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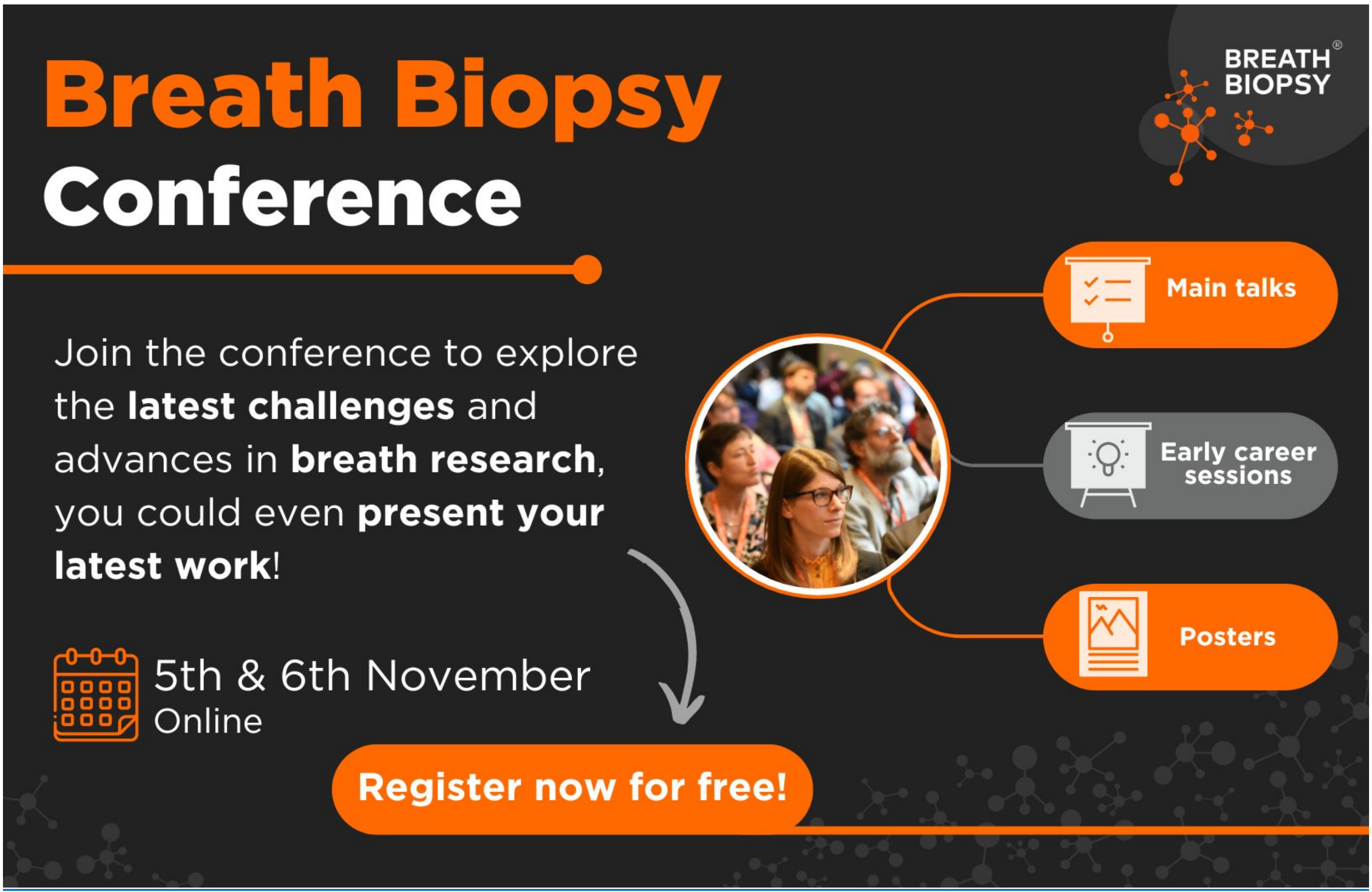

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TOPICAL REVIEW

Environmental impacts from large-scale offshore renewable-energy deployment

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Abstract

The urgency to mitigate the effects of climate change necessitates an unprecedented global deployment of offshore renewable-energy technologies mainly including offshore wind, tidal stream, wave energy, and floating solar photovoltaic. To achieve the global energy demand for terawatt-hours, the infrastructure for such technologies will require a large spatial footprint. Accommodating this footprint will require rapid landscape evolution, ideally within two decades. For instance, the United Kingdom has committed to deploying 50 GW of offshore wind by 2030 with 90–110 GW by 2050, which is equivalent to four times and ten times more than the 2022 capacity, respectively. If all were 15 MW turbines spaced 1.5 km apart, 50 GW would require 7500 km^2 and 110 GW would require 16 500 km^2. This review paper aims to anticipate environmental impacts stemming from the large-scale deployment of offshore renewable energy. These impacts have been categorised into three broad types based on the region (i.e. atmospheric, hydrodynamic, ecological). We synthesise our results into a table classifying whether the impacts are positive, negative, negligible, or unknown; whether the impact is instantaneous or lagged over time; and whether the impacts occur when the offshore infrastructure is being constructed, operating or during decommissioning. Our table benefits those studying the marine ecosystem before any project is installed to help assess the baseline characteristics to be considered in order to identify and then quantify possible future impacts.

1. Introduction

The global energy sector emitted 37.4 $GtCO_2$ in 2023, being 1.1% higher than in 2022, accounting for 70% of global emissions (Energy Institute 2023, International Energy Agency 2024). With the 1.5 °C limit, set during the Paris Agreement in 2015—already breached in 2023—a paradigm shift in cleaner energy production is needed to help mitigate impacts of climate change (Friedlingstein *et al* 2023) and air pollution health issues that cause more than 3.6 million deaths per year (Lelieveld *et al* 2019), and offshore renewable energy is one contribution to solving this demand for energy. Offshore renewable-energy technologies harness kinetic energy from wind, tides, or waves, or harness solar radiation in floating photovoltaic systems. Renewable energy is the fastest-growing sector within the energy industry

(Strielkowski *et al* 2021), with technologies such as onshore wind and solar photovoltaics becoming the cheapest forms of energy generation (IRENA 2020). As of 2020, renewable-energy technologies generated approximately one-seventh of the world's primary energy with offshore wind energy alone preventing direct emissions of 0.15 $GtCO_2$ (Global Wind Energy Council 2023, International Energy Agency 2023). Thus, offshore renewable energies are cleaner, increasingly popular, and rapidly advancing technologies, becoming the cheapest energy generation technologies as installed capacity grows (IRENA 2020).

These benefits of offshore renewable energy, however, can be offset by potential atmospheric, hydrodynamic and ecological environmental impacts, whose effects on the local environment needs to be better understood and quantified. For example, marine life can have its habitat disrupted by the infrastructure, its population displaced, its undersea environment polluted by noise, and the flow in the atmosphere and ocean altered (Isaksson *et al* 2023). However, not all impacts are necessarily negative (Galparsoro Iza *et al* 2022, Pouran *et al* 2022). For example, not only do offshore renewable-energy systems help to mitigate climate change and reduce the likelihood of ocean acidification, but the infrastructure itself can serve as artificial reefs for marine life and foster marine biodiversity. Many impacts are negligible or remain unquantified.

Prior studies have explored the environmental impacts of offshore renewable energy development such as Boehlert and Gill (2010) (focuses on ecological impacts), Dannheim *et al* (2020) (impacts of offshore renewable energy devices on benthic environments), and Copping *et al* (2020) (describes stressor–receptor relationships). Thus, the purpose of this review article is to synthesise the existing literature to examine the range of environmental impacts of offshore renewable-energy technologies, specifically bottom-fixed and floating offshore wind turbines, tidal-stream turbines, wave energy converters and floating solar-photovoltaics systems. Impacts related to the manufacturing process, supply chain, raw materials, and degradation of blades (e.g. microplastic emission) and of the infrastructure are outside the scope of this article. We classify the impacts as atmospheric (section 2), hydrodynamic (section 3), or ecological (section 4). In section 5, we identify whether the impacts are positive, negative, negligible, or unknown, if possible. We also identify whether the impact is instantaneous or lagged over time, and whether the impacts occur when the offshore infrastructure is being constructed, in operation or during decommissioning. These results are synthesised into a table that can be used by others to help anticipate possible future impacts. Section 6 concludes this review.

2. Atmospheric impacts

We classify impacts above the surface of the water as atmospheric impacts. The principal impacts are disruption of the ambient flow, microclimate and synoptic weather, either on a scale similar to the infrastructure as for floating solar photovoltaic or on a larger regional scale as for offshore wind farms. Both floating tidal-stream turbines and wave-energy converters are not included in this section as they are expected to have negligible atmospheric effects (e.g. derived from disturbance from the wave field that affect air–water interface and exchange processes).

2.1. Ambient flow

Floating solar-photovoltaic facilities produce a localised footprint due to mechanical turbulence as the wind blows through the infrastructure. This infrastructure can have a non-negligible impact on the local micro-climate, particularly because it would occupy a large surface area (e.g. a 1 MW array would occupy about 10 000 m^2). The panels would have a higher surface temperature compared to the surrounding air, potentially producing a heat island with its associated circulations (Barron-Gafford *et al* 2016, Branch *et al* 2024). Because floating solar photovoltaic is still in its infancy, few studies have quantified these effects from existing facilities. Thus, the deployment of future MW-scale projects should involve research to examine potential impacts on the environment (Claus and López 2022).

In contrast to floating solar-photovoltaic farms that just introduce turbulence, offshore wind turbines not only introduce turbulence within the wind-farm region (Ali *et al* 2023) but also mix the air due the rotating turbines. The extraction of kinetic energy from the flow within offshore wind farms can create low-velocity, turbulent regions in the atmospheric boundary layer flow in the downwind direction known as *wakes*. In some cases, wakes can extend downwind of wind-farm arrays by 60 km or more and impact land, as in the case of wakes that are often generated in Liverpool Bay, United Kingdom (figure 1).

The dimensions of such wind-farm wakes are related to meteorological conditions, with stably stratified conditions favouring longer wakes (Stevens and Meneveau 2017, Porté-Agel *et al* 2020, Zhou *et al* 2022). The wake will also be determined by the dimensions of the individual wind turbines, as well as the number and spatial density of the turbines in the wind farm (Porté-Agel *et al* 2020). Currently, installed offshore wind farms around the world have hundreds of medium-sized turbines, with 8 MW rated power and 220 m top-tip height. For many marine environments, the mixing due to the turbines will occur within the marine boundary layer, the region

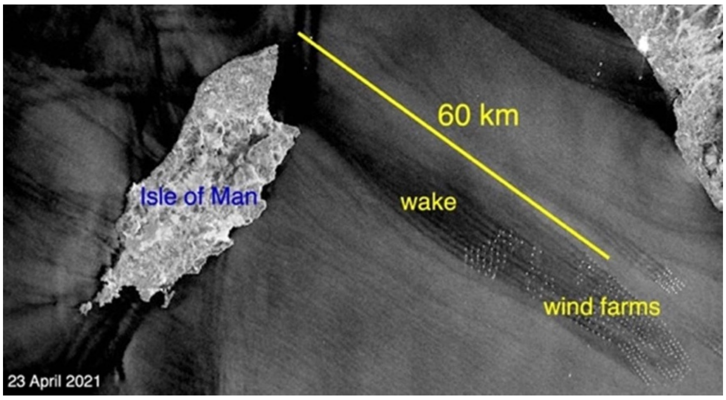


Figure 1. *Sentinel–1* synthetic aperture radar image showing a wake (long length of dark shades) from the wind farms in Liverpool Bay, United Kingdom, on 23 April 2021. Shading represents wind speed over water (dark is light winds, light is strong winds). Near-surface flow is from the southeast. Brightness in the image has been enhanced to bring out the contrast between the wake and the unaltered environmental flow. Figure adapted from the original imagery obtained from Sentinel Hub.

of well-mixed air above the ocean surface. The marine boundary layer tends to be warm and moist, compared to usually drier and cooler air aloft. Thus, impacts on downstream weather tend to be small, producing a wake 50 km or less and temperature and absolute humidity changes of order 0.5 °C and 0.5 g kg^{-1} (Siedersleben *et al* 2018).

Future offshore wind farms will have hundreds of more powerful and taller turbines: 20 MW devices with 275 m diameter that will exceed 320 m top-tip height (Global Wind Energy Council 2022), with mixing extending over 600 m deep in the downwind direction. As these larger turbines are increasingly installed within expanding wind farms, encompassing a wider spatial and vertical footprint, their influence extends over a greater horizontal area and depth of the marine boundary layer. This expansion heightens the likelihood of breaching the free atmosphere (i.e. the layer above the capping inversion layer) and increases the depth of the boundary layer (Abkar and Porté-Agel 2013). Given that the boundary layer is often capped by much drier and potentially warmer air aloft with higher wind speeds, breaching the free atmosphere will lead to much larger changes to the wake and may sharply increase the power generated (i.e. power scales as the cube of wind speed). Thus, the impact on the near-surface meteorology once the breach occurs will not be linear, but a step change.

2.2. Microclimate

Understanding the impact of offshore wind turbines on weather is complicated by the fact that different weather conditions can lead to warming and drying, cooling, and moistening, or have no effect at all (e.g. table 1 in Siedersleben *et al* 2018). This complexity is partially addressed by categorising the stability of the boundary layer (Fitch *et al* 2013). During stable atmospheric conditions, near-surface temperatures tend to rise (e.g. when temperature decreases or increases slowly with height), whereas during unstable atmospheric conditions, near-surface temperatures typically decrease (e.g. when temperature decreases rapidly with height) (Rajewski *et al* 2016, 2020). Over time, the hour-to-hour and day-to-day variability in stability may offset the changes from individual events, resulting in minimal net changes. Consequently, case studies, which form the basis of much of our understanding, may not fully capture the long-term environmental implications of wind farms. This knowledge gap provides an opportunity to explore and foresee the impacts of offshore wind farms in the future.

Clouds and precipitation may also be altered by offshore wind farms. Modelling studies of large-scale onshore and offshore wind farms show spatial changes in precipitation both near and well away from the farm (e.g. Wang and Prinn 2010, Fiedler and Bukovsky 2011, Vautard *et al* 2014, Lauridsen and Ancell 2018, Li *et al* 2019). Arrays of offshore wind farms surrounding coastal cities have also been suggested to reduce precipitation (Pan *et al* 2018, Lee *et al* 2022a) and storm surges (Jacobson *et al* 2014) from land-falling tropical cyclones. The increased turbulence within the wake also has the potential to increase evaporation and heat fluxes from the ocean surface (Foreman *et al* 2017). Furthermore, changes in clouds and precipitation will alter downstream temperature and salinity of the ocean (Ludewig 2015), potentially affecting marine ecosystems (Øijorden 2016) and energy production from any neighbour floating solar-photovoltaic array.

2.3. Synoptic weather

The installation of wind farms has also been suggested to change, not just local climate, but also large-scale weather patterns. For example, Barrie and Kirk-Davidoff (2010) suggested that a 1.5 GW onshore wind farm would change the track and development of cyclones in the North Atlantic on a scale that would exceed that of the uncertainty inherent in forecasts. Lauridsen and Ancell (2018) showed that such changes to cyclones could be 1 hPa for sea-level pressure, 4 m s^{-1} surface wind speed, and 15 mm for maximum 30 min accumulated precipitation. For different-sized onshore wind farms over the central United States, Fiedler and Bukovsky (2011) found that the wind farms inhibited the movement of dry air from the northwest, increasing precipitation by 1%. However, other studies downplay these impacts (e.g. Vautard *et al* 2014). Importantly, much of our current understanding above predominantly stems from studies conducted with onshore deployment, suggesting there are likely opportunities to further our understanding of offshore deployments.

3. Hydrodynamic impacts

Hydrodynamic impacts comprise alterations to the wave fields and tidal currents. These alterations are primarily caused by tidal-stream turbines (both bottom-fixed and floating), wave-energy converters, floating solar-photovoltaic platforms, and vertical support structures from offshore wind turbines. These structures generate localised disturbances to the flow, except for tidal-stream turbines whose wakes can generate larger regional-scale impacts.

3.1. Mean tidal flow and turbulence

As with wind turbines, the wakes in the water generated by tidal-stream turbines, wave-energy converters, and support structures potentially impact the circulation in the upper layer of the ocean in two distinct ways. First, these structures block the ambient flow, reducing the circulation and limiting the movement of water behind the turbine. Second, devices create turbulence, disrupting flow patterns and increasing mixing. This turbulence agitates sediment causing disturbances to the seabed, and tends to be predominantly localised in scale (Wang *et al* 2023). Thus, the impact of wakes on the water varies based on the type of offshore renewable energy technology.

Tidal-stream turbines extract energy from the movement of the tidal currents. The effects of these turbines on the far-field flow, the flow circulation, the tidal asymmetry and the water level were investigated in numerical modelling studies (Neill *et al* 2021, Stansby and Ouro 2022). Guillou and Chapalain (2017) found that tidal extraction can influence the existing circulation pattern in the Passage du Fromveur, France. Potter (2019) investigated the effect of a single and an array of tidal-stream turbines on shallow-water tides and the tidal asymmetry, which in turn can affect sediment transport. Guillou *et al* (2019) simulated the effect of tidal-stream turbines on flow renewal and found that the turbines only had a small influence, with less than 5% change in residence times. Whereas Robins *et al* (2014) focused on tidal regime and flushing and their findings suggest that tidal-stream arrays with capacities less than 50 MW did not cause changes to the sediment concentration beyond natural variability. Model simulations indicate that extracting energy from areas with strong tidal asymmetry results in a 20% increase in the average magnitude of bed-level change across a large estuarine system compared to regions with tidal symmetry (Neill *et al* 2009). Regardless of the placement of a tidal-stream array within the tidal system, energy extraction diminishes the overall magnitude of bed-level change compared to scenarios with no extraction (Musa *et al* 2018). However, a group of turbines can have different impact on the tidal flow depending on their layout (Vennell *et al* 2015, Ouro and Nishino 2021). Tidal-stream turbine arrays can affect suspended sediment levels beyond their immediate area, possibly noticeable from a considerable distance away extending up to 10 km downstream (Robins *et al* 2014, Neill *et al* 2017). Ahmadian *et al* (2012) found that an array of 2,000 turbines, each with a 20 m diameter, would slightly reduce sediment concentration upstream and downstream of the turbine array in the Severn Estuary, United Kingdom.

As waves propagate from offshore to nearshore, energy is lost due to the turbulent marine boundary layer suspending and transporting sediment. Arrays of wave-energy converters (even floating tidal-stream turbines or floating wind turbines) will inevitably modify the wave field, potentially absorbing energy and hence decreasing its effect nearer to shore. One of the rare field measurements is a study by Contardo *et al* (2018) near three wave-energy converters off Perth, Australia, which enabled the quantification of an overall reduction in the wave height in the swell and wind-sea band compared to natural variability. A reduction in waves can serve as coastal protection against extreme weather events (such as reducing storm surge) (Stansby *et al* 2022) or can alter long-shore drift, impacting beach morphology, shallow-water bathymetry, and substrata (Defeo *et al* 2008). Furthermore, wave-energy converters can increase bed shear stresses by 8%–20% (Dalyander *et al* 2013), affecting sediment suspension more in shallower water (<20 m) than in deeper water (>40 m) (Coughlan *et al* 2021). This impact extends to sediment transport in both the near- and far-field (Neill *et al* 2021). Deployment of wave-energy converters can reduce nearshore sediment transport. Wave-energy converter arrays can potentially reduce the long-shore sediment transport (O'Dea *et al* 2018) showing that the location of the array along the shoreline determines whether a beach experiences erosion or accretion, highlighting its effectiveness in mitigating erosion when strategically placed (Rodriguez-Delgado *et al* 2018).

The presence of offshore wind-turbine foundations in the water column of the sea shelf introduces a source of turbulence, removing energy from the tidal currents and inducing turbulent mixing in the wake downstream. Field observations can assess the loss of stratification within the wake of a single offshore wind-farm structure. The turbulent wake of a cylindrical structure (e.g. a monopile) is narrow and highly energetic within a distance of about four to six diameters. After this, the introduced turbulent kinetic energy is dissipated to reach levels similar to those found in the ambient flow (Schultze *et al* 2020). However, the more instant hydrodynamic impact of monopile turbulent wakes are changes to the seabed, known as *scouring*, which occurs in areas of intense tidal flow (Den Boon *et al* 2004). The development of scour around monopiles of offshore wind turbines has been studied considering only tidal currents (Whitehouse *et al* 2011, McGovern *et al* 2014) and also combining waves and currents (Sumer and Fredsøe 2001). Offshore sand banks serve as crucial natural defences against storm waves. These sand banks are often shaped and sustained by strong tidal currents and bathymetric irregularities, typically found in areas conducive to tidal-energy extraction (Huthnance 1982, Neill *et al* 2012). As they act as vital nursery grounds for fisheries (van Slobbe *et al* 2013, Spalding *et al* 2014), understanding their morphodynamic (i.e. the study of how the shape of the seabed changes over time) interaction with the offshore renewable energy infrastructure is necessary.

3.2. Ocean circulation

The combination of upwelling and downwelling creates a dipole, which is a pair of opposite movements or flows within the ocean. These dipoles play a crucial role in ocean circulation, nutrient cycling and distribution of marine biota (Pathirana *et al* 2024). Christiansen *et al* (2022) applied a hydrodynamic model to simulate the effects of temporally changing wind fields on these dipoles. Their findings revealed that upwelling and downwelling dipoles shifted position based on shifts in wind wakes, occasionally leading to the overlap of specific dipoles. This overlap resulted in either the strengthening or weakening of their effects. Empirical and modelling studies have examined the pelagic effects (i.e. relating to regions of the ocean far from the shore – *pelagic zone*) of offshore wind-farm foundations in the stratified North Sea (Floeter *et al* 2017, Schultze *et al* 2020, Dorrell *et al* 2022). However, there is limited empirical data on how offshore wind farms, which alter wind stress at the sea surface, impact the upper ocean and pelagic ecosystem. Theoretical island effects (i.e. when turbine spacing is close enough to create a cumulative effect) can also contribute to destratification and upwelling behind the offshore wind turbine support structure, which can increase primary production (van Berkel *et al* 2020, Daewel *et al* 2022). However, these island effects appear negligible when compared to downstream wake effects (van Berkel *et al* 2020).

4. Ecological impacts

The deployment of offshore renewable-energy technologies also has an impact on marine life and its ecosystem. Here, we discuss six effects: sediment transport, artificial reefs, population dynamics, collision risk, noise, and electromagnetic fields.

4.1. Sediment transport

Sediment transport alters turbidity levels, which in turn influences predator–prey encounters. Prey species may evacuate affected areas to avoid predation risk, whereas predators using chemosensory or mechanosensory detection are drawn to areas with increased opportunities for ambushing prey (Bergström *et al* 2013, 2014, Lunt and Smee 2015). Even if it seems natural that turbidity would negatively impact predation rates, some studies suggest that turbidity has little or no effect on predation rates for both visually oriented (Figueiredo *et al* 2015) and non-visually oriented predators (Ohata *et al* 2011). The impact could be due to habitat characteristics such as refuge availability (Gregor and Anderson 2016) or predators' ability to efficiently perceive non-visual cues in the absence of visual information (Hartman and Abrahams 2000). Organisms in wave-exposed areas, commonly found in offshore wind-farm locations, are generally expected to be tolerant to turbidity (Bergström *et al* 2014) with no significant changes to fish mobility (Rodrigues *et al* 2023). However, some studies suggest that elevated turbidity levels may harm sensitive organisms, such as in the case of juvenile chinook salmon (Kjelland *et al* 2015, Lowe *et al* 2015).

As sediment is transported, it can undergo changes in its composition, such as becoming coarser or finer. These changes can affect biogeochemical processes in the long-term. For instance, if sediment distribution at a site becomes coarser, it may provide a different habitat for microorganisms or affect how nutrients are stored and cycled (Huettel *et al* 2014). Carbon storage is facilitated by these microorganisms; therefore, changes in sediment composition can be detrimental to native ecosystem dynamics. For example, the common heart urchin, a crucial bioturbator in the German part of the North Sea, favours organically enriched sediments (Dannheim *et al* 2020).

4.2. Artificial reefs

Artificial reefs built up at the offshore renewable-energy infrastructure or debris on the seabed provide an anchor point for marine life and form the basis of a food chain. The influence of artificial reefs can be either beneficial or detrimental to both, predator and prey populations. One scenario is that these artificial reefs could establish new habitats (Adams *et al*

2014) which, in turn, may lead to non-native species competing in the same ecological niche as native species. For instance, offshore wind farms in the shallow southern North Sea facilitated the colonisation of non-native species such as Pacific oyster (De Mesel *et al* 2015, Kamermans *et al* 2018) and marine splash midge (Brodin and Andersson 2008). In other cases, apex predators appear to actively seek offshore wind farms and tidal-stream turbines as sources of food and/or shelter (Lieber *et al* 2019, Degraer *et al* 2020). Also, harbour seals use the submerged infrastructure of wind farms as foraging grounds (Sparling *et al* 2018).

The scour protection in offshore wind farms, usually comprising of a rock layer unevenly covered by rock and gravel at the bottom of the wind-turbine support structure, creates additional microhabitats for a diverse array of species (Degraer *et al* 2020, Pardo *et al* 2023). Even if this rock layer resembles a natural rock reef, the fauna associated with offshore wind-farm scour protection remains distinct from that found on natural reefs (Glarou *et al* 2020). Studies have been focused on assessing the feasibility of refining scour protection designs by predicting scour holes (Pourzangbar *et al* 2017, Habib *et al* 2024) or by using microbial-induced carbonate precipitation, which is an eco-friendly alternative to cement (Wei *et al* 2024). Making these changes can contribute to the restoration of natural gravel-bed ecosystems (Reubens *et al* 2011). Quantifying the overall artificial reef effects, and distinguishing them as positive or negative based on previous studies that are mostly qualitative, is difficult. Becker *et al* (2018) suggest that setting quantitative goals and monitoring the changes against these goals will provide a better understanding as this was proven to be a successful approach adopted in aquaculture-based fishery industries.

4.3. Population dynamics

Establishing offshore wind farms may inhibit commercial fishing operations near their location, as these farms are commonly designated as marine protected areas. This restriction in fishing activities alleviates pressure on fish populations by enhancing the birth rate and fertility, and reduced death rates (Henry *et al* 2018). Additionally, offshore wind turbine structures act as protective spaces, mitigating predation risks for fish eggs and larvae (Degraer *et al* 2020). The absence of assessment tools to evaluate the impacts of these structures on the displacement of fish species and the associated implications for fisheries inhibits informed policy. However, offshore wind farms themselves could mitigate the negative socio-economic impact of access loss on fishing activities. Predicted results suggest a potential increase in catches of up to 7% near the wind farms located in the Bay of Seine (English Channel, France) (Halouani *et al* 2020), and a slight rise in the proportion of high trophic-level species such as fish, marine mammals, and sea birds (Raoux *et al* 2017). Organisms reliant on stratified water columns, such as phytoplankton, will experience changes due to the disruption of stratification caused by increased turbulent mixing from offshore renewable infrastructures (Dorrell *et al* 2022). This increased mixing will modify the temperature and salinity gradients of the water column and thus changes water density (Inall *et al* 2021). Phytoplankton and zooplankton experience positive or adverse effects from the *wave effect* (i.e. influence of internal waves on the movement and distribution of suspended particles and plankton species), *shading effect* (i.e. reduction in algae growth, natural reflectivity of the water surface and sunlight penetration) (Ostrovsky 2022, Pouran *et al* 2022), oxygen depletion, and predation pressure, leading to a fluctuation of primary production by approximately 10% (Wang *et al* 2024). Wind wakes of large offshore wind-farm clusters in the North Sea led to differences of up to 10% in annual primary production (i.e. the conversion of inorganic carbon compounds into organic matter by autotrophs such as phytoplankton or blue-green algae, facilitating energy assimilation and storage) (Daewel *et al* 2022). The removal or addition of species from a system due to biological or environmental factors changes the ecological dynamics of the entire system (Shennan 2008). Evidence suggests that species interactions (particularly indirect interspecific interactions) can disturb populations, and non-equilibrium dynamics (such as those in food webs) can impact ecological functioning (Berlow *et al* 2004, Zhang *et al* 2015, Landi *et al* 2018).

4.4. Collision risk

Operating offshore wind turbine rotor blades pose a risk of collision to birds although most studies suggest that this risk is lower for offshore wind farms than onshore (Tikkanen *et al* 2018). The risk is lower offshore (>5 km from the coast) as bird species of the region flew at lower altitudes above the sea (Marques *et al* 2014, Tikkanen *et al* 2018) and less often at at-risk heights, which is anywhere between 50 and 200 m (Balotari-Chiebao *et al* 2018). However, Kurian *et al* (2010) suggested that wind farms and risk heights for bird species are greater at sea. Species in coastal and offshore regions exhibit distinct behavioural patterns compared to those on land, resulting in species-specific collision risk, vulnerability, and displacement (Farr *et al* 2021). Evidence indicates species-specific responses to turbines, with many birds adjusting their flight paths at a distance before approaching the turbines rather than making adjustments in the last second to avoid collisions (Cook *et al* 2018). There is a growing concern about awareness of factors such as the percentage of migrating birds flying at at-risk heights, as well as their casualty, mortality, and avoidance rates in offshore wind-farm regions. These areas would otherwise be important habitats or traditional passage routes (Cook *et al* 2011). In 2023, Borssele and Egmond aan Zee offshore wind farms in the Netherlands were shutdown for four hours because flocks of migrating birds were observed (Brabant *et al* 2021). Alternative proposals concern reducing rotational speeds to two revolutions per minute during nighttime. Direct observations entail field surveys and monitoring programs to identify and collect data on such factors, often through visual inspections and necropsies.

Hypothetical calculations employ mathematical models to estimate collision risk based on factors such as bird flight patterns and turbine characteristics (Masden and Cook 2016, Horne *et al* 2023). The collision index is a metric used to assess the probability of bird collisions with turbines in each area, under the previously mentioned factors (D'Amico *et al* 2019). Calculations of this index for marine bird populations of herring gulls, great black-backed gulls, and lesser black-backed gulls exhibit the highest total risk scores, indicating a heightened likelihood of collision with offshore wind turbines in Scottish waters (Furness *et al* 2013). The calculated death rate for a scenario involving 10 000 turbines spread over the North Sea is estimated to be 9.4% and 8.7% higher than the baseline scenario for lesser and great black-backed gulls, respectively (Brabant *et al* 2015). Furthermore, the same collision index identified that black-backed gulls are susceptible to collision risk with a high probability of flight near blade height (Furness *et al* 2013). Additionally, species such as white-tailed eagles, northern gannets, and skuas were also identified as being at risk of collision (Wade 2015). Divers and common scoters were found to be vulnerable to population-level impacts due to displacement from increased avoidance rates linked to high collision risk (Furness *et al* 2013).

In shallower waters, the potentially largest negative effect for marine species, particularly larger fish and marine mammals, comes from the collision with wind turbine structures, tidal-stream turbine rotors or neutrally-buoyant cables and moorings from floating wind and tidal-stream turbines, wave energy devices and floating photovoltaic systems (Williamson *et al* 2019, Hutchison *et al* 2022, Copping *et al* 2023, Rezaei *et al* 2023). However, Cotter and Staines (2023) found that no marine mammal had been struck by a turbine but did witness fish coming in close proximity to a turbine. Onoufriou *et al* (2021) quantified the distribution of harbour seals before and after the installation of tidal turbines and found no significant changes. Their study also suggested that the avoidance response of these seals to the presence of turbines were high indicating that collision rates could be overestimated (Onoufriou *et al* 2021). Furthermore, tidal-stream turbines can be equipped with sonars or echo-sounders to detect the presence of large marine mammals to minimise risk of collision (Williamson *et al* 2017, Gillespie *et al* 2022). Vertical-axis tidal stream turbines rotate at lower rotational speeds than their horizontal-axis counterparts, which decreases collision risk (Müller *et al* 2023), increases risk perception and generates lower acoustic noise. Blade colour different to white can also notably reduce the collision risk (Sonnino-Sorisio *et al* 2023). Limited studies to date have focused on the collision risk associated with wave-energy devices and floating solar-photovoltaic systems, but some risks can be linked to direct entanglement of marine mammals with mooring lines (Hutchison *et al* 2022, Pouran *et al* 2022) or impact from diving birds as in ground-mounted solar-photovoltaic facilities (Hernandez *et al* 2014).

4.5. Undersea noise

Marine animals rely on sound for navigation, communication, hunting, and foraging (Copping and Hemery 2020). Thus, any disturbance that hinders the ability of marine animals to perceive and use the sounds relevant to them everyday would affect their fitness and survival (Hawkins and Popper 2014). The vibrations and undersea noise generated by pile-drilling activities during offshore wind turbine construction can result in short-term displacement, cause mortality and tissue damage in fish (Thomsen *et al* 2006), and disorient large marine mammals. The smaller scale of construction activities may lead to more localised effects on fish and benthic communities, impacting local marine life. Observed changes include alterations in behaviour, communication, and migration patterns of fish (Benincà *et al* 2008, Popper *et al* 2022). The compression and expansion of gas-filled organs and hearing structures can result in temporary or permanent injuries, and even death (Copping *et al* 2021). Young life stages with limited mobility likely have reduced abilities to avoid harmful noise levels. In a comparative analysis with baseline conditions, a decline of 8%–17% in the occurrence of porpoise was noted in proximity to the activity zone during pile-driving and construction (Benhemma-Le Gall *et al* 2021). Porpoises avoided active pile-driving locations by up to 12 km and construction vessels by up to 4 km (Benhemma-Le Gall *et al* 2021). Extreme-noise events from drilling during construction phase posed a high risk on the threatened population of Atlantic cod especially during December–June (i.e. spawning period of cod) at a proposed 300 MW wind farm project in the Kattegat Sea, Sweden (Hammar *et al* 2014).

4.6. Undersea electromagnetic fields

Offshore renewable-energy technologies are connected to land via large undersea export cables that transmit electricity and have inter-array cables between the devices resulting in electromagnetic fields (Hutchison *et al* 2021). Industry-standard medium and high voltage alternating-current (HVAC) cables are commonly used in offshore renewable systems. These cables can effectively block the electric fields but are less successful at blocking magnetic fields (Hutchison *et al* 2020b). Thus, there is a concern that marine mammals might be sensitive to minor changes in magnetic fields associated with these cables (Collin *et al* 2003, Gill 2005). Gill *et al* (2012) suggest that electromagnetic fields from HVAC cables may have limited impacts on migrating diadromous fishes, with only a momentary change in swimming direction in shallow waters (<20 m). However, even if the electric fields were contained by grounding them, the magnetic field emitted and the movement of animals or water currents can continue to induce electric fields (Gill and Desender 2020).

High-voltage direct-current (HVDC) cables are also used in offshore renewable systems, having greater capacity and efficacy for longer electricity transmissions. Exposure to HVDC cables can detrimentally affect swimming speed of fish, as observed for haddock larvae (Cresci *et al* 2022), and cause oxidative damage and neurotoxicity in bivalves (Jakubowska-Lehrmann *et al* 2022). For instance, when exposed to electromagnetic fields from a HVDC cable at a constant power of 330 MW, magneto-sensitive American lobsters stayed closer to the sea bed and changed direction of travel more than normal, and electro-sensitive little skates travelled further but at slower speeds with an increase in exploratory activity (Hutchison *et al* 2018).

Given such case-specific electromagnetic-field effects on the marine ecosystem, it is crucial to determine the spatial extent of affection from electromagnetic fields, as electric current varies depending on turbine and farm output and cable size (Gill *et al* 2014, Willsteed *et al* 2017). Furthermore, different species have different responses to electromagnetic fields (i.e. electro- and magneto-sensitive species) (Hutchison *et al* 2020a). Cartilaginous fishes (such as elasmobranchs) and some bony fish species (such as sturgeons, salmon, lampreys, and paddlefish) are known to be electro-sensitive (Gill *et al* 2014). Electromagnetic-field detection in elasmobranchs (such as sharks, rays, and skates) has been more thoroughly understood, making them valuable model species for studying the effects of electromagnetic fields from undersea cables on fish (Tricas and Sisneros 2004).

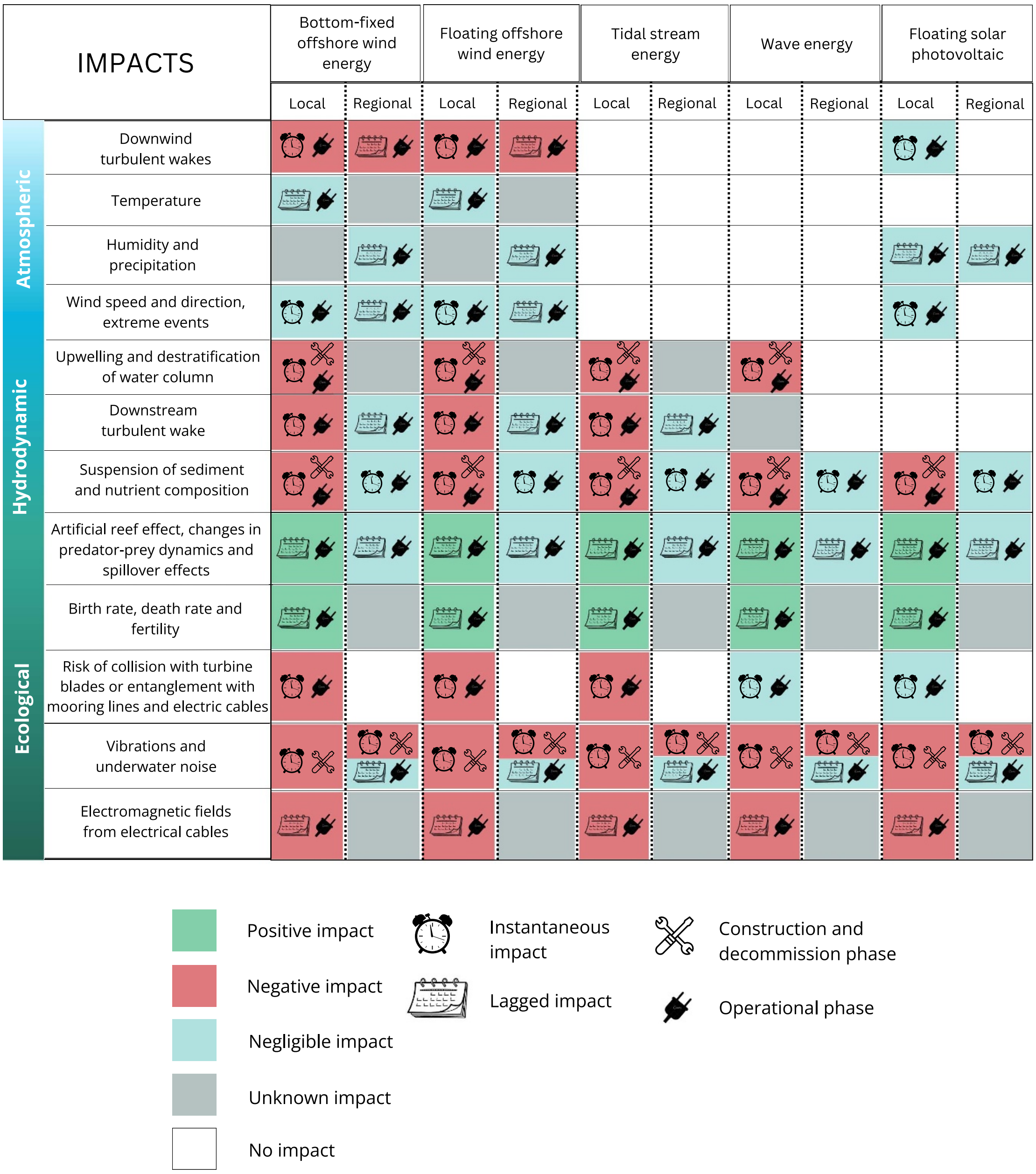
5. Synthesis

The results of the previous sections are summarised in figure 2. The figure lists the five main offshore renewable-energy technologies and classifies whether each atmospheric, hydrodynamic, and ecological impact is positive, negative, negligible or unknown. These impacts are classified as to whether they happen instantaneously or lagged in time, and whether they occur during the construction phase or the operational phase. Although some impacts, such as collision risk for fish and marine mammals (section 4.4), occur instantaneously, others, such as alterations to micro-climate by offshore wind farm wakes (section 2.2), may develop gradually over time, producing a lagged impact.

Tidal-stream and wave energy together with floating solar-photovoltaic systems lead to only impacts in the water column and air–water interface. Offshore wind farms have impacts on the atmosphere and extending to the water column, and is the only known technology causing regional effects during the operation phase due to their turbine rotor wakes (figure 1). During the construction phase, there are three impacts: (i) changes to water column upwelling and stratification, (ii) changes to sediment transport and nutrient composition, and (iii) effect of vibration and undersea noise (figure 2). The first two continue during the operation phase, and their effect on a regional scale needs to be further studied, especially considering that hundreds of turbines in relative proximity will be deployed already by 2030 in regions such as the North Sea, Eastern Coast of the United States, Brazil or China, thus creating cumulative effects.

Decommissioning of offshore wind farms can have effects on sediment transport and turbidity (excavation or scour protection removal) or habitat loss (especially if the artificial reef effect is removed) (Hall *et al* 2022). Removal of large floating solar-photovoltaic facilities will remove the physical obstruction to light penetration in the water column, leading to an opposite effect on the algae population as that occurring during installation. Originally impacted ecosystem could reach equilibrium after end of life of these technologies; hence important population dynamic changes can be repeated. Further consideration of alternative decommissioning options to full removal related to *leave better than it was* to become a viable—and valuable—option in project bidding during decommissioning, notably improving the *leave as it was* standard (Topham *et al* 2019). In this context, concrete-made gravity-based foundations can have design lifespans close to 100 years, enabling the installation of three or four series of wind turbines whose lifespan is about 25 years (Smyth *et al* 2015). No study to date has been found to analyse the environmental impacts arising from decommissioning wave-energy converter farms or tidal-stream turbine arrays. Two tidal-stream turbines have remained inoperative in the water for several years, namely the OpenHydro turbine in Nova Scotia (Canada) and DeltaStream turbine at Ramsey Sound (Wales) and their future retrieval can inform decommissioning studies.

Ecological impacts on the local ecosystem need to be quantified depending on the project site as ecosystem and habitat characteristics change. To anticipate and mitigate such potential negative impacts, (Bonar *et al* 2015) suggest conducting baseline surveys before installing any offshore renewable-energy



	IMPACTS	Bottom-fixed offshore wind energy		Floating offshore wind energy		Tidal stream energy		Wave energy		Floating solar photovoltaic	
		Local	Regional	Local	Regional	Local	Regional	Local	Regional	Local	Regional
Atmospheric	Downwind turbulent wakes	🟥 ⏰🔌	🟥 📅🔌	🟥 ⏰🔌	🟥 📅🔌	⬜	⬜	⬜	⬜	🟦 ⏰🔌	⬜
	Temperature	🟦 📅🔌	▨	🟦 📅🔌	▨	⬜	⬜	⬜	⬜	⬜	⬜
	Humidity and precipitation	▨	🟦 📅🔌	▨	🟦 📅🔌	⬜	⬜	⬜	⬜	🟦 📅🔌	🟦 📅🔌
	Wind speed and direction, extreme events	🟦 ⏰🔌	🟦 📅🔌	🟦 ⏰🔌	🟦 📅🔌	⬜	⬜	⬜	⬜	🟦 ⏰🔌	⬜
Hydrodynamic	Upwelling and destratification of water column	🟥 ⏰🛠🔌	▨	🟥 ⏰🛠🔌	▨	🟥 ⏰🛠🔌	▨	🟥 ⏰🛠🔌	⬜	⬜	⬜
	Downstream turbulent wake	🟥 ⏰🔌	🟦 📅🔌	🟥 ⏰🔌	🟦 📅🔌	🟥 ⏰🔌	🟦 📅🔌	▨	⬜	⬜	⬜
	Suspension of sediment and nutrient composition	🟥 ⏰🛠🔌	🟦 ⏰🔌	🟥 ⏰🛠🔌	🟦 ⏰🔌	🟥 ⏰🛠🔌	🟦 ⏰🔌	🟥 ⏰🛠🔌	🟦 ⏰🔌	🟥 ⏰🛠🔌	🟦 ⏰🔌
Ecological	Artificial reef effect, changes in predator-prey dynamics and spillover effects	🟩 📅🔌	🟦 📅🔌	🟩 📅🔌	🟦 📅🔌	🟩 📅🔌	🟦 📅🔌	🟩 📅🔌	🟦 📅🔌	🟩 📅🔌	🟦 📅🔌
	Birth rate, death rate and fertility	🟩 📅🔌	▨	🟩 📅🔌	▨	🟩 📅🔌	▨	🟩 📅🔌	▨	🟩 📅🔌	▨
	Risk of collision with turbine blades or entanglement with mooring lines and electric cables	🟥 ⏰🔌	⬜	🟥 ⏰🔌	⬜	🟥 ⏰🔌	⬜	🟦 ⏰🔌	⬜	🟦 ⏰🔌	⬜
	Vibrations and underwater noise	🟥 ⏰🛠	🟥 ⏰🛠 🟦 📅🔌	🟥 ⏰🛠	🟥 ⏰🛠 🟦 📅🔌	🟥 ⏰🛠	🟥 ⏰🛠 🟦 📅🔌	🟥 ⏰🛠	🟥 ⏰🛠 🟦 📅🔌	🟥 ⏰🛠	🟥 ⏰🛠 🟦 📅🔌
	Electromagnetic fields from electrical cables	🟥 📅🔌	▨	🟥 📅🔌	▨	🟥 📅🔌	▨	🟥 📅🔌	▨	🟥 📅🔌	▨

🟩 Positive impact
🟥 Negative impact
🟦 Negligible impact
▨ Unknown impact
⬜ No impact

⏰ Instantaneous impact
📅 Lagged impact

🛠 Construction and decommission phase
🔌 Operational phase

Figure 2. Identification of the main impact categories of offshore renewable-energy technologies, including whether this has a positive, negative, negligible, or unknown impact on the hosting ecosystem, temporal and spatial frames, and stage of the projects.

infrastructure. Such surveys can help address the paucity of observed data, enabling the quantification of negative and positive impacts that motivate research activities to mitigate any adverse effects or support environmental impact assessment.

6. Conclusion

Offshore renewable-energy systems are being deployed at a fast rate worldwide to reduce the carbon intensity in the energy generation from most countries and meet net-zero targets. To ensure their sustainable deployment into the marine environment, meticulous planning, continuous research, and vigilant monitoring is needed to mitigate potential negative impacts but also unveil positive impacts, such as reducing greenhouse gas emissions compared to carbon-based energy sources, the main trigger of climate change. Proactively addressing challenges and proposing viable measures are imperative steps in the current massive deployment-scale phase worldwide. This review acknowledges challenges and opportunities relative to impacts at the atmospheric (mainly from offshore wind turbines and floating solar-photovoltaic systems), hydrodynamics (tidal-stream turbines, wave energy converters and wind-turbine support structures), and ecological levels. The main impacts at these levels have been identified and associated with the different technologies, dividing also into effects that may happen during construction or operation only, extending over a local or regional spatial scale, and whether they will be developed immediately or lagged in time.

Characterising the what, when, and where is crucial to determine how any impact will be felt by the marine ecosystem. At present, there is an opportunity to take baseline measurements of current environmental characteristics, so that the effects of further deployment of offshore renewable infrastructure can be quantified. The breadth of the perspective paper presents a limitation, yet it also holds implications for future research. However, this limitation can be leveraged to offer an overview of impacts and models for their measurement. This paper can serve as a reference for addressing problems and formulating solutions through policy revision or tool development.

Current technologies for offshore wind turbines, especially floating, or tidal-stream turbines are still evolving to become an established technology to be deployed at large scale worldwide. Hence, alternative innovative solutions for these technologies can be developed over the forthcoming years. For instance, concrete-made gravity-based structures for offshore wind turbines are directly laid on the seabed without the need for drilling operations, foster marine life as new artificial reefs, and have longer lifespans compared to steel-made support structures, enabling the installation of a second set of turbines once the initial ones reach the end of their approximately 25 year lifespan. Vertical-axis tidal-stream turbines operate at lower rotational speeds than their horizontal-axis counterparts, lowering the footprint of impacts related to noise generation or risk of collision, among others. Additionally, exploring co-location opportunities with fishing activities can further enhance sustainability and synergy in marine renewable projects.

Data availability statement

The data cannot be made publicly available upon publication because no suitable repository exists for hosting data in this field of study. The data that support the findings of this study are available upon reasonable request from the authors.

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