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10 Things to consider before approving another offshore wind farm: A case study for Highland, Scotland

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ABSTRACT

The sea is often seen as an empty and quiet place, and hence, an appealing location for wind farms and related installations. However, the sea is dynamic, there is a wealth of wildlife, and there are different users of the sea who can conflict with each other. Offshore wind farms must go through planning applications in which a range of concerns have to be addressed for each individual wind farm. There are the obvious concerns, such as visual impacts and risks to birds, bats, fish, and sea mammals, but there is a range of other issues in need of attention. This document presents 10 overlooked and underestimated impacts on the health of the natural environment, from the smallest plankton to the great whales, and the human population. It appears that offshore wind farms are being consented before new models and measurements have become available to assess their impact. Also, recent experiences with terroristic, militaristic and criminal attacks on the offshore wind industry, and disputes between offshore wind farm developers have given reason to reflect. All parties involved in the wind industry are seen to be learning as it goes at the rate at which it is deployed on a large scale. Current impact assessments are for each individual wind farm, ignoring cumulative effects of multiple large offshore wind farms. There will be many unforeseen consequences and what is acceptable today, may not be in the not-too-distant future.

1. Introduction

Wind farms require a lot of space due to the small energy density of wind energy and the low efficiency of the transformation of wind energy into electricity (MacKay, 2008). Wind turbines and wind farms are getting ever larger to mitigate these shortcomings, and since the sea is often seen as 'empty' it is an appealing location for offshore wind farms and related installations. The Scottish seas are particularly interesting because the wind is strongest in the north of the UK; several large offshore wind farms are in operation and many more are in the pipeline (Fig. 1). There is a wide range of marine activities and users that can conflict with each other and need to be regulated (Fig. 2). In the planning system for offshore wind farms in Scotland, several groups are involved: the public, who can submit representations (letters of support or objections); local authority planning officers and councillors, when they prepare and agree the council's consultation response to the Scottish Government; and the Marine Directorate, which assesses applications and provides advice (Scottish Borders Council, 2025; UK Government, 2025; The National, 2025). The Scottish Government (Scottish Ministers) has the final say, particularly on larger developments. Highland is by far the largest of all counties in Scotland and receives numerous applications for large offshore wind farms and related infrastructures. This investigation of 10 often underestimated and overlooked issues can help the Highland Council and all other parties involved in new offshore wind energy projects and in policy development make an informed decision. The selected issues cover a wide range of concerns: the sea as a legal person, vulnerability to terroristic, militaristic, and criminal attacks; unexploded munition on the seabed; phytoplankton; dirty sides to offshore wind turbines; noise and light pollution; changes to the surf; floating offshore wind farms; cumulative impact; and mental health. Though other relevant issues could be addressed, the selected cases sufficiently demonstrate the complexity and scope of the topic.

2. The sea as legal entity

The ocean is the largest space on Earth, covering approximately 70 % of Earth's surface and holding about 97 percent of all the water on Earth. If we take care of the ocean, the ocean will take care of us. But the ocean is not there for us to do with as we please, to dump our waste in, to sustain blue economies, or to remove CO_2 from the atmosphere. There is only one ocean on planet Earth, and it belongs to no one. The ocean should have a voice in decisions that affects its existence. This may sound incredible, but the feasibility of giving the ocean or other natural resources legal personhood is subject of serious studies (United Nations, 2025; Mühlrel, 2025). The idea has already been put in practice in different parts of the world. New Zealand granted legal personhood to the Whanganui River in 2017 (BBC, 2020) and this year the River Ouse in England has been given its own rights (Time Out, 2025). The Constitutional Court of Ecuador has ruled that the ocean has ocean

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rights to enhance its legal protection (Ocean Vision Legal, 2025) while in Oban, the Ocean has been given a place at the boardroom of the Scottish Association for Marine Science (SAMS) (The Scottish Association for Marine Science, 2025). These developments show how our relationship with the ocean is changing and that what is acceptable today, may not be in the not-too-distant future.

3. Vulnerability to terroristic, militaristic, and criminal attacks

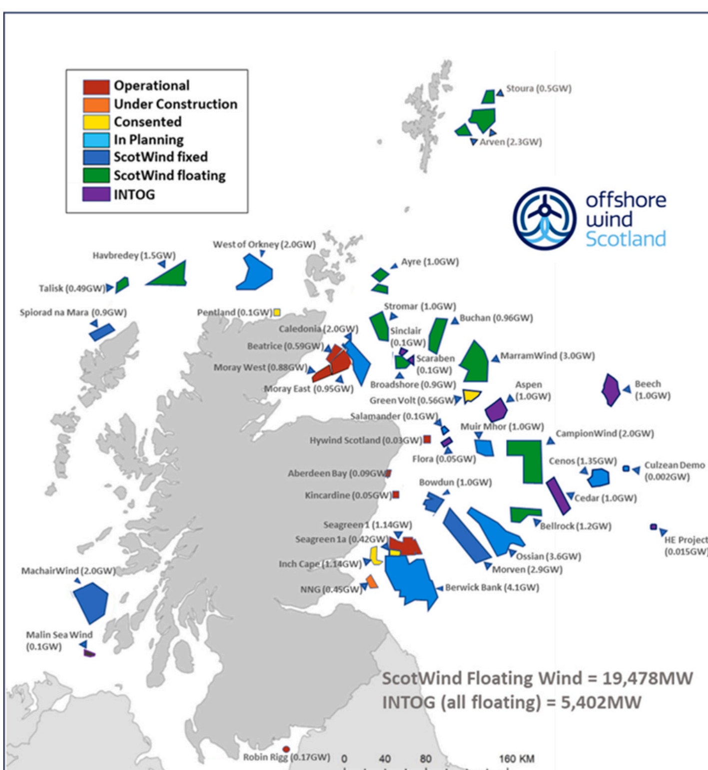
Bueger & Edmunds (Bueger and Edmunds, 2024) review the technical vulnerabilities of offshore wind farm systems to threats from terrorism, crime and hostile states, including physical and cyber risk scenarios. Hostile states can operate in the so-called “grey zone”, meaning they intend to harm their opponent, especially their infrastructure assets, but don’t go as far as committing an act of war. In the North Sea and Baltic Sea regions, specific concerns are linked to Russia and their plans for acts of sabotage while in the waters around Taiwan as well as those of the South China Sea the Chinese government is frequently accused of grey zone activities (Bueger and Edmunds, 2024). These vulnerabilities are not part of public planning applications for offshore wind farms and related infrastructure in Highland. It is likely that these vulnerabilities have been evaluated and that plans for protection are in place but have not been made public for obvious reasons. In the following, known issues with military- and energy security are described.

3.1. Cable damage

Energy from offshore wind farms is brought ashore through undersea power cables. For the situation in Highland, see the map on the Highland Renewables Database website (Haltiner, 2025). According to this map, electricity generated at sea must travel long distances before it reaches our shores. The estimation that 80 percent of financial losses suffered by offshore wind farms are caused by cable failure (Bueger and Edmunds, 2024) confirms how critical these subsea cables are. An estimated 70 percent of cable failures are caused by damage from shipping, fishing, or boating activities, accidently or otherwise (Bueger and Edmunds, 2024). Due to their remote and hard to survey locations, cable failures can be subject to crime, terrorism and grey zone activities. The Russian military uses the Main Directorate for Deep Sea Research (GUGI) for deep-sea intelligence gathering, such as mapping the location of offshore wind farms or the points at which cables come ashore, and sabotage operations (BBC, 2025a). GUGI operates deep-diving submarines that can sever cables at great depths but sometimes they are suspected of simply dragging an anchor along the seabed to damage a subsea cable (BBC, 2025a). The Chinese government has recently revealed a deep-sea cable-cutting device capable of severing undersea communication and power cables at depths of up to 4000 m (Asia Times, 2025).

3.2. Cyberattacks

A cyberattack is any intentional effort to steal, expose, alter, disable, or destroy data, applications, or other assets through unauthorized access to a network, computer system or digital device (IBM, 2025). Offshore wind farms are at cyber risk due to the convolution of wind farm components and the numerous suppliers and operators usually involved (Bueger and Edmunds, 2024). A cyberattack could physically damage offshore wind farm turbines, land-based sub stations and undersea connections, and has the potential to shut down a wind farm network as a whole (Bueger and Edmunds, 2024). In Germany three cyber-attacks led to turbines losing connection with satellites and the corruption of internal IT systems (Knack et al., 2024). Danish wind company, Vestas, faced a ransomware attack in 2021 whereby data retrieved from Vestas’ IT systems were used to extort their customers (Knack et al., 2024). Cyberattacks are happening in the UK, but there is no public available information on this (The Alan Turing Institute, 2024). Cyberattacks on wind farms could also be used to steal privileged technical data. MI5 (the United Kingdom’s Security Service, Military



Floating Wind in Scotland (24.9GW)

SITE	DEVELOPERS	CAPACITY
Hywind	Equinor	30MW
Kincardine	KOWL	48MW
Pentland	Copenhagen Infrastructure Partners	100MW
SCOTWIND		
Muir Mhor	Vattenfall and Fred Olsen Renewables	1,000MW
Ossian	SSE Renewables, CIP and Marubeni	3,610MW
Bellrock	BlueFloat Energy/Nadara Partnership	1,200MW
CampionWind	Shell and ScottishPower Renewables	2,000MW
Ayre	Thistle Wind Partners (DEME, Aspiravi and Qair)	1,008MW
Stromar	Orsted/BlueFloat Energy/Nadara Partnership	1,000MW
Broadshore	BlueFloat Energy/Nadara Partnership	900MW
MarramWind	Shell and ScottishPower Renewables	3,000MW
Buchan	Floating Energy Allyance (Baywa r.e. Elicio and BW Ideol)	960MW
Hevbredey	Northland Power and ESB	1,500MW
Talisk	Magnora ASA and Technip UK	495MW
Arwen	Mainstream Renewable Power and Ocean Winds	2,300MW
Stoura	ESB Asset Management	500MW
INTOG		
Green Volt	Flotation Energy/Vargrønn	560MW
Culzean Demo	TotalEnergies	3MW
Salamander	Ørsted/Simply Blue Group	100MW
Cenos	Flotation Energy/Vargrønn	1,350MW
Sinclair	BlueFloat Energy/Nadara Partnership	100MW
Scaraben	BlueFloat Energy/Nadara Partnership	100MW
Flora	bp Alternative Energy Investments	50MW
Malin Sea Wind	ESB Asset Development	100MW
Aspen	Cerulean Winds	1008MW
Beech	Cerulean Winds	1,008MW
Cedar	Cerulean Winds	1,008MW
HE Project	Harbour Energy	15MW

Fig. 1. Offshore wind farms that are in development, under construction, and operational off the Scottish coast; Scotwind and INTOG (Innovation and Targeted Oil and Gas) are areas for lease (Offshore Wind Scotland, 2025a).

Intelligence, Section 5) is concerned with the consented Green Volt offshore wind turbine project to be built off the East Coast of Scotland (Fig. 1) because of their potential Chinese hardware supplier Mingyang (Interesting Engineering, 2025; Financial Times, 2025). Chinese hardware installed at sea could give China access to sensitive information without the UK's knowledge. The Caledonia, Stromar and Ayre wind farm sites are located inside military zones, while West of Orkney, Beatrice, Moray East and Scaraben are adjacent (Figs. 1–2), which raises concerns about the security of the UK's military secrets. Recently, U.S. experts found rogue communication devices in Chinese solar inverters providing a built-in way to physically destroy the grid (Reuters, 2025). In conclusion, all components, suppliers, infrastructure and operators that make an offshore wind farm work need to be continually assessed to guarantee miliary-as well as energy security.

3.3. Drone attacks and autonomous vessels

According to world leaders in offshore wind electricity producers, AI-equipped drones can perform complex inspections, maintenance, and cargo delivery in offshore wind farms (Vattenfal, 2025; Ørsted, 2024). Flying a drone, also known as unmanned aerial vehicle (UAV), in UK airspace is subject to UK laws, rules and regulations. Drones are controlled by a nearby drone pilot or by an operator at distance in a remote-control centre, possibly in another country and bypassing all UK legislation (Wind Systems Magazine, 2023). Drone attacks on wind farms can cut off electricity supply to the consumer by damaging wind turbines as happened in 2024 when a Russian drone attacked a UK owned wind farm in the Ukraine (National Wind Watch, 2024). Autonomous vessels are also deployed for offshore surveying of wind farms (Ørsted, 2024). According to the Swedish' defence minister, Pål Jonson, both cruise robots and ballistic robots are a big problem if you have offshore wind power (The Guardian, 2024). A Polish study warns for the ease at which an explosive charge can be moved into the region of a wind turbine or submarine cables using either a drone or autonomous vessel (Baltic Wind, 2022).

3.4. Blinding onshore radars

Radar (radio detection and ranging) is used for air traffic, coastal surveillance, air defence, and weather forecasting/monitoring for civilian and military purposes (Bueger and Edmunds, 2024; Auld et al., 2013). A basic radar system emits electromagnetic energy and measures its reflectance off targets in the radar's line of sight; reflections from other objects such as active wind farms can interfere with the radar signal of the target, creating gaps in the observations (Auld et al., 2013). Sweden cancelled 13 offshore wind farms in the Baltic Sea Wind because they could affect sensors and radars used in Sweden's defence (The Guardian, 2024). The UK Government is concerned about keeping the skies above the UK safe from aerial threats and has funded research projects in innovative future windfarm mitigations for UK Air Defence (UK Government, 2021). While these new technologies are being developed and tested, new offshore wind farm infrastructures need to be managed carefully, especially where military zones and offshore wind farms are co-located (Fig. 2).

3.5. Blue crime

Blue crime is a criminal activity that takes place on, in, or across the sea (Bueger and Edmunds, 2024). Examples of crime at sea are piracy, smuggling of illicit goods, people trafficking, and environmental crimes such as illegal fishing and hazardous waste disposal. Crimes at sea are aided by the difficulty of routine surveillance and increased response times for law enforcement due to their remote locations. Being located at sea, offshore wind farms are vulnerable to theft and vandalism. Offshore wind turbines require more copper (an estimated eight tonnes of copper per megawatt) than onshore wind turbines (about three tonnes of copper per megawatt) because of more copper in further cabling (International Energy Agency, 2022; Coppers Development Association Inc, 2025). The scrap value of copper is the highest of all scrap metals (UK Metals, 2025). Copper theft, whereby highly professional offenders steal copper cabling from inside the wind turbine, is on the rise from onshore wind farms in the UK (International Security Journal, 2025). It is conceivable that these organized crime groups move their attention to remote offshore wind farms. Offshore wind farms could also be put at risk by nearby illegal fishing as it more likely involves destructive methods such as bottom trawling and explosives fishing which could damage cables and other infrastructure (Bueger and Edmunds, 2024). In Scotland, incidents of illegal scallop dredging and prawn trawling to supply a

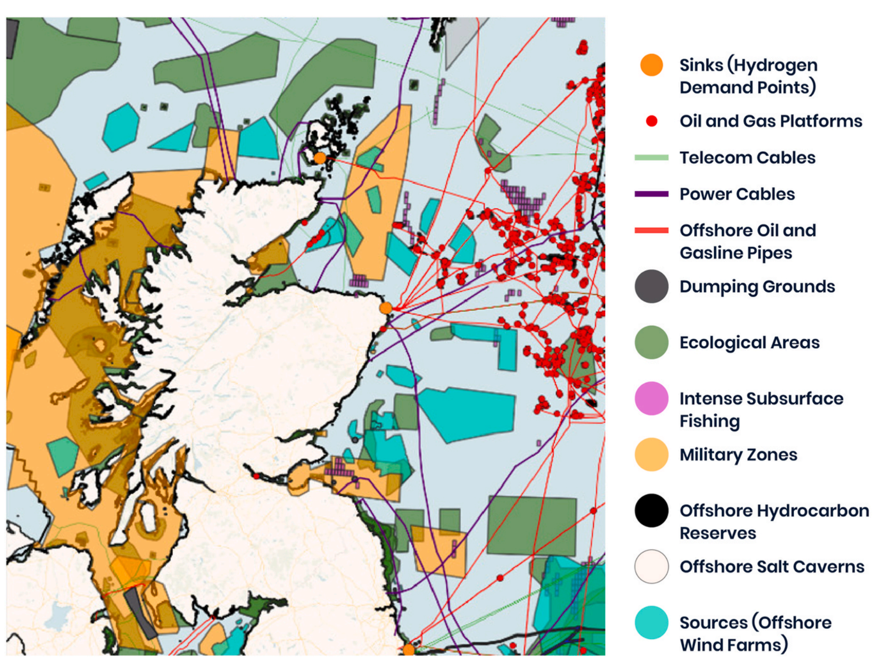


Fig. 2. Map showing many different marine activities and functions, adapted from the North Sea Energy Road Map (North Sea Energy, 2025). The Ecological Areas represent Marine protected areas (MPAs), covering around 37 % of the seas around Scotland (Scottish Government, 2025a).

lucrative black market in seafood have been reported (The Ferret, 2019). Finally, turbines and sub-stations could be used as transshipment points for smuggling operations (Bueger and Edmunds, 2024). The UK Border Force has warned that South American drug gangs are dropping cocaine worth tens of millions of pounds in the sea around the UK to be picked up and brought to shore by smaller boats (BBC, 2025b). Offshore wind turbines and energy islands can be used as transshipment points for smuggling narcotics, as well as small arms, counterfeits and even people trafficking (Bueger and Edmunds, 2024).

4. Unexploded munition on the seabed

Explosives, chemical munitions, bombs, and artillery shells have been dumped during and after the two World Wars, and there are still hundreds of thousands of unexploded ammunitions in European seas and UK waters today (European Commission, 2024; BBC, 2025c). Fig. 3 shows locations of known submerged munition dump sites around the north of Scotland (European Commission, 2025), but there are many more that lie underwater undiscovered. Unexploded munitions on the seabed pose severe threats to marine and human lives during the construction and operation of offshore wind farms. They must be cleared using quiet technologies (less noisy than "high-order" detonations) for wind projects to go ahead (BBC, 2025c). Another concern is wind farms and their cable corridors forcing fishermen further out to sea into danger zones of unexploded bombs, as is happening in the Firth of Forth (East Lothian Courier, 2025). Unexploded munitions on the seabed are all around the Scottish coast (Fig. 3), necessitating surveying for unexploded munitions on and near the locations of large offshore wind farms that are in development, under construction, and operational (Fig. 2).

Areas where offshore power cables make land fall can also be contaminated. On the Caithness coast radioactive contamination has been found in Dounreay believed to have come from military aircraft instruments dumped around the time of the Second World War. This discovery has prevented SSEN (Scottish and Southern Electricity Networks) to progress construction of a substation for the Orkney-Caithness high-voltage electricity cable (The National, 2024). It is also the landfall site of the Pentland Floating Offshore Windfarm (Fig. 2 (Pentland Floating Offshore Windfarm, 2025);). According to the Scottish Environment Protection Agency, SSEN needs to acquire an Environmental (Scotland) Authorisations Regulations 2018 (EASR) permit to complete the work (BBC, 2024). Other areas in Scotland where there have been similar worries about radioactive pollution due to suspected buried airplanes are Dalgety Bay, Kingsteps Quarry at Nairn, and sand dunes near Kinloss in Moray (BBC, 2024). This problem shows that issues associated with military and maritime security (as described in section 3) can go back as long as 80 years and stay around for another hundreds of years.

5. Phytoplankton

The Amazon rain forest is widely known as the 'lungs of the world' because its trees and plants produce atmospheric oxygen (O_2) and absorb massive amounts of the greenhouse gas carbon dioxide (CO_2) through the process of photosynthesis. Consequently, news about the cutting down of trees in the Amazon rainforest in Brazil leads to public outrage (BBC, 2025d). Phytoplankton in the sea, single-cell organisms that are plants (algae), also photosynthesise, producing an estimated 80 % of the world's oxygen and playing a key role in the ocean uptake of CO_2 (Witman, 2017). The ocean absorbs about a quarter of the atmospheric CO_2 emitted by human activities (Watson et al., 2020). However, when the environment that supports this 'biological pump of carbon' in the sea is threatened on our doorstep we don't hear much about it. Another reason why phytoplankton is extremely important is because phytoplankton is at the bottom of the food chain and essentially the foundation of all life in the sea (Witman, 2017). On the other hand, phytoplankton colonies growing out of control lead to harmful algal blooms (National Oceanic and Atmospheric Administration, 2025). Harmful algal blooms can produce toxins, they can smother underwater life, and decaying algal blooms can suffocate underwater life by consuming all the oxygen in the water. Toxic blooms occur regularly along the east coast as well as other waters around Scotland, with health implications for shellfish, fish, fish eating predators and humans (Kershaw et al., 2021). Toxic blooms are difficult to predict but human activities that disturb ecosystems seem to play a role in the more frequent occurrence and intensity of harmful algal blooms (National Oceanic and Atmospheric Administration, 2025). Phytoplankton growth

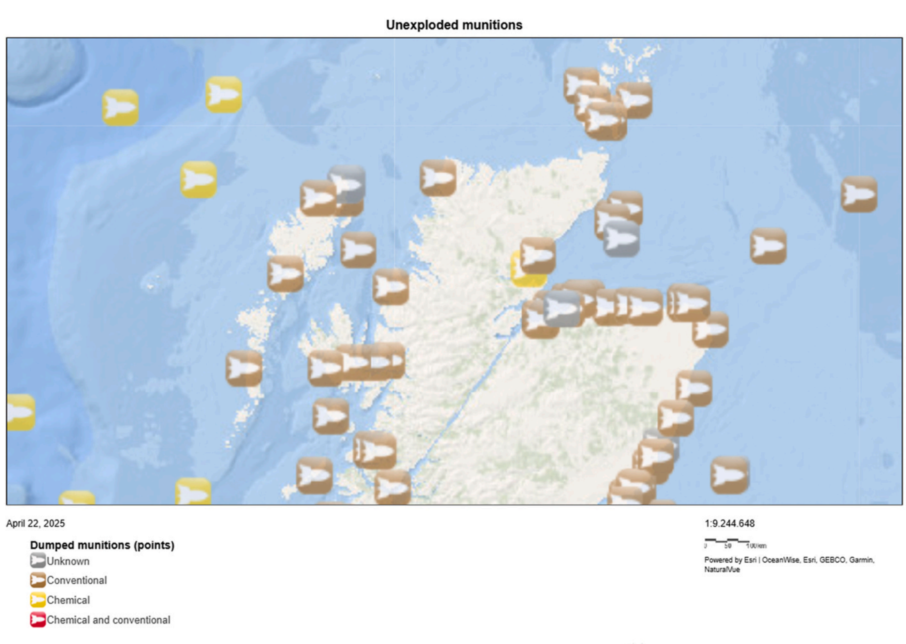


Fig. 3. Unexploded munitions on the seabed available online from the European Atlas of the Seas by EMODnet, Layer: Litter, Dumped munitions (points) (European Commission, 2025).

is controlled by sunlight, CO_2, and nutrients in the water, as well as water temperature and salinity, water depth, wind, and predators grazing on them (National Oceanic and Atmospheric Administration, 2025; NASA Earth Observatory, 2025). In general, when vertical mixing of water layers brings nutrients into the sunlit layers at the sea surface, phytoplankton starts to grow. Phytoplankton growth is seasonal, relating to the presence of sunshine and wind, and depends on the latitude of their location.

Offshore wind turbines can affect phytoplankton growth in several ways: (1) the submerged parts acting as artificial reefs for marine life (ICES, 2025), (2) more mixing of nutrient-arm and nutrient-rich water due to changes in the water flow around offshore wind turbine foundations (Dorrell et al., 2022), and (3) less mixing due to reduced surface wind in the offshore wind farm wake (Daewel et al., 2022; Zampollo et al., 2025). Significant changes were found [e.g., (Dorrell et al., 2022), (Daewel et al., 2022), (Zampollo et al., 2025)], both increases and decreases depending on environmental conditions such as water depth, time of the year, and type of offshore wind turbine. Modelling shows that in wind wakes of large offshore wind farm clusters in the North Sea can change primary production up to ±10 % (Daewel et al., 2022). Many scientific studies have necessarily focussed on examining the influence of a single specific factor. In the future we need to look at the cumulative impact of large offshore wind farms on all combined atmospheric, hydrodynamic, biogeochemical and ecosystem processes that control phytoplankton growth (ICES, 2025; Daewel et al., 2022). At present, phytoplankton are not routinely evaluated in the environmental impact assessment of a planned offshore wind farm (Scottish Government, 2019) and does not appear on the list of 35 marine pressures within the Feature Activity Sensitivity Tool (FeAST) used by Marine Scotland (NatureScot, 2025). At the higher level of strategic research programs, however, the consequences of large upscaling of offshore wind on phytoplankton are evaluated [e.g., (ICES, 2025), (Deltares, 2021)]. Progress would be demonstrated if insights gained were systematically incorporated into planning applications.

6. Dirty sides to offshore wind turbines

Toxins are persistently released by offshore wind turbines both above and below the sea surface. Offshore wind turbines possibly emit over 200 contaminants into the environment, with coatings accounting for the majority of substances, followed by anti corrosion systems on the metal, and oil and grease for operation (Hengstmann et al., 2025), as described in more detail in respective sub sections 6.1 to 6.3 below. Marine toxins and litter are not confined to one location as they are easily moved around by dynamic processes in the sea such as, currents, waves, tides, and the mixing of oceanic waters with shelf sea waters (van Sebille et al., 2020). MPAs are designed to protect Scotland's seas, marine life and habitats from damage caused by human activities (Scottish Government, 2025a). It is therefore a concern to locate large offshore wind farms near MPAs (Fig. 2); for example the planned West of Orkney Wind Farm is enclosed by MPAs on three sides while peak tidal flows move water back and forth at top speeds that exceed 1 m/s (ABPmer, 2025). The pollution is not only a local and regional problem as large-scale ocean flow can transport durable pollution, such as plastics, over large distances on a global scale (van Sebille et al., 2020). Snapping turbine blades or turbine fires occasionally launch litter into the ocean (ICES, 2025; Reuters, 2024a; WorkBoat, 2024). One offshore wind turbine can contain up to 1400 L of various oils (LAIIER, 2025) that could be discharged in a catastrophic natural event or accident (WorkBoat, 2024; Gunter, 2014). However, in the following sections the focus is on the often overlooked continous direct pollution from offshore wind turbines. The Marine Directorate does not mention direct pollution by offshore wind turbines in the strategic environmental assessment for offshore wind energy (Scottish Government, 2019).

6.1. *Microplastics pollution from leading edge erosion*

Offshore wind farms shed paint particles from offshore structures and plastic particles from the rotor blades of turbines (Hengstmann et al., 2025). Repeated impacts by raindrops and other substances in the atmosphere ultimately lead to coating cracking, debonding of layers, cracks in composite, and surface roughening of the wind turbine blades (Mishnaevsky et al., 2021). It has been subject of many studies for the wind energy industry because surface erosion roughens the leading edge of wind turbine blades, reducing efficiency as they become less aerodynamic. This so-called 'leading edge erosion' becomes increasingly problematic as blades grow longer and tip speeds increase and hence the impacts. In the process of leading-edge erosion, plastic particles are released into the environment about which research is only just emerging. A preliminary estimate of the plastic mass loss for offshore wind turbines is 80–1000 g/year per blade (Mishnaevsky et al., 2024). Recent research of offshore wind turbines in the North Sea shows that a substantial part of leading edge erosion happens within just 12 h of the year during specific rain and wind events and there are regional differences (TNO, 2025). The combination of more wind and rain in the northeastern part of the North Sea leads to more damage of the protective coatings on the blades, so that they last about 20 % less long than in the southwestern part (TNO, 2025). Seeing that the west coast of northern Scotland is more exposed to the rain-bearing westerly winds during winter storms than the east coast (Met Office, 2025), leading edge erosion is expected to be worse in wind farms near the Western Isles and west of Orkney than in the North Sea (Fig. 1).

6.2. *Pollution from anti corrosion systems on the metal*

The underwater zone of an offshore wind turbine needs protection from metal corrosion (rusting). Corrosion-protection systems are used to protect turbines from rusting which can release metals into the ocean over time (Hengstmann et al., 2025; University of Portsmouth, 2025; Watson et al., 2025). Of particular concern is the method of galvanic anode cathodic protection (GACP) of underwater metal, with substantial amounts of anode (aluminium or zinc) dissolving for decades (Watson et al., 2025). Metal inputs released from operational offshore wind farms and their ecotoxicological risks are under assessed, probably because this is a new area of research. A recent study estimates annual inputs of metals from current European wind farms to be substantial (3219 tonnes of aluminum, 1148 tonnes of zinc, and 1.9 tonnes of indium) (University of Portsmouth, 2025; Watson et al., 2025). Watson et al. (2025) advice against co-locating aquaculture with offshore wind farms without taking measurements to mitigate their metal pollution because metals in water accumulate in kelp and the tissues of oysters and mussels. While artificial reef effects and the sanctuary inside for fish from fisheries are often mentioned as positive side effects of offshore wind farms, this research warns for health risks. Inside or near an offshore wind farm, fish residing there may be adversely affected, and oysters and mussels grown there may pose a risk to human health (Watson et al., 2025). Watson et al. (2025) provide a road map for industry and regulators for implementing key policy to minimise these risks.

6.3. *Oil and grease leakages*

Wind turbines use oils in lubrication, hydraulics and gear boxes, which requires regular manual servicing. As soon as turbines start to leak oil, immediate action must be taken as it can lead to more serious failures and even turbine collapse (LAIIER, 2025). Oil leakages are therefore a great concern of the offshore wind industry and the harsh environment and the remoteness of wind turbines at sea makes servicing very difficult. Oil leaks damage the environment, and at sea, a small amount of oil carrying all sorts of chemical compounds (Hengstmann et al., 2025) can spread over a large area. There are large knowledge gaps in the composition of the oils and their environmental impacts, but awareness is growing, and research has started to come out (e.g. (Hengstmann et al., 2025),).

7. Noise and light pollution

7.1. Noise pollution

It is well recognized that underwater noise from piledriving during the construction of offshore wind farms can harm fish and sea mammals (Ouro et al., 2024). This is often deemed acceptable as it is a temporary disturbance. Although low frequency sound and vibrations of onshore operating wind turbines are known to trouble human neighbours (Flemmer and Flemmer, 2023), the impact of long-term noise from operating offshore wind farms on marine life has been studied less. According to Tougard et al. (Tougaard et al., 2020), the noise of an individual turbine is below ambient levels unless it is closer than a few kilometers. The underwater sound scape depends on the type of wind turbine; it is different in level and character coming from floating wind turbines for which it can exceed ambient levels at distances as far as 4 km (Harris et al., 2025). However, these studies are based on acoustic measurements at small test sites and do not cover infrasound. The frequency of infrasound is lower than 20 Hz and well below the human hearing but people living near an onshore wind farm can become sensitive to infrasound and suffer from chronic noise stress (Flemmer and Flemmer, 2023). Infrasound behaves very differently from audible sound, for example, the very long wavelengths of infrasound do not interact with small objects and fades very little with distance (Flemmer and Flemmer, 2023). Infrasound produced by offshore wind turbines can travel underwater as far as 100 km (Duarte et al., 2021). Natural sources of infrasound in the sea include ocean waves, thunder and sound produced by large animals such as baleen whales who can communicate across ocean basins to make reproductive and social calls (Flemmer and Flemmer, 2023; Duarte et al., 2021). Less well studied marine animals that can perceive infrasound of operating offshore wind turbines are invertebrates such as jellyfish, fishes, reptiles, and cetaceans, which they use for navigating, foraging, socializing, attracting mates, courting, and defending territory (Duarte et al., 2021).

7.2. Light pollution

As part of the planning application of an offshore wind farm, impacts on seascape are envisioned for the human observer (Scottish Government, 2019). The consequences of introduction of light and shading for marine species and communities should also be assessed (NatureScot, 2025). After dark, offshore wind turbines and related vessels and infrastructure are lit up during the construction as well as operation of the offshore wind farm. Marine light pollution at night illuminates marine ecosystems up to 100 times brighter than the light of the full moon at night which has various environmental impacts because marine organisms, from the smallest plankton to great whales, are very light sensitive during every stage of their lives (GOALANN, 2025). Light flicker from offshore wind turbines is not routinely assessed in offshore planning applications and neither are visual impacts on marine life (Scottish Government, 2019; NatureScot, 2025). For many aquatic species vision is important for detecting prey, predators and each other, but the potential impacts of visual cues from offshore wind turbines have not been investigated and are unknown at present (Williamson et al., 2024). Visual cues such as moving wind turbine blades as seen from below the water surface and moving underwater shadows of the wind turbine blades may be perceived as overhead predators and act as a barrier (Williamson et al., 2024). This could interfere with the return migration of wild Atlantic salmon in the northern coastal waters of Scotland (Williamson et al., 2024; Malcolm et al., 2010). This iconic species is already suffering as it is estimated that the total number of salmon returning to Scottish rivers has declined from around 1 million to 400,000 since the 1970s (Middlemas and Hanson, 2024). The planning application for the Tormsdale onshore wind farm near Thurso River and its tributary, where Atlantic Salmon reside, includes an evaluation of shadow cast by the turbines over the water (ERM, 2025). It is acknowledged that salmon parr younger than one year favouring the water of shallow riffles could be exposed to 'shadow flicker'. However, they state that this has no impact as "natural 'flicker light' produced by the lens effect of water surface ripple/wave (Fig. 4a) will obscure the penetration and definition of shadow cast underwater". This statement is not correct. As seen from beneath the surface, the refracted glitter is confined to a smaller angle and is of the order of 1000 times more intense than the reflected glitter (Cox and Munk, 1956). Due to the lens action of the individual waves, the flashes can attain extremely high levels for the upwardly directed eye (Cox and Munk, 1956). Lens action of the water waves makes the contrast with shadows on the water surface (where sun glitter does not occur) more effectual instead of less (Fig. 4b). The potential impact can therefore not be considered low and insignificant and should be included in future environmental impact assessments.

8. Changes to the surf

There are many studies on the impact of ocean currents and waves on offshore wind farms to improve their design and layouts, but not the other way around. Gautier et al. (2025) have assessed the effect of large offshore wind farms on North Sea waves, currents and tides. They use hydrodynamic models in which offshore wind turbines are represented by fixed monopiles of a diameter of up to 12 m. The impact on passing swells is expected to be negligible because 12 m is small compared to the swells' wavelengths (distance between two following wave peaks). They find that the most significant influence of an offshore wind farm is by changing the wind speed at the sea surface leading to changes in wave growth, and this is the only influence modelled in their wave computations. Although they confirm small changes inside and in the vicinity of the offshore wind farms in general, they advise linking their study with shipping safety because the effects can be significantly larger for individual instances. A marine physical and coastal processes assessment evaluation as part of the application for the West of Orkney Wind Farm, consisting of 125 wind turbines fixed to the seabed, predicts no change in the wave climate near the coast and it is concluded that the West of Orkney Wind Farm poses no risk to the Pentland Offshore Wind Farm and nearby surfing beaches (West of Orkney Windfarm, 2023a). They use a wave model to predict the blockage effect of the monopile foundations on passing waves and do not mention the influence of changing wind speed at the sea which may help explain the low impact (West of Orkney Windfarm, 2023b).

Unlike for a fixed monopile, for a floating offshore wind turbine, the diameter of the cylinder cannot be neglected compared to the wavelength as the wave forces become more complex and inertial forces (forces due to the movement of the floating structure in the water) need to be accounted for (Deng et al., 2024). A semisubmersible wind turbine uses a floating platform, usually three connected columns, that is partly submerged and anchored to the seabed. Deng et al. (2024) calculate that under certain conditions, the side columns of semisubmersible floating turbines can reduce the significant wave height by more than half, with a 1 km long wave wake occurring. The wavelength and direction are also changed. This means that the consented Pentland Offshore Wind Farm, consisting of six massive floating wind turbines (reaching up to almost 300 m above the sea with blades 250 m across; for reference, a football pitch is 105 m long) located only 7.5 km off the coast of Dounreay in Caithness (Fig. 1) may have serious consequences for a popular surf spot in Sandside Bay (Surfline, 2025). It is likely that incoming swells will be attenuated and disrupted by the floating wind turbines as the floating turbines in the Pentland Offshore Wind Farm are semisubmersible (Pentland floating offshore wind farm, 2022). This is ignored in its Environmental Impact Assessment Report which simply states "… floating offshore wind farm structure would be expected to have a much

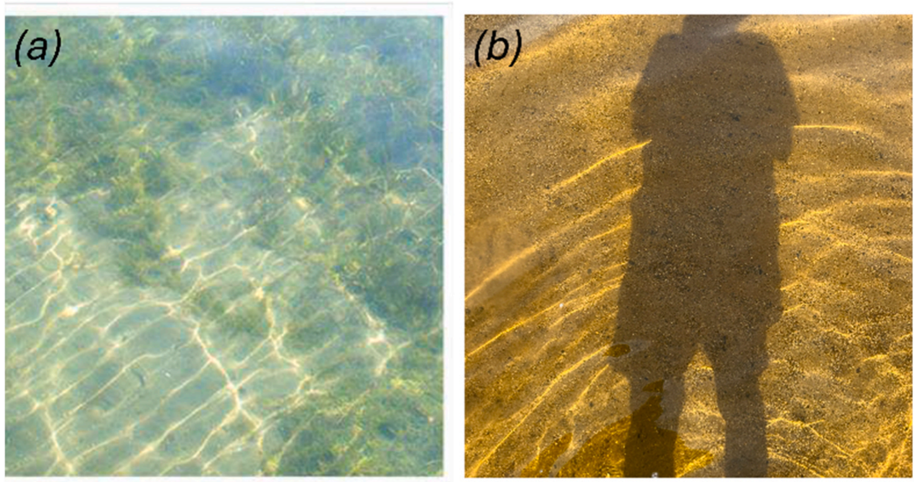


Fig. 4. (a) from Tormsdale wind farm application, Image 4.1 Natural 'flicker light' produced by the lens effect of a moving water (image caption in application) (ERM, 2025), and (b) photo showing how refracted glitter in fact enhances the contrast of the underwater shadow.

lesser blockage effect on tidal flows and waves than a fixed foundation structure …" (Pentland floating offshore wind farm, 2022), contradicting the latest research (Deng et al., 2024).

Water sport activities improve connectedness to the natural environment as well as physical and mental wellbeing. Surfing ocean waves is particularly effective as it is both immersive in terms of contact with the natural environment and physically demanding, as demonstrated by a surfing programme for vulnerable young people (Hignett et al., 2018). Surfing is also a growing industry in Scotland. Surfing is therefore recognized as something that could be affected by marine plans and policies (Scottish Government, 2019). Sandside Bay has been used as a back-up location for national surfing championships when strong westerly winds made Thurso East unsurfable. Sandside Bay needs a big swell to wrap in, so the interruption to incoming waves puts this surfing location at risk. Other nearby surf locations popular with locals and visitors that could be affected are Strathy, Melvich, and Brims Ness (Surfline, 2025).

In FeAST, local wave exposure changes are listed as one of the marine pressures on habitats in (NatureScot, 2025) as communities of animals and plants on rocky shores also depend on waves arriving at the coast (Scottish Government, 2020). The shores that are most exposed are the Atlantic swells receiving west coast on the outer coasts of the Hebrides, the North Coast, and Orkney (Scottish Government, 2020); their ecosystems are threatened by the planned large floating offshore wind farms blocking the waves they need to thrive (Fig. 1). More on floating wind farms in the next section 9.

9. Rapid expansion of floating offshore wind farms

Offshore floating wind turbines are a novel wind power technology that was thought to be unachievable only 10 years ago. Floating offshore wind farms make it possible to move from nearshore to deeper waters of water depths greater than 50 m, and many are in development (Fig. 1). However, floating wind turbines are expensive and there are no floating offshore wind farms operating at a commercial scale yet anywhere in the world. The Pentland Offshore Wind Farm is a trial site near the Caithness coast. The site is near a location where a commercial scale (50 MW) wave energy farm was planned due to high wave power in the area (since stopped due to liquidation of the developer) (Goddijn-Murphy et al., 2015). In addition to big waves, strong tidal currents (peak flows of over 1 m/s) run back and forth along the coast (ABPmer, 2025), which will put the floating turbine designs to the test of extreme dynamic loads.

Like fixed wind turbines, floating offshore wind turbines have potential negative as well as positive effects on their marine environment, but they are mostly presumed given the newness of the technology (Harris et al., 2025; Farr et al., 2021). As explained in section 8, the assumption of reduced impact on waves contradicts the results of a new wave model specifically designed for a floating wind farm (Deng et al., 2024). So far, artificial reef effects have been observed such as colonisation of the underwater structures, but the expected consistent increase of fish biomass across to the sites has not been proven (Harris et al., 2025). There is a risk of non-indigenous species spreading through turbine transport between ports and wind farms (ICES, 2025). Enhanced mixing by floating offshore turbines in deeper waters may have consequences for the distribution of nutrients, and hence phytoplankton growth (section 5). Floating platforms may also lead to much higher inputs of trace metals as the subsurface structures are generally larger requiring more galvanic anode cathodic protection (Watson et al., 2025) (section 6.2). Many knowledge gaps remain regarding potential environmental impacts such as, entanglement of marine mammals, perception of dynamic mooring noises, obstruction of migration routes, changes to atmospheric and oceanic dynamics, and changes to water quality (Harris et al., 2025; Farr et al., 2021).

Currently only two small floating offshore wind farms are in operation in operation in Scotland off the Aberdeen coast, Hywind and Kincardine (Fig. 1). Given the novelty there are very few observations of the impacts of offshore floating wind (and certainly not multiple large floating wind farms) (Fig. 1). According to Farr et al. (2021), developers adopting appropriate mitigation strategies and best-practice protocols could lower the risks of a lot of potential effects of floating offshore wind farm. They emphasise that future empirical studies and monitoring of the environmental impacts of deepwater, floating offshore wind farms are essential.

10. Cumulative impacts of many large offshore wind farms

10.1. Supersizing of wind turbines and offshore wind farms

Wind turbines are getting bigger all the time. Bigger wind turbines deliver financial economies of scale, but they don't greatly increase the total power per unit area because they must be spaced further apart (MacKay, 2008). Most environmental impacts described above increase with turbine size. The number of wind turbines in offshore wind farms are increasing as well while there are still many unanswered questions around their cumulative environmental impact (Harris et al., 2025; BBC, 2021). The size of a wind farm in Fig. 1 is expressed in peak capacity; the actual average power is about 30 % of the peak power as the turbines don't run at peak output all the time (MacKay, 2008). In more representative turbine numbers, the planned West of Orkney Wind Farm comprises of 125 wind turbines, the operating Moray West 60, Moray East 100, Beatrice 84 plus many more are in development (Fig. 1). North Sea countries have pledged to build 8000 offshore wind turbines by 2030 (more than three times currently installed) and at least a staggering 20,000 by 2050 (North Sea Energy, 2025; Reuters, 2024b). Other future offshore infrastructures are offshore energy islands, solar farms, and carbon capture installations. This comes on top of extensive existing economic activities at sea, such as fisheries, shipping, and oil and gas (North Sea Energy, 2025; Paolo et al., 2024). It is difficult to keep up to date with the offshore wind developments. The map of major energy related planning applications made available by the Highland Council (The Highland Council, 2025) does not show the area covered by the wind farms nor offshore substation platforms, inter-array cables, export cables and associated infrastructure; applications at consultation stages are absent. The Highland Renewables Database gives a more complete picture (Haltiner, 2025). Fig. 2 shows offshore wind farms at different stages including those in the pipeline including subsea power cables; if all these opportunities are realised their cumulative impact will be unprecedented.

10.2. Collision risk with marine traffic

Not only are offshore wind turbines and wind farms getting bigger, shipping with ever-larger vessels is on the increase as well (Dutch Safety Board, 2024). The North Sea is a particular busy place but the risk for shipping is not properly understood (Dutch Safety Board, 2024). Ultra large container ships can get in trouble in no more than a strong breeze (6 Beaufort), and if they want to move away from danger there may not be enough room to make a complete turn if wind turbines are nearby. A 3.5 km distance between a 400-m-long ship and a wind farm, currently considered safe, may not always be enough (Dutch Safety Board, 2024). Also, the existing emergency response towing vessels cannot always assist in hazardous conditions (Dutch Safety Board, 2024). In early 2022, the Maltese bulk carrier Julietta D drifted towards the Dutch coast in a winter storm. It collided with a tanker and then with two structures of a wind farm under construction (Dutch Safety Board, 2024; Captain's Mode, 2025). The incident triggered an investigation by the Dutch Safety Board resulting in a report 'Compromise on room to Manoeuvre' (Dutch Safety Board, 2024). According to this report, "It is highly likely that – with an improved understanding of the risks – the installation of fixed objects in the North Sea will in some cases prove incompatible with the goal of shipping safety. In such cases, the zoning plans will need to be revised, …". The findings and recommendations in the report should apply to the risks of industrious shipping traffic around offshore wind farms in Scotland, in the North Sea as well as through the Pentland Firth and the Minches where many transatlantic ships pass without stopping at a Scottish port (Scottish Government, 2011).

10.3. Wind theft

As offshore wind farms and turbines are getting bigger and more numerous, wind wakes from offshore wind farms can reduce the power generated by neighbouring farms (Platis et al., 2018). The wind wake describes how a wind turbine extracting energy from the incoming wind, leaves lower energy behind in its 'wake'. The wake can be 50 km long and reduce the yield of turbines in the wake by tens of percents (BBC, 2025e). We can identify several clusters of offshore wind projects crammed together in Scotland and Highland, where wind theft by neighbouring developments could result in disputes (Fig. 1). Iberdrola, Ørsted and RWE are among the developers already involved in wake effect disputes at 20 GW of UK offshore wind projects (Tamarindo, 2025). The UK Government is now backing research to find out how to solve wake disputes between different offshore wind developers in the planning system (Tamarindo, 2025). This needs to be resolved as profit loss and financial uncertainty could result in higher costs for the energy consumers. However, the Strategic Investment Model (SIM) Milestone Map made available by Offshore Wind Scotland and showing the sites of the ScotWind and INTOG leasing rounds (Offshore Wind Scotland, 2025b) does not show the large offshore wind farms already in operation (Beatrice 84 turbines, and Moray East 100 turbines), and under construction (Moray West 60 turbines). Hence, this map tool does not account for potential wake disputes between the different developers, for example between those of Beatrice, Morray East and Caledonia (Fig. 1).

10.4. Limits of the transmission grid

When there is too much wind for the transmission system to cope with the flow of electricity, the energy producer receives constraints payments for reducing output (paid for by the consumer). Concerns have been raised over Moray East offshore windfarm, situated off the north-east coast of Scotland between the Beatrice and Moray West wind farms (Fig. 1), about over-charging millions of pounds for switching off wind turbines. Reportedly, the owners of Moray East were paid £100m from September 2021 to September 2023 (Telegraph, 2025). Ofgem, the energy regulator for Great Britain who works to protect energy consumers, especially vulnerable people, has launched an inquiry into the owner of Moray East to investigate these concerns (Ofgem, 2025). The West of Orkney Wind Farm and Pentland Offshore Wind Farm will rely on new massive cable trenches across Caithness, new massive substations near Spittal, plus a new subsea cable south with more cable trenches across Caithness and the hugely controversial proposed 400 kV Spittal - Beauly super pylon line (Haltiner, 2025), which has upset many affected locals (The Inverness Courrier, 2023, 2025).

10.5. Habitats

Old research may suggest that habitat loss from offshore wind farms is not harmful because species that avoid the site, seabirds for example, can relocate (Factor This, 2013; The Guardian, 2011). However, if all the planned Offshore Wind Scotland projects are successful, seabirds for example will be squeezed out with nowhere to go (Fig. 1). It has also been suggested that offshore wind turbine foundations provide new habitats for seabed organisms like seaweed, mussels, crabs, oysters, and reef fish, while certain species can also find shelter inside wind farms [e.g., (Harris et al., 2025), (Farr et al., 2021), (Russell et al., 2021)]. Fish that reside in offshore wind farms can attract seals and other predators, the ecological consequences of which depend on whether such reefs produce prey or just concentrate prey (Russell et al., 2021). Counting selected species, such as mussels, seabirds, sea mammals, or fish, is not sufficient in an ecological survey of offshore wind farms. We need to evaluate the whole ecosystem, from the smallest plankton to the largest top predators, not only at the level of a single offshore wind turbine or wind farm, but also the cumulative impact of very large and multiple offshore wind farms [e.g., (ICES, 2025), (Isaksson et al., 2025)], and even of other marine industrial activities (Fig. 2).

11. Mental health

The residents and visitors of the Highland area have seen an unprecedented increase in wind farms and related structures in recent years and many more are planned (The Highland Council, 2025; Haltiner, 2025). It is hard to find a location where a wind turbine cannot be seen, and one of the last unspoiled views are those of the open ocean. The horizon of the east coast is already heavily impacted by large offshore wind farms in the North Sea, and the north coast is under threat (Fig. 1). Big vistas, wide open spaces, long views, horizon lines, and a star-stuffed night sky matter to the health of the human soul (Psychology Today, 2023). Connecting with nature has emotional, psychological and physical benefits and the more unspoilt and serene the better (Mental Health Foundation, 2025). According to the Mental Health Foundation (2025), people noticing nature is a key factor in supporting their wellbeing. Exposure to 'blue space' (aquatic environment) has its own unique health and well-being benefits (Mental Health Foundation, 2025; White et al., 2020). Higher levels of perceived biodiversity in the blue space result in reduction of perceived stress (White et al., 2020). This echoes research by Methorst (2024) that proofs that the presence of many different bird species in a person's area of residence benefits mental health, especially of those with lower socioeconomic status. Hence, if seabirds unable to make their home around the Scottish coast and stay away, not only biodiversity conservation suffers but precious public mental health as well.

12. Conclusion

The 10 things described in this paper can inform the different parties that are involved in the planning system for offshore wind farms about commonly overlooked issues. It uses Highland County in Scotland to illustrate these things, but they are relevant anywhere. The public can use this information in writing representations. Councillors need to understand the wide range of questions about large offshore wind farms when they vote on the council's response to the Scottish Government. The Scottish Government, who has the final say in planning applications for large offshore wind farms, also has the power to address concerns about large offshore wind farms in strategic research programmes and policies. The Scottish Government currently looks to a more flexible and pragmatic approach to environmental compensation (Scottish Government, 2025b), which may lead to unforeseeable consequences. More time is needed for monitoring programmes that measure the consequences of large offshore wind farms as to date studies of their impacts are mostly theoretical due to their novelty. The complexity of the impacts of large offshore wind farms has necessitated most scientific studies to single out the influence of a single specific factor. In the future, we need to look at the cumulative impact of large offshore wind farms on all combined atmospheric, hydrodynamic, biogeochemical and ecosystem processes. Ensuring that research outputs, including advanced modelling approaches and empirical datasets, are systematically integrated into environmental impact assessments of offshore wind farms is of critical importance.

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