-green-deal-means-uk

[63] https://www.eda.admin.ch/missions/mission-eu-brussels/en/home/key-issues/enviroment-climate.html

3.1.1 Marine Strategy Framework Directive

The most comprehensive European Ocean-related Directive is the Marine Strategy Framework Directive (MSFD) (European Parliament and the Council of the European Union, 2008). The MSFD lists eleven Descriptors of Good Environmental Status (GES), and embraces the ecosystem approach, recognising the paramount importance of biodiversity and ecosystem functioning. Descriptor 1 prescribes that biodiversity is maintained. Descriptors 2-11 consider a series of impacts arising from human activities and require that they do not cause significant harm to ecosystem functioning. The installation and operation of ORE must thus respect these prescriptions.

3.1.2 Biodiversity Strategy and Nature Restoration Law

In May 2020, the European Commission (EC) published a Communication on the Biodiversity Strategy to 2030 (European Commission, 2020c). The strategy outlines the need to address the significant biodiversity loss that has been witnessed over the last four decades. The Communication recognises that *"more sustainably sourced renewable energy will be essential to fight climate change and biodiversity loss"*. It also states that the *"EU will prioritise solutions such as ocean energy, offshore wind, which also allows for fish stock regeneration"*. However, the Communication also calls for 30% of the sea to be protected and at least 10% of EU seas to be strictly protected. Currently 19% of EU waters are protected, and only 1% strictly protected[64]. Member States have until the end of 2023 to demonstrate significant progress in legally designating new protected areas and integrating ecological corridors. Member States should also effectively manage all protected areas, defining clear conservation objectives and measures, and monitor them appropriately. These requirements will add to competition for Ocean space and impact the selection of viable locations for ORE installations. There are, however, potential opportunities to be considered e.g. in relation to co-location of Marine Protected Areas (MPAs) and ORE sites.

In 2022, the EC proposed a new Nature Restoration Law[65] aiming to restore ecosystems, as a key component of the Biodiversity Strategy. This Law, if approved, would require Member States to develop nature restoration plans to *"cover at least 20% of the EU's land and sea areas by 2030, and ultimately all ecosystems in need of restoration by 2050."* In relation to ORE, the EC highlights the importance of considering the aims and requirements, including for Ocean space, of other relevant Directives (outlined in this Section), and recommends mapping areas ideal for ORE installations, while ensuring that their impact would be low and that areas assigned for protection or restoration are avoided.

3.1.3 Maritime Spatial Planning

Spatial planning has been introduced as a tool to manage the use of marine space, creating synergies between different activities. There are two differing terminologies that are often used: *Marine* Spatial Planning and *Maritime* Spatial Planning (both abbreviated as MSP). Based on the UNESCO approach, Marine Spatial Planning mainly considers the development, conservation and promotion of marine biodiversity and ecosystem functioning. Maritime Spatial Planning, as used by the European Commission, involves all human use of the Ocean and seas, e.g. fishing, aquaculture, mining, transportation (from ships to pipelines), tourism and leisure and the installation of infrastructure such as ORE platforms (Ehler *et al.*, 2019). We use the EC approach, which considers marine and maritime as synonyms[66] since Maritime Spatial Planning *sensu* EC merges the natural aspects with human uses. This should result in a holistic approach that nests maritime activities into the natural world, and the term MSP in this case is used to cover both aspects.

The EU MSP Directive (European Parliament and Council, 2014) was adopted in 2014 in response to the high and rapidly increasing demand for Ocean space for different purposes, including ORE installations. Member States are supported in producing national plans for their waters (e.g. via an expert group who provides advice, and in cross-border cooperation), which should include the placement of all OREs and other spatial uses of the marine environment and must be reviewed at least once every 10 years.

3.1.4 European Green Deal and Offshore Renewable Energy Strategy

The production and use of energy accounts for more than 75% of the EU's greenhouse gas emissions (European Commission, 2019). Decarbonising the EU's energy system is therefore critical. The EU Green Deal focuses on three key principles for the clean energy transition:

1. Ensuring a secure and affordable EU energy supply;
2. Developing a fully integrated, interconnected and digitalised EU energy market; and
3. Prioritising energy efficiency, improving the energy performance of buildings and developing a power sector based largely on renewable sources.

In 2021, the installed offshore wind capacity of Europe was 28.33GW (see Figure 3.2), of which 15.59GW was in EU Member State waters (WindEurope, 2022b). Installed Ocean energy capacity in European waters was 11.5MW for wave and 1.4MW for tidal current (OEE, 2022). The Offshore Renewable Energy Strategy (European Commission, 2020b), which is part of the Green Deal, outlines what the EU considers to be realistic and achievable objectives to contribute to its climate neutrality vision. This includes a requirement to increase capacity in European waters to:

- At least 60GW of installed offshore wind and 1GW of installed Ocean energy in 2030; and
- At least 300GW of installed offshore wind and 40GW of installed Ocean energy in 2050.

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[64] https://www.europarc.org/european-policy/eu-biodiversity-strategy-protected-areas/eu-2030-biodiversity-strategy/

[65] https://environment.ec.europa.eu/topics/nature-and-biodiversity/nature-restoration-law_en

[66] https://www.msp-platform.eu/msp-eu/introduction-msp

This requires an approximate 30-fold increase in ORE capacity by 2050, divided into a 25-fold increase in wind energy capacity, and over 3000-fold increase in Ocean energy capacity. The current national targets as expressed in the Member States' National Energy and Climate Plans (NECPs) suggest that this can be achieved. However, as discussed in Chapter 2, the renewable energy resource is not equally distributed, and therefore a regional approach will be needed, considering the available potential and specific capacities of each European sea basin. Individual technologies will also need to be adapted for different regions and support infrastructure considered (e.g. in terms of grid connections).

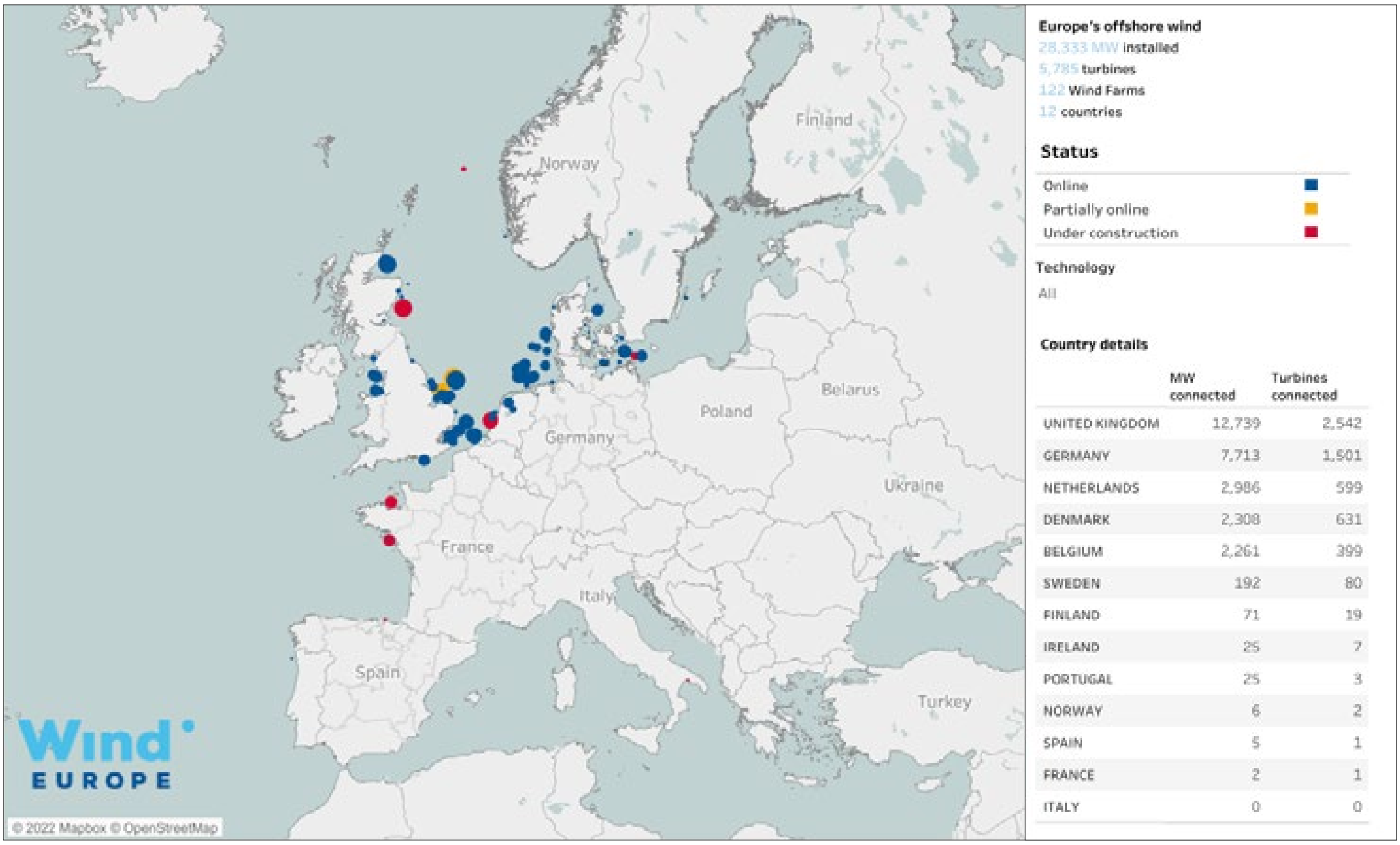
In its Offshore Renewable Energy Strategy, the EC also addresses broader issues, such as:

- Access to sea-space;
- Industrial and employment dimensions;
- Regional and international cooperation; and
- The technological transfer of research projects from the laboratory into practice.

National governments and authorities must plan for this long-term European evolution, assessing Member States' environmental, social and economic sustainability, and ensuring coexistence with other maritime activities, while remaining compatible with other EU policies, strategies and Directives.

To ensure progress towards EU climate neutrality in 2050, negotiations are ongoing around a proposed intermediate 'Fit for 55' package[67] of measures, first published in 2021, which intend to reduce emissions by at least 55% by 2030. This package includes plans to further boost the share of European renewable energy by 2030[68]. It also revises climate and energy legislation to reduce the reliance on fossil fuels and to expand the use of renewable energy sources (among others). In this respect, the EC is proposing a more ambitious target for the renewable energy share of 40% by 2030 instead of 32%.

In response to the economic and geopolitical challenges in Europe, the EC adopted the REPowerEU Plan[69] in 2022. This plan aims to both reduce European reliance on Russian fossil fuels and address climate change. For renewable energy, this plan calls for increased acceleration of the energy transition, further increasing the ambitions set out in the Fit for 55 Package. In September 2022, the European Parliament voted to increase the renewable energy share target to 45% and added a sub-target requiring that 5% of all new renewable energy capacity installed in Europe should be from innovative sources, including Ocean energy[70]. At the time of writing, negotiations on these targets are ongoing between European bodies.



Country details

	MW connected	Turbines connected
UNITED KINGDOM	12,739	2,542
GERMANY	7,713	1,501
NETHERLANDS	2,986	599
DENMARK	2,308	631
BELGIUM	2,261	399
SWEDEN	192	80
FINLAND	71	19
IRELAND	25	7
PORTUGAL	25	3
NORWAY	6	2
SPAIN	5	1
FRANCE	2	1
ITALY	0	0

Credit: WindEurope

Figure 3.2 European offshore wind farms map[71].

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[67] https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/

[68] https://www.consilium.europa.eu/en/infographics/fit-for-55-how-the-eu-plans-to-boost-renewable-energy/

[69] https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3131

[70] https://www.oceanenergy-europe.eu/strong-support-for-innovative-renewables-must-continue-into-next-stage-of-red-iii-negotiations/

[71] https://windeurope.org/intelligence-platform/product/european-offshore-wind-farms-map-public/

Credit: European Marine Board

Sea Installer vessel loaded with offshore wind turbine towers and blades in Ostend, Belgium.

3.1.5 European governance initiatives

There are several additional European governance initiatives which relate to the development of ORE.

The 2007 European Strategic Energy Technology Plan[72] (SET Plan) is a European initiative to accelerate the development and deployment of low-carbon technologies, through cooperation amongst EU countries, companies, research institutions, and the EC. In relation to ORE, implementation plans have been developed for offshore wind, Ocean energy, integrated energy systems and High Voltage Direct Current (HVDC). Annual reports have been published on the progress of the implementation plans since 2019, with the most recent report being from 2021[73].

In parallel to the launch of the SET Plan, the European Energy Research Alliance[74] (EERA) was created to align the research and development activities of individual research organisations with the SET Plan priorities and to establish a joint programming framework at EU level. EERA operates using joint programmes on technologies and cross-cutting issues including Ocean and wind energy, as well as energy storage.

European Technology Innovations Platforms (ETIPs) are industry-led stakeholder Platforms recognised by the EC as key actors for driving innovation, knowledge transfer and European competitiveness in their sector. ETIPs develop research and innovation agendas, and roadmaps for action at EU and national levels to be supported by both private and public funding. They mobilise stakeholders to actively contribute to the agreed priorities and share information across the EU. There are ETIPs dedicated to both wind[75] and Ocean energy[76], which have worked to support the SET Plan and have identified research priorities and roadmaps for these technologies.

3.2 Overview of offshore renewable energy implementation and capacity in Europe

This section will present an overview of the present and planned capacity of ORE in European waters. Related enablers and infrastructure (e.g. grid connectivity) are discussed in Chapter 6.

3.2.1 Mature technologies

Mature ORE technology installations are those at TRL 6-9, including offshore wind, tidal current and range, and wave energy.

Offshore wind

According to WindEurope (2022a), by mid-2022 there was 28,363MW installed offshore wind capacity in Europe (with 30MW installed in early 2022), corresponding to 123 offshore wind farms with 5,795 grid-connected wind turbines. Only 103MW (0.36%) of this total installed capacity involved floating offshore wind farms. However, this represents 83% of floating wind capacity globally, indicating the relative immaturity of this sector and the ongoing dominance of Europe in offshore renewable energy installation, including for floating wind installations.

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[72] https://energy.ec.europa.eu/topics/research-and-technology/strategic-energy-technology-plan_en

[73] https://setis.ec.europa.eu/set-plan-progress-report-2021_en

[74] https://www.eera-set.eu/

[75] https://etipwind.eu/

[76] https://www.etipocean.eu/

In Europe as of June 2022 (WindEurope, 2022a), the UK lead in offshore wind production, with a cumulative capacity of 12,739MW (i.e. the total of all the capacity that has at some point been installed, including some devices that have since been removed from the water), and 2,542 grid connected wind turbines. The UK is followed by Germany (7,713MW and 1,501 turbines), the Netherlands (2,986MW and 599 turbines), Denmark (2,308MW and 631 turbines) and Belgium (2,261MW and 399 turbines). These countries represent 99% of the total installed capacity in Europe. The North Sea hosts almost 20GW (79% of the total offshore wind capacity in Europe), followed by the Irish Sea (12%), the Baltic Sea (9%), and the Atlantic Ocean (<1%). The dominance of northern European seas in offshore wind energy production is due to a combination of factors including wind resource availability, and the fact that these regions have shallower waters which enable easier installation.

Although the oceanographic and atmospheric conditions and the seafloor geomorphology in the Mediterranean Sea are quite different from the northern European seas, the available wind potential is significant. The first operational (since April 2022) offshore wind farm in the Mediterranean Sea is located off the Italian Puglia coast. It comprises 10 wind turbines each with a nominal capacity (in optimal wind conditions) of 3MW, giving a total capacity of 30MW[77]. However, ORE developments in the Mediterranean Sea are experiencing opposition on both environmental and social-economic grounds (see e.g. Lloret *et al.,* 2022).

Over the next three years, several floating offshore wind projects are expected to be commissioned including four projects in France (with a total capacity 113.5MW), one in Norway (88MW) and one in the UK (50MW). Three of the floating projects in France will be in the Mediterranean Sea with a total capacity of 85MW.

Tidal current and range, and wave energy

According to Ocean Energy Europe (OEE, 2021), the cumulative tidal current energy potential (i.e. the total capacity of all tidal current devices that have been installed, even if some of them have now been removed, operating at their maximum in ideal conditions) installed in Europe since 2010 is 27.9MW, which is nearly 77% of the global cumulative installed potential of 36.3MW, showing European leadership. By the end of 2020, 10.1MW was still deployed in European waters, with other installations having been decommissioned. The corresponding figures for wave energy are 12MW cumulative energy potential in Europe (51% of the global cumulative installed potential of 23.3MW) and 1.1MW of capacity still installed in 2020. These figures indicate the lower maturity of tidal current and wave energy, with most devices being installed for limited durations to facilitate testing and prototyping, rather than in permanent commercial farms.

In 2021, a major advance in tidal current energy was achieved through the deployment of O2[78]: the world's largest tidal turbine (2MW capacity), by Orbital Marine Power in the Orkney Islands, UK. Another Orbital turbine is scheduled to be deployed in the same area in combination with a hydrogen production facility and a battery system within the scope of the EU's Horizon 2020-funded FORWARD2030 project[79]. In another relevant Horizon 2020-funded project, EnFAIT[80] (Enabling Future Arrays in Tidal), Nova Innovation has installed a commercial turbine as part of the tidal array deployed in Shetland, as noted in Section 2.2.3.

At present there are only two operational tidal range energy plants in Europe: La Rance tidal barrage in France, and a smaller scale tidal range power plant (of 1.2MW capacity) installed in Oosterschelde in the Netherlands (see Figure 3.3).

Credit: European Marine Board

Figure 3.3 Oosterschelde tidal range power plant in the Netherlands.

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[77] https://www.offshorewind.biz/2022/04/22/first-mediterranean-offshore-wind-farm-up-and-running-in-italy/

[78] https://orbitalmarine.com/o2/

[79] https://forward2030.tech

[80] https://www.enfait.eu/

Regarding wave energy, two pioneering oscillating water column (OWC, see Section 2.2.2) power plants in Europe were the 400kW Pico in the Azores that was constructed in 1999 as part of a pilot project and closed in 2018[81], and the Mutriku 296kW plant constructed in 2011 in the Basque country which is still operational[82]. In 2018, a 200kW Wavepiston wave energy converter (WEC) oscillating body device was also installed in Gran Canaria, Spain as a demonstrator. This latter device will be in the water until 2023 and a second device is expected to be installed in the same area for desalination and power production purposes[83]. However, except for a 600kW oscillating body WEC that was deployed by Wello at the Biscay Marine Energy Platform in July 2021 and was connected to the grid[84], most deployed devices are of limited capacity, many of them being sub-scale prototypes under development. The Wello device is undergoing two years of testing in real conditions to better assess its reliability and robustness.

3.2.2 Technologies in pilot/demonstration phase

Less mature ORE technology installations, considered at TRL 1-5, include floating solar, salinity gradient, marine biomass and hydrogen production.

Floating solar energy

Although floating solar parks have been installed and are operating in artificial lakes etc. in Europe, especially in the Netherlands[85], no solar park has yet been installed offshore. In 2019, the Dutch company, Oceans of Energy[86], installed a pilot floating solar module in the North Sea. The system survived the harsh environmental conditions in the installation area for 18 months[87]. This was followed in 2022 by the installation of a 1MW system of 200 floaters 12km offshore in the North Sea[88].

Salinity gradient

At present, European activities utilising salinity gradients are very limited. The first pilot osmotic power plant was developed by the Norwegian company, Statkraft, in 2009 but ceased operations in 2014 due to viability issues[89]. The first Reverse Electro Dialysis (RED) power plant (50kW) was installed in 2014 in the Afsluitdijk dam in the Netherlands (Wadden Sea) and is still operational[90]. Within the context of the EU's FP7 REAPower project[91], a pilot-scale plant was installed in 2014 at Trapani (Italy), with 48m^2 of total membrane area and one RED unit (Tedesco *et al.,* 2016). A further scale-up (of 1kW power capacity) of the original pilot plant resulted in three RED units and 400m^2 of total membrane area (Tedesco *et al.,* 2017). The pilot plant is no longer in operation. The EU Horizon 2020 project INTELWATT[92] aims *inter alia* to develop an integrated pilot unit in Castellgalí near Barcelona, Spain. This unit will comprise of RED and solar powered membrane distillation systems and should demonstrate a TRL of 7.

Marine biomass

In Europe, there are 13 countries developing macroalgae production (Araújo *et al.,* 2021), with the top three producers being France, Ireland and Spain. Macroalgae is mostly wild harvested and used in food related products and not in energy production. For more on the state of knowledge on the potential for macroalgae cultivation see the EKLIPSE report (Bermejo *et al.,* 2022).

For microalgae, the current production methods are not yet ready to support large-scale biofuel production. Despite there being a growing interest in algae production, the status of the algae industry for biofuel production in Europe is currently unknown (Araújo *et al.,* 2021).

For a review of marine biomass energy in general and its status in Europe see Araújo *et al.,* (2021) and Thomas *et al.,* (2021).

Hydrogen

The EU has fixed an ambitious target of developing 40GW of hydrogen generation capacity by 2030. To achieve this target, renewable energy will be needed to power this process. The main OREs targeted are solar and wind, and more specifically offshore wind, due to its higher capacity factor (i.e. the ratio of the electrical energy produced for a specific time-period to the theoretical maximum electrical energy produced in the same period, see Section 2.1.1). Projects for coupling electrolysers with offshore wind turbines are under development (e.g. in the North Sea off Denmark) and being assessed (Singlitico *et al.,* 2021).

3.3 Barriers

Even though the increase in ORE proposed by the EU is realistic and achievable, it is ambitious and will need to be supported across a wide range of sectors. A broad range of technological issues are constraints or bottlenecks to the expansion of this industry (see Chapter 6). The ability of the supply chain to adapt and respond to the exponential demand is questionable: There are many constraints and bottlenecks in the various domains of the supply chain at all stages of the life cycle of an ORE device (see Chapter 5).

Poulsen & Lema (2017) found that the installation of sub-stations and export cables and unscheduled or contingency maintenance operations pose logistical challenges, which will need to be overcome. The lack of ports equipped with adapted infrastructure and located in the vicinity of deployment sites, also limits optimal exploitation of sites with a good level of resource (Cradden *et al.,* 2016).

[81] http://www.pico-owc.net/en/

[82] https://www.eve.eus/Jornadas-y-Noticias/Noticias/La-planta-de-energia-de-las-olas-de-Mutriku-bate?lang=en-gb

[83] https://www.wavepiston.dk/

[84] https://wello.eu/2021/07/28/wellos-wave-energy-converter-deployed-in-basque-country

[85] The largest one (Zonnepark Bomhofsplas) in Europe is located in the Netherlands and has 72,000 solar panels. The park, of 27.4MW installed capacity, is installed in a sand extraction lake and was connected to the grid in 2020.

[86] https://oceansofenergy.blue/

[87] https://www.offshore-energy.biz/oceans-of-energys-floating-solar-system-weathers-through-all-north-sea-storms/

[88] https://oceansofenergy.blue/north-sea-2/

[89] https://www.powermag.com/statkraft-shelves-osmotic-power-project/

[90] https://www.power-technology.com/features/making-blue-from-red-the-potential-of-salinity-gradient-power/

[91] https://www.reapower.eu/

[92] https://www.intelwatt.eu/

3.4 Expansion to key markets

Key objectives for ORE are to provide grid-connected electricity, contributing to global decarbonisation and energy transition, and to provide energy in a predictable, environmentally sustainable and affordable manner. In addition to the grid power market, other potential markets have been explored. The 'Blue Economy'[93], involving the sustainable use of the Ocean and economic growth, comprises a range of sectors, some of which represent additional opportunities for ORE. Sectors such as aquaculture are expanding into the open Ocean, requiring consistent and reliable energy and provide an opportunity for ORE market expansion. For example, the EU Horizon 2020-funded Blue Growth Farm project[94] aims to design an environmentally friendly multi-purpose offshore platform, which accommodates an industrial aquaculture platform and includes a wind turbine and a set of wave energy converters.

Islands are at present heavily reliant on costly fossil fuels for electricity generation, and are looking to address supply security, environmental sustainability and energy affordability. Small Island Developing States (SIDS) pay some of the highest energy costs in the world, largely due to high fuel transportation costs. ORE can be an attractive option for these energy markets, as these locations tend to coincide with good ORE resource potential (OES, 2020). Specific market opportunities also exist for offshore energy technologies coupled with desalination projects (see Section 2.1.5), which are usually energy intensive. This is an opportunity for handling the water crisis on islands. For example, there is an increasing need for fresh water in the Aegean Sea and Canary Islands; desalination using renewable energy could be an optimal solution for resolving the adverse impacts that the shortage of fresh water has on economic activities in these areas (e.g. Kyriakarakos *et al.*, 2022).

Alternative non-utility markets may help reduce costs by allowing rapid innovation and testing to a level where ORE technologies can be cost competitive to provide grid power and have offered a unique opportunity for the development of emerging ORE technologies (Cantarero *et al.*, 2020). Röckmann *et al.*, (2017) also suggest that operating and maintenance reductions could be achieved through cooperation with other sectors in hybrid installations (e.g. wind energy and aquaculture) by sharing costs and by reducing logistical waiting times.

LiVecchi *et al.*, (2019) investigated possible applications of ORE in key markets of the Blue Economy as shown in Table 3.1.

	NEAR TERM	EMERGING	FUTURE
Power at sea			
Ocean Observation and Navigation	✔		
Underwater Vehicles Charging	✔		
Marine Aquaculture		✔	
Marine Algae		✔	
Mining Seawater Mineral and Gases			✔
Resilient coastal communities			
Desalination	✔		
Disaster Resiliency and Recovery		✔	
Community-scale Isolated Power Systems	✔		

Credit: Based on (LiVecchi *et al.*, 2019)

Table 3.1 Market opportunities for offshore renewable energy technologies.

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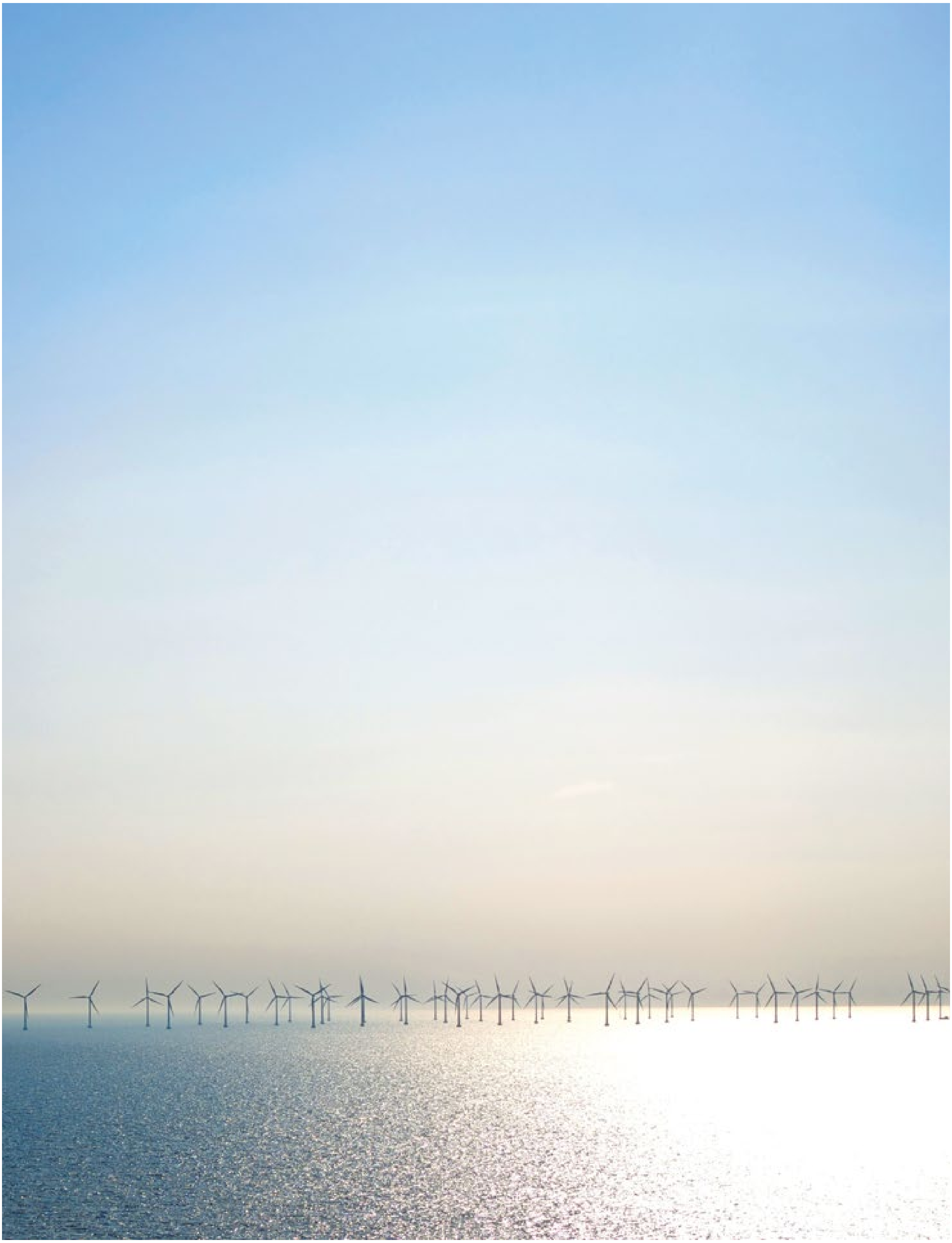
[93] https://oceans-and-fisheries.ec.europa.eu/ocean/blue-economy/sustainable-blue-economy_en

[94] https://cordis.europa.eu/project/id/774426



Credit: Foundry Co, Pixabay

Offshore wind farm

4 Environmental impacts from offshore renewable energy: Lessons learnt

Observed and measured impacts of offshore renewable energy (ORE) installations on the marine environment exist for offshore wind turbines and wind farms. Such information also exists for Ocean energy technologies (primarily wave and tidal) though this tends to be limited to single devices deployed for time-limited periods. It is critical that international and European efforts continue to measure and monitor environmental effects, particularly as more and more commercial scale deployments become operational. This extends to all phases of development from project planning through to decommissioning.

This chapter presents the state-of-the-art in understanding the positive and negative impacts of offshore wind installations on marine environments and ecosystems and proposes mitigation measures. It also notes the potential for similar impacts arising from different installations.

4.1 Positive and adverse impacts

Since the first wind turbines at sea were installed in Danish waters in 1991, monitoring programmes to investigate their impact on the surrounding marine ecosystems have been a pre-operational requirement and many of those results have now been published (e.g. Degraer *et al.,* 2018). European and global research covers a wide range of potential positive and adverse impacts on all ecosystem components. In relation to Ocean energy technologies in particular, the International Energy Agency's (IEA) Ocean Energy Systems – Environmental (OES-E) initiative produces a bi-annual State of the Science report which integrates the latest scientific information and research on a range of environmental impacts at a global scale[95]. This complements the IEA's Technical Collaboration Programme on Wind Energy[96], that has included a task on social, environmental and economic impacts of wind energy since 2012. This task, more commonly known as Working Together to Resolve Environmental Effects of Wind Energy (WREN), was created to address the environmental issues associated with commercial development of land-based and offshore wind energy projects. The outputs from both these programmes, together with studies conducted by international bodies (e.g. OSPAR), developers, governments and researchers, have contributed to a solid understanding of the potential impacts of offshore energy on marine ecosystems.

Current knowledge indicates that fish, marine mammals, invertebrates, seabirds and benthic species can be affected by ORE installations. Data on short-term species-level impacts for some species (e.g. seabirds, marine mammals, fish) are available (e.g. Lindeboom *et al.,* 2011). Over the long-term (e.g. around 10 years), marine ecosystem changes have been linked to offshore wind farms, predominantly in the North Sea due to the high abundance of farms in this location (Galparsoro *et al.,* 2022). These short- and long-term impacts on species and ecosystems may be either positive or negative. Detailed evidence maps for different species have been produced by ScotMER[97] and by Natural England[98]. A systematic review of the potential environmental effects of ORE is provided by Martínez *et al.,* (2021).

ORE installations also impact abiotic elements of the marine environment, for example wave energy farms acting as wave breakers may have important effects on shoreline dynamics by affecting the coastal sea state conditions and circulation patterns (Onea & Rusu, 2019).

The lists below present the main positive and negative effects of ORE on the marine environment and ecosystems. Annex 4 includes key references that support the effects outlined.

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[95] https://tethys.pnnl.gov/about-oes-environmental

[96] https://iea-wind.org/

[97] https://www.gov.scot/policies/marine-renewable-energy/science-and-research/

[98] https://naturalengland.blog.gov.uk/2022/04/13/offshore-wind-best-practice-advice-to-facilitate-sustainable-development/

Credit: Gilles Lagnel, Pixabay

Current knowledge indicates that marine mammals, such as these Common Bottlenose Dolphins, can be affected by ORE installations.

Positive

- Changes in physical environment: reductions in flow discharge, reduced erosion along coastlines;
- Creation of new habitats, potential increase of biodiversity from artificial reef effect;
- Fishing exclusion zones;
- Potential increase of benthos/fish biomass from 'reserve effect' (i.e. from the creation of an area where fishing is effectively not taking place), and related feeding opportunities;
- Creation of refuges for agile invertebrates and fish;
- Enhanced ecosystem connectivity via 'stepping-stones' created by installed structures;
- Reduction of GHG emissions and global warming effects; and
- Reduced risk of fuel (e.g. oil, gas, nuclear) discharges into the environment.

Adverse

- Changes in the physical environment: energy removal, temperature change, discharges, stratification, changes in air and/or water flow, sediment resuspension, deoxygenation, changes to shoreline dynamics;
- Changes in benthic communities through hard substrate introduction or increase in erosion effects on the seabed;
- Collisions with (moving) installation components and possible subsequent fatalities, impacts on migration and connectivity;
- Potential habitat and foraging site loss for some species through introduction of installations or avoidance of specific areas;
- Noise during installation and operation;
- Emission of contaminants (e.g. in anti-fouling paints, ballast water);
- Electromagnetic fields; and
- Increase in non-indigenous and invasive species through additional habitat provision and increased connectivity.

Several studies have outlined how basic monitoring alone may not be sufficient to disentangle specific cause–effect relationships, especially for systems with high natural variability (e.g. Lindeboom *et al.,* 2011). However, targeted monitoring activities such as the near-turbine effect studies on benthos (e.g. Degraer *et al.,* 2018), the feeding behaviour of demersal fish in wind farms (e.g. Derweduwen *et al.,* 2016) and the escape behaviour of harbour porpoises during piling (e.g. Haelters *et al.,* 2015), have provided significant new and important knowledge on cause–effect relationships (Degraer *et al.,* 2013).

Boehlert & Gill (2015) distinguish between effects and impacts in their synthesis of environmental and ecological effects of ORE development. An 'effect' does not indicate a magnitude or significance, whereas an 'impact' implicitly deals with severity, intensity or duration of the effect. Several studies have identified elements that suggest an effect, but further work is usually required for it to be interpreted as an impact. The same rationale is present in the extensive review of monitoring data derived from the licence conditions of offshore wind farms conducted by the UK Marine Management Organisation (MMO) (Marine Management Organisation, 2014). The aim was to validate predictions made in Environmental Impact Assessments (EIAs, see Section 4.5) or Habitat Regulations Assessments (HRA)[99] to detect any unforeseen impacts and to ensure compliance with identified mitigation measures. The MMO provides a set of cross-topic recommendations, suggesting that monitoring should be species-driven, using EIA and HRA impact statements as a hypothesis for investigation. The MMO proposes that post-consent monitoring should be requested where there is uncertainty regarding scientific understanding, in the significance of an impact on a sensitive species or on the effectiveness of the proposed mitigation measure. They propose that environmental surveys should collect data which help to better understand the significance of impacts on marine environments and species. They also suggest that post-consent monitoring is not recommended for impacts that are already well understood and/or where the mitigation measures for impact have been tried and tested. A study with similar recommendations has also been conducted by the Renewables Grid Initiative (Stephenson, 2021).

4.2 Short-term and long-term effects

Monitoring of the potential environmental effects of human activities is required by environmental legislation across many countries and is addressed at EU level in the amended Environmental Impact Assessment Directive[100] (see Section 4.5) of 2014. Short-term or basic monitoring focusing on the resultant effect of human activities, including the construction and operation of offshore wind farms, is the most common. The design of these monitoring studies (e.g. Before-After-Control-Impact or the Before-After design) may be different but they always need to include the assessment of a baseline to be used as a reference to assess major and even unforeseen impacts. It may also trigger adjustment to or even halting of activities if unacceptable impacts (e.g. excessive noise) occur. Longer-term strategic monitoring studies are useful for future planning and policymaking as they can provide insight into population and ecosystem effects as well as implications for other sectors and marine users. It is essential that the results of these monitoring studies are used to design future research programmes and refine scientific knowledge. A key issue in relation to the marine environment is the level of information and knowledge that is available on the environmental baseline prior to deployments/installations. This is critical to understanding whether observed changes are a result of the development occurring or alternatively if they are due to other stressors on the environment at a particular location, including climate related changes.

Most evidence indicates that ecosystems containing ORE devices continue to alter over time, and the patterns observed so far are considered short-term effects, likely reflecting the initial stages of ecological change and succession (Lindeboom *et al.,* 2011). Offshore wind farms have only been installed for a maximum 32 years, and there has not been consistent monitoring of impacts for the full period. There are also difference between countries for what is permitted in these areas, e.g. whether or not certain types of fishing can still be conducted in these areas or whether all other activities are banned. For other ORE devices, the period for which they have been installed in the Ocean is significantly shorter and limited to specific areas. In short, we simply do not presently have data covering a long enough period, and therefore some impacts may not yet be detectable.

As an example, the enrichment of soft sediment macrobenthos observed close to wind turbines has been demonstrated to spatially extend over time (Mendel *et al.,* 2019) although it might not have reached the spatial extent to be picked up by the basic monitoring of macrobenthos, where samples are collected at a distance more than 200m from the turbines (Gill *et al.,* 2012; Krägefsky, 2014). In another example, and contrary to expectation, six years after the construction of the Thornton and Bligh Bank offshore wind farms in Belgium, no effects from the exclusion of fishing activities were detected in soft sediment epibenthos and fish populations between the turbines (de Backer & Hostens, 2017) and no change had been observed in macrobenthos related to fisheries exclusion (Reubens *et al.,* 2016). The duration for which monitoring was conducted after construction was probably too short and the fisheries exclusion zones linked to the wind farms were not sufficiently large for the effect of the fisheries exclusion to be detected away from the area around each individual turbine. By contrast, in the same offshore wind farms, temporary effects have been observed such as density and biomass peaks of epibenthos that lasted only two years post-construction and decreased towards levels similar to the reference areas three years post-construction (de Backer *et al.,* 2017). A similar positive short-term effect was observed at the Horns Rev offshore wind farm in Denmark, where an initial increase in the abundance of juvenile sand eels (a fish species associated with sediment) was observed one year after construction (Danish Energy Agency, 2013). Long-term continuation of basic monitoring of all ecosystem components is recommended to record any long-term effects. However, it is still unclear what the appropriate time window is for capturing short-term and long-term effects since this varies for different species and devices and is also dependent on the state of the ecosystems that these devices are installed within.

[99] In the UK, a Habitats Regulations Assessment (HRA) refers to an assessment that must be undertaken to comply with the Conservation of Habitats and Species Regulations 2017 (as amended) and the Conservation of Offshore Marine Habitats and Species Regulations 2017 (as amended) to determine if a plan or project may affect the protected features of a habitats site before deciding whether to undertake, permit or authorise it. It is largely equivalent to the Appropriate Assessment process required under Article 6 of the EU Habitats Directive.

[100] https://ec.europa.eu/environment/eia/eia-legalcontext.htm

Credit: David Mark, Pixabay

Marine species such as sharks, rays and skates are sensitive to electromagnetic fields.

4.3 Physical agents of adverse impact

There are several negative physical impacts that ORE installations can have on marine species and ecosystems that have been studied scientifically and have come to the attention of policymakers, namely underwater noise, electromagnetic fields, collisions and strikes, and seabed damage. A review of potential environmental effects from ORE, including these physical impacts, is given by Copping *et al.,* (2020). Underwater noise and electromagnetic fields are discussed in more detail below.

4.3.1 Underwater noise

As discussed by Thomsen *et al.,* (2021), marine animals use sound in the Ocean in the same way as terrestrial animals and humans use sight on land; to communicate, navigate, find food, socialise and evade predators. Anthropogenic noise in the marine environment interferes with these activities, so it has received considerable attention by the scientific community. In the context of ORE devices, these impacts can arise both during the installation (e.g. from pile-driving) and operational phases. These and other noise sources can cause impacts including auditory masking, stress, behavioural changes, acoustic responses (temporary or permanent reduction in hearing sensitivity), injuries and strandings (Southall *et al.,* 2007). The possible impact that noise might have on a marine species depends on the frequency (Hz), intensity and time duration of the noise. A significant amount of current underwater noise research and regulations have focused on noise sources that are more pervasive (e.g. vessel traffic) and/or are comparatively "louder" (e.g. seismic surveys). In 2019, the International Electrotechnical Commission published a standard for the acoustic characterisation of marine energy devices[101] to support this research. However, more recent studies have considered noise from ORE devices and its potential impacts (e.g. Popper *et al.,* 2022), concluding that at present, knowledge gaps around the effects of sound on some marine species and a lack of data under actual conditions preclude assessment of any potential cumulative impacts.

Globally, the regulatory protection afforded to marine animals, particularly marine mammals (e.g. the 1972 Marine Mammal Protection Act in the United States[102], the EU's 2008 Marine Strategy Framework Directive[103] and the 1992 Habitats Directive[104]) mandate that measures should be taken to minimise any ecological impacts arising from emissions of anthropogenic underwater noise. As such, consideration of the potential impact of ORE device noise is often required as part of the EIA carried out in support of licensing processes. Although significant uncertainty remains about the risk posed to marine species by noise, the evidence acquired from post-consent monitoring studies (e.g. Marine Management Organisation, 2014) suggests that underwater noise emitted from operational ORE devices is unlikely to significantly alter behaviour or cause physical harm to marine animals. Most adverse effects are observed during the construction phase of an ORE farm.

The EU's Marine Strategy Framework Directive's (MSFD) Good Environmental Status (GES) Descriptor 11 (D11) relates to the introduction of energy, including underwater noise, at levels that do not adversely affect the marine environment. The Directive will result in the enforcement of recently established threshold values for Good Environmental Status for underwater noise, which will affect the ORE sector. While the threshold values are prescribed at EU level[105], the noise sources of relevance and species of concern will be identified at regional and Member State level. There is significant opportunity to strengthen the interplay between EIA and MSFD requirements at government level, with input from scientists and other experts.

As the number of ORE devices being installed in the Ocean increases, it will be important to consider noise impacts not only for a single device, but also cumulatively for multiple activities in a short time, multiple installations generating noise over a larger area and a longer timescale and in combination with existing noise sources such as shipping.

4.3.2 Electromagnetic fields

In the marine environment, electrical cables induce electromagnetic fields (EMF) along their entire length, regardless of whether they transmit high-voltage direct currents or alternating currents. At present, high voltage alternating current electrical cables are used to connect all types of ORE devices between units in an array and to connect these to marine substations. High voltage alternating current or direct current can be used to export power to shore.

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[101] https://webstore.iec.ch/publication/31031

[102] https://www.fisheries.noaa.gov/national/marine-mammal-protection/marine-mammal-protection-act-policies-guidance-and-regulations

[103] https://ec.europa.eu/info/research-and-innovation/research-area/environment/oceans-and-seas/eu-marine-strategy-framework-directive_en

[104] https://ec.europa.eu/environment/nature/legislation/habitatsdirective/index_en.htm

[105] https://environment.ec.europa.eu/news/zero-pollution-and-biodiversity-first-ever-eu-wide-limits-underwater-noise-2022-11-29_en

The Earth generates its own naturally-occurring geomagnetic field (GMF), which is used by some marine species to navigate and guide migration. Interaction between EMFs emitted by ORE power generation and the Earth's natural GMF can alter the behaviour of some species. Current interest is focused on EMFs generated within the cable and existing along its length, propagating away from the cable into the surrounding environment and decaying in relation to distance from the source. Information on the intensity of the emitted EMF, which depends on the type of current (direct or alternating current, or a transformation between them), the cable characteristics and configuration, the power transmitted, the local GMF and surrounding environmental factors, is very important to assess potential impacts. The more and/or larger the ORE devices and the higher power-rated the cables the stronger the EMF.

The biological response to this EMF depends on the sensitivity of the species, which is determined by their sensory systems (CSA Ocean Sciences Inc. and Exponent, 2019). The movement and distribution of animals also plays a role and may depend on their life stage, as well as how they use the areas where the EMF occurs in time and space. The literature on whether EMF impacts marine species, at which levels and over which timescales, is often contradictory (e.g. Cresci *et al.,* 2022; Hutchison *et al.,* 2020), indicating that more research is needed to better understand potential impacts and their significance at individual- through to population level (Hutchison *et al.,* 2020).

4.4 Mitigation measures

Potential adverse impacts from ORE projects may be temporary or permanent and may occur at different times during a project lifetime. They also occur in several development phases of an ORE farm. However, mitigation measures are usually categorised according to the species and habitats under consideration for the main phases (materials and manufacturing; transport and assembly; installation; operation and maintenance; and decommissioning and disposal) of the project lifetime. As an example, marine mammals may be the main species under consideration for the transport and assembly phase, as these activities are noise generating and marine mammals are particularly sensitive to noise. Relevant mitigation measures would then relate to noise mitigation or ensuring that marine mammal species are not present in the area where noise is being generated. Moreover, combinations of large ORE installations with other human activities in the same area may also produce cumulative effects that are difficult to assess, although they are very important. An attempt to develop a conceptual model to quantify cumulative impacts on the supply of marine ecosystem services using the case study of offshore wind in the Belgian North Sea is outlined in van de Pol *et al.,* (2023) and further such research will be needed.

The most important and efficient mitigation measure to avoid or minimise potential effects on the surrounding species and environment is the appropriate selection of the farm location. This, however, requires a very detailed Environmental Impact Assessment (EIA) study based on actual monitoring and the development and/or availability of a robust baseline of environmental information (see Section 4.5). The most relevant mitigation measures for specific species and habitats are described below, some of which should already be applied from the onset of the design phase of an ORE farm, e.g. during the design of the particular wind turbines and decisions on the number to be installed.

For marine mammals, the most common mitigation measures include:

i) exclusion of areas with habitats that are important for marine mammals[106];

ii) avoiding or suspending noise generating construction activities during biologically sensitive seasons such as breeding or feeding periods;

iii) measures related to the type of turbine foundation (low-noise foundations);

iv) noise-restriction measures (e.g. bubble curtains) to reduce the levels of noise emitted during construction, mainly pile-driving and detonation of historic unexploded ordnance that may lie in the construction area;

v) surveillance (visual and acoustic) of marine mammal presence in exclusion areas; and

vi) measures to actively deter animals away from such areas (e.g. by gradually starting the pile-driving process to allow marine mammals to leave the area, or by restricting the process during peak abundance).

For fishes some of the most common measures taken are:

i) seasonal restrictions on pile-driving to minimise vibration effects and strong impulsive underwater noise (Juretzek *et al.,* 2021); and

ii) burying cables at depths greater than 1m, and/or protection of the cables with appropriate material to minimise the effects of EMF.

For birds, Johnston *et al.,* (2014) suggest that increasing hub height and using fewer and bigger wind turbines can reduce bird collisions. Flashing lights marking the location of ORE turbines are also suggested instead of steady red lights as they are more easily seen by birds. Operational mitigation measures for reducing bird collisions include halting operation during migration periods or changing rotor direction away from the direction of migration. The use of deterrents (visual or audible) that are activated after receiving feedback from a bird-detection radar system is another option, while permanent deterrents e.g. painting, may also be applied to the tower and blades (Gradolewski *et al.,* 2021). May *et al.,* (2020) propose painting one of the rotor blades black to reduce the visual effect of motion smear.

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[106] https://www.marinemammalhabitat.org/imma-eatlas/

Credit: Sheila Heymans

Seabirds such as gulls can collide with offshore wind turbines.

Aside from addressing spatial conflicts on a case-by-case basis, EIA necessitates the inclusion of cumulative impacts and a mitigation hierarchy that can help in the management of spatial conflicts. The mitigation hierarchy routinely utilised in EIA consists of avoiding, minimising and mitigating. Where mitigation is not possible, reasons for proceeding should be proposed to the relevant national bodies during the consenting process. In specific cases where mitigation is not possible, offsetting or compensation should be considered. This does not imply financial compensation but rather actions to redress disruption to ecological integrity or damage to the supply of natural resources.

Whilst there are a variety of technical measures used to address specific environmental impacts as discussed above, avoidance of such impacts is the most effective option and needs to be thoroughly embedded in strategic planning processes such as MSP. This can include factors such as timing of construction to minimise impact on habitats and species, sensitive siting of cables and related infrastructure and overall project/farm layout. Greenhill *et al.,* (2021) found that there are currently no feasible options for the mitigation of displacement effects during operation. Whilst there may be theoretical options such as array design and corridors, these can result in collision and navigational risks.

4.5 Environmental assessment and monitoring

Strategic Environmental Assessment (SEA) and Environmental Impact Assessment (EIA) are processes that seek to ensure that the environmental implications of decisions are considered *a priori*. In the EU, the EIA Directive[107] requires an EIA to be undertaken for a wide range of public and private projects. However, ORE installations are not explicitly included, leading to discrepancies in how they are addressed by Member States. SEA is applied earlier in the decision-making process and covers public plans and programmes, including those in the energy sector, in accordance with the requirements of SEA Directive[108]. In addition, a plan or programme that sets the framework for future development consent of projects listed in Annexes I and II of the EIA Directive, or which have been determined to require an assessment under Habitats and/or Birds Directives, will be subject to a SEA. Public plans and programmes covered by the Directive are subject to an environmental assessment during their preparation and before their formal adoption and require public consultation (including transboundary consultation) in a similar way to EIA. A key difference between SEA and EIA is scale: an SEA is usually conducted at national or regional scale whereas an EIA is conducted at site or project level. The requirement to conduct SEAs has been approached differently in different Member States, where some countries specify in legislation what plans require SEAs whereas elsewhere a case-by-case basis is adopted. Wide consultation of relevant authorities and the public are key features of both EIA and SEA procedures, as discussed in Chapter 5.

SEA involves the preparation of an Environmental Report, where the likely significant environmental effects are identified and evaluated. Article 10(1) of the SEA Directive states that *"Member States shall monitor the significant environmental effects of the implementation of plans and programmes in order, inter alia, to identify at an early stage unforeseen adverse effects, and to be able to undertake appropriate remedial action."* Existing monitoring arrangements can be used, if appropriate, to avoid duplication of monitoring. In the absence of a clear reporting obligation, however, the implementation of monitoring arrangements is not always apparent, and this is something that could be addressed by consenting authorities in the future. This would include monitoring of how the plan/programme has been implemented but also more strategic-level (national or regional) monitoring of the anticipated likely significant environmental effects identified.

With respect to EIA at the project/site level, in cases where a significant impact is expected on a given species and/or habitat, Member States typically require developers to monitor those impacts to verify whether the expected impact is being observed. This is primarily achieved by the terms and conditions attached to the granted consent. For comparison between before and after construction, the monitoring activity should consider whether changes in the environment because of the development have had an effect (positive or negative) on existing environmental conditions. The EIA Directive stipulates that the types of parameters to be monitored and the duration of the monitoring should be proportionate to the nature, location and size of the project and the significance of its effects on the environment. Subsequent monitoring reports should highlight the perceived reasons for the impact and draw conclusions based on comparison with the original assessment(s) contributing to the evolving cycle of EIAs and subsequent licensing and monitoring conditions for future developments, with relevant, re-usable and publicly available data.

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[107] EIA Directive: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32014L0052

[108] SEA Directive: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex%3A32001L0042

5 Socioeconomic impacts from offshore renewable energy: Lessons learnt

People are as much a part of the marine ecosystem as marine habitats and species and therefore it is equally relevant to consider the socioeconomic impacts of offshore renewable energy developments.

The purpose of this chapter is to provide a succinct overview of the current, documented socioeconomic impacts of different offshore renewable energy installations. Given the maturity level of offshore wind, more is known about it in terms of socioeconomic benefits than other developments. An overview of experience garnered to date from community benefit and ownership schemes is also presented. Social impacts have received less attention in the literature and in practice, yet it is often these types of impacts that can stymie developments through public objections and delays.

This chapter therefore looks at how socioeconomic impacts are considered in existing decision-making processes, and how new approaches and concepts might assist in embedding these important impacts into planning and decision-making. The chapter concludes with a section on consenting and governance which identifies some common challenges to decision-making processes, including spatial conflicts.

5.1 Why are socioeconomic aspects important?

Socioeconomics is a branch of economics, but it also refers to the social science that studies how economic activity affects and is shaped by social processes. Socioeconomic theories often consider factors outside of mainstream economics, including the effect of the environment and ecology on consumption and wealth, and how a particular social group or socioeconomic class behaves within a society. Socioeconomics can impact a single individual, a community, a region or even larger geographic areas. Broadly speaking, the socioeconomic impacts from offshore renewable energy (ORE) can be categorised according to direct economic interests, infrastructure, education and other impacted industries (e.g. fisheries, maritime transport) along with quality of life, health and wellbeing aspects. The latter human impacts tend to be overlooked within ORE planning and development processes, perhaps because these developments are offshore and regarded as less important (Alem *et al.*, 2020). Another reason why socioeconomics is not included in existing planning and management processes, is that these processes were not designed with socioeconomic impacts in mind and because ORE is still a relatively recent marine sector with limited longitudinal studies conducted to provide an evidence base. Discrete studies on certain socioeconomic impacts, such as jobs created or supply chain impacts, tend to be commissioned by developers to garner support from local communities, politicians and/or funding bodies. To foster public acceptance and trust in planning and consenting processes, socioeconomic valuation surveys conducted by impartial (academic) researchers are needed at the planning stage with explicit inclusion of follow-up monitoring.

In the context of ORE, the benefits of commercial-scale deployments are direct economic impacts such as increased jobs and the creation of, or strengthening of, the supply chain. Whilst predominantly local to development(s), these economic benefits can have wider regional and sometimes national impacts through investment in grid development, port development and/or other infrastructure. Indirect benefits from ORE development are much more difficult to define and quantify but could include new specialist training programmes or educational courses that are designed to 'supply' the needs of the new industry. Glasson *et al.*, (2022) , in their review of socioeconomic impacts of offshore wind, found a clear focus on economic impacts, especially jobs, and Gross Value Added of the offshore element of the wind farm construction stage, but very little coverage of the onshore element or of social impacts.

It is important to consider and address how offshore renewable energy developments will impact on coastal communities. View of the harbour at Luarca, Asturias, Spain.

Consideration and knowledge of the potential socioeconomic effects of ORE developments are important because local communities want to know what they can expect in terms of employment opportunities and service industries, and how their local environment might be impacted. Existing businesses and marine sectors are interested in whether and how the new activity will impact them. Developers want to know if their project is economically viable and sustainable in terms of available workforce, service provision, available housing and facilities for relocating staff. At a national level, commercial-scale ORE developments have been heralded as a way to revitalise coastal communities, which can experience higher rates of deprivation and peripherality.

A common perception by affected communities is that large-scale development only benefits large companies and has little positive impact on the local community. As a result, many countries are looking at ways to ensure more local employment in ORE developments. In the UK, there was a non-binding proposal to gradually increase the proportion of 'local content' (e.g. direct contracts with UK-registered companies) going into UK offshore wind farms from a target of 50% today to 60% by 2030[109]. This requirement is however being challenged by the EU as a discriminatory practice[110].

Potential socioeconomic benefits currently tend to be studied by project developers as an optional extra rather than a requirement. Research for the Danish Maritime Foundation recently found that there have been limited efforts to study the socioeconomic impacts of the expansion of offshore wind in terms of economic value-added and jobs, particularly locally (QBIS, 2020). The work acknowledges that with substantial expansions planned in the coming decade, including to meet the vision of the European Green Deal (see Section 3.1.4), governments and other stakeholders are increasingly expecting to know what costs and benefits to expect from their investments.

5.2 Socioeconomic benefits

5.2.1 Direct economic benefits

Several financial metrics can be used to quantify the economic viability of an ORE project, e.g. the cost of electricity and net present value[111]. These metrics are used by policymakers and investors to determine the pure economic value of a project and depend on the energy yield of the system and on expenditure. Capital expenditure (CAPEX) includes the cost of the ORE devices, their cables/pipelines,

[109] https://www.greentechmedia.com/articles/read/over-zealous-local-content-rules-could-slow-energy-transition-warns-siemens

[110] https://policy.trade.ec.europa.eu/news/eu-challenges-discriminatory-practices-uks-green-energy-subsidy-scheme-wto-2022-03-28_en

[111] Net present value is a means for expressing the current value of future of future incomes and expenditures for a project against the initial capital investment.

foundations and installation costs such as moorings and electrical connection and can vary substantially depending on technology type and location. The operational expenditure (OPEX) includes actual operation and maintenance costs, insurance, monitoring activities and licence/lease costs.

Controlling OPEX costs is key to developing economically viable projects. It is generally assumed that the cost of electricity will reduce with cumulative installed capacity, although this is not always the case: Costs can fluctuate according to changes in material costs, supply chain constraints and broader geopolitical factors. As more technologies are being tested and proven in deeper waters, their deployment will lead to increases in CAPEX and OPEX. Actual project costs are difficult to obtain due to confidentiality constraints, however according to The Carbon Trust (2018), CAPEX typically ranges from £1-3 billion per project for large-scale deployments, although this varies according to the total installed capacity. There is thus a need for more research and analysis of the factors influencing CAPEX and OPEX so that developers have a better basis for estimating project costs. This also needs to reflect current trends for larger devices with more generating capacity.

5.2.2 Job creation, training and skills

In deciding what support to provide to ORE developers, governments and policymakers often look at the wider economic benefits of the development and the opportunities it presents to boost the local, regional or national economy. A key aspect of this is in job creation, including the training and skills development needed for those jobs.

Employment in ORE has increased significantly in recent years. According to WindEurope (2017), the offshore wind sector was responsible for ~10,900 jobs in 2011 and ~20,500 in 2016 in the EU. The EU's Offshore Renewable Energy Strategy (see Section 3.1.4) states that in 2020, 62,000 people worked in the offshore wind sector and ~2,500 in the Ocean energy sector (European Commission, 2020b, 2020d). To meet the ambitions of the Strategy further, job creation will be required, leading to a skilled workforce estimated at 3.5 million people working full-time in Europe by 2040 (QBIS, 2020). Similarly, IRENA's energy transition modelling[112] suggests that the onshore and offshore wind industry alone may employ 3.7 million people by 2030 and more than 6 million people by 2050. While there may be some variation in the exact figures, it is obvious that a significant increase in skilled workers will be needed to support the growing ORE sector, although improved productivity has reduced the labour requirement per installed ORE capacity (QBIS, 2020).

Supply chain

In addition to the direct jobs arising from designing, building and operating ORE devices, a significant number of jobs will also be created in the supporting supply chain. Ocean Energy Europe (2020) broke down the Ocean energy supply chain into four categories: operations, specialised manufacturing, heavy manufacturing and services. Operations include deployment, assembly, maintenance and decommissioning of devices on site, and accordingly must take place near the location of the deployment. Specialised manufacturing includes the design and manufacture of components and sub-systems and could occur further afield, representing a wider opportunity for regional or national companies. The heavy manufacturing component usually occurs in places with a history of heavy manufacturing, appropriate port infrastructure, shipyard facilities etc., which may be further away from the device deployment location. It is likely that most additional jobs will be created in the service sector, including environmental monitoring and impact assessment, IT, finance, project management and administrative roles.

In Europe, most supply chain activity for ORE installations occurs in the UK, Germany, Denmark, the Netherlands, and Belgium. For floating offshore wind devices, most fabrication and installation activities related to pilot schemes have been undertaken in Spain and Norway (ORE Catapult, 2020). As projects increase in size, fabrication moves from being tailored, to requiring assembly line production methods, which may be beyond the current capability and scale of regional supply, creating further development opportunities. IRENA & ILO (2021) state that job creation depends partly on the ability to establish a strong local supply chain through investment in manufacturing, grids, port infrastructure and specialised vessels. Job creation also depends on the capacity and political will of stakeholder countries to apply performance requirements such local content rules (see Section 5.1).

An IRENA study in 2018 found that for a 500MW offshore wind farm, the human resources required from planning to decommissioning account for up to 2.1 million person-days (IRENA, 2018). The vast majority of these activities are concentrated in the manufacturing and procurement phases of development. For example, 1,500 people were employed in the construction of Scotland's second largest offshore wind farm (Beatrice, 588MW installed capacity), with a further ~90 full-time local jobs created for the duration of its 25-year lifespan. Completed in June 2019, the project is estimated to have created 800 jobs across the UK supply chain per year, with 370 jobs per year in Scotland during its operational phase (The Carbon Trust, 2020). In Hull, UK, £310 million investment to assemble turbines and manufacture blades created ~1,000 direct and indirect jobs (IRENA, 2020a). We recommend that data on job creation be gathered, consolidated and interpreted at the European scale to better understand the market.

Training and skills

ORE is often heralded as a significant opportunity for providing alternative employment to skilled workers affected by the energy transition and/or job losses in more traditional maritime industries such as fisheries, shipping, and oil and gas. Similarly, the operations and maintenance associated with ORE deployments could have balancing economic effects in areas with a high proportion of seasonal industries such as tourism and leisure. A wide variety of skills are needed in the sector, ranging from technical and vocational skills to professional and academic qualifications as illustrated in Figure 5.1.

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[112] https://www.irena.org/energytransition

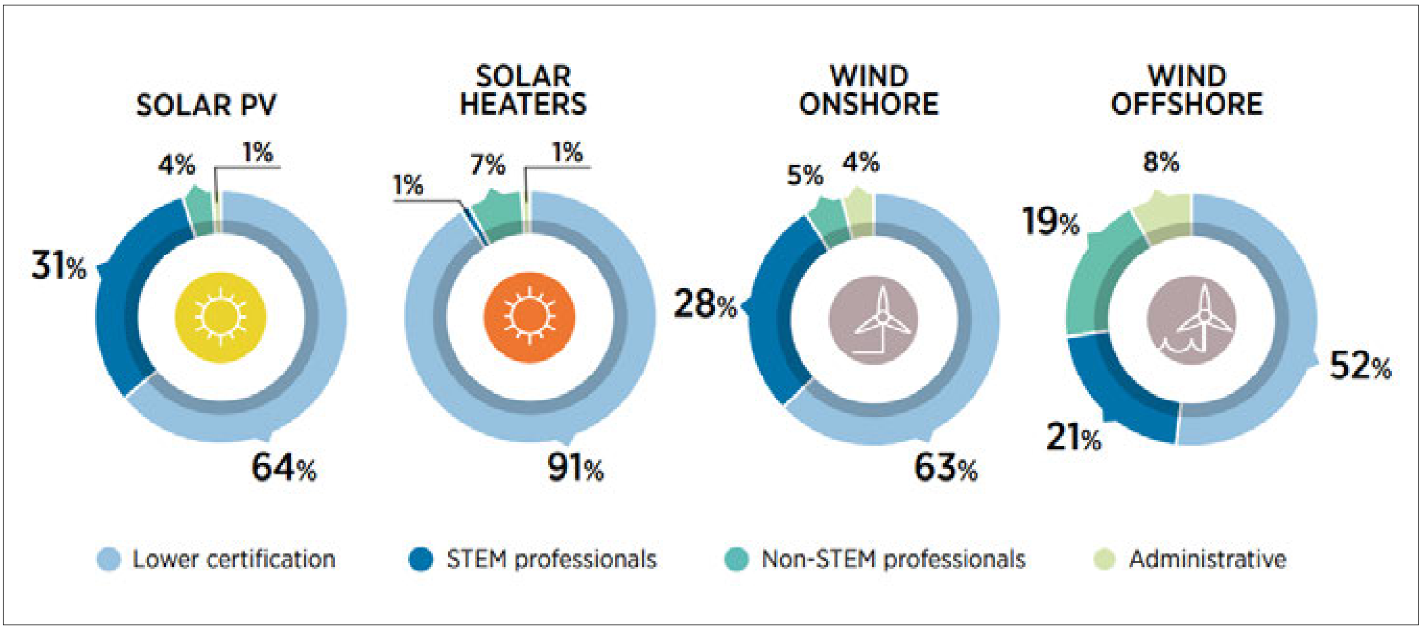
Credit: Pixabay

A wide range of existing and new skills will be required to support the development of the offshore renewable energy sector.

The EU's ORE strategy reports that 17-32% of companies are already experiencing skills gaps, with technical occupations experiencing 9-30% skills shortages (European Commission, 2020b). Existing studies on the opportunities associated with increasing offshore energy deployment are mostly country or region specific, but all conclude that increased investment is needed to develop a skilled workforce.

The majority of science, technology, engineering and mathematics (STEM) jobs are in the development and consenting phase of the project, with some opportunities in other phases (e.g. environmental surveys, meteorological, oceanographic and resource assessment, geophysical and geotechnical investigations, planning and legal advisory services, and stakeholder engagement). Appropriate training must be provided to build relevant professional skills. Higher education institutions and industry will play an important role in ensuring the requirements of the evolving ORE sector are met (e.g. Vincx *et al.*, 2018), however it is not clear whether they will have sufficient resources and expertise, including on topics such as safety training and certification, to do so. There will also be a need for the provision of industrial apprenticeships and vocational training by industry and other training providers.

The EU Horizon 2020 project MATES[113] focused specifically on the shipbuilding and ORE sectors and noted that the requirement for jobs at all levels in a growing ORE sector will cover existing and new roles (Ergas & Smyrnakis, 2020). This will require significant (re)skilling across all job categories. The MATES Skills Strategy (MATES Project, 2022a) outlines the key areas (e.g. training in digital technologies, energy storage, soft skills and developing maritime intersectoral synergies), whereas the Sustainability and Long-Term Action Plan (MATES Project, 2022b) presents practical ways in which these needs could be met. In addition, in 2021 the ORE Pact for Skills was established under the EU Pact for Skills initiative[114], which supports a *'shared engagement model for skills development in Europe'*. This group, comprising training, industry and academic partners, will monitor and develop dedicated ORE training in Europe, providing an invaluable resource to the sector.



Credit: (IRENA *et al.*, 2021)

Figure 5.1 Human resource requirements for workers in solar energy (PV), wind energy (onshore and offshore), and solar water heaters. STEM = Science, technology, engineering, and mathematics.

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[113] Maritime Alliance for fostering the European Blue Economy through a Maritime Technology Skilling Strategy, https://www.projectmates.eu/

[114] https://pact-for-skills.ec.europa.eu/index_en

Research, development and innovation activities are expected to continue as large-scale ORE deployment increases, requiring highly skilled professionals. Over the last 10 years, EU research and innovation funding programmes (i.e. Horizon 2020 and its predecessor FP7) granted approximately €496 million to offshore wind, focusing primarily on offshore technology, floating offshore wind, new materials and components, and maintenance and monitoring (Telsnig & WindEurope, 2020). Floating offshore wind, and other less mature ORE technologies, will need further research and innovation as they present new technical and scientific challenges.

In their new EU Action Plan for protecting and restoring marine ecosystems for sustainable and resilient fisheries, the European Commission (2023) specifically outlined the need for *"targeted training and upskilling programmes run with EU support under the Erasmus+, EMFAF or ESF+ funds"* to help build bridges with other blue economy sectors, including renewable energy, hereby recognising the importance of working across sectors and supporting training to enable a sustainable blue economy.

5.2.3 Community benefits and ownership

One frequently cited criticism of large-scale ORE developments is the lack of positive impact on the local community, with a perception that most profits go to large multinational companies (Haggett, 2011). Community benefits are a form of additional voluntary measure that are provided by a developer outside of the planning and licensing processes (The Scottish Government, 2018). As such, they are separate to funds from consents/leases or annual payments made in compliance with the planning process (received by the State or consenting authority) and to the supply chain dimension discussed above. These funds are also different to compensation payments, which may arise from disruption, loss or perceived negative impacts from a project to an individual or group. Generally, community benefits refer to directly funded projects of benefit to the community, in-kind work or other site-specific but voluntary interventions.

The rationale for community benefits is to facilitate a positive relationship between the developer and the community and to share some of the economic benefits from a common energy resource. The Carbon Trust (2020) identifies a range of different community benefits, including:

- Contributions to charitable organisations;
- Development and upgrades to areas of environmental and/or cultural interest;
- Educational support, including apprenticeships and training schemes;
- Environmental support;
- Local business support;
- Combating fuel poverty through local electricity discounts;
- Creation and development of local facilities, infrastructure or services;
- Support for local tourism facilities i.e. museums or visitor centres;
- Building capacity in the community;
- Support for local marine management issues; and
- Support for and development of women's empowerment networks.

In the context of offshore developments, discussion often surrounds what constitutes a local community: those living and working closest to a deployment or those most impacted by it, visually or in another way. A secondary issue is who defines the communities that benefit from ORE and how they are defined, and who has the power over how and when benefits are delivered (Rudolph *et al.,* 2017). In addition, local benefits from smaller-scale Ocean energy installations are likely to be to smaller communities than those of large offshore wind farms as the latter require larger ports and facilities for installation and maintenance, impacting more activities and users (e.g. Kerr & Weir, 2018). Best practice approaches recommend early case-specific discussions about what is the relevant, including with other resource users and residents. This information can also be used later during formal consultation processes.

There is no standard community benefits package because offshore projects vary greatly in terms of the project scale, technology utilised, distance from shore and whether the project is a research demonstration or fully commercial. The level of 'organisation' within a community and whether there are structures (e.g. local authorities, community councils, charitable organisations) in place that could administer certain types of benefit, necessitates flexibility in the package of benefits proposed and implemented. Community benefit schemes should be tailored to local contexts and circumstances and Rudolph *et al.,* (2014) recommended avoiding the use of restrictive guidance on community benefit scheme design. However, with the growing number of operational and planned ORE installations, and the lack of guidance for developers, entering negotiations with communities could be problematic.

Currently, few countries stipulate a legal requirement to operate community benefits, but this may change in the future. Denmark had a legally mandated 'Green Scheme' from 2008-2018, where funding was provided to community projects close to wind energy projects that enhanced the landscape, improved recreational values and supported cultural and informative activities of local associations in municipalities. However, this scheme did not boost local acceptance due to concerns around bribery, inappropriateness and unfairness (Jørgensen, 2020). There is a persistent perception that communities are being bribed into accepting a particular development, which in turn influences the stage at which community benefits are proposed (Cass *et al.,* 2010). As an alternative, research involving stakeholders of an offshore wind development in North Carolina, USA found that there was a preference for a dedicated community fund to distribute benefits, to be administered by local government or another trusted local organisation, and in this way priority issues could be properly addressed (Tyler *et al.,* 2022).

Community ownership, where a community together owns an ORE development, is one form of benefit but very rare in practice. There are a few examples, including offshore wind projects in Denmark (Middelgrunden, now closed), Germany (Windreich) and The Netherlands (Westermeerwind and Windpark Krammer) (Rudolph *et al.,* 2014; The Scottish Government, 2018). In these cases, benefits accrue from the revenue generated by shareholdings through partial ownership, rather than a truly voluntary model of community benefits.

Community ownership can be administered in different ways. For example, in Denmark there is a legal requirement for 20% community ownership of nearshore wind farms. Elsewhere, such as in the UK, operating companies sometimes offer the community an option to buy-in to the development. The EU Directive on Common Rules for the Internal Market for Electricity[115] recognises certain categories of citizen energy initiatives as ‘citizen energy communities’, and provides them *“with an enabling framework, fair treatment, a level playing field and a well-defined catalogue of rights and obligations”*. This may act as a stimulus for further consideration and realisation of community ownership of ORE projects. The European federation of citizen energy cooperatives[116] has set up an offshore working group to foster cooperation and facilitate the exchange of best practice among members from different countries. Such best practice should be openly shared and adhered to at Member State level, and studied academically to understand whether they succeed or not.

5.3 Social impacts

Social impacts refer to ways in which a project will directly or indirectly affect people. The effect can be physical or mental, and experienced at the level of the individual, family, social group, workplace, or community. In other words, almost anything can be considered as a social impact if it has been identified as important or valuable to a specific group of people. In comparison to environmental effects, the social and human impacts of ORE have been much less studied (Glasson *et al.,* 2022). Impacts on quality of life include effects on the surrounding sea- and landscape, the historic environment, cultural heritage and tourism/recreation opportunities. Health and wellbeing impacts include those from noise, vibration and increased traffic. Wider negative social impacts include house price inflation, competition for local services, rising unemployment in traditional maritime industries such as fisheries and population increase, all of which could lead to social tension.

Studies concentrating on social impacts require long-term data to enable trends to emerge, which is why limited research findings have been reported to date. Individuals and local communities take time to develop firm views on the impact of a large ORE development on their local area. Moreover, these views alter as people become more accustomed to the ORE installation and its consequences. In short, the social impacts of ORE development and operation will only become fully evident over decadal or longer timescales. In addition, there is a lack of appropriate data to create usable indicators for most ecosystem services provided by marine systems (Hattam *et al.,* 2015).

In the USA, there is an ongoing research programme focusing on the social impacts of the Block Island offshore wind farm i.e. the effects of the development on recreation and tourism activities, recreational fishing, boating, indigenous life, and more general engagement and perceived fairness in the planning and development process. However, to our knowledge, there is no equivalent European research programme dedicated to social impacts of ORE, although a few project-specific studies have been carried out, such as the work by Allen-Jacobsen *et al.,* (2023) looking specifically at impact of offshore wind on fishing operations.

Credit: Dzintra Grinbergs

The impact of offshore renewable energy installations on sea views and tourism are not yet a core part of impact assessments. View from the Cornwall coast, UK.

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[115] Internal Market for Electricity Directive: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32019L0944

[116] https://www.rescoop.eu/

5.4 How are socioeconomics currently included in decision-making processes?

There is often no explicit requirement to consider socioeconomic impacts in the planning and development process for offshore renewable energy projects. To a certain extent, the Environmental Impact Assessment (EIA) process could address this, but it very much depends on the type of development being planned and where it will be located. The EIA process is designed to *'identify, predict, evaluate and mitigate the biophysical, social and other relevant effects of proposed development proposals prior to major decisions being taken and commitments made'* (IAIA, 2009). The EU EIA Directive (2014/52/EU) stipulates that the direct and indirect significant effects of projects and the interactions between them, should be identified, described and assessed in an appropriate manner. Some of these effects include population and human health; biodiversity; land, soil, water, air, and climate; and material assets, cultural heritage, and landscape.

The term human health is quite broad and should include changes in living conditions and effects on vulnerable groups, exposure to noise and toxic substances (European Commission *et al.,* 2017). The EIA baseline requires socioeconomic considerations including demography, infrastructure facilities, economic activities (e.g. fisheries) and recreational users of the area. Culturally meaningful aspects should also be included because these can affect community attitudes and perceptions (European Commission *et al.,* 2017). Although such approaches are more challenging to assess, they are crucial to understanding a community's response to an ORE installation, i.e. whether or not the cultural importance of the seascape plays an important role (Wiersma & Devine Wright, 2014).

EIAs address biophysical effects more thoroughly than the impact on the human environment, involving local and regional coastal communities adjacent to projects. However, this is changing, possibly due to more local community interest and involvement in development planning processes. The inclusion of socioeconomics should be seen as an integral part of EIA, relevant to all stages of a project's life cycle.

5.4.1 Social Impact Assessment

Due to the growing realisation that social issues are intrinsically different to the impacts covered by EIAs, there is a movement towards a separate requirement for Social Impact Assessment (SIA) in certain countries. However, SIAs are not always part of the EIA process. Social impacts can already be felt within a project even before development consent has been obtained. A key purpose of an SIA is to improve the management of social issues, rather than to merely take them into account in a decision; thus, social impact is relevant to all stages of ORE project development. The way individuals and communities are engaged during the project planning process, the sincerity of the engagement and the extent to which views are considered all have a significant bearing on the extent to which social impacts are experienced.

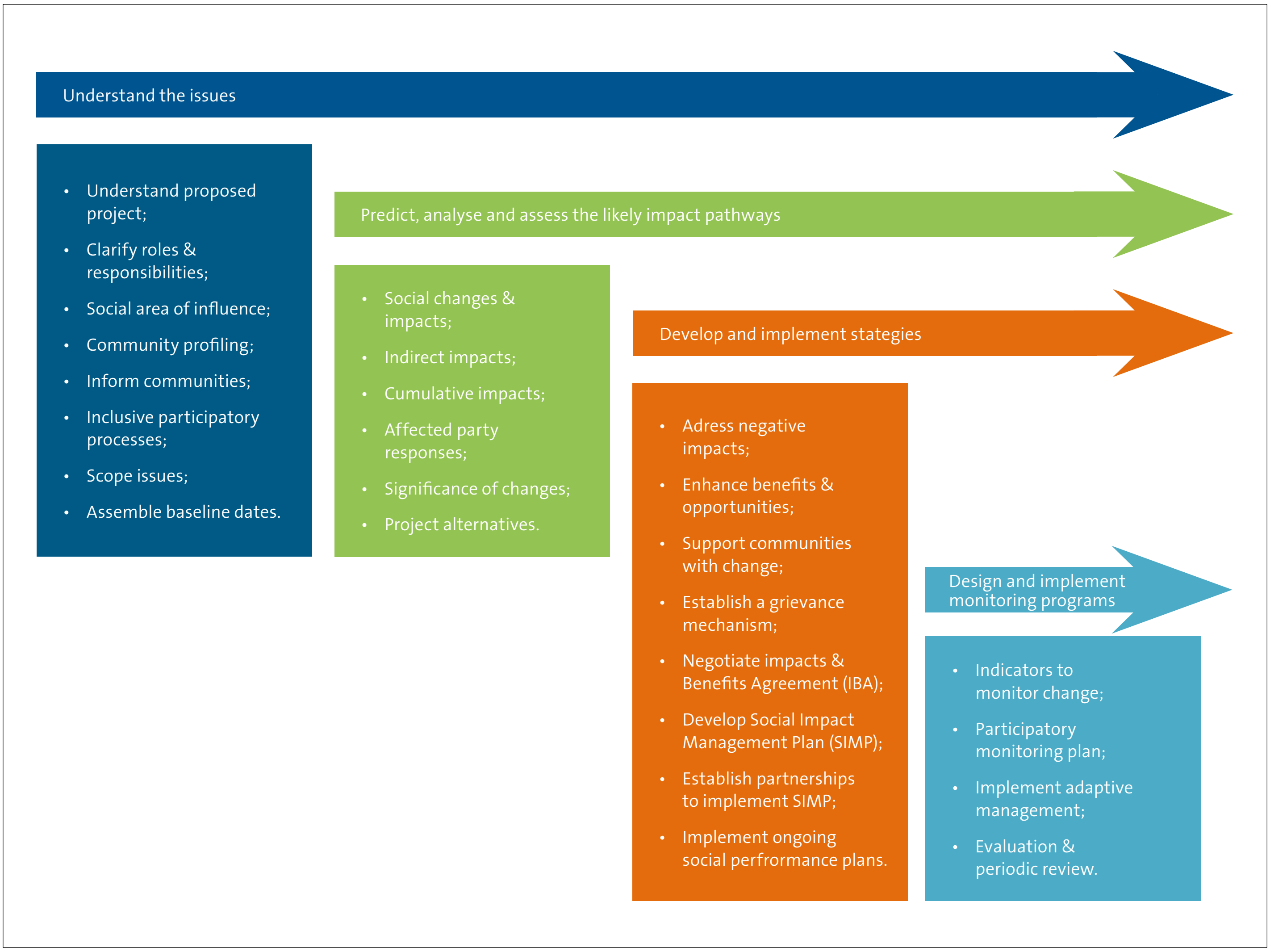
SIAs are not the same as public participation and/or statutory consultation, where the law requires a specific group to be consulted on a given matter. A SIA is designed to influence the decision-making process and the management of social issues, which necessitates the involvement of people in a genuine, meaningful way. Unfortunately, public participation processes, a requirement under EIA legislation, often consist of informing the public and allowing them to submit their opinion on the planned project with no guarantee that this will be considered in decision-making. This negatively influences current and future projects as local communities become disillusioned and cynical about the process and the project, leading to direct action (protesting) rather than engaging with a (perceived) flawed process. Best practice, as shown in Figure 5.2 (Vanclay *et al.,* 2015) highlights the need for deliberative and collaborative processes, where a range of options can be discussed in an open and inclusive way. These discussions should reflect the views of all stakeholders, and enable co-produced, agreed and actionable outcomes. These types of approaches are more time consuming and costly to implement and ideally should occur within the framework of regional/local Maritime Spatial Plans rather than at the level of an individual project. It may be relevant to consider communities in bordering countries as well, as they can also be impacted by a given development.

5.4.2 Social Licence to Operate

Social licence to operate (SLO) refers to the level of social approval, support and cooperation that exists in communities surrounding private or public projects (Moffat *et al.,* 2016). Essentially, SLO is grounded in the perceptions and world views held by local communities, how they perceive a proposed development and how they are engaged in its planning and development process. SLO has no legal basis, but for developers it represents an informal, ongoing contract with communities that demonstrate a willingness to go beyond what is required by the regulatory framework to mitigate social and environmental harm (Gunningham *et al.,* 2004). As such, the concept can be manipulated and used opportunistically to progress private industry agendas (Bice & Moffat, 2014). On the other hand, SLO can be used by communities to impose conditions on developers for (expected) better societal outcomes. SLO is frequently mentioned by both developers and regulators as a critical element to advance large scale development. While consideration of SLO and its implications at sectoral level exist (Billing *et al.,* 2021), its understanding and application to marine sectors remains limited (Kelly *et al.,* 2017).

Whilst SIA, EIA and national consenting processes incorporate public consultation, the requirement for SLO is more difficult to determine. The degree to which impact assessment processes reflect the reality of social acceptance is very limited, and these processes largely neglect important social impacts such as community wellbeing, social identity, community leadership, resilience and developer-community relations, opening opportunities for more use of SLO.

Van Putten *et al.,* (2018) contend that whilst developers and regulators have a role to play in building public trust, ensuring the protection and sustainability of public natural resources is best achieved through formal regulatory and assessment processes,



Credit: (Vanclay *et al.*, 2015) CC BY 4.0

Figure 5.2 The phases of social impact assessment.

such as EIA and SIA. They also attribute the growing pressure to achieve SLO to widespread mistrust in government processes and regulation. They propose five principles that should be applied to reform regulatory processes, which are also fitting for ORE planning and consenting processes. These are: 1) clear regulatory objectives; 2) transparent regulatory approval processes; 3) clear ways to appeal and review; 4) early and inclusive collaborative consultation processes; and 5) independence of decision-making bodies. It is recommended that efforts focus on these principles and better governance of the ORE sector generally rather than relying on the concept of SLO, which can be difficult to define and measure.

5.5 Consenting and governance

Responsibility for national consenting systems (i.e. the process that is required for developers to gain permission for their ORE development) is a Member State competence but must comply with over-arching EU law, particularly in relation to requirements from the EIA and Habitats Directives. Stronger EU and national targets for renewable energy have driven reform of the planning and consenting of strategic developments such as ORE. There is a need for continuing reforms in this area to streamline and accelerate applicable processes as well as the use of approaches like Maritime Spatial Planning (MSP, see Section 3.1.3) for better strategic planning and zoning.

Bottlenecks in consenting include the time taken to obtain the necessary permissions; the time needed for multiple consent applications; the lack of clarity and guidance around the processes; the need to carry out more than one EIA (e.g. at sea, on land and for grid aspects); the level of environmental monitoring and documentation required to support consenting applications; and the lack of design flexibility to change technology specifications once consent has been granted. Most of these bottlenecks are difficult to resolve without significant national investment and support. In certain locations, consenting processes have been designed around fixed offshore wind technologies, and as such are not fully suited to other ORE installations, which are different in terms of suitable locations, foundation design, construction activities, impact on marine species and other marine users/sectors that may be affected. These issues were recently highlighted at the World Economic Forum in Davos[117], and have been discussed in a number of papers including Bald *et al.,* (2020).

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[117] https://www.weforum.org/agenda/2023/01/speeding-up-sustainable-energy-bottlenecks-and-how-you-resolve-them-davos2023/

Credit: Sheila Heymans

National legislation on what is permitted in terms of fisheries close to or within wind farms varies.

In a positive step, some national governments, including several in Northern Europe, are starting to use a more planned approach to consenting by pre-identifying suitable sites, carrying out preliminary technical and environmental surveys, and consulting with the public and other marine users. This front-loaded process reduces risk for developers who can then respond to a centrally administered call for tenders by proposing their most suitable technology and best price. If successful, the project proponent then becomes responsible for obtaining consent (licence/permission) to occupy the sea space, often incorporating EIA and authorisation to generate electricity and connect to the grid. The national consenting authority may differ according to the scale of the proposed development, and there is a possibility to designate large-scale infrastructure projects as nationally significant and therefore subject them to a more streamlined, centralised process. In December 2022, the Council of the European Union also agreed accelerated permitting rules for renewables under the REPowerEU initiative (see Section 3.1.4) to address some of these issues[118].

As ORE developments move further offshore, the challenges associated with environmental surveys and data collection may lead to increased costs and longer timeframes. However, limited data and limited understanding of cumulative environmental impacts should lead to a more precautionary approach being taken by consenting authorities to limit risk. In terms of socioeconomic impact, the larger spatial footprints of floating developments mean there are likely to be more impacts on established marine sectors such as shipping, navigation and commercial fisheries. Assessment and management of these impacts and balancing the trade-offs will require dedicated mechanisms within consenting processes.

5.5.1 Spatial conflicts

Although co-location of marine activities is advocated in many policies, examples of successful implementation are still relatively limited. Co-location necessitates sharing of space and resources, and those required to share are often private companies/developers with explicit requirements to minimise risk and adhere to strict insurance and liability policies, which at present restrict co-location. Health and safety issues can also be a barrier.

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[118] https://www.consilium.europa.eu/en/press/press-releases/2022/12/19/repowereu-council-agrees-on-accelerated-permitting-rules-for-renewables/

A study conducted by WindEurope in 2018 found seven relevant projects and more than 90 scientific articles on the feasibility of combining offshore activities but acknowledged that new pilot projects are needed to achieve full commercialisation (WindEurope, 2018). In the Belgian part of the North Sea, WindEurope found offshore wind to be compatible with aquaculture, other ORE devices and energy storage (e.g. hydrogen), nature conservation and passive fishing. The Edulis project[119], which ended in 2019, demonstrated the feasibility of the co-location of mussel aquaculture within an offshore wind farm in harsh conditions approximately 30-50km off the Belgian coast. Such activities are now promoted as part of the multiple-use concept embedded in the most recent Belgian Maritime Spatial Plan[120].

Where co-location or co-existence is not possible, or if other marine activities have been impacted or displaced, financial compensation becomes relevant. This is particularly true in the case of commercial fisheries. Commercial fisheries that utilise active gear e.g. bottom trawling are usually not permitted in or close to wind farms, or other ORE installations, primarily due to their potential to damage cables and due to navigational risks (Gray *et al.,* 2016). In general, a 500m Exclusion Safety Zone is required around all installations and wind farm construction areas, but this is location specific and subject to national legislation.

Loss of access to fishing grounds and displacement can lead to a reduction in annual income and increased competition in other fishing grounds for the displaced fishers (Gray *et al.,* 2005). Experience with compensation schemes varies according to location: Belgium, Germany and the Netherlands have no compensation process, whereas Danish legislation requires that all fishermen who usually fish within the impacted area must be compensated for loss of income. In the UK, best practice guidance states that compensation should only be paid as a last resort and based on accurate and justifiable claims such as three years' worth of catch records (Dupont *et al.,* 2020; FLOWW, 2014). Van Hoey *et al.,* (2021) state that the lack of examples of management approaches to mitigate the effects of ORE on fisheries and aquaculture is due to the lack of real-world cases and/or grey literature on the topic. MSP has a central role to play in addressing how conflicts between sectors are managed in future, but this also requires robust economic and environmental data, and engagement with the process.

There are clear, small-scale examples of co-existence (e.g. Alexander *et al.,* 2012) across the fisheries, aquaculture and shipping sectors. However, difficulties persist regarding large-scale pilot projects and there is a need for more engagement from the insurance, health and safety, and industry sectors. Less is known about how cultural heritage will co-exist with ORE. Opportunities could arise from scientific tourism, nature conservation and specifically Other Effective area-based Conservation Measures[121] (OECMs) and combined uses, but these need more research.


Credit: Jimmy Ramirez, Pexels

The many conflicting demands for Ocean space, including for transport, energy and food, will need to be resolved for the scale-up of ORE.

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[119] https://bluegent.ugent.be/edulis

[120] Royal Decree establishing the marine spatial planning for the period 2020 to 2026 in the Belgian sea areas, https://www.health.belgium.be/en/royal-decree-msp-2020-english-courtesy-translation (accessed 29 August 2022).

[121] According to CBD Decision 14/8 *"Other effective area-based conservation measure"* means *"a geographically defined area other than a Protected Area, which is governed and managed in ways that achieve positive and sustained long-term outcomes for the in situ conservation of biodiversity, with associated ecosystem functions and services and where applicable, cultural, spiritual, socio–economic, and other locally relevant values"*; https://www.cbd.int/doc/decisions/cop-14/cop-14-dec-08-en.pdf

6 Knowledge and capacity gaps

This chapter presents the knowledge and capacity gaps related to the further development and understanding of offshore renewable energy and its impacts. The main research opportunities and recommendations corresponding to these gaps are presented in Chapter 7.

6.1 Effect of climate change on offshore renewable energy

As highlighted in Section 1.3, climate change and climate variability are likely to affect the offshore renewable energy (ORE) sector by altering resource availability, and have knock-on effects on the design, operation, maintenance and survivability of devices. As well as climate change impacting ORE energy resource potential, the intensity and frequency of extreme events are also expected to increase (WMO, 2022). Climate change will also impact marine species' populations and their vulnerability, which has implications when assessing the additional impacts from ORE installations. The extent of these changes depends on the measures taken by global societies to curb emissions and actively tackle climate change.

For a given resource, the long-term energy produced by ORE extraction depends on the variability of the local meteorological and oceanographic conditions (e.g. wind speed, wave height, period and direction, Ocean current speed, sea level), which is affected by climate change. Global warming also causes mean sea level to rise, increasing coastal water depths at many locations, tidal elevations and wave heights, which has an impact on the design of ORE devices and their foundations.

Climate change effects on the ORE sector could be assessed by using climate models to simulate future conditions associated with different emission scenarios e.g. those provided in the Intergovernmental Panel on Climate Change (IPCC)'s interactive Atlas[122], where a regional synthesis is presented regarding climatic impact drivers and anticipated future changes. More research is needed on downscaling the climate models to understand the impacts of different climate change scenarios on ORE resource availability. The spatial and temporal variability of meteorological and oceanographic parameters imply that this will need to be done on a case-by-case basis for the specific region of interest. These assessments will need to be done during feasibility studies of new projects and will also need to consider economic factors (such as levelised cost of electricity, i.e. the average cost of generating electricity over the generation lifetime) for the project lifetime relating to these resource availability effects and trends.

There is a critical need for extreme event probability and magnitude information for the whole of Europe under different climate change scenarios, so that this information can be considered for the design, installation, operation and maintenance of ORE devices. This is especially important because reduction of operation and maintenance costs and increases in reliability are the key drivers of this sector. Commercial offshore wind turbines typically have an operational lifetime of 20-25 years due to the harsh marine environment, however not all designs have taken into account increasing extremes. There is no such long-term experience for other ORE devices, however the expected operational lifetime for devices such as Wave Energy Converters (WECs) is 25 years, with the understanding that specific elements of the device may have shorter lifetimes and should be replaced (Bruno *et al.,* 2022). ORE devices can only be maintained when the weather conditions are calm enough to enable support vessels to approach the devices and deploy people safely. If extreme weather events become more severe and frequent, this will reduce the already limited opportunities for conducting maintenance. Further exacerbating the problem, structural issues such as fatigue damage are sensitive to these changes, so devices might require more maintenance as weather becomes progressively more severe. Extreme weather events may also cause issues in the balancing of the electricity loads, installation of power devices, etc.

Another key gap concerns the ability to accurately forecast short- and long-term conditions in ORE locations for suitable and realistic operating and maintenance plans. It will be important to develop technology and conduct demonstrations of marine operations related to the installation, operation, maintenance and decommissioning of ORE in different environmental conditions, especially in those sectors where a large variety of design concepts are utilised.

Climate change impacts will also have consequences for Maritime Spatial Planning (MSP) and potentially Ocean zoning, as well as environmental impacts, where species and effects may change as Ocean warming forces species to move to other areas. Another aspect to consider is biofouling, where marine organisms grow on the devices and their supporting structures, creating another significant maintenance challenge (Loxton *et al.,* 2017a). It is

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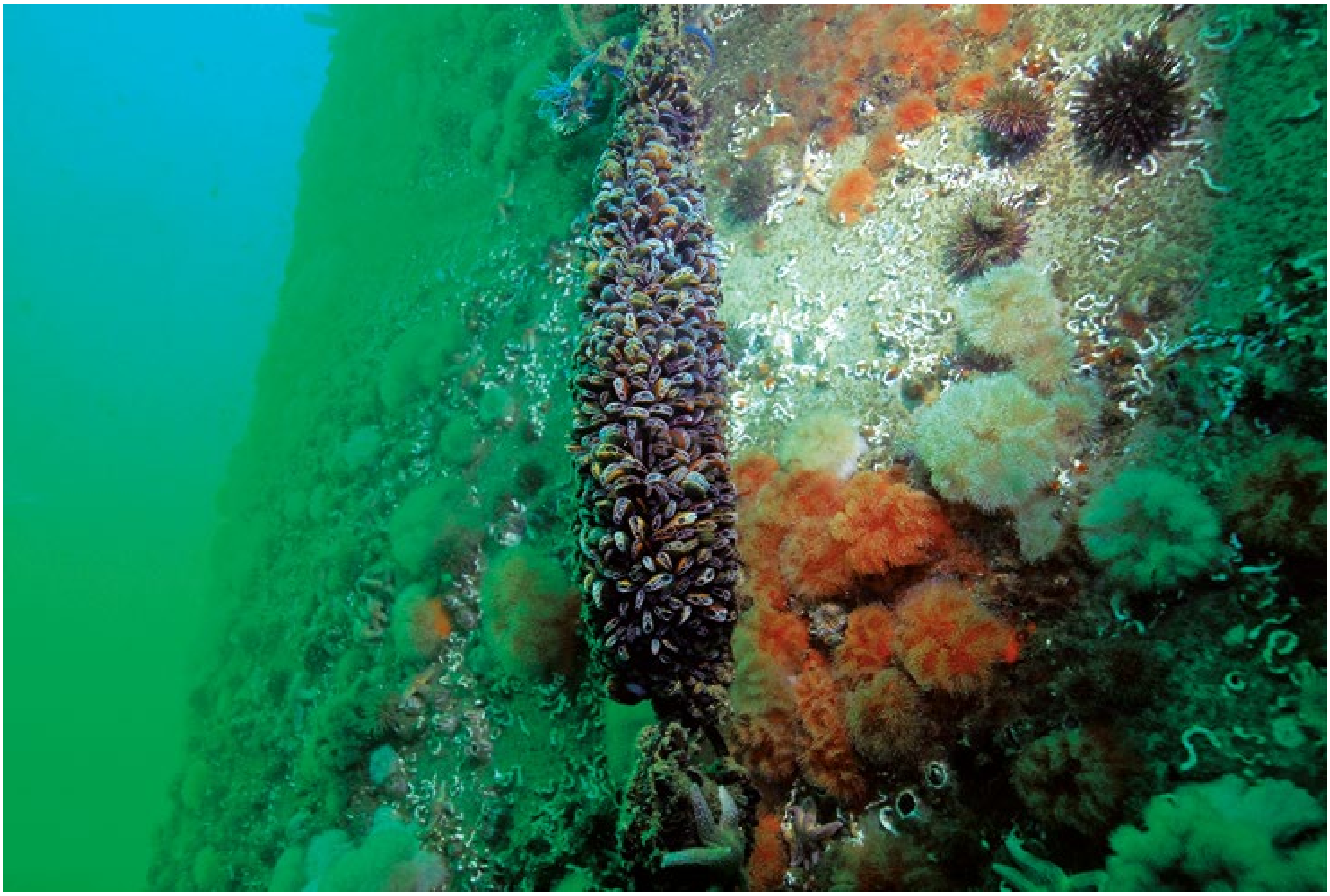
[122] https://interactive-atlas.ipcc.ch/



Credit: Photo A. Norro / RBINS

Biofouling on offshore wind farms in the Belgian part of the North Sea.

not clear what the impacts of climate change will be on the occurrence and abundance on these species, except that changes can be expected.

Indirectly, climate change may also impact ORE via impacts on supply chains for components and raw materials, e.g. in the case of an increase in extreme weather events.

6.2 Technology and infrastructure

This section examines challenges and capacity gaps relating to grid connection, energy storage, materials and full Life Cycle Assessment. It is anticipated that digital and technological advances, such as artificial intelligence, deep learning, smart and remote sensing, and robotics will help to revolutionise the ORE sector in the coming years. However, these advances are only beginning to be discussed in this context and therefore will not be addressed further here.

6.2.1 Strategic grid

The main goal of ORE generation is to produce electricity and ultimately to make that electricity available to citizens via the grid. As they are deployed offshore, electricity-generating ORE devices require subsea cables and electrical infrastructures to be installed, both between separate devices and to export electricity to land. Grid integration issues associated with offshore wind farms differ significantly from other devices due to their higher technological maturity and scale. Therefore, grid connection and integration issues should be investigated at a sector-specific level (Tedeschi & Taffese, 2019). As highlighted by the EC (European Commission, 2020b), despite the existence of European-level rules on grid connections to the electricity network, the grid has not been developed with ORE in mind and is not optimised, and therefore requires further development. Related to this point is the need for new Maritime Spatial Plans to include grid planning as early as possible, at a variety of scales.

While small-scale wind farms relatively close to shore are connected to the main power system using traditional High Voltage Alternating Current (HVAC) technology, wind farms of higher power capacity (~hundreds of MW) and distance from shore (~hundreds of km) rely on High Voltage Direct Current (HVDC) technology. Today, most HVDC-connected wind farms have a direct connection from the farm to the receiver (ENTSO-E *et al.,* 2021). Within the context of increasingly ambitious targets for offshore wind, constructing individual connections for each offshore wind farm may not be the most efficient approach and could become a major barrier to delivery, given the considerable environmental and local impacts, particularly from the associated onshore infrastructure required to connect to the national transmission network[123]. Large-scale exploitation of wind resource requires integration of individual

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[123] https://www.gov.uk/government/groups/offshore-transmission-network-review

wind farms into the power interconnectors built between countries to support security of supply and electricity trading (European Commission, 2020b). However, there are currently limited examples in operation. Combining interconnection and direct connections to offshore wind farms reduces infrastructure capital cost and coastal landing points, hence requiring less land-based infrastructure, and enabling more efficient use of offshore wind resources. This will be an intermediate step towards the implementation of a multi-terminal and then fully meshed offshore grid (i.e. a Super Grid as outlined by (Purvins *et al.,* 2011)), which will include energy hubs, or energy islands, among its components. Eventually, energy hubs are envisaged using 100% renewable electricity and allowing offshore wind energy to be harvested, rerouted to land and traded on different markets, or converted into other energy forms for final use (Cutululis *et al.,* 2021). These hubs bring challenges of their own, not only technologically in terms of building an island 'from scratch' and from a knowledge perspective for understanding the environment and socioeconomic impacts these hubs will have, but also future-proofing systems to enable later upgrades to support functionalities such as Power-to-X (see Sections 2.5 and 6.2.2).

Emerging small-scale non-wind ORE farms are often connected to coastal distribution grids, which can be quite weak with low-capacity limits, particularly in sparsely populated areas (IRENA, 2020b) and experience power quality problems. Despite the uncertainties that are inherent in the nature of ORE variables, the fairly accurate predictions provided by modern numerical tools (Sasaki, 2017) are beneficial to stabilise delivery to the local power system. However, grid reinforcement may still be needed to enable full exploitation. The problem of local grid strength, due to limited size and/or lack of interconnection, is exacerbated in small islands, which represent a primary target for emerging renewables such as wave and tidal. One mitigation strategy could be to combine different renewable sources, to reduce the intermittency of the total power generation (IRENA, 2020a, 2020b). Moreover, to overcome grid capacity limitations while avoiding power curtailment, the excess power can be used to produce green hydrogen with electrolysers (NorthWind *et al.,* 2021), or generally stored in energy storage solutions as introduced in Section 2.1.5. Further research, most likely on a case-by-case basis, is needed into how these challenges can be overcome, and into further technology needs to support this.

Globally, there is also an urgent need to facilitate grid integration of energy storage systems (see Section 6.2.2) e.g. by removing legislative barriers for energy storage projects and innovating the supporting policy, regulatory and market frameworks (Stenclik *et al.,* 2017), such as is already being done in the UK[124]. Lack of, or difficult access to, suitable grid infrastructures remain a critical barrier to the large-scale development of ORE, and the high costs and low return associated with addressing this needs to be considered. Even if Europe has rules on grid connections, transnational electric grid expansion (or strengthening) lacks strategic policy mechanisms, government plans (IRENA, 2020b), and international coordination, all of which will be needed, at least at sea-basin scale, to support ORE expansion.

6.2.2 Energy storage

The variability that characterises all ORE sources occurs at different timescales, as discussed in Section 2.1. This leads to an intermittent power delivered to the electricity grid, which is challenging for grid stability and operation in the short-term. Energy storage (via Power-to-X approaches, see Section 2.2.5) can be a key asset in stabilising the electrical power delivered by ORE converters and help compensate supply and consumption imbalances, while ensuring efficient operation of the system.

The next step to consolidate integration between offshore wind farms and storage technologies will be to deploy an offshore storage solution close to the energy source, thus providing a much more stable power flow throughout the entire power chain. However, the marine environment brings challenges in terms of material degradation, weight/space issues, and high safety and reliability constraints. Tailored solutions, integrating the storage solution directly into the ORE device structure (e.g. in a wind turbine tower (Simpson *et al.,* 2021)) or in dedicated platforms[125]) are being considered on a case-by-case basis. Further research and development into optimised design solutions guided by more data and knowledge from operational experience is necessary.

Different battery types have different characteristics and maturity levels (Wang *et al.,* 2019). The final selection greatly depends on the services needed, which depend on the size and nature of the ORE system. The application of offshore batteries, as well as fuel cells, for ORE integration may be eased by their recent, increased use in adjacent sectors, such as the maritime industry (EMSA, 2020) and the oil and gas industry[126]. Hybrid energy storage solutions may also need to be considered to overcome shortcomings in the different technologies, however more research into and operational experience of these solutions is needed to better understand what they can offer in different scenarios.

Knowledge gaps that hinder the large-scale deployment of ORE storage include gaps in our understanding of the storage technologies themselves, and these gaps also apply to other sectors such as the maritime industry. The knowledge gaps include the need for quality assurance of battery lifetime, as well as battery (EMSA, 2020) and fuel cell (EMSA, 2017) safety for offshore use. Moreover, while many energy storage systems and related technological solutions are emerging, and their costs are expected to reduce within this decade (IRENA, 2017), there is still a need to develop improved battery software solutions, and advanced energy management systems (EMSA, 2020) capable of integrating information such as weather forecasts, maintenance schedules, market prices, consumption patterns and desired grid services[127].

6.2.3 Materials and related challenges

Given the harsh environment in which ORE devices operate (i.e. high salinity, high environmental loading, presence of biofouling species), appropriate materials are critical to their survival.

Biofouling in particular has gained attention in recent years from the ORE industry since it is a critical parameter with adverse

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[124] https://www.gov.uk/government/news/battery-storage-boost-to-power-greener-electricity-grid

[125] https://www.wartsila.com/media/news/09-03-2021-wartsila-s-flexible-floating-barge-mounted-energy-storage-system-will-aid-a-philippine-operator-in-meeting-grid-requirements-2875070

[126] https://www.dnv.com/news/northern-drilling-s-west-mira-first-rig-to-receive-dnv-gl-battery-power-class-notation-161303

[127] https://www.equinor.com/news/archive/26june2018-equinor-has-installed-batwind

impacts on the functionality, integrity, mechanical performance, efficiency and maintenance costs of ORE devices. Site specific data on biofouling and predictions of future population movements of biofouling species will greatly assist in making rational design/antifouling choices (Loxton *et al.,* 2017b).

With an increasing number of offshore wind installations, the main support structure challenge is to design and deploy cost-effective structures considering both material selection and fabrication/transport costs. Most support structures for offshore wind turbines (see Section 2.2.1) are made of welded steel, which can be easily recycled. These structures are typically mass-produced relatively cheaply in shipyards in Asian countries but incur high transport costs for European sites. Concrete support structures, which can also be re-used or recycled, could instead be built locally to reduce transport costs, as Equinor is doing for its Tampen project[128]. However, the environmental costs of concrete vs steel production should also be considered. For floating wind turbines, the durability of steel or concrete materials in cost-optimised floating structures still needs to be proven and should be the focus of future research and development.

Material cost and availability are major concerns for developing large-scale commercial products of ORE devices. Costs, including material, fabrication and installation costs, need to be further reduced for novel offshore wind turbines, such as floating wind turbines. According to the ambitious plan to develop offshore wind energy around the world, a large amount of steel, concrete and composites are needed and in general there is a shortage of material supply globally (Carrara *et al.,* 2020).

Copper and zinc are the main minerals used in the electrical infrastructure of offshore wind installations. Compared to other clean energy technologies, such as solar Photovoltaic (PV) systems and nuclear plants, the mineral use in terms of weight per MW of offshore wind power generation is much higher, reaching 15 ton/MW, largely due to the demand for copper in their design (IEA, 2021b). These critical minerals are concentrated in specific geographic areas outside Europe and are not sufficient for future large-scale development of offshore wind, which requires a well-planned recycling policy and practice for such materials. This is especially important given the significant environmental and socioeconomic concerns regarding mining of these mineral resources in the deep sea (ActionAid, 2018; Rogers *et al.,* 2015). The supply chains for these materials are also affected by uncertainties linked to geopolitical issues.

Corrosion and marine biofouling are major problems for marine structures that are exposed to the sea air and sea water environments. They induce material loss and reduce the strength of structures. In the case of ORE devices, this issue is most often associated with alterations in the hydrodynamic properties, structural mass and roughness of submersed devices/components, leading to loss of integrity and performance. For offshore wind turbines or tidal turbines, corrosion may occur at critical locations, such as the bolted connection at the tower bottom or the welded joints in support structures and may significantly reduce the strength of such connections. For wave energy converters which often involve multiple bodies at the surface that move relative to each other along guides, corrosion or biofouling may significantly increase their resistance and

Credit: Global Fiberglass Solutions

Traditional wind turbines blades cannot be recycled and often end up in landfill, however some companies are looking at options to develop recyclable blade, or at ways to reuse them.

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[128] https://www.equinor.com/en/what-we-do/hywind-tampen.html

Credit: Arhnue Tan, Pixabay

Underwater structures can create artificial reefs.

therefore reduce the power absorption efficiency, in addition to the strength (Musabika *et al.*, 2016). Alternative anticorrosion and antifouling protections that are economical and environmentally sustainable are needed.

The composite materials used for both onshore and offshore wind turbine blades, and for some wave energy devices, have a high stiffness-to-weight ratio, which is very important for large-scale wind turbines under loads induced by gravity due to rotation (Mishnaevsky *et al.*, 2017). However, traditional composite materials are not recyclable, partly because of the difficulties in separating different material components caused by embedded sensors, and they are often taken to landfill. Re-use and/or recyclability of composites are key to the future sustainability of ORE. Re-use of blade cross-sections is possible but with limited repeatability (Liu & Barlow, 2017). However, research is underway to explore re-use and recycling of composite materials at a commercial scale, while retaining the required strength properties of the material. This includes trying to recover some of the composite material base components (of the resin[129]) or using thermoplastic materials[130] which melt at lower temperatures than they decompose allowing the thermoplastics to be reshaped and re-used upon melting. The main challenges include temperature control during manufacturing and making the manufacturing process more economical (Murray *et al.*, 2019).

The development of new materials to achieve a higher level of circularity within ORE is worth specific attention. Significant experience has been accumulated in other offshore industries, which use these materials and specialist coatings (e.g. for corrosion and/or biofouling protection). Further understanding needs to be developed of the potential benefits of these new materials for ORE devices whilst ensuring structural integrity and durability.

6.2.4 Full Life Cycle Assessment

Life Cycle Assessment is commonly used to account for both economic (Shafiee *et al.*, 2016) and environmental (Uihlein, 2016) impacts of ORE projects over their full lifetime, using detailed modelling of each life cycle stage. Life cycle stages are often divided into five areas: 1) materials and manufacturing; 2) transport and assembly; 3) installation; 4) operation and maintenance; and

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[129] Vestas, Circular Economy for Thermosets Epoxy Composites project, 2021 https://www.vestas.com/en/media/company-news/2021/new-coalition-of-industry-and-academia-to-commercialise-c3347473#!NewsView

[130] https://www.siemensgamesa.com/en-int/newsroom/2021/09/launch-world-first-recyclable-wind-turbine-blade

5) decommissioning and disposal. While it is relatively straightforward to predict the (input) materials and manufacturing requirements for ORE device components, uncertainties increase in later life cycle stages. This is particularly the case for emerging ORE technologies such as wave, tidal current and floating offshore wind.

While the ORE devices themselves are able to generate energy, it is important to consider the energy requirements linked to all stages of their life when making predictions about the overall energy generation and emission reduction capabilities of ORE installations.

Decommissioning of offshore wind farms is still a relatively new exercise, with limited data and/or experience available, which can lead to many uncertainties, increased assumptions, and less accurate estimates of the overall cost and environmental impacts. A study based on data available from recently decommissioned offshore wind farm projects showed that offshore removal operations account for up to 58% of the overall cost and 67% of overall lifetime emissions (Milne *et al.*, 2021). Uncertainty in estimates of cost and impact of the later life cycle stages of offshore wind farms need to be addressed.

The cost and emissions of offshore operations are directly related to their duration. The duration of offshore operations is sensitive to the technology used to remove the devices, logistics, planning strategies and site characteristics. Therefore, advances in removal technologies, such as the development of new cutting techniques, are required to reduce removal time and thus emissions and cost of decommissioning.

The final stage of ORE decommissioning involves disposal, recycling or re-use of components and materials, as discussed in Section 6.2.3. It is particularly important to account for the technical, economic and environmental considerations for ORE decommissioning at the early design stage. The new generation of ORE device components should be designed for decommissioning and recycling and be compatible with different ways to extend their lifespan, i.e. re-utilisation, re-powering, and re-purposing.

In addition to considering the devices themselves, the environmental impacts of the decommissioning phase are also important. As noted in Chapter 4, the placement of hard structures on the seabed can have positive impacts on the marine ecosystem by acting as artificial reefs. It is therefore important to consider the most appropriate decommissioning approach from this perspective (European Marine Board, 2017).

6.3 Environmental impacts of offshore renewable energy

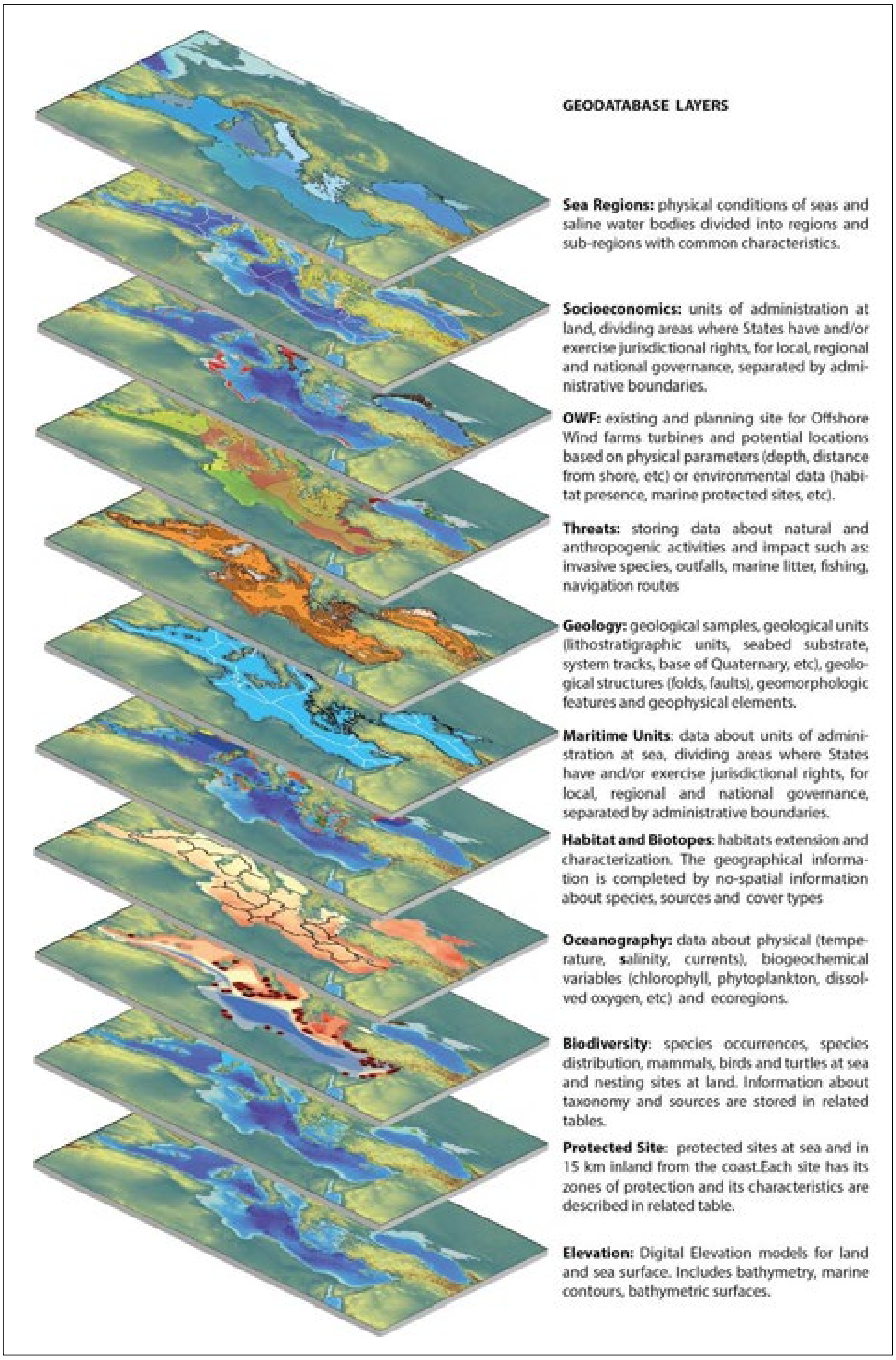
As discussed in Section 3.1 and Chapter 4, ORE capacity in Europe will need to be developed in a manner that sufficiently considers and mitigates environmental impacts, in line with relevant EU policy objectives and legislation. The Environmental Impact Assessments (EIA) Directive (see Section 4.5) already requires that likely significant effects *"should cover the direct effects and any indirect, secondary, cumulative, transboundary, short-term, medium-term and long-term, permanent and temporary, positive and negative effects of the project"*. However, more work is needed to assess cumulative effects as these occur at a large scale, the ecological processes at work are complex and environmental baseline information is inadequate.

The guidelines produced by the EC FP7-funded project CoCoNet (Boero *et al.*, 2016) outline a procedure that a project should adopt for the construction of an offshore wind farm, which could be an example for other ORE installations. This proposed procedure involves apparently straight-forward phases. However, to conduct these phases thorough knowledge is required of the conditions of biodiversity and ecosystem functioning in the area that is viable in terms of wind farm profitability. This is far from straightforward. Figure 6.1 presents the different layers of information needed for a given sea space to carry out the aforementioned procedure. Ensuring that all the observations and data are available to undertake this procedure and assess the environmental impacts will depend on the site-specific information and will need thorough research.

6.3.1 Cumulative impacts

Integration of the layers of the CoCoNet 'GEODATABASE', as shown in Figure 6.1, is also crucial for identifying cumulative environmental impacts. The concept of cumulative impacts stems from the necessity of upgrading reductionist approaches (considering one impact at a time) to holistic approaches (considering the overall impact of all human activities, as a single whole). This is why the EU's Marine Strategy Framework Directive (MSFD, see Section 3.1.1) calls for Good Environmental Status focusing on the overall state of biodiversity and ecosystem functioning and not on single impacts. If a series of pressures is applied on an ecosystem (see Chapter 4), each might individually be below pre-determined thresholds but, if the environment passes from good to bad status, the cumulative effects are unbearable. The environmental impacts (via the descriptors of the MSFD) must be considered both one at a time and as a whole.

A major challenge is to assess these cumulative impacts and to upscale locally observed impacts to the scale at which several ecological processes take place. In addition, impacts may affect only part of the marine species populations extending over larger areas, so the investigation of an impact should be widened to consider the whole population of a species. Only the assessment of the whole population, considering the multitude of marine uses present throughout the range of their spatial distribution, can indicate whether local impacts may affect population survival (Brabant *et al.*, 2015). ORE extraction is only one of the many human activities in the marine environment that can influence ecosystem structure and its functionality. Assessment of the combined effect of all these activities, framing the observed impact of ORE activities in a broader setting, also demands a holistic (European Marine Board, 2019) and a strategic multi-array (Howell Marine Consulting, 2021) approach. However, research designs to appropriately tackle this issue are largely lacking, with significant knowledge gaps.



GEODATABASE LAYERS

Sea Regions: physical conditions of seas and saline water bodies divided into regions and sub-regions with common characteristics.

Socioeconomics: units of administration at land, dividing areas where States have and/or exercise jurisdictional rights, for local, regional and national governance, separated by administrative boundaries.

OWF: existing and planning site for Offshore Wind farms turbines and potential locations based on physical parameters (depth, distance from shore, etc) or environmental data (habitat presence, marine protected sites, etc).

Threats: storing data about natural and anthropogenic activities and impact such as: invasive species, outfalls, marine litter, fishing, navigation routes

Geology: geological samples, geological units (lithostratigraphic units, seabed substrate, system tracks, base of Quaternary, etc), geological structures (folds, faults), geomorphologic features and geophysical elements.

Maritime Units: data about units of administration at sea, dividing areas where States have and/or exercise jurisdictional rights, for local, regional and national governance, separated by administrative boundaries.

Habitat and Biotopes: habitats extension and characterization. The geographical information is completed by no-spatial information about species, sources and cover types

Oceanography: data about physical (temperature, salinity, currents), biogeochemical variables (chlorophyll, phytoplankton, dissolved oxygen, etc) and ecoregions.

Biodiversity: species occurrences, species distribution, mammals, birds and turtles at sea and nesting sites at land. Information about taxonomy and sources are stored in related tables.

Protected Site: protected sites at sea and in 15 km inland from the coast.Each site has its zones of protection and its characteristics are described in related table.

Elevation: Digital Elevation models for land and sea surface. Includes bathymetry, marine contours, bathymetric surfaces.

Credit: (Boero *et al.*, 2016) CC BY-NC-ND 4.0

Figure 6.1 Relevant variables needed to determine the use of sea space for maritime activities, using the example of the CoCoNet project GEODATABASE information layers.

6.3.2 Environmental monitoring

EIAs (see Section 4.5) should reveal where ORE installations are ecologically sustainable. It is therefore critical that findings from the EIA process align with the terms and conditions attached to project consent, so that post-consent monitoring can identify and quantify subsequent impacts as thoroughly as possible. An initial on-site survey, which is usually an initial part of an EIA, should be conducted prior to installation to obtain reference conditions as a requirement of the licensing. Some changes in the conditions compared to the baseline results might not be (entirely) due to the presence of the ORE installations but could also be due to other variables such as global change or pollution generated elsewhere. Thus, monitoring should also be conducted at control sites where installations are not present and that have similar features to those at the sites of installation. This could be part of a more strategic monitoring programme conducted by national or regional bodies and linked to Strategic Environmental Assessments (SEA) for example. The ability to separate the ecological impacts from different anthropogenic pressures, to understand their individual as well as cumulative contributions is another important knowledge gap. It is essential that information and data gathered throughout the various environmental assessment processes are used, not only to learn more about the impacts and response of the environment but also to refine and adapt planning and consenting processes. In time, this could mean that certain parameters no longer need to be monitored as frequently for every EIA, or that certain risks could be retired.

Most monitoring programmes include physical, biogeochemical, chemical, and geological variables, whereas the biological components (biodiversity) and ecosystems are addressed far less. Benedetti-Cecchi *et al.*, (2018) stressed the urgent need of upgrading current monitoring programmes into observation systems to cover the biological component of the environment. Ecological complexity makes the goal of both traditional and innovative monitoring methods very challenging (Boero *et al.*, 2004) and sensors or other automatic detection methods that can capture the mechanism of ecosystem functioning do not exist yet. Integrated monitoring approaches (e.g. She *et al.*, 2019) are therefore needed to enhance our Ocean ecosystems observing capacity. Nevertheless, innovative methods are available for environmental monitoring, such as eDNA, Ocean acoustic methods or underwater imagery automatic detection methods and will complement traditional and well-established methodologies. Some of these innovative techniques have even been specifically developed in the context of environmental impact assessment studies for OREs (e.g. Hasselman *et al.*, 2020), for example active and passive acoustic systems for identifying marine mammals designed specifically for highly energetic conditions near ORE devices, or underwater imagery with specially adapted algorithms to enable target detection in low light and contrast sites.

Monitoring of basin-wide cumulative effects is very ambitious and difficult for a single country or research team to conduct. Close collaboration between scientists and administrators, across country borders, is needed to assemble and comprehensively analyse the information (see Figure 6.1). This accentuates the need for regional and transboundary data portals (e.g. EMODnet) and other dedicated information exchange mechanisms, such as Virtual Research Environments and Big Data (Guidi *et al.,* 2020). This will necessitate some additional work on legislative and privacy aspects that currently inhibit re-use and accessibility of environmental data. Future monitoring programmes should upscale their surveys to take account of cumulative impacts as far as practicable and include international collaboration to develop the strategies needed. Lack of sustained funding for Ocean observations and marine monitoring (European Marine Board, 2021) has created the lack of baseline knowledge across European seas needed to develop the ORE required by European ambitions. This needs to be addressed to ensure the carbon neutral future of Europe.

6.4 Maritime Spatial Planning

Maritime Spatial Planning (MSP, see Section 3.1.3) is a well-established tool that integrates traditional and emerging sectors, while preserving the marine ecosystem, preventing and mitigating conflicts between political priorities, and creating synergies between economic sectors. This approach will enable the responsible exploitation of ORE resources. The EU's MSP Directive requires planning cycles of a maximum of 10 years, during which changes in the environment, Ocean governance, ORE technology, society and economy inevitably take place. The plans must therefore be sufficiently responsive to these changes while still delivering on the requirements of MSFD and considering socioeconomic aspects (see Chapter 5).

As discussed in Section 6.3, spatial information on the current physical and biological characteristics of the marine area in question is crucial to be able to manage it appropriately. A strategy for data compilation and management in the context of MSP is needed for the development of national plans. This will require appropriate data gathering, harmonisation, standardisation and sharing at European level. Data collection is both time-consuming and expensive, so it is equally important to identify existing relevant data and make these accessible. The data should support the proposed holistic consideration of maritime activities (including ORE) and the marine ecosystem. At present, the available data are not sufficient to enable this, although the European Marine Observation and Data Network (EMODnet) is working to include Member States' MSP data within its Human Activities portal[131].

An emerging approach already touched upon in Section 3.4 is the multiple use of maritime space between users. This is crucial for having cost-effective and socially acceptable ORE installations, which will naturally compete with other users in the maritime space. If the aims of both the EU Green Deal and the EU Biodiversity Strategy (see Section 3.1.2) are to be met, a multi-user approach will be needed to allocate more space for ORE. This will require better understanding of the policy, economic and environmental impact implications of space sharing, as well as the development of stakeholder mediation approaches to account for these more complex situations. It is recommended that units of management and conservation should be identified to plan observation and monitoring strategies according to the natural connectivity between the species and environment in question, and the scale of the impacts of our activities in the Ocean. Boero *et al.,* (2019) proposed the concept of Cells of Ecosystem Functioning to define the units that could guide this process.

6.5 Data sharing

A vital barrier faced by ORE researchers is the inaccessibility of working data from industry (i.e. raw data generated at the installation location of the ORE device) and the lack of raw data from previously published work. The last decade brought a new era for data sharing in Europe, with the European Commission promoting open and free access to data and information. It has seen the launch of initiatives such as the European Open Science Cloud[132] (EOSC) as well as open access marine data portals such as EMODnet[133] and Copernicus Marine[134]. These initiatives are engaging with maritime industries and aiming to gain access to (some of) their data. For the ORE industry and the companies researching new technologies, close partnership with academic institutes is often a crucial requirement. However, confidentiality issues can arise, as industry partners have concerns about the competitiveness and financial implications of sharing their data for free. These are challenges that will need to be overcome.

Some progress is already being made, for instance in Germany, where the MARLIN[135] system collects environmental data on marine species to form an assessment benchmark for environmentally friendly and sustainable expansion of offshore wind energy. In the UK, it is mandatory for all data from EIAs to be added to the MEDIN[136] system. It will be important to ensure that these national systems connect to those at European level and the data within them conform to appropriate FAIR principles (Guidi *et al.,* 2020) so they can be used to inform future policymaking.

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[131] https://www.emodnet-humanactivities.eu/view-data.php

[132] https://www.eosc.eu/

[133] https://emodnet.ec.europa.eu/en

[134] https://marine.copernicus.eu/

[135] https://www.bsh.de/EN/TOPICS/Offshore/Environmental_assessments/Biology/biology_node.html

[136] https://medin.org.uk/

7 Policy, governance, and research recommendations

This chapter presents the main policy, research and technology, and data and capacity recommendations for offshore renewable energy (ORE) arising from the key messages of the document.

7.1 Policy

Policy relevant to offshore renewables is generally enshrined within overarching policies related to renewable energy, decarbonisation, and marine environmental policy and planning. The following actions are recommended to facilitate consistent support and development of ORE:

- Address misalignment within policy, which counters the development and cost-efficient delivery of ORE, including compromises with other sectors, third market interventions and competing policy objectives regarding climate change and environmental restoration;
- Create financing solutions for research and development to support scaling-up of ORE and increasing its technology readiness level (TRL), including support for both low TRL systems and pre-commercial demonstration projects;
- Develop requirements and funding opportunities for more consistent (national) datasets and make pre- and post-installation environmental monitoring data, and data from EIAs publicly available in existing European databases such as EMODnet;
- Refine monitoring strategies to ensure that all relevant variables, including bio-ecological ones, are being collected and shared;
- Require relevant sensors to be added to all maritime installations to support ongoing data gathering and monitoring;
- Encourage transdisciplinary cooperation, including between policy- and decision-makers to collaborate with scientists to fully utilise and learn from data collected in order to refine planning, design, consenting and management processes;
- Extend and integrate frameworks to enable trans-national access to European test sites into long-term EU structures (e.g. European Strategy Forum on Research Infrastructures, ESFRI); and
- Develop European-level best practice guidance for re-use and recycling of ORE materials, including composites, concrete, metals, and rare Earth minerals.

7.2 Research and technology

There is considerable research capability across the ORE spectrum in Europe and significant effort is being made to support the development of emerging technologies at EU and national levels. However, research gaps and opportunities remain. We recommend to:

- Develop additional modelling capability and tools to predict environmental parameters and extreme events to better understand implications for ORE resource availability. This will support realistic operation and maintenance planning, and improve understanding of the impact on deployment at various scales (e.g. from single installation to sea basin);
- Conduct additional case studies to better understand the (positive and negative) marine species population and ecosystem consequences of environmental impacts from ORE, especially for regions where ORE is less well or not developed at all, or where new technologies are to be introduced;
- Develop research frameworks to conduct holistic environmental and socioeconomic studies and develop mitigation strategies considering multiple devices and farms / cumulative impacts / ecosystem-level considerations;
- When possible, design ORE installations as Other Effective Conservation Measures (OECMs), for instance using their bases as artificial reefs to enhance biodiversity;
- Plan decommissioning carefully, with the aim of using the installations as OECMs;

- Develop research frameworks and explore data needs to enable an overarching study of the balance between positive and negative aspects of ORE, taking into account climate change, and environmental and socio-economic impacts;
- Conduct research on how to establish and integrate cultural aspects into EIA and SIA when looking at socio-economic impacts of ORE;
- Conduct further research into the factors influencing capital and operation expenses of ORE and how they change over time / region, to provide developers with a better foundation for estimating project costs;
- Analyse the ways in which local rules and measures have or have not worked, to support future decision-making and develop relevant metrics to support this;
- Develop new cost-effective monitoring solutions and devices;
- Conduct research into new materials that allow for re-use / recyclability / corrosion prevention while also complying with structural integrity and durability requirements; and
- Analyse grid infrastructure update requirements to identify specific cases where it would be viable and/or critical to do these upgrades at a European level, also considering ways to reduce costs or collaboration opportunities with other sectors.

7.3 Data and capacity

Working in the marine environment poses significant problems with accessing consistent long-term baseline data sets and requires specific skills and qualified workers. Focus must be on better use of data already acquired and systems to allow for better access and sharing of newly gathered data. Our recommendations include to:

- Scale-up data collection and monitoring to increase regularity, spatial and temporal coverage, specifically focusing on key areas of interest for ORE, e.g. those with high resource availability and/or high potential environmental and/or socioeconomic impacts;
- Explore ways to gather and/or share (long-term) environmental monitoring data (e.g. environmental impacts, resource availability) with all relevant stakeholders (e.g. policymakers, science, industry, financing, regulators) and make it openly available at European level;
- Explore the gaps in current training, including academic, vocational, continuous professional development, and for re-skilling, to highlight additional needs to support the development and expansion of ORE. This should cover natural, technical and social fields;
- Consolidate data and information on jobs, training and skills needs in Europe; and
- Make basic ORE-relevant social science awareness training available to STEM professionals and vice versa for social science professionals.

Credit: Norbert Pietsch, Pixabay

Wind turbines at sea.

References

ActionAid. (2018). *HUMAN RIGHTS IN WIND TURBINE SUPPLY CHAINS Towards a truly sustainable energy transition.* Retrieved from http://www.mhivestasoffshore.com/worlds-most-powerful-available-wind-turbine-gets-major-power-boost/

Alem, M., Herberz, T., Karanayil, V. S., & Fardin, A. A. H. (2020). Qualitative meta-analysis of the socioeconomic impacts of offshore wind farms. *Sustinere: Journal of Environment and Sustainability, 4*(3), 155–171. https://doi.org/10.22515/sustinere.jes.v4i3.121

Alexander, K. A., Janssen, R., Arciniegas, G., O'Higgins, T. G., Eikelboom, T., & Wilding, T. A. (2012). Interactive Marine Spatial Planning: Siting Tidal Energy Arrays around the Mull of Kintyre. *PLoS ONE, 7*(1), e30031. https://doi.org/10.1371/journal.pone.0030031

Allen Jacobson, L. M., Jones, A. W., Mercer, A. J., Cadrin, S. X., Galuardi, B., Christel, D., … Haugen, J. B. (2023). Evaluating Potential Impacts of Offshore Wind Development on Fishing Operations by Comparing Fine and <scp>Coarse Scale Fishery Dependent</scp> *Data. Marine and Coastal Fisheries, 15*(1). https://doi.org/10.1002/mcf2.10233

Araújo, R., Calderón, F. v., López, J. S., Azevedo, I. C., Bruhn, A., Fluch, S., … Ullmann, J. (2021). Current Status of the Algae Production Industry in Europe: An Emerging Sector of the Blue Bioeconomy. *Frontiers in Marine Science.* https://doi.org/10.3389/fmars.2020.626389

Arredondo-Galeana, A., & Brennan, F. (2021). Floating Offshore Vertical Axis Wind Turbines: Opportunities, Challenges and Way Forward. *Energies, 14*(23), 8000. https://doi.org/10.3390/en14238000

Bald, J., Menchaca, I., O'Hagan, A. M., le Lièvre, C., Culloch, R., Bennet, F., … Mascarenhas, P. (2020). Risk-Based Consenting of Offshore Renewable Energy Projects (RICORE). In H.-J. Ceccaldi, Y. Hénocque, T. Komatsu, P. Prouzet, B. Sautour, & J. Yoshida (Eds.), *Evolution of Marine Coastal Ecosystems under the Pressure of Global Changes* (pp. 227–242). https://doi.org/10.1007/978-3-030-43484-7_16

Barthelmie, R. J., & Pryor, S. C. (2021). Climate Change Mitigation Potential of Wind Energy. *Climate, 9*(9), 136. https://doi.org/10.3390/cli9090136

Benedetti-Cecchi, L., Crowe, T. P., Boehme, L., Boero, F., Christensen, A., Gremare, A., … Zingone, A. (2018). Strengthening Europe's Capability in Biological Ocean Observations. In A. M. Piniella, P. Kellett, K. Larkin, & S. J. J. Heymans (Eds.), *EMB Future Science Brief 3.* Retrieved from http://www.marineboard.eu/publication/strengthening-europes-capability-biological-ocean-observations-future-science-brief

Bermejo, R., Buschmann, A., Capuzzo, E., Cottier-Cook, E., Fricke, A., Hernández, I., … van den Burg, S. (2022). *State of knowledge regarding the potential of macroalgae cultivation in providing climate-related and other ecosystem services.* Retrieved from https://eklipse.eu/wp-content/uploads/website_db/Request/Macro-Algae/EKLIPSE_DG-Mare-Report-PrintVersion_final.pdf

Bhuiyan, M. A., Hu, P., Khare, V., Hamaguchi, Y., Thakur, B. K., & Rahman, M. K. (2022). Economic feasibility of marine renewable energy: Review. *Frontiers in Marine Science, 9.* https://doi.org/10.3389/fmars.2022.988513

Bice, S., & Moffat, K. (2014). Social licence to operate and impact assessment. *Impact Assessment and Project Appraisal, 32*(4), 257–262. https://doi.org/10.1080/14615517.2014.950122

Billing, S.-L., Rostan, J., Tett, P., & Macleod, A. (2021). Is social license to operate relevant for seaweed cultivation in Europe? *Aquaculture, 534,* 736203. https://doi.org/10.1016/j.aquaculture.2020.736203

Boehlert, G. W., & Gill, A. B. (2015). Environmental and Ecological Effects of Ocean Renewable Energy Development: A Current Synthesis. *Oceanography, 23*(2), 68–81. https://doi.org/10.5670/oceanog.2010.46

Boero, F., Belmonte, G., Bussotti, S., Fanelli, G. , Fraschetti, S., Giangrande, A., … Geraci, S. (2004). From biodiversity and ecosystem functioning to the roots of ecological complexity. *Ecological Complexity, 1*(2), 101–109. https://doi.org/10.1016/j.ecocom.2004.01.003

Boero, Ferdinando, de Leo, F., Fraschetti, S., & Ingrosso, G. (2019). The Cells of Ecosystem Functioning: Towards a holistic vision of marine space. In *Advances in Marine Biology* (pp. 1–26). https://doi.org/10.1016/bs.amb.2019.03.001

Boero, Ferdinando, Foglini, F., Fraschetti, S., Goriup, P., Macpherson, E., Planes, S., ... The CoCoNet Consortium. (2016). CoCoNet: Towards Coast to Coast Networks of Marine Protected Areas (From the Shore to the High and Deep Sea), Coupled with Sea-Based Wind Energy Potential. SCIentific RESearch and Information Technology, 6, 1–95. https://doi.org/10.2423/i22394303v6SpI

Boers, N. (2021). Observation-based early-warning signals for a collapse of the Atlantic Meridional Overturning Circulation. *Nature Climate Change, 11*(8), 680–688. https://doi.org/10.1038/s41558-021-01097-4

Bosch, J., Staffell, I., & Hawkes, A. D. (2018). Temporally explicit and spatially resolved global offshore wind energy potentials. *Energy, 163*, 766–781. https://doi.org/10.1016/j.energy.2018.08.153

Brabant, R., Vanermen, N., Stienen, E. W. M., & Degraer, S. (2015). Towards a cumulative collision risk assessment of local and migrating birds in North Sea offshore wind farms. *Hydrobiologia, 756*(1), 63–74. https://doi.org/10.1007/s10750-015-2224-2

Bruno, M., Maccanti, M., Pulselli, R. M., Sabbetta, A., Neri, E., Patrizi, N., & Bastianoni, S. (2022). Benchmarking marine renewable energy technologies through LCA: Wave energy converters in the Mediterranean. *Frontiers in Energy Research, 10*. https://doi.org/10.3389/fenrg.2022.980557

Cantarero, M. v., Domene, G. A., Noble, D. R., Pennock, S., Jeffrey, H., Minguela, P. R., ... Moutel, M. (2020). Advanced Design Tools for Ocean Energy Systems Innovation, Development and Deployment. In *DTOcean+ Deliverable 8.1: Potential Markets for Ocean Energy*. Retrieved from https://www.dtoceanplus.eu/Publications/Deliverables/Deliverable-D8.1-Potential-Markets-for-Ocean-Energy

Carrara, S., Alves Dias, P., Plazzotta, B., & Pavel, C. (2020). *Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system*. Retrieved from https://publications.jrc.ec.europa.eu/repository/handle/JRC119941

Cass, N., Walker, G., & Devine-Wright, P. (2010). Good Neighbours, Public Relations and Bribes: The Politics and Perceptions of Community Benefit Provision in Renewable Energy Development in the UK. *Journal of Environmental Policy & Planning, 12*(3), 255–275. https://doi.org/10.1080/1523908X.2010.509558

Cipollina, A., & Micale, G. (Eds.). (2016). *Sustainable Energy from Salinity Gradients*. https://doi.org/10.1016/C2014-0-03709-4

Coates, D. A., Deschutter, Y., Vincx, M., & Vanaverbeke, J. (2014). Enrichment and shifts in macrobenthic assemblages in an offshore wind farm area in the Belgian part of the North Sea. *Marine Environmental Research, 95*, 1–12. https://doi.org/10.1016/j.marenvres.2013.12.008

Coles, D., Angeloudis, A., Greaves, D., Hastie, G., Lewis, M., Mackie, L., ... Williamson, B. (2021). A review of the UK and British Channel Islands practical tidal stream energy resource. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 477*(2255). https://doi.org/10.1098/rspa.2021.0469

Copping, A. E., & Hemery, L. G. (2020). OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. In R*eport for Ocean Energy Systems (OES)*.

Copping, Andrea E., Hemery, L. G., Overhus, D. M., Garavelli, L., Freeman, M. C., Whiting, J. M., ... Tugade, L. G. (2020). Potential Environmental Effects of Marine Renewable Energy Development—The State of the Science. *Journal of Marine Science and Engineering, 8*(11), 879. https://doi.org/10.3390/jmse8110879

Cradden, L., Kalogeri, C., Barrios, I. M., Galanis, G., Ingram, D., & Kallos, G. (2016). Multi-criteria site selection for offshore renewable energy platforms. *Renewable Energy, 87*, 791–806. https://doi.org/10.1016/j.renene.2015.10.035

Cranmer, A., & Baker, E. (2020). The global climate value of offshore wind energy. *Environmental Research Letters, 15*(5), 054003. https://doi.org/10.1088/1748-9326/ab7667

Cresci, A., Perrichon, P., Durif, C. M. F., Sørhus, E., Johnsen, E., Bjelland, R., ... Browman, H. I. (2022). Magnetic fields generated by the DC cables of offshore wind farms have no effect on spatial distribution or swimming behavior of lesser sandeel larvae (Ammodytes marinus). *Marine Environmental Research, 176*, 105609. https://doi.org/10.1016/j.marenvres.2022.105609

CSA Ocean Sciences Inc. and Exponent. (2019). Evaluation of Potential EMF Effects on Fish Species of Commercial or Recreational Fishing Importance in Southern New England. In *OCS Study BOEM 2019-049*. Retrieved from U.S. Dept. of the Interior, Bureau of Ocean Energy Management website: https://espis.boem.gov/final reports/BOEM_2019-049.pdf

Cutululis, N. A., Blaabjerg, F., Østergaard, J., Bak, C. L., Anderson, M., da Silva, F. M. F., ... Jørgensen, B. H. (2021). *The Energy Islands: A Mars Mission for the Energy system*. Retrieved from Aalborg University, DTU website: https://windenergy.dtu.dk/english/-/media/Institutter/Vindenergi_ny/Om-os/Hvidbog/gigapower_whitepaper_5.ashx?la=da&hash=DED8E4B1759B24956DC5769C37F2802CB983212A

Dähne, M., Gilles, A., Lucke, K., Peschko, V., Adler, S., Krügel, K., ... Siebert, U. (2013). Effects of pile-driving on harbour porpoises (Phocoena phocoena) at the first offshore wind farm in Germany. *Environmental Research Letters, 8*(2). https://doi.org/10.1088/1748-9326/8/2/025002

Danish Energy Agency. (2013). *Danish Offshore Wind. Key Environmental Issues – a Follow-up*. Retrieved from The Environmental Group: The Danish Energy Agency, The Danish Nature Agency, DONG Energy and Vattenfall website: https://tethys.pnnl.gov/sites/default/files/publications/Danish_Energy_Agency_2013.pdf

Darda, S., Papalas, T., & Zabaniotou, A. (2019). Biofuels journey in Europe: Currently the way to low carbon economy sustainability is still a challenge. Journal of Cleaner Production, 208, 575–588. https://doi.org/10.1016/j.jclepro.2018.10.147

Dasgupta, P. (2021). *The Economics of Biodiversity: The Dasgupta Review*. Retrieved from HM Treasury website: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/962785/The_Economics_of_Biodiversity_The_Dasgupta_Review_Full_Report.pdf

de Backer, A., & Hostens, K. (2017). Effects of Belgian offshore wind farms on soft sediment epibenthos and fish: an updated time series. In *Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: A Continued Move Towards Integration and Quantification* (pp. 59–71). Retrieved from https://tethys.pnnl.gov/sites/default/files/publications/Degraer-et-al-2017.pdf

de Dominicis, M., Wolf, J., & O'Hara Murray, R. (2018). Comparative Effects of Climate Change and Tidal Stream Energy Extraction in a Shelf Sea. *JGR Oceans, 123*(7), 5041–5067. https://doi.org/10.1029/2018JC013832

Degraer, S., Brabant, R., & Rumes, B. (Eds.). (2013). *Environmental impacts of offshore wind farms in the Belgian part of the North Sea: Learning from the past to optimise future monitoring programmes*. Retrieved from Royal Belgian Institute of Natural Sciences, Operational Directorate Natural Environment, Marine Ecology and Management Section website: https://odnature.naturalsciences.be/downloads/winmonbe2013/winmonbe_report.pdf

Degraer, Steven, Brabant, R., Rumes, B., & Vigin, L. (2018). *Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: Assessing and Managing Effect Spheres of Influence*. Retrieved from https://tethys.pnnl.gov/sites/default/files/publications/Degraer-et-al-2018_0.pdf

Derweduwen, J., Ranson, J., Wittoeck, J., & Hostens, K. (2016). Feeding behaviour of lesser weever (Echiichthys vipera) and dab (Limanda limanda) in the C-Power wind farm. In S. Degraer, R. Brabant, B. Rumes, & L. Vigin (Eds.), *Environmental impacts of offshore wind farms in the Belgian part of the North Sea: Environmental impact monitoring reloaded* (pp. 143–166). Retrieved from https://tethys.pnnl.gov/sites/default/files/publications/Degraer-et-al-2016.pdf

Dorrell, R. M., Lloyd, C. J., Lincoln, B. J., Rippeth, T. P., Taylor, J. R., Caulfield, C. P., ... Simpson, J. H. (2022). Anthropogenic Mixing in Seasonally Stratified Shelf Seas by Offshore Wind Farm Infrastructure. *Frontiers in Marine Science, 9*. https://doi.org/10.3389/fmars.2022.830927

Dupont, C., Herpers, F., & le Visage, C. (2020). *Recommendations for positive interactions between offshore wind farms and fisheries: Short background study*. Retrieved from https://op.europa.eu/en/publication-detail/-/publication/056c9ec0-d143-11ea-adf7-01aa75ed71a1/language-en

Ehler, C., Zaucha, J., & Gee, K. (2019). Maritime/Marine Spatial Planning at the Interface of Research and Practice. In J. Zaucha & K. Gee (Eds.), *Maritime Spatial Planning* (pp. 1–21). https://doi.org/10.1007/978-3-319-98696-8_1

Elliott, K., Smith, H. C. M., Moore, F., van der Weijde, A. H., & Lazakis, I. (2018). Environmental interactions of tidal lagoons: A comparison of industry perspectives. *Renewable Energy, 119,* 309–319. https://doi.org/10.1016/j.renene.2017.11.066

EMSA. (2017). *Study on the Use of Fuel Cells in Shipping*. Retrieved from http://emsa.europa.eu/csn-menu/download/4545/2921/23.html

EMSA. (2020). *Study on Electrical Energy Storage for Ships*. In 2019-0217, Rev. 04. Retrieved from http://www.emsa.europa.eu/publications/download/6186/3895/23.html

ENTSO-E, T&D Europe, & Wind Europe. (2021). *Workstream for the development of multi-vendor HVDC systems and other power electronics interfaced devices. Retrieved* from https://windeurope.org/intelligence-platform/product/workstream-for-the-development-of-multi-vendor-hvdc-systems/

Ergas, I., & Smyrnakis, G. (2020). *Foresight scenarios identifying future skills needs and trends. Results of the MATES project.* Retrieved from https://www.projectmates.eu/wp-content/uploads/2021/01/MATES-D2.3-Foresight-scenarios-Jan-2020.pdf

ETIPOcean. (2020). *Strategic Research and Innovation Agenda for Ocean Energy*. Retrieved from https://www.oceanenergy-europe.eu/wp-content/uploads/2020/05/ETIP-Ocean-SRIA.pdf

European Commission. (2019). *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS The European Green Deal*. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1588580774040&uri=CELEX:52019DC0640

European Commission. (2020a). *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS A hydrogen strategy for a climate-neutral Europe COM(2020) 301 final*. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0301

European Commission. (2020b). *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS An EU Strategy to harness the potential of offshore renewable energy for a climate neutral future COM/2020/741 final*. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2020%3A741%3AFIN

European Commission. (2020c). *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS EU Biodiversity Strategy for 2030 Bringing nature back into our lives*.

European Commission. (2020d). *The EU Blue Economy Report 2020.* Retrieved from Publications Office of the European Union website: https://ec.europa.eu/maritimeaffairs/sites/maritimeaffairs/files/2020_06_blueeconomy-2020-ld_final.pdf

European Commission. (2023). *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS EU Action Plan: Protecting and restoring marine ecosystems for sustainable and resilient fisheries*. Retrieved from https://oceans-and-fisheries.ec.europa.eu/system/files/2023-02/COM-2023-102_en.pdf

European Commission, Joint Research Centre, Ferraro, G., & Ellis, G. (2017). *The social acceptance of wind energy: Where we stand and the path ahead.* https://doi.org/https://data.europa.eu/doi/10.2789/696070

European Marine Board. (2017). Decommissioning of offshore man-made installations. In P. Kellett & N. McDonough (Eds.), *EMB Policy Brief 3*. Retrieved from http://marineboard.eu/publication/decommissioning-offshore-man-made-installations-taking-ecosystem-approach-policy-brief

European Marine Board. (2019). Navigating the Future V: Marine Science for a Sustainable Future. In J. J. Heymans (Ed.), *EMB Position Paper* (Vol. 24). https://doi.org/DOI: 10.5281/zenodo.2809392

European Marine Board. (2021). Sustaining *in situ* Ocean Observations in the Age of the Digital Ocean. In S. J. J. Heymans, E. Hill, K. Hill, M. Hood, P.-Y. le Traon, G. Petihakis, ... Á. Muñiz Piniella (Eds.), *EMB Policy Brief 9*. Retrieved from https://www.marineboard.eu/publications/sustaining-situ-ocean-observations-age-digital-ocean

European Parliament and Council. (2014). *Directive 2014/89/EU of the European Parliament and of the Council of 23 July 2014 establishing a framework for maritime spatial planning*. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32014L0089

European Parliament and the Council of the European Union. (2008). Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive) Strategy Framework Directive). *Official Journal of the European Union,* 19–40. Retrieved from http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:164:0019:0040:EN:PDF

Falcão, A. F. d. O. (2010). Wave energy utilization: A review of the technologies. *Renewable and Sustainable Energy Reviews,* 14(3), 899–918. https://doi.org/10.1016/j.rser.2009.11.003

FLOWW. (2014). *FLOWW Best Practice Guidance for Offshore Renewables Developments: Recommendations for Fisheries Liaison*. Retrieved from https://www.sff.co.uk/wp-content/uploads/2016/01/FLOWW-Best-Practice-Guidance-for-Offshore-Renewables-Developments-Jan-2014.pdf

Frid, C., Andonegi, E., Depestele, J., Judd, A., Rihan, D., Rogers, S. I., & Kenchington, E. (2012). The environmental interactions of tidal and wave energy generation devices. *Environmental Impact Assessment Review, 32*(1), 133–139. https://doi.org/10.1016/j.eiar.2011.06.002

Galparsoro, I., Menchaca, I., Garmendia, J. M., Borja, Á., Maldonado, A. D., Iglesias, G., & Bald, J. (2022). Reviewing the ecological impacts of offshore wind farms. *Npj Ocean Sustainability, 1*(1), 1. https://doi.org/10.1038/s44183-022-00003-5

Gernaat, D. E. H. J., de Boer, H. S., Daioglou, V., Yalew, S. G., Müller, C., & van Vuuren, D. P. (2021). Climate change impacts on renewable energy supply. *Nature Climate Change, 11,* 119–125. https://doi.org/10.1038/s41558-020-00949-9

Gill, A. B., Bartlett, M., & Thomsen, F. (2012). Potential interactions between diadromous fishes of U.K. conservation importance and the electromagnetic fields and subsea noise from marine renewable energy developments. *Journal of Fish Biology, 81*(2), 664–695. https://doi.org/10.1111/j.1095-8649.2012.03374.x

Glasson, J., Durning, B., Welch, K., & Olorundami, T. (2022). The local socio-economic impacts of offshore wind farms. *Environmental Impact Assessment Review, 95*. https://doi.org/10.1016/j.eiar.2022.106783

Goodwin, P., Williams, R. G., Ridgwell, A., & Follows, M. J. (2009). Climate sensitivity to the carbon cycle modulated by past and future changes in ocean chemistry. *Nature Geoscience, 2,* 145–150. https://doi.org/10.1038/ngeo416

Gradolewski, D., Dziak, D., Martynow, M., Kaniecki, D., Szurlej-Kielanska, A., Jaworski, A., & Kulesza, W. J. (2021). Comprehensive Bird Preservation at Wind Farms. *Sensors, 21*(1), 267. https://doi.org/10.3390/s21010267

Gray, M., Stromberg, P.-L., & Rodmell, D. (2016). *Changes to fishing practices around the UK as a result of the development of offshore windfarms - Phase 1 (Revised)*. https://doi.org/978-1-906410-64-3

Gray, T., Haggett, C., & Bell, D. (2005). Offshore wind farms and commercial fisheries in the UK: A study in Stakeholder Consultation. *Ethics, Place & Environment, 8*(2), 127–140. https://doi.org/10.1080/13668790500237013

Greenhill, L., Howell, D., King, S., & Risch, D. (2021). *Mitigating the impacts of offshore wind farms on protected sites and species in the UK.* Retrieved from http://randd.defra.gov.uk/Document.aspx?Document=15217_HMC_MitigationofOW-Final.pdf

Guidi, L., Guerra, A. F., Bakker, D. C. E., Canchaya, C., Curry, E., Foglini, F., ... Tjiputra, J. (2020). Big Data in Marine Science. In S. J. J. Heymans, B. Alexander, Á. Muñiz Piniella, P. Kellett, & J. Coopman (Eds.), *EMB Future Science Brief 6.* https://doi.org/10.5281/zenodo.3755793

Gunningham, N., Kagan, R. A., & Thornton, D. (2004). Social License and Environmental Protection: Why Businesses Go Beyond Compliance. *Law & Social Inquiry, 29*(2), 307–341. https://doi.org/10.1111/j.1747-4469.2004.tb00338.x

Guo, B., & Ringwood, J. v. (2021). A review of wave energy technology from a research and commercial perspective. *IET Renewable Power Generation, 15*(14), 3065–3090. https://doi.org/10.1049/rpg2.12302

Haelters, J., Dulière, V., Vigin, L., & Degraer, S. J. (2015). Towards a numerical model to simulate the observed displacement of harbour porpoises Phocoena phocoena due to pile driving in Belgian waters. *Hydrobiologia, 756,* 105–116. https://doi.org/10.1007/s10750-014-2138-4

Haggett, C. (2011). Understanding public responses to offshore wind power. *Energy Policy, 39*(2), 503–510. https://doi.org/10.1016/j.enpol.2010.10.014

Halo, I., & Raj, R. P. (2020). Comparative oceanographic eddy variability during climate change in the Agulhas Current and Somali Coastal Current Large Marine Ecosystems. *Environmental Development, 36.* https://doi.org/10.1016/j.envdev.2020.100586

Han, X.-W., Zhang, W.-B., Ma, X.-J., Zhou, X., Zhang, Q., Bao, X., ... Long, J. (2021). Review—Technologies and Materials for Water Salinity Gradient Energy Harvesting. *Journal of The Electrochemical Society, 168*(9), 090505. https://doi.org/10.1149/1945-7111/ac201e

Hasselman, D., Barclay, D., Cavagnaro, R., Chandler, C., Cotter, E., Gillespie, D., ... Williamson, B. (2020). *2020 State of the Science Report, Chapter 10: Environmental Monitoring Technologies and Techniques for Detecting Interactions of Marine Animals with Turbines.* https://doi.org/10.2172/1633202

Hattam, C., Atkins, J. P., Beaumont, N. J., Börger, T., Böhnke-Henrichs, A., Burdon, D., ... Austen, M. C. (2015). Marine ecosystem services: Linking indicators to their classification. *Ecological Indicators, 49,* 61–75. https://doi.org/10.1016/j.ecolind.2014.09.026

Herrera, J., Sierra, S., & Ibeas, A. (2021). Ocean Thermal Energy Conversion and Other Uses of Deep Sea Water: A Review. *Journal of Marine Science and Engineering, 9*(4), 356. https://doi.org/10.3390/jmse9040356

Hoegh-Guldberg, O., Caldeira, K., Chopin, T., Gaines, S., Haugan, P., Hemer, M., ... Tyedmers, P. (2019). *The Ocean as a Solution to Climate Change: Five Opportunities for Action.* Retrieved from High Level Panel for A Sustainable Ocean Economy website: https://oceanpanel.org/publication/the-ocean-as-a-solution-to-climate-change-five-opportunities-for-action/

Howell Marine Consulting. (2021). *Mitigating the impacts of offshore wind farms on protected sites and species in the UK.* Retrieved from ttp://randd.defra.gov.uk/Document.aspx?Document=15217_HMC_MitigationofOW-Final.pdf

Hutchison, Z. L., Gill, A. B., Sigray, P., He, H., & King, J. W. (2020). Anthropogenic electromagnetic fields (EMF) influence the behaviour of bottom-dwelling marine species. *Scientific Reports, 10*(1), 4219. https://doi.org/10.1038/s41598-020-60793-x

Hutchison, Z., Secor, D., & Gill, A. (2020). The Interaction Between Resource Species and Electromagnetic Fields Associated with Electricity Production by Offshore Wind Farms. *Oceanography, 33*(4), 96–107. https://doi.org/10.5670/oceanog.2020.409

IAIA. (2009). *What Is Impact Assessment?* Retrieved from https://www.iaia.org/pdf/special-publications/What%20is%20IA_web.pdf

IEA. (2021a). *Net Zero by 2050: A Roadmap for the Global Energy Sector.* Retrieved from https://www.iea.org/reports/net-zero-by-2050

IEA. (2021b). The Role of Critical Minerals in Clean Energy Transitions. In *World Energy Outlook Special Report*. Retrieved from https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

IPCC. (2011). R*enewable Energy Sources and Climate Change Mitigation*. Retrieved from https://www.ipcc.ch/site/assets/uploads/2018/03/SRREN_Full_Report-1.pdf

IPCC. (2019). *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* (H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, ... N. M. Weyer, Eds.). Retrieved from https://www.ipcc.ch/site/assets/uploads/sites/3/2019/12/SROCC_FullReport_FINAL.pdf

IPCC. (2022a). *Climate Change 2022: Impacts, Adaptation and Vulnerability.* Retrieved from https://www.ipcc.ch/report/ar6/wg2/

IPCC. (2022b). *Summary for Policymakers. Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (P. R. Shukla, J. Skea, R. Slade, A. al Khourdajie, R. van Diemen, D. McCollum, ... J. Malley, Eds.). ttps://www.ipcc.ch/report/ar6/wg3/

IRENA. (2014a). *Ocean Energy: Technology Readiness, Patents, Deployment Status and Outlook.* Retrieved from https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2014/IRENA_Ocean_Energy_report_2014.pdf

IRENA. (2014b). *Salinity Gradient Energy Technology Brief.* Retrieved from https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2014/Salinity_Energy_v4_WEB.pdf

IRENA. (2017). *Electricity storage and renewables: Costs and markets to 2030.* Retrieved from , International Renewable Energy Agency website: https://www.irena.org/publications/2017/oct/electricity-storage-and-renewables-costs-and-markets

IRENA. (2018). *Renewable Energy Benefits: Leveraging local capacity for offshore wind.* Retrieved from https://www.irena.org/publications/2018/May/Leveraging-Local-Capacity-for-Offshore-Wind

IRENA. (2019). *Global Energy Transformation: A Roadmap to 2050.* Retrieved from International Renewable Energy Agency website: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Apr/IRENA_Global_Energy_Transformation_2019.pdf

IRENA. (2020a). *Fostering a blue economy: Offshore renewable energy.* Retrieved from International Renewable Energy Agency website: https://www.irena.org/publications/2020/Dec/Fostering-a-blue-economy-Offshore-renewable-energy

IRENA. (2020b). *Innovation Outlook: Ocean Energy Technologies.* Retrieved from s, International Renewable Energy Agency website: https://www.irena.org/publications/2020/Dec/Innovation-Outlook-Ocean-Energy-Technologies

IRENA. (2021). *Tracking the impacts of innovation: Offshore wind as a case study.* Retrieved from https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jun/IRENA_Impacts_Innovation_2021.pdf

IRENA. (2022). *World Energy Transitions Outlook: 1.5°C Pathway.* Retrieved from https://irena.org/publications/2022/mar/world-energy-transitions-outlook-2022#:~:text=By%20laying%20out%20a%20map,use%20sectors%3A%20electrification%20and%20bioenergy.

IRENA, & ILO. (2021). *Renewable energy and jobs: Annual review 2021.* Retrieved from https://www.irena.org/publications/2021/Oct/Renewable-Energy-and-Jobs-Annual-Review-2021

Jiang, Z. (2021). Installation of offshore wind turbines: A technical review. *Renewable and Sustainable Energy Reviews, 139,* 110576. https://doi.org/10.1016/j.rser.2020.110576

Johnston, A., Cook, A. S. C. P., Wright, L. J., Humphreys, E. M., & Burton, N. H. K. (2014). Modelling flight heights of marine birds to more accurately assess collision risk with offshore wind turbines. *Journal of Applied Ecology, 51*(1), 31–41. https://doi.org/10.1111/1365-2664.12191

Jørgensen, M. L. (2020). Low-carbon but corrupt? Bribery, inappropriateness and unfairness concerns in Danish energy policy. *Energy Research & Social Science, 70,* 101663. https://doi.org/10.1016/j.erss.2020.101663

Juretzek, C., Schmidt, B., & Boethling, M. (2021). Turning Scientific Knowledge into Regulation: Effective Measures for Noise Mitigation of Pile Driving. *Journal of Marine Science and Engineering, 9*(8), 819. https://doi.org/10.3390/jmse9080819

Karagali, I., Badger, M., Hahmann, A. N., Peña, A., Hasager, C. B., & Sempreviva, A. M. (2013). Spatial and temporal variability of winds in the Northern European Seas. *Renewable Energy, 57,* 200–210. https://doi.org/10.1016/j.renene.2013.01.017

Kelly, R., Pecl, G. T., & Fleming, A. (2017). Social licence in the marine sector: A review of understanding and application. *Marine Policy, 81,* 21–28. https://doi.org/10.1016/j.marpol.2017.03.005

Kerr, S., & Weir, S. (2018). Community Benefit Schemes: fair shares or token gestures? In G. Wright, S. Kerr, & K. Johnson (Eds.), *Ocean Energy: Governance Challenges for Wave and Tidal Stream Technologies* (pp. 191–205). Retrieved from https://researchportal.hw.ac.uk/en/publications/community-benefit-schemes-fair-shares-or-token-gestures

Khare, V., Khare, C., Nema, S., & Baredar, P. (2019). Prefeasibility Assessment of a Tidal Energy System. In *Tidal Energy Systems* (pp. 115–188). https://doi.org/10.1016/B978-0-12-814881-5.00003-X

Krägefsky, S. (2014). Effects of the Alpha Ventus offshore test site on pelagic fish. In A. Beiersdorf & K. Wollny-Goerke (Eds.), *Ecological Research at the Offshore Windfarm Alpha Ventus: Challenges, Results and Perspectives* (pp. 83–94). Retrieved from https://link.springer.com/chapter/10.1007%2F978-3-658-02462-8_10

Kyriakarakos, G., Papadakis, G., & Karavitis, C. A. (2022). Renewable Energy Desalination for Island Communities: Status and Future Prospects in Greece. *Sustainability, 14*(13), 8176. https://doi.org/10.3390/su14138176

Langer, J., Quist, J., & Blok, K. (2020). Recent progress in the economics of ocean thermal energy conversion: Critical review and research agenda. *Renewable and Sustainable Energy Reviews, 130,* 109960. https://doi.org/10.1016/j.rser.2020.109960

le Boulluec, M., da Rocha, A. B., Rey, C. C., Dalen, J., Jeffrey, H., Nielsen, F. G., … Wolf, J. (2010). Marine Renewable Energy. In N. McDonough & M. Evrard (Eds.), *EMB Vision Document 2*. Retrieved from http://marineboard.eu/publication/marine-renewable-energy

Lindeboom, H. J., Kouwenhoven, H. J., Bergman, M. J. N., Bouma, S., Brasseur, S., Daan, R., … van Hal, R. (2011). Short-term ecological effects of an offshore wind farm in the Dutch coastal zone; a compilation. *Environmental Research Letters, 6*(3). https://doi.org/10.1088/1748-9326/6/3/035101

Liu, P., & Barlow, C. Y. (2017). Wind Turbine Blade Waste in 2050. *Waste Management, 62,* 229–240. https://doi.org/10.1016/j.wasman.2017.02.007

LiVecchi, A., Copping, A., Jenne, D., Gorton, A., Preus, R., Gill, G., … Spence, H. (2019). *Powering the Blue Economy; Exploring Opportunities for Marine Renewable Energy in Maritime Markets*. Retrieved from https://www.energy.gov/sites/prod/files/2019/03/f61/73355.pdf

Lloret, J., Turiel, A., Solé, J., Berdalet, E., Sabatés, A., Olivares, A., … Sardá, R. (2022). Unravelling the ecological impacts of large-scale offshore wind farms in the Mediterranean Sea. *Science of The Total Environment, 824*. https://doi.org/10.1016/j.scitotenv.2022.153803

Loxton, J., Macleod, A. K., Nall, C. R., McCollin, T., Machado, I., Simas, T., … Miller, R. G. (2017a). Setting an agenda for biofouling research for the marine renewable energy industry. *International Journal of Marine Energy, 19,* 292–303. https://doi.org/10.1016/j.ijome.2017.08.006

Loxton, J., Macleod, A. K., Nall, C. R., McCollin, T., Machado, I., Simas, T., … Miller, R. G. (2017b). Setting an agenda for biofouling research for the marine renewable energy industry. *International Journal of Marine Energy, 19,* 292–303. https://doi.org/10.1016/j.ijome.2017.08.006

Manzano-Agugliaro, F., Sánchez-Calero, M., Alcayde, A., San-Antonio-Gómez, C., Perea-Moreno, A.-J., & Salmeron-Manzano, E. (2020). *Wind Turbines Offshore Foundations and Connections to Grid. Inventions, 5*(1), 8. https://doi.org/10.3390/inventions5010008

Marine Management Organisation. (2014). Review of post-consent offshore wind farm monitoring data associated with licence conditions. In *A report produced for the Marine Management Organisation MMO Project N^o: 1031*. Retrieved from https://cieem.net/resource/review-of-post-consent-offshore-wind-farm-monitoring-data-associated-with-licence-conditions/

Martinez, A., & Iglesias, G. (2020). Wave exploitability index and wave resource classification. *Renewable and Sustainable Energy Reviews, 134,* 110393. https://doi.org/10.1016/j.rser.2020.110393

MATES Project. (2022a). *Maritime Technologies Skills Strategy.* https://doi.org/10.5281/zenodo.6676557

MATES Project. (2022b). *Sustainability and Long-Term Action Plan*. Retrieved from https://www.projectmates.eu/wp-content/uploads/2022/03/MATES-Long-term-action-plan-and-sustainability.pdf

Matoug, C., Augier, B., Paillard, B., Maurice, G., Sicot, C., & Barre, S. (2020). An hybrid approach for the comparison of VAWT and HAWT performances for floating offshore wind turbines. *Journal of Physics: Conference Series, 1618*(3), 032026. https://doi.org/10.1088/1742-6596/1618/3/032026

May, R., Nygård, T., Falkdalen, U., Åström, J., Hamre, Ø., & Stokke, B. G. (2020). Paint it black: Efficacy of increased wind turbine rotor blade visibility to reduce avian fatalities. *Ecology and Evolution, 10*(16), 8927–8935. https://doi.org/10.1002/ece3.6592

Mendel, B., Schwemmer, P., Peschko, V., Müller, S., Schwemmer, H., Mercker, M., & Garthe, S. (2019). Operational offshore wind farms and associated ship traffic cause profound changes in distribution patterns of Loons (Gavia spp.). *Journal of Environmental Management, 231*, 429–438. https://doi.org/10.1016/j.jenvman.2018.10.053

MetOffice. (2019). *The slowdown or shutdown of AMOC - a key regulator of global climate*. Retrieved from https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/climate/ocean-and-cryosphere-report/srocc_amoc.pdf

Milne, C., Jalili, S., & Maheri, A. (2021). Decommissioning cost modelling for offshore wind farms: A bottom-up approach. *Sustainable Energy Technologies and Assessments, 48.* https://doi.org/10.1016/j.seta.2021.101628

Mishnaevsky, L., Branner, K., Petersen, H. N., Beauson, J., McGugan, M., & Sørensen, B. F. (2017). *Materials for Wind Turbine Blades: An Overview. Materials, 10*(11), 1285. https://doi.org/10.3390/ma10111285

Moffat, K., Lacey, J., Zhang, A., & Leipold, S. (2016). The social licence to operate: a critical review. *Forestry, 89*(5), 477–488. https://doi.org/10.1093/forestry/cpv044

Murray, R. E., Penumadu, D., Cousins, D., Beach, R., Snowberg, D., Berry, D., … Stebner, A. (2019). Manufacturing and Flexural Characterization of Infusion-Reacted Thermoplastic Wind Turbine Blade Subcomponents. *Applied Composite Material, 26,* 945–961. https://doi.org/10.1007/s10443-019-9760-2

Musabika, S., Utama, I. K. A. P., & Mukhtasor, M. (2016). Corrosion in the Marine Renewable Energy: A Review. *Proceeding of Ocean, Mechanical and Aerospace Science and Engineering, 3.* Retrieved from https://isomase.org/OMAse/Vol.3-2016/Section-2/3-2.pdf

Neill, S. P., Haas, K. A., Thiébot, J., & Yang, Z. (2021). A review of tidal energy—Resource, feedbacks, and environmental interactions. *Journal of Renewable and Sustainable Energy, 13*(6), 062702. https://doi.org/10.1063/5.0069452

Newby, A. N., Bartholomew, T. v., & Mauter, M. S. (2021). The Economic Infeasibility of Salinity Gradient Energy via Pressure Retarded Osmosis. *ACS ES&T Engineering, 1*(7), 1113–1121. https://doi.org/10.1021/acsestengg.1c00078

NorthWind, NCCS, LowEmission, & NTRANS. (2021). *The North Sea as a springboard for the green transition*. Retrieved from https://www.sintef.no/globalassets/sintef-energi/cop26_northsea.pdf

OEE. (2020). *2030 Ocean Energy Vision: Industry analysis of future deployments, costs and supply chains*. Retrieved from https://www.oceanenergy-europe.eu/wp-content/uploads/2020/10/OEE_2030_Ocean_Energy_Vision.pdf

OEE. (2021). *Ocean Energy: Key trends and statistics 2020*. Retrieved from https://www.oceanenergy-europe.eu/wp-content/uploads/2021/05/OEE-Stats-Trends-2020-3.pdf

OEE. (2022). *Ocean Energy: Key trends and statistics 2021*. Retrieved from https://www.oceanenergy-europe.eu/wp-content/uploads/2022/03/OEE_Stats_and_Trends_2021_web.pdf

OES. (2020). *Ocean Energy in Islands and Remote Coastal Areas: Opportunities and Challenges. In IEA Technology Collaboration Programme for Ocean Energy Systems*. Retrieved from https://www.ocean-energy-systems.org/press-release/oes-releases-a-ocean-energy-in-islands-and-remote-coastal-areasa-/

OES. (2021a). *Tidal Current Energy Developments: Highlights. In Ocean Energy Systems*. Retrieved from https://www.ocean-energy-systems.org/documents/42658-tidal-current-energy-highlights-april-2021.pdf/

OES. (2021b). *Wave Energy Developments: Highlights. In Ocean Energy Systems*. Retrieved from https://www.ocean-energy-systems.org/documents/95502-wave-energy-highlights-march-2021.pdf/

OES. (2021c). *White Paper on Ocean Thermal Energy Conversion (OTEC)*. Retrieved from www.ocean-energy-systems.org

Olafsson, H., & Bao, J.-W. (Eds.). (2020). *Uncertainties in Numerical Weather Prediction*. Retrieved from https://www.elsevier.com/books/uncertainties-in-numerical-weather-prediction/olafsson/978-0-12-815491-5

Oliveira-Pinto, S., & Stokkermans, J. (2020). Assessment of the potential of different floating solar technologies – Overview and analysis of different case studies. *Energy Conversion and Management, 211,* 112747. https://doi.org/10.1016/j.enconman.2020.112747

Onea, F., & Rusu, E. (2019). The Expected Shoreline Effect of a Marine Energy Farm Operating Close to Sardinia Island. *Water, 11*(11), 2303. https://doi.org/10.3390/w11112303

Oppenheimer, M., Glavovic, B. C., Hinkel, J., van de Wal, R., Magnan, A. K., Abd-Elgawad, A., … Sebesvari, Z. (2019). Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, … N. M. Weye (Eds.), I*PCC Special Report on the Ocean and Cryosphere in a Changing Climate*. Retrieved from https://www.ipcc.ch/srocc/chapter/chapter-4-sea-level-rise-and-implications-for-low-lying-islands-coasts-and-communities/

ORE Catapult. (2020). *Supply Chain Report: Benefits of Floating Offshore Wind to Wales and the South West*. Retrieved from https://ore.catapult.org.uk/wp-content/uploads/2020/01/8996-OREC-Wales-Report-WEB.pdf

Petersen, J. K., & Malm, T. (2006). Offshore Windmill Farms: Threats to or Possibilities for the Marine Environment. *AMBIO, 35*(2), 75–80. Retrieved from https://www.jstor.org/stable/4315689seq=1#metadata_info_tab_contents

Petley, S., & Aggidis, G. (2016). Swansea Bay tidal lagoon annual energy estimation. *Ocean Engineering, 111,* 348–357. https://doi.org/10.1016/j.oceaneng.2015.11.022

Popper, A. N., Hice-Dunton, L., Jenkins, E., Jenkins, E., Higgs, D. M., Krebs, J., … Williams, K. A. (2022). Offshore wind energy development : Research priorities for sound and vibration effects on fishes and aquatic invertebrates. *The Journal of the Acoustical Society of America 1, 205*. https://doi.org/10.1121/10.0009237

Portilla, J., Sosa, J., & Cavaleri, L. (2013). Wave energy resources: Wave climate and exploitation. *Renewable Energy, 57,* 594–605. https://doi.org/10.1016/j.renene.2013.02.032

Pörtner, H. O., & Peck, M. A. (2010). Climate change effects on fishes and fisheries: towards a cause-and-effect understanding. *Journal of Fish Biology, 77*(8), 1745–1779. https://doi.org/0.1111/j.1095-8649.2010.02783.x

Poulsen, T., & Lema, R. (2017). Is the supply chain ready for the green transformation? The case of offshore wind logistics. *Renewable and Sustainable Energy Reviews, 73,* 758–771. https://doi.org/10.1016/j.rser.2017.01.181

Puruncajas, B., Vidal, Y., & Tutivén, C. (2020). Vibration-Response-Only Structural Health Monitoring for Offshore Wind Turbine Jacket Foundations via Convolutional Neural Networks. *Sensors, 20*(12), 3429. https://doi.org/10.3390/s20123429

Purvins, A., Wilkening, H., Fulli, G., Tzimas, E., Celli, G., Mocci, S., ... Tedde, S. (2011). A European supergrid for renewable energy: local impacts and far-reaching challenges. *Journal of Cleaner Production, 19*(17–18), 1909–1916. https://doi.org/10.1016/j.jclepro.2011.07.003

QBIS. (2020). Socioeconomic impacts of offshore wind. *Executive Presentation.* Retrieved from https://um.fi/documents/384951/0/presentation-socioeconomic-impacts-of-offshore-wind-24.06.2020-003.pdf

Ren, Z., Verma, A. S., Li, Y., Teuwen, J. J. E., & Jiang, Z. (2021). Offshore wind turbine operations and maintenance: A state-of-the-art review. *Renewable and Sustainable Energy Reviews, 144,* 110886. https://doi.org/10.1016/j.rser.2021.110886

Retiere, C. (1994). Tidal power and the aquatic environment of La Rance. *Biological Journal of the Linnean Society, 51*(1–2), 25–36. https://doi.org/10.1006/bijl.1994.1004

Reubens, J. T., Alsebai, M., & Moens, T. (2016). Expansion of small-scale changes in microbenthic community inside an offshore wind farm? In S. Degraer, R. Brabant, B. Rumes, & L. Vigin (Eds.), *Environmental impacts of offshore wind farms in the Belgian part of the North Sea: Environmental impact monitoring reloaded* (pp. 77–92). Retrieved from https://tethys.pnnl.gov/sites/default/files/publications/Degraer-et-al-2016.pdf

Reubens, J. T., de Rijcke, M., Degraer, S. J., & Vincx, M. (2014). Diel variation in feeding and movement patterns of juvenile Atlantic cod at offshore wind farms. *Journal of Sea Research, 85.* https://doi.org/10.1016/j.seares.2013.05.005

Reubens, J. T., Degraer, S. J., & Vincx, M. (2011). Aggregation and feeding behaviour of pouting (Trisopterus luscus) at wind turbines in the Belgian part of the North Sea. *Fisheries Research, 108*(1), 223–227. https://doi.org/10.1016/j.fishres.2010.11.025

Reubens, J. T., Degraer, S. J., & Vincx, M. (2014). The ecology of benthopelagic fishes at offshore wind farms: a synthesis of 4 years of research. *Hydrobiologia, 727,* 121–136. https://doi.org/10.1007/s10750-013-1793-1

Rogers, A. D., Brierley, A., Croot, P., Cunha, M. R., Danovaro, R., Devey, C., ... Visbeck, M. (2015). Delving Deeper: Critical Challenges for 21st Century Deep-Sea Research. In K. Larkin, K. Donaldson, & N. McDonough (Eds.), *EMB Position Paper 22.* Retrieved from http://marineboard.eu/publication/delving-deeper-critical-challenges-21st-century-deep-sea-research

Rudolph, D., Haggett, C., & Aitken, M. (2014). Community Benefits from Offshore Renewables: Good Practice Review. Retrieved from https://www.climatexchange.org.uk/media/1536/full_report_-_community_benefits_from_offshore_renewables_-_good_practice_review.pdf

Rudolph, D., Haggett, C., & Aitken, M. (2017). Community benefits from offshore renewables: The relationship between different understandings of impact, community, and benefit. *Environment and Planning C: Politics and Space, 36*(1). https://doi.org/10.1177/2399654417699206

Sadykova, D., Scott, B. E., de Dominicis, M., Wakelin, S. L., Wolf, J., & Sadykov, A. (2020). Ecological costs of climate change on marine predator–prey population distributions by 2050. *Ecology and Evolution, 10*(2), 1069–1086. https://doi.org/10.1002/ece3.5973

Sarwer, A., Hamed, S. M., Osman, A. I., Jamil, F., Al-Muhtaseb, A. H., Alhajeri, N. S., & Rooney, D. W. (2022). Algal biomass valorization for biofuel production and carbon sequestration: a review. *Environmental Chemistry Letters*. https://doi.org/10.1007/s10311-022-01458-1

Sasaki, W. (2017). Predictability of global offshore wind and wave power. *International Journal of Marine Energy, 17,* 98–109. https://doi.org/10.1016/j.ijome.2017.01.003

Shafiee, M., Brennan, F., & Espinosa, I. A. (2016). A parametric whole life cost model for offshore wind farms. *The International Journal of Life Cycle Assessment, 21,* 961–975. https://doi.org/10.1007/s11367-016-1075-z

She, J., Muñiz Piniella, Á., Benedetti-Cecchi, L., Boehme, L., Boero, F., Christensen, A., ... Zingone, A. (2019). An Integrated Approach to Coastal and Biological Observations. *Frontiers in Marine Science, 6*. https://doi.org/10.3389/fmars.2019.00314

Simpson, J. G., Hanrahan, G., Loth, E., Koenig, G. M., & Sadoway, D. R. (2021). Liquid metal battery storage in an offshore wind turbine: Concept and economic analysis. *Renewable and Sustainable Energy Reviews, 149*. https://doi.org/10.1016/j.rser.2021.111387

Singlitico, A., Østergaard, J., & Chatzivasileiadis, S. (2021). Onshore, offshore or in-turbine electrolysis? Techno-economic overview of alternative integration designs for green hydrogen production into Offshore Wind Power Hubs. *Renewable and Sustainable Energy Transition, 1,* 100005. https://doi.org/10.1016/j.rset.2021.100005

Sobey, R. J. (2005). Extreme low and high water levels. *Coastal Engineering, 52*(1), 63–77. https://doi.org/10.1016/j.coastaleng.2004.09.003

Solaun, K., & Cerdá, E. (2019). Climate change impacts on renewable energy generation. A review of quantitative projections. *Renewable and Sustainable Energy Reviews, 116*. https://doi.org/10.1016/j.rser.2019.109415

Soukissian, T. H., Karathanasi, F. E., & Zaragkas, D. K. (2021). Exploiting offshore wind and solar resources in the Mediterranean using ERA5 reanalysis data. *Energy Conversion and Management, 237*. https://doi.org/10.1016/j.enconman.2021.114092

Soukissian, Takvor H., & Karathanasi, F. E. (2021). Joint Modelling of Wave Energy Flux and Wave Direction. *Processes, 9*(3), 460. https://doi.org/10.3390/pr9030460

Southall, B. L., Bowles, A. E., Ellison, W. T., Finneran, J. J., Gentry, R., Greene Jr., C. R., ... Tyack, P. L. (2007). Marine mammal noise exposure criteria: initial scientific recommendations. *Aquatic Mammals, 33*(4), 273–275. https://doi.org/10.1080/09524622.2008.9753846

Stenberg, C., Deurs, M. v., Støttrup, J., Mosegaard, H., Grome, T., Dinesen, G. E., ... Støttrup, J. (2011). Effect of the Horns Rev 1 Offshore Wind Farm on Fish Communities. Follow-up Seven Years after Construction. In D*TU Aqua Report Nº. 246-2011*. Retrieved from DTU Aqua website: https://backend.orbit.dtu.dk/ws/portalfiles/portal/7615058/246_2011_effect_of_the_horns_rev_1_offshore_wind_farm_on_fish_communities.pdf

Stenclik, D., Denholm, P., & Chalamala, B. (2017). Maintaining Balance: The Increasing Role of Energy Storage for Renewable Integration. *IEEE Power and Energy Magazine, 15*(6), 31–39. https://doi.org/10.1109/MPE.2017.2729098

Stephenson, P. J. (2021). *A Review of Biodiversity Data Needs and Monitoring Protocols for the Offshore Wind Energy Sector in the Baltic Sea and North Sea*. Retrieved from https://renewables-grid.eu/fileadmin/user_upload/_RGI_Report_PJ-Stephenson_October.pdf

Stramma, L., & Schmidtko, S. (2019). Global evidence of ocean deoxygenation. In D. Laffoley & J. M. Baxter (Eds.), *Ocean Deoxygenation: Everyone's Problem - Causes, Impacts, Consequences and Solutions* (pp. 25–36). Retrieved from https://portals.iucn.org/library/sites/library/files/documents/2019-048-En.pdf

Stringer, C. C., & Polagye, B. L. (2020). Implications of biofouling on cross-flow turbine performance. *SN Applied Sciences, 2*(3), 464. https://doi.org/10.1007/s42452-020-2286-2

Strivens, S., Evans, H., Northridge, E., Harvey, M., Camp, T., & Terry, N. (2021). *Phase III Summary Report: Floating Wind Joint Industry Project.* Retrieved from https://energycentral.com/system/files/ece/nodes/491706/flwjip-phase3-summary-report.pdf

Syarif Arief, I., Aria Pria Utama, I. K., Hantoro, R., Prananda, J., & Muhammad Megawan, A. (2020). Computational Fluid Dynamics (CFD) Simulation for Designing Mooring Bitts Position at the Barge for Wave Energy Conversion (WEC). *E3S Web of Conferences, 190*, 00017. https://doi.org/10.1051/e3sconf/202019000017

Tedeschi, E., & Taffese, A. A. (2019). Electrical power transmission and grid integration. In D. Coiro & T. Sant (Eds.), *Renewable Energy from the Oceans: From wave, tidal and gradient systems to offshore wind and solar.* https://doi.org/10.1049/pbpo129e_ch8

Tedesco, M., Cipollina, A., Tamburini, A., & Micale, G. (2017). Towards 1 kW power production in a reverse electrodialysis pilot plant with saline waters and concentrated brines. *Journal of Membrane Science, 522,* 226–236. https://doi.org/10.1016/j.memsci.2016.09.015

Tedesco, M., Scalici, C., Vaccari, D., Cipollina, A., Tamburini, A., & Micale, G. (2016). Performance of the first reverse electrodialysis pilot plant for power production from saline waters and concentrated brines. *Journal of Membrane Science, 500,* 33–45. https://doi.org/10.1016/j.memsci.2015.10.057

Telsnig, T., & WindEurope. (2020). *Wind Energy - Technology Development Report 2020.* https://doi.org/10.2760/425873

The Carbon Trust. (2018). *Future Potential for Wind in Wales.* Retrieved from https://gov.wales/sites/default/files/publications/2019-07/future-potential-for-offshore-wind.pdf

The Carbon Trust. (2020). *Harnessing our potential: Investment and jobs in Ireland's offshore wind industry.* Retrieved from https://www.carbontrust.com/resources/harnessing-our-potential-investment-and-jobs-in-irelands-offshore-wind-industry

The Scottish Government. (2018). *Offshore renewable energy developments - good practice principles for community benefits: consultation.* Retrieved from https://www.gov.scot/publications/consultation-scottish-government-good-practice-principles-community-benefits-offshore-renewable-energy-developments/

Thomas, J. E., Sinha, R., Strand, Å., Söderqvist, T., Stadmark, J., Franzén, F., ... Hasselström, L. (2021). Marine biomass for a circular blue-green bioeconomy?: A life cycle perspective on closing nitrogen and phosphorus land-marine loops. *Journal of Industrial Ecology.* https://doi.org/10.1111/jiec.13177

Thomsen, F., Mendes, S., Bertucci, F., Breitzke, M., Ciappi, E., Cresci, A., ... dos Santos, M. E. (2021). *Addressing underwater noise in Europe: Current state of knowledge and future priorities.* https://doi.org/10.5281/zenodo.5534224

Trapani, K., & Santafé, M. R. (2014). A review of floating photovoltaic installations: 2007–2013. *Progress in Photovoltaics, 23*(4), 524–532. https://doi.org/10.1002/pip.2466

Trolliet, M., Walawender, J. P., Bourlès, B., Boilley, A., Trentmann, J., Blanc, P., ... Wald, L. (2018). Downwelling surface solar irradiance in the tropical Atlantic Ocean: a comparison of re-analyses and satellite-derived data sets to PIRATA measurements. *Ocean Science, 14*(5), 1021–1056. https://doi.org/10.5194/os-14-1021-2018

Tyler, G., Bidwell, D., Smythe, T., & Trandafir, S. (2022). Preferences for community benefits for offshore wind development projects: A case study of the Outer Banks of North Carolina, U.S. *Journal of Environmental Policy & Planning, 24*(1), 39–55. https://doi.org/10.1080/1523908X.2021.1940896

Uihlein, A. (2016). Life cycle assessment of ocean energy technologies. *The International Journal of Life Cycle Assessment, 21,* 1425–1437. https://doi.org/10.1007/s11367-016-1120-y

UNECE. (2021). *Life Cycle Assessment of Electricity Generation Options.* Retrieved from https://unece.org/sites/default/files/2021-10/LCA-2.pdf

US Department of the Interior. (2006). *Technology White Paper on Ocean Current Energy Potential on the US Outer Continental Shelf.* Retrieved from https://www.boem.gov/sites/default/files/renewable-energy-program/Renewable-Energy-Guide/OCSOceanCurrentTechWhitePaper2006.pdf

van de Pol, L., van der Biest, K., Taelman, S. E., de Luca Peña, L., Everaert, G., Hernandez, S., … Meire, P. (2023). Impacts of human activities on the supply of marine ecosystem services: A conceptual model for offshore wind farms to aid quantitative assessments. *Heliyon, 9*(3), e13589. https://doi.org/10.1016/j.heliyon.2023.e13589

van Hoey, G., Bastardie, F., Birchenough, S., de Backer, A., Gill, A., de Koning, S., … van den Burg, S. (2021). *Overview of the effects of offshore wind farms on fisheries and aquaculture er: Final report.* https://doi.org/10.2826/63640

van Putten, I. E., Cvitanovic, C., Fulton, E., Lacey, J., & Kelly, R. (2018). The emergence of social licence necessitates reforms in environmental regulation. *Ecology and Society, 23*(3), art24. https://doi.org/10.5751/ES-10397-230324

Vanclay, F., Esteves, A. M., Aucamp, I., & Franks, D. M. (2015). *Social Impact Assessment: Guidance for assessing and managing the social impacts of projects.* Retrieved from https://www.iaia.org/uploads/pdf/SIA_Guidance_Document_IAIA.pdf

Vila-Concejo, A., Gallop, S. L., & Largier, J. L. (2020). Sandy beaches in estuaries and bays. In D. W. T. Jackson & A. D. Short (Eds.), *Sandy Beach Morphodynamics* (pp. 343–362). https://doi.org/10.1016/B978-0-08-102927-5.00015-1

Vincx, M., Antia, A., Deprez, T., Fiksen, O., Koski, M., MacKenzie, B., … Roullet, G. (2018). Training the 21st Century Marine Professional. In P. Kellett, K. Larkin, S. J. J. Heymans, N. McDonough, N. Wouters, & N.-C. Chu (Eds.), *EMB Future Science Brief 2.* Retrieved from http://www.marineboard.eu/publication/training-21st-century-marine-professional

Vo, T. T. E., Ko, H., Huh, J., & Park, N. (2021). Overview of Possibilities of Solar Floating Photovoltaic Systems in the OffShore *Industry. Energies, 14*(21). https://doi.org/10.3390/en14216988

Walters, R. A., Gillibrand, P. A., Bell, R. G., & Lane, E. M. (2010). A study of tides and currents in Cook Strait, New Zealand. *Ocean Dynamics, 60*(6), 1559–1580. https://doi.org/10.1007/s10236-010-0353-8

Wang, Z., Carriveau, R., Ting, D. S.-K., Xiong, W., & Wang, Z. (2019). A review of marine renewable energy storage. *International Journal of Energy Research, 43*(12), 6108–6150. https://doi.org/10.1002/er.4444

Weiss, C. V. C., Menendez, M., Ondiviela, B., Guanche, R., Losada, I. J., & Juanes, J. (2020). Climate change effects on marine renewable energy resources and environmental conditions for offshore aquaculture in Europe. *ICES Journal of Marine Science, 77*(7–8). https://doi.org/10.1093/icesjms/fsaa226

Wiersma, B., & Devine Wright, P. (2014). Public engagement with offshore renewable energy: a critical review. *WIREs Climate Change, 5*(4), 493–507. https://doi.org/10.1002/wcc.282

Wilson, A. B. (2020). Offshore wind energy in Europe. In *European Parliament Briefing*. Retrieved from https://www.europarl.europa.eu/RegData/etudes/BRIE/2020/659313/EPRS_BRI(2020)659313_EN.pdf

WindEurope. (2017). *Wind energy and on-site energy storage: Exploring market opportunities.* Retrieved from https://windeurope.org/wp-content/uploads/files/policy/position-papers/WindEurope-Wind-energy-and-on-site-energy-storage.pdf

WindEurope. (2018). *Multiple-uses of offshore wind energy areas in the Belgian North Sea.* Retrieved from https://windeurope.org/intelligence-platform/product/multiple-uses-of-offshore-wind-areas-in-the-belgian-north-sea/#overview

WindEurope. (2020). *Making the most of Europe’s grids: Grid optimisation technologies to build a greener Europe.* Retrieved from https://windeurope.org/wp-content/uploads/files/policy/position-papers/20200922-WindEurope-Grid-optimisation-technologies-to-build-a-greener-Europe.pdf

WindEurope. (2022a). *Offshore wind energy 2022 mid-year statistics.* Retrieved from https://windeurope.org/intelligence-platform/product/offshore-wind-energy-2022-mid-year-statistics/

WindEurope. (2022b). *Wind energy in Europe 2021: Statistics and the outlook for 2022-2026*. Retrieved from https://windeurope.org/intelligence-platform/product/wind-energy-in-europe-2021-statistics-and-the-outlook-for-2022-2026/

WMO. (2022). *State of the Global Climate 2021*. Retrieved from https://library.wmo.int/index.php?lvl=notice_display&id=22080#.YtqHdHZByUk

Wolf, J., de Dominicis, M., Lewis, M., Neill, S., O'Hara Murray, R., Scott, B. E., ... Declerck, M. (2021). Environmental Issues for Offshore Renewable Energy. *Reference Module in Earth Systems and Environmental Sciences*. https://doi.org/10.1016/B978-0-12-819727-1.00036-4

Wood, E. E., Ross, M. E., Jubeau, S., Montalescot, V., & Stanley, M. S. (2022). Progress towards a targeted biorefinery of Chromochloris zofingiensis: a review. *Biomass Conversion and Biorefinery*. https://doi.org/10.1007/s13399-022-02955-7

Yang, Z., Ren, Z., Li, Z., Xu, Y., Li, H., Li, W., & Hu, X. (2022). A comprehensive analysis method for levelized cost of energy in tidal current power generation farms. *Renewable Energy, 182,* 982–991. https://doi.org/10.1016/j.renene.2021.11.026

Yousuf, H., Khokhar, M. Q., Zahid, M. A., Kim, J., Kim, Y., Cho, E.-C., ... Yi, J. (2020). A Review on Floating Photovoltaic Technology (FPVT). *Current Photovoltaic Research, 8*(3), 67–78. https://doi.org/10.21218/CPR.2020.8.3.067

Zhou, Z., Benbouzid, M., Charpentier, J. F., Scuiller, F., & Tang, T. (2013). A review of energy storage technologies for marine current energy systems. *Renewable and Sustainable Energy Reviews, 18,* 390–400. https://doi.org/10.1016/j.rser.2012.10.006

List of abbreviations and acronyms

CAPEX	Capital expenditure
CH_4	Methane
CO_2	Carbon Dioxide
CoCoNet	Towards COast to COast NETworks of marine protected areas (from the shore to the high and deep sea), coupled with sea-based wind energy potential project
EC	European Commission
ECMWF	European Centre for Medium-Range Weather Forecasts
EEC	European Economic Community
EERA	European Energy Research Alliance
EIA	Environmental Impact Assessment
EMEC	European Marine Energy Centre, UK
EMF	Electromagnetic field
EMODnet	European Marine Observation and Data Network
EMSA	European Maritime Safety Agency
EnFAIR	Enabling Future Arrays in Tidal
EOSC	European Open Science Cloud
ESFRI	European Strategy Forum on Research Infrastructures
ETIP	European Technology & Innovation Platforms
EU	European Union
GES	Good Environmental Status
GHG	Greenhouse gas
GIEC	Guangzhou Institute of Energy Conversion, China
GMF	Geomagnetic field
Gt	Gigaton
GW	Gigawatt
HAWT	Horizontal axis wind turbine
HCMR	Hellenic Centre for Marine Research, Greece
IAIA	International Association for Impact Assessment

IEA	International Energy Agency
IFREMER	Institut Français de Recherche pour l'Exploitation de la Mer, France
ILO	International Labour Organization
INTELWATT	Intelligent Water Treatment for water preservation combined with simultaneous energy production and material recovery in energy intensive industries project
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
JRC	European Commission’s Joint Research Centre
KRISO	Korea Research Institute of Ships and Ocean Engineering
kW	Kilowatt
kWh	Kilowatt hour
LIDAR	Light Detection and Ranging
MARINET	Marine Renewables Infrastructure Network for Emerging Energy Technologies project
MEDIN	Marine Environmental Data and Information Network, UK
MMO	Marine Management Organisation, UK
MSFD	Marine Strategy Framework Directive
MSP	Maritime Spatial Planning
MW	Megawatt
N_2O	Nitrous Oxide
NEA	Nuclear Energy Agency
NOAA	National Oceanic and Atmospheric Administration, US
NREL	National Renewable Energy Laboratory, US
NTNU	Norwegian University of Science and Technology
OECM	Other Effective Conservation Measures
OEE	Ocean Energy Europe
OES	Ocean Energy Systems
OPEX	Operational expenditure
ORE	Offshore renewable energy

OSPAR	Convention for the Protection of the Marine Environment of the North-East Atlantic
OTEC	Ocean Thermal Energy Conversion
OWC	Oscillating water column
PNNL	Pacific Northwest National Laboratory, US
PRO	Pressure-retarded osmosis
PV	Photovoltaic
R&D	Research and development
RED	Reverse Electro Dialysis
SEA	Strategic Environmental Assessment
SET	European Strategic Energy Technology Plan
SGE	Salinity gradient energy
SIA	Social Impact Assessment
SIDS	Small Island Developing States
SLO	Social licence to operate
SRIA	Strategic Research & Innovation Agenda
STEM	Science, technology, engineering, and mathematics
TRL	Technology Readiness Level
UCC	University College Cork, Ireland
UK	United Kingdom
US	United States of America
VAWT	Vertical axis wind turbine
WEC	Wave energy converter

Annexes

Annex 1: Members of the European Marine Board Working Group on offshore renewable energy

NAME	INSTITUTION	COUNTRY
Working Group Chairs		
Takvor Soukissian	Hellenic Centre for Marine Research (HCMR)	Greece
Anne Marie O’Hagan	MaREI: the SFI Research Centre for Energy, Climate and Marine, University College Cork	Ireland
Contributing Authors		
Arianna Azzellino	Polytechnic University of Milan	Italy
Ferdinando Boero	CoNISMa, Stazione Zoologica Anton Dohrn, CNR-IAS	Italy
Ana Brito e Melo	WavEC	Portugal
Patricia Comiskey	Simply Blue Group	Ireland
Zhen Gao	Norwegian University of Science and Technology (NTNU)	Norway
Dickon Howell	Howell Marine Consulting	UK
Marc Le Boulluec	Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER)	France
Christophe Maisondieu	Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER)	France
Beth E. Scott	University of Aberdeen	UK
Elisabetta Tedeschi	Norwegian University of Science and Technology (NTNU) & University of Trento	Norway & Italy
Additional Contributions		
Alireza Maheri	University of Aberdeen	UK
Shona Pennock	University of Edinburgh	UK

Annex 2: European policies, strategies and directives relevant to ORE

EUROPEAN POLICY / STRATEGY / DIRECTIVE	YEAR	LINK
Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora (Habitats Directive)	1992	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31992L0043
Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy (Water Framework Directive)	2000	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32000L0060
Directive 2001/42/EC of the European Parliament and of the Council of 27 June 2001 on the assessment of the effects of certain plans and programmes on the environment (SEA Directive)	2001	https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex%3A32001L0042
European Strategic Energy Technology Plan (SET Plan)	2007	https://setis.ec.europa.eu/index_en
Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive)	2008	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32008L0056
Directive 2009/147/EC of the European Parliament and of the Council of 30 November 2009 on the conservation of wild birds	2009	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32009L0147
Directive 2014/89/EU of the European Parliament and of the Council of 23 July 2014 establishing a framework for maritime spatial planning	2014	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32014L0089
Directive 2014/52/EU of the European Parliament and of the Council of 16 April 2014 amending Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment (EIA Directive)	2014	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32014L0052
Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources	2018	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.328.01.0082.01.ENG
Directive (EU) 2019/1024 of the European Parliament and of the Council of 20 June 2019 on open data and the re-use of public sector information	2019	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2019.172.01.0056.01.ENG
A European Green Deal	2019	https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1588580774040&uri=CELEX:52019DC0640
Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity	2019	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32019L0944
An EU Strategy to harness the potential of offshore renewable energy for a climate neutral future	2020	https://ec.europa.eu/energy/sites/ener/files/offshore_renewable_energy_strategy.pdf
EU Biodiversity Strategy for 2030 Bringing nature back into our lives	2020	https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1590574123338&uri=CELEX:52020DC0380
Powering a climate-neutral economy: An EU Strategy for Energy System Integration	2020	https://ec.europa.eu/energy/sites/ener/files/energy_system_integration_strategy_.pdf
A hydrogen strategy for a climate-neutral Europe	2020	https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf
European Climate Pact	2020	https://europa.eu/climate-pact/system/files/2020-12/20201209%20European%20Climate%20Pact%20Communication.pdf
Forging a climate-resilient Europe - the new EU Strategy on Adaptation to Climate Change	2021	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2021:82:FIN

EUROPEAN POLICY / STRATEGY / DIRECTIVE	YEAR	LINK
Pathway to a Healthy Planet for All	2014	Norway
EU Action Plan: 'Towards Zero Pollution for Air, Water and Soil'	2021	https://ec.europa.eu/environment/pdf/zero-pollution-action-plan/communication_en.pdf
A new approach for a sustainable blue economy in the EU Transforming the EU's Blue Economy for a Sustainable Future	2021	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2021:240:FIN
REPowerEU: Joint European Action for more affordable, secure and sustainable energy	2022	https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A108%3AFIN
EU Nature Restoration Law	2022	https://environment.ec.europa.eu/publications/nature-restoration-law_en

Annex 3: Comparing units of power

FACTOR	NAME	SYMBOL
10^{-3}: 0.001 W	Milliwatt	mW
1	Watt	W
10^{3}: 1000 W	Kilowatt	kW
10^{6}: 1,000,000 W	Megawatt	MW
10^{9}: 1,000,000,000 W	Gigawatt	GW
10^{12}: 1,000,000,000,000 W	Terawatt	TW
10^{15}: 1,000,000,000,000, 000 W	Petawatt	PW

Annex 4: Examples of references supporting positive and negative environmental impacts of ORE as outlined in Section 4.1

Banach, J. L., van den Burg, S. W. K., & van der Fels-Klerx, H. J. (2020). Food safety during seaweed cultivation at offshore wind farms: An exploratory study in the North Sea. *Marine Policy, 120,* 104082. https://doi.org/10.1016/j.marpol.2020.104082

Bergström, L., Kautsky, L., Malm, T., Rosenberg, R., Wahlberg, M., Capetillo, N. Å., & Wilhelmsson, D. (2014). Effects of offshore wind farms on marine wildlife—a generalized impact assessment. *Environmental Research Letters, 9*(3). https://doi.org/10.1088/1748-9326/9/3/034012

Bishop, M. J., Mayer-Pinto, M., Airoldi, L., Firth, L. B., Morris, R. L., Loke, L. H. L., Hawkins, S. J., Naylor, L. A., Coleman, R. A., Chee, S. Y., & Dafforn, K. A. (2017). Effects of ocean sprawl on ecological connectivity: impacts and solutions. *Journal of Experimental Marine Biology and Ecology, 492,* 7–30. https://doi.org/10.1016/j.jembe.2017.01.021

Busch, M., Kannen, A., Garthe, S., & Jessopp, M. (2013). Consequences of a cumulative perspective on marine environmental impacts: Offshore wind farming and seabirds at North Sea scale in context of the EU Marine Strategy Framework Directiv. *Ocean & Coastal Management, 71*, 213–224. https://doi.org/10.1016/j.ocecoaman.2012.10.016

Coates, D. A., Deschutter, Y., Vincx, M., & Vanaverbeke, J. (2014). Enrichment and shifts in macrobenthic assemblages in an offshore wind farm area in the Belgian part of the North Sea. *Marine Environmental Research, 95,* 1–12. https://doi.org/10.1016/j.marenvres.2013.12.008

Coates, D. A., Kapasakali, D.-A., Vincx, M., & Vanaverbeke, J. (2016). Short-term effects of fishery exclusion in offshore wind farms on macrofaunal communities in the Belgian part of the North Sea. *Fisheries Research, 179,* 131–138. https://doi.org/10.1016/j.fishres.2016.02.019

COWRIE, & Huddleston, J. (2010). Understanding the Environmental Impacts of Offshore Windfarms. In *Understanding the Environmental Impacts of Offshore Windfarms.* https://www.worldcat.org/title/understanding-the-environmental-impacts-of-offshore-windfarms/oclc/806192635

Cresci, A., Perrichon, P., Durif, C. M. F., Sørhus, E., Johnsen, E., Bjelland, R., Larsen, T., Skiftesvik, A. B., & Browman, H. I. (2022). Magnetic fields generated by the DC cables of offshore wind farms have no effect on spatial distribution or swimming behavior of lesser sandeel larvae (Ammodytes marinus). *Marine Environmental Research, 176,* 105609. https://doi.org/10.1016/j.marenvres.2022.105609

Daewel, U., Akhtar, N., Christiansen, N., & Schrum, C. (2022). Offshore wind farms are projected to impact primary production and bottom water deoxygenation in the North Sea. *Communications Earth & Environment, 3(*1), 292. https://doi.org/10.1038/s43247-022-00625-0

Dähne, M., Gilles, A., Lucke, K., Peschko, V., Adler, S., Krügel, K., Sundermeyer, J., & Siebert, U. (2013). Effects of pile-driving on harbour porpoises (Phocoena phocoena) at the first offshore wind farm in Germany. *Environmental Research Letters, 8*(2). https://doi.org/10.1088/1748-9326/8/2/025002

de Backer, A., & Hostens, K. (2017). Effects of Belgian offshore wind farms on soft sediment epibenthos and fish: an updated time series. In *Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: A Continued Move Towards Integration and Quantification* (pp. 59–71). Royal Belgian Institute of Natural Sciences, OD Natural Environment, Marine Ecology and Management Section. https://tethys.pnnl.gov/sites/default/files/publications/Degraer-et-al-2017.pdf

de Mesel, I., Kerckhof, F., Norro, A., Rumes, B., & Degraer, S. J. (2015). Succession and seasonal dynamics of the epifauna community on offshore wind farm foundations and their role as stepping stones for non-indigenous species. *Hydrobiologia, 765*, 37–50. https://doi.org/10.1007/s10750-014-2157-1

Degraer, S., Brabant, R., Rumes, B., & Vigin, L. (2018). *Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: Assessing and Managing Effect Spheres of Influence.* https://tethys.pnnl.gov/sites/default/files/publications/Degraer-et-al-2018_0.pdf

Derweduwen, J., Vandendriessche, S., & Hostens, K. (2016). Effects of Belgian wind farms on the epibenthos and fish of the soft sediment. In S. Degraer, R. Brabant, B. Rumes, & L. Vigin (Eds.), *Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: Environmental Impact Monitoring Reloaded* (p. 95 115). Royal Belgian Institute of Natural Sciences, OD Natural Environment, Marine Ecology and Management Section. https://tethys.pnnl.gov/sites/default/files/publications/Degraer-et-al-2016.pdf

Drewitt, A. L., & Langston, R. H. W. (2006). Assessing the impacts of wind farms on birds. *IBIS, 148*(s1), 29–42. https://doi.org/10.1111/j.1474-919X.2006.00516.x

Elliott, M. (2002). The role of the DPSIR approach and conceptual models in marine environmental management: an example for offshore wind power. *Marine Pollution Bulletin, 44*(6). https://doi.org/10.1016/S0025-326X(02)00146-7

Gill, A. B., Bartlett, M., & Thomsen, F. (2012). Potential interactions between diadromous fishes of U.K. conservation importance and the electromagnetic fields and subsea noise from marine renewable energy developments. *Journal of Fish Biology, 81*(2), 664–695. https://doi.org/10.1111/j.1095-8649.2012.03374.x

Haelters, J., Dulière, V., Vigin, L., & Degraer, S. J. (2015). Towards a numerical model to simulate the observed displacement of harbour porpoises Phocoena phocoena due to pile driving in Belgian waters. *Hydrobiologia, 756,* 105–116. https://doi.org/10.1007/s10750-014-2138-4

Hammar, L., Perry, D., & Gullström, M. (2016). Offshore Wind Power for Marine Conservation. *Open Journal of Marine Science, 06*(01), 66–78. https://doi.org/10.4236/ojms.2016.61007

Hutchison, Z., Secor, D., & Gill, A. (2020). The Interaction Between Resource Species and Electromagnetic Fields Associated with Electricity Production by Offshore Wind Farms. *Oceanography, 33*(4), 96–107. https://doi.org/10.5670/oceanog.2020.409

Kerckhof, F., Degraer, S. J., Norro, A., & Rumes, B. (2011). Offshore intertidal hard substrata: a new habitat promoting non-indigenous species in the Southern North Sea: an exploratory study. In S. Degraer, R. Brabant, & B. Rumes (Eds.), *Offshore wind farms in the Belgian part of the North Sea: Selected findings from the baseline and targeted monitoring.* Royal Belgian Institute of Natural Sciences, Management Unit of the North Sea Mathematical Models. Marine ecosystem management unit. https://odnature.naturalsciences.be/downloads/mumm/windfarms/monwin_report_2011_final.pdf

Krägefsky, S. (2014). Effects of the Alpha Ventus offshore test site on pelagic fish. In A. Beiersdorf & K. Wollny-Goerke (Eds.), *Ecological Research at the Offshore Windfarm Alpha Ventus: Challenges, Results and Perspectives* (pp. 83–94). Springer Spektrum, Wiesbaden. https://link.springer.com/chapter/10.1007%2F978-3-658-02462-8_10

Krone, R., Dederer, G., Kanstinger, P., Krämer, P., Schneider, C., & Schmalenbach, I. (2017). Mobile demersal megafauna at common offshore wind turbine foundations in the German Bight (North Sea) two years after deployment - increased production rate of Cancer pagurus. *Marine Environmental Research, 123,* 53–61. https://doi.org/10.1016/j.marenvres.2016.11.011

Lindeboom, H. J., Degraer, S. J., Dannheim, J., Gill, A. B., & Wilhelmsson, D. (2015). Offshore wind park monitoring programmes, lessons learned and recommendations for the future. *Hydrobiologia, 756*, 169–180. https://doi.org/10.1007/s10750-015-2267-4

Lindeboom, H. J., Kouwenhoven, H. J., Bergman, M. J. N., Bouma, S., Brasseur, S., Daan, R., Fijn, R. C., de Haan, D., Dirksen, S., & van Hal, R. (2011). Short-term ecological effects of an offshore wind farm in the Dutch coastal zone; a compilation. *Environmental Research Letters, 6*(3). https://doi.org/10.1088/1748-9326/6/3/035101

Marine Management Organisation. (2014). Review of post-consent offshore wind farm monitoring data associated with licence conditions. In *A report produced for the Marine Management Organisation MMO Project Nº: 1031*. https://cieem.net/resource/review-of-post-consent-offshore-wind-farm-monitoring-data-associated-with-licence-conditions/

Mendel, B., Kotzerka, J., Sommerfeld, J., Schwemmer, H., Sonntag, N., & Garthe, S. (2014). Effects of the alpha ventus offshore test site on distribution patterns, behaviour and flight heights of seabirds. In A. Beiersdorf & K. Wollny-Goerke (Eds.), *Ecological Research at the Offshore Windfarm alpha ventus* (pp. 95–110). Springer Spektrum, Wiesbaden. https://link.springer.com/chapter/10.1007/978-3-658-02462-8_11

Mendel, B., Schwemmer, P., Peschko, V., Müller, S., Schwemmer, H., Mercker, M., & Garthe, S. (2019). Operational offshore wind farms and associated ship traffic cause profound changes in distribution patterns of Loons (Gavia spp.). *Journal of Environmental Management, 231*, 429–438. https://doi.org/10.1016/j.jenvman.2018.10.053

Norro, A. M. J., Rumes, B., & Degraer, S. J. (2013). Differentiating between Underwater Construction Noise of Monopile and Jacket Foundations for Offshore Windmills: A Case Study from the Belgian Part of the North Sea. *The Scientific World Journal, 2013*. https://doi.org/10.1155/2013/897624

Onea, F., & Rusu, E. (2019). The Expected Shoreline Effect of a Marine Energy Farm Operating Close to Sardinia Island. *Water, 11*(11), 2303. https://doi.org/10.3390/w11112303

Petersen, J. K., & Malm, T. (2006). Offshore Windmill Farms: Threats to or Possibilities for the Marine Environment. *AMBIO, 35*(2), 75–80. https://www.jstor.org/stable/4315689seq=1#metadata_info_tab_contents

Popper, A. N., Hice-Dunton, L., Jenkins, E., Jenkins, E., Higgs, D. M., Krebs, J., Mooney, A., Rice, A., Roberts, L., Thomsen, F., Vignes-Raposa, K., Zeddies, D., & Williams, K. A. (2022). Offshore wind energy development : Research priorities for sound and vibration effects on fishes and aquatic invertebrates. *The Journal of the Acoustical Society of America 1,* 205. https://doi.org/10.1121/10.0009237

Reubens, J. T., Alsebai, M., & Moens, T. (2016). Expansion of small-scale changes in microbenthic community inside an offshore wind farm? In S. Degraer, R. Brabant, B. Rumes, & L. Vigin (Eds.), *Environmental impacts of offshore wind farms in the Belgian part of the North Sea: Environmental impact monitoring reloaded* (pp. 77–92). Royal Belgian Institute of Natural Sciences: OD Natural Environment, Marine Ecology and Management Section. https://tethys.pnnl.gov/sites/default/files/publications/Degraer-et-al-2016.pdf

Reubens, J. T., de Rijcke, M., Degraer, S. J., & Vincx, M. (2014). Diel variation in feeding and movement patterns of juvenile Atlantic cod at offshore wind farms. *Journal of Sea Research, 85*. https://doi.org/10.1016/j.seares.2013.05.005

Reubens, J. T., Degraer, S. J., & Vincx, M. (2014). The ecology of benthopelagic fishes at offshore wind farms: a synthesis of 4 years of research. *Hydrobiologia, 727,* 121–136. https://doi.org/10.1007/s10750-013-1793-1

Stenberg, C., Deurs, M. v., Støttrup, J., Mosegaard, H., Grome, T., Dinesen, G. E., Christensen, A., Jensen, H., Kaspersen, M., Berg, C. W., Leonhard, S. B., Skov, H., Pedersen, J., Hvidt, C. B., Klaustrup, M., Leonhard, S. B., Stenberg, C., & Støttrup, J. (2011). Effect of the Horns Rev 1 Offshore Wind Farm on Fish Communities. Follow-up Seven Years after Construction. In *DTU Aqua Report Nº. 246-2011*. DTU Aqua. https://backend.orbit.dtu.dk/ws/portalfiles/portal/7615058/246_2011_effect_of_the_horns_rev_1_offshore_wind_farm_on_fish_communities.pdf

van den Eynde, D., Baeye, M., Brabant, R., Fettweis, M., Francken, F., Haerens, P., Mathys, M., Sas, M., & van Lancker, V. (2013). *All quiet on the sea bottom front? Lessons from the morphodynamic monitoring* (S. Degraer, R. Brabant, & B. Rumes, Eds.). Royal Belgian Institute of Natural Sciences, Operational Directorate Natural Environment, Marine Ecology and Management Section. https://odnature.naturalsciences.be/downloads/winmonbe2013/winmonbe_report.pdf

van Hal, R., Griffioen, A. B., & van Keeken, O. A. (2017). Changes in fish communities on a small spatial scale, an effect of increased habitat complexity by an offshore wind farm. *Marine Environmental Research, 126,* 26–36. https://doi.org/10.1016/j.marenvres.2017.01.009

Vanermen, N., Onkelinx, T., Courtens, W., van de Walle, M., Verstraete, H., & Stienen, E. W. M. (2014). Seabird avoidance and attraction at an offshore wind farm in the Belgian part of the North Sea. *Hydrobiologia, 756,* 51–61. https://doi.org/10.1007%2Fs10750-014-2088-x

Wilson, J. C., Elliott, M., Cutts, N. D., Mander, L., Mendão, V., Perez-Dominguez, R., & Phelps, A. (2010). Coastal and Offshore Wind Energy Generation: Is It Environmentally Benign? *Energies, 3*(7), 1383–1422. https://doi.org/10.3390/en3071383

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