Routes Journal Special Issue: Young People & Rewilding

Blue rewilding and nature-inclusive design: Offshore wind farms as anchors for marine biodiversity recovery in the UK

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Abstract

Offshore Wind Farms (OWFs) have become a critical component of the UK's transition into decarbonising the energy industry yet there are underexplored opportunities for concurrent ecological restoration. Additionally, they can cause unintended anthropogenic impacts meaning sustainable innovation is needed beyond impact mitigation. Marine Rewilding Initiatives (MRIs) and Nature-inclusive Design (NID) can offset these environmental disturbances through self-sustaining strategies such as artificial reef structures and bivalve reef restoration, with the 'stepping stone' effect of hard substrate species combining both to broaden marine connectivity. Northwestern Europe are trailblazers in integrating these approaches with OWF developers and mandating net gain policies through schemes such as the Rich North Sea programme. Case studies further underscore replenishing threatened species through integrating MRIs with OWFs. This study aims to evaluate the role of MRIs as mitigators of OWFs as part of Offshore Renewable Energy Development (ORED) policy and emphasises the need for long-term research to ensure ecological and socio-economic viability.

1. Introduction

The UK is expanding into decarbonising the energy industry with Labour (2024) proposing to quadruple offshore wind by the end of this decade. In addition to meeting national Net Zero standards, the 30by30 initiative endeavours to protect 30% of land and sea (Department for Environment, Food & Rural Affairs, 2024). This focus on marine biodiversity has also contributed to the more climate-focused 2015 UN Sustainable Development Goals (SDGs) which may factor into contextualising international governance of energy systems (Velenturf et al., 2021). When considering SDG 14.2: Sustainably Managing and Protecting Marine Ecosystems (Moretti et al., 2024), there is a globally understudied potential for a net biodiversity gain within the physical offshore structures and conserving these unique marine habitats.

To limit these direct anthropogenic drivers of ecological change, marine rewilding initiatives (MRIs) seek to establish marine protected areas (MPAs) and facilitate the abundance of threatened habitats and species (Rees et al., 2020). Carver et al. (2021) proposed that the process of rewilding involves restoring natural processes and degrees of the food web at all trophic levels to be self-sufficient with biota that would have existed prior to anthropogenic interference.

This study reviews how marine rewilding and nature-inclusive designs can offset the adverse ecological impacts of offshore wind farms (OWFs) based on published literature spanning the UK and Europe. This can offer a critical starting point for marine biodiversity recovery (Sheehan et al., 2021) against the increasing human reliance on ocean resources, notably within benthic regions to match the growing development of offshore energy structures. Nonetheless, the effectiveness of MRIs may be restrained by governance and policy frameworks in the UK, which lack mandatory biodiversity offsetting requirements for developers and prominent regulatory incentives.

2. The unintended ecological impacts of offshore wind energy

Whilst OWFs pioneer the transition to renewable energy, the stages to their life cycle introduce substantial ecological challenges, and if not effectively counterbalanced, may undermine the lasting viability of marine ecosystems.

2.1. Acoustic and hydrodynamic disturbances

The installation and operation of OWFs significantly alter marine habitats through seabed degradation and acoustic pollution. According to Madsen et al. (2006), pile-driving generates the highest sound pressure levels during the OWF construction phase, disrupting long-range marine mammals and having implications on hearing impairment with harbour porpoises (Brandt et al., 2011). Acoustic trauma has also been theorised to acutely impact cephalopod populations and their offspring (Solé et al., 2022) and this has commercial implications for species such as the common cuttlefish which are vital to both marine ecosystems and fisheries.
Furthermore, the presence of OWFs can cause alterations in hydrodynamic conditions which can further disrupt larval survival and recruitment. Due to the inevitable overlap between OWFs and spawning grounds, such as of flatfish species as depicted by Figure 1, the differences between settlement rates of distinct species can have long-term implications on population dynamics and Barbut et al. (2019) further proposes that these impacts should be studied in situ.

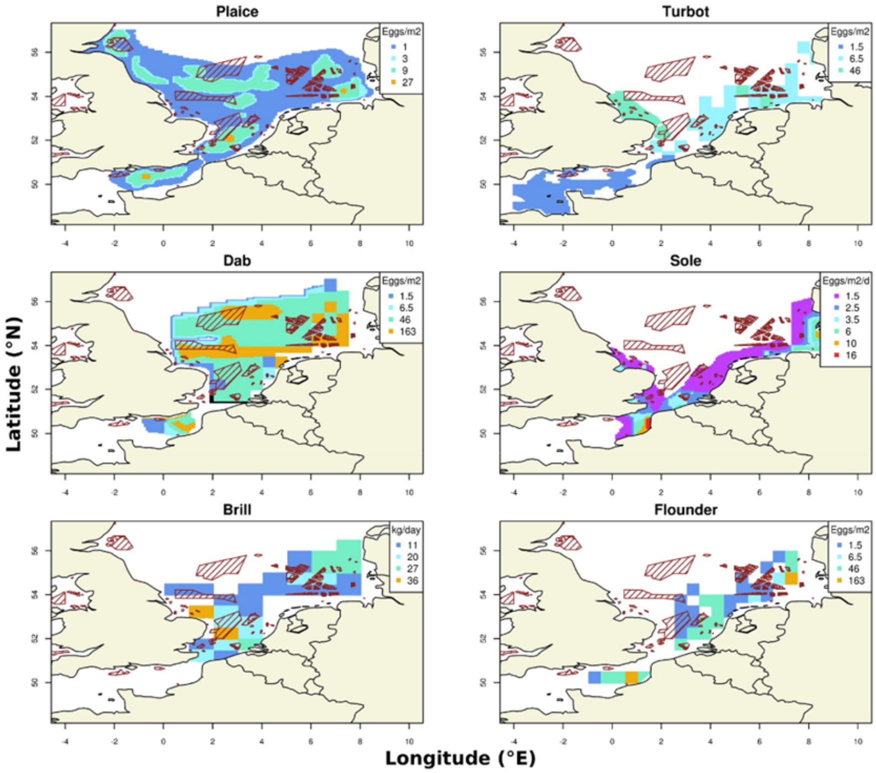

Figure 1. The overlap of six flatfish spawning grounds (plaice, turbot, dab, sole, brill and flounder) with offshore wind farms (depicted by hatched areas) shown in biomass or egg density (Barbut et al., 2019).

2.2. Seabed disruptions

OWFs further impact hydrodynamics by increasing current speeds around monopile foundations (Rivier et al., 2015) which can cause sediment resuspension (Rivier et al., 2016). De Smit et al. (2021) further highlighted how disrupting macrobenthic species' habitats alters sediment stability as these organisms regulate sediment erodibility.

The oceanic water column and benthos are inherently linked (Gray and Elliott, 2009, p. 260) and as OWFs create artificial hard substrata, they can cause erosion of the natural seabed which changes its sediment composition (Mangi, 2013). This can result in habitat loss for some benthic species as the construction phase particularly reduces nutrient cycling (Burkhard et al., 2011) and natural bioturbation is disrupted. As the OWF industry expands, its unintended marine impacts underscore the necessity in safeguarding ecosystem stability to support its growing offshore resource demands, and these combined stressors illustrate the imminence to enhance ecosystem resilience as well as restore habitats.

3. Reefs and recovery for offshore wind futures

Nature-based solutions are now an emerging strategy as OWFs transition from sites of ecological disruption to facilitators of ecosystem regeneration. By creating self-sufficient refuges and restoring degraded habitats, marine rewilding strategies can help bypass the negative impacts of OWFs and this ensures ecological sustainability in the growing offshore renewable energy sector.

3.1 Artificial reefs and habitat restoration

In optimal conditions, offshore wind turbine foundations provide hard substrate for marine life. These structures can facilitate the settlement and dispersal of non-indigenous species such as Codium fragile ssp. tomentosoides (Bulleri and Airoldi, 2005) due to differing fluid dynamics providing new shelters and acting as marine corridors. Scour protection structures can also act as artificial reefs, increasing fish biomass around artificial reefs and the settlement of crustaceans and algae improves food availability.

As illustrated in Figure 2a, man-made polypropylene fronds used to resist erosion also resemble seagrass beds (Langhamer, 2012) and possess the ability to conceal diverse food webs enhancing marine biodiversity. This increased habitat complexity advances ecological functioning to diversify marine life and can act as ‘acoustic refuges’ to protect resident fish populations by buffering underwater noise (Wilson et al., 2013) such as pile-driving activity.

Figure 2b also shows hard substrates on the seabed that may be re-colonised by epibenthic communities such as crustaceans, molluscs, and other invertebrates (Kingma et al., 2024) notably as they are a suitable attachment point for shellfish. Scour protections made of excavated rock at Lillgrund OWF in Sweden for instance, were a nature-inclusive design to attract biodiversity around the site (Langhamer, Dahlgren and Rosenqvist, 2018). Though scour protections potentially could induce the artificial reef effect (Langhamer, 2012), naturally occurring shellfish aggregations are particularly advantageous in contributing to ecosystem recovery, with as their role in offsetting sediment disturbance on the seafloor caused by OWFs.

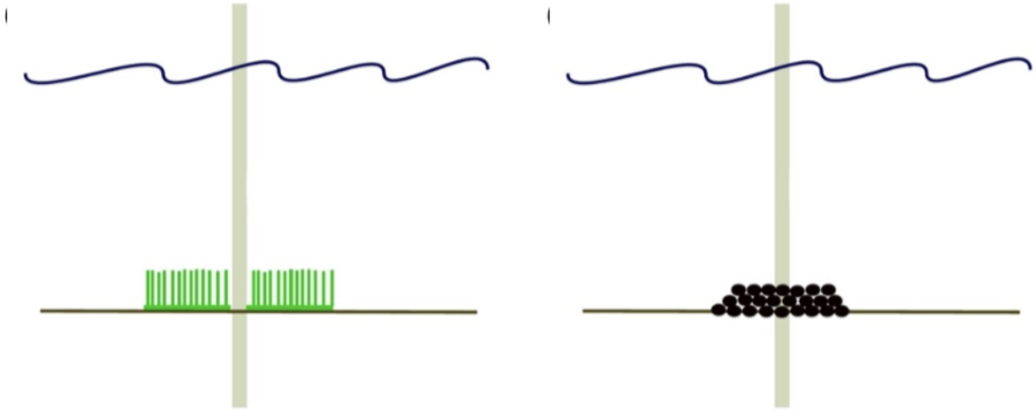

Figure 2. *Illustrations of common scour protection procedures around monopile OWF foundations such as (a) Polypropylene fronds (b) Hard substrate (e.g. boulders or gravel). Adapted from Langhamer (2012).*

3.2. Bivalve marine rewilding initiatives

Oyster reefs have roles in engineering productive habitats to support complex marine food webs (Vaughn and Hoellein, 2018) and Crain and Bertness (2006) further explored that in the changing offshore environment, oyster reefs can even mitigate against physical stresses providing a natural, self-sustaining habitat for more fragile species.

Bivalve molluscs, such as oysters, also filter pollutants and impact nutrient cycling (Ferreira et al., 2018) and therefore bivalve marine rewilding initiatives can improve seabed integrity by stabilising sediments. Coco et al. (2006) theorised that increased bivalve density reduces sediment resuspension which can counteract hydrodynamic fluctuations generated by OWFs.

Historically, much of the southern North Sea seabed was covered by broad stretches of hard substrates such as gravel beds and until the late 19 th century, the European flat oyster (*Ostrea edulis*) occupied the Central North Sea (Bennema, Engelhard and Lindeboom, 2020). Nonetheless, populations deteriorated due to overfishing and subsequently lower chances of inter-colony fertilisation (Gross and Smyth, 1946).

According to ter Hofstede, Williams, and M. van Koningsveld (2023), there is a potential in using the hard substrate rock installations in southern North Sea OWFs to connect new or prevalent oyster reefs to restore the abundance of these protected species. The integration of using artificial reefs with hard substrates to create small habitat patches in OWFs (Henry et al., 2018) can develop into secondary biogenic reefs (Fowler et al., 2019), providing homes for rarer species and enhancing overall ecosystem functionality. Adams et al. (2014) coined the ‘stepping stone’ effect as a population structure model referring to how new habitats can serve as intermediate sites to promote connectivity between previously isolated areas and result in species dispersal for both native and invasive species. Figure 3 illustrates how artificial reefs at OWFs create both small-scale effects around individual turbines and a larger-scale impact that extends beyond the farm, through the connectivity of hard substrate species (Degraer et al., 2020).

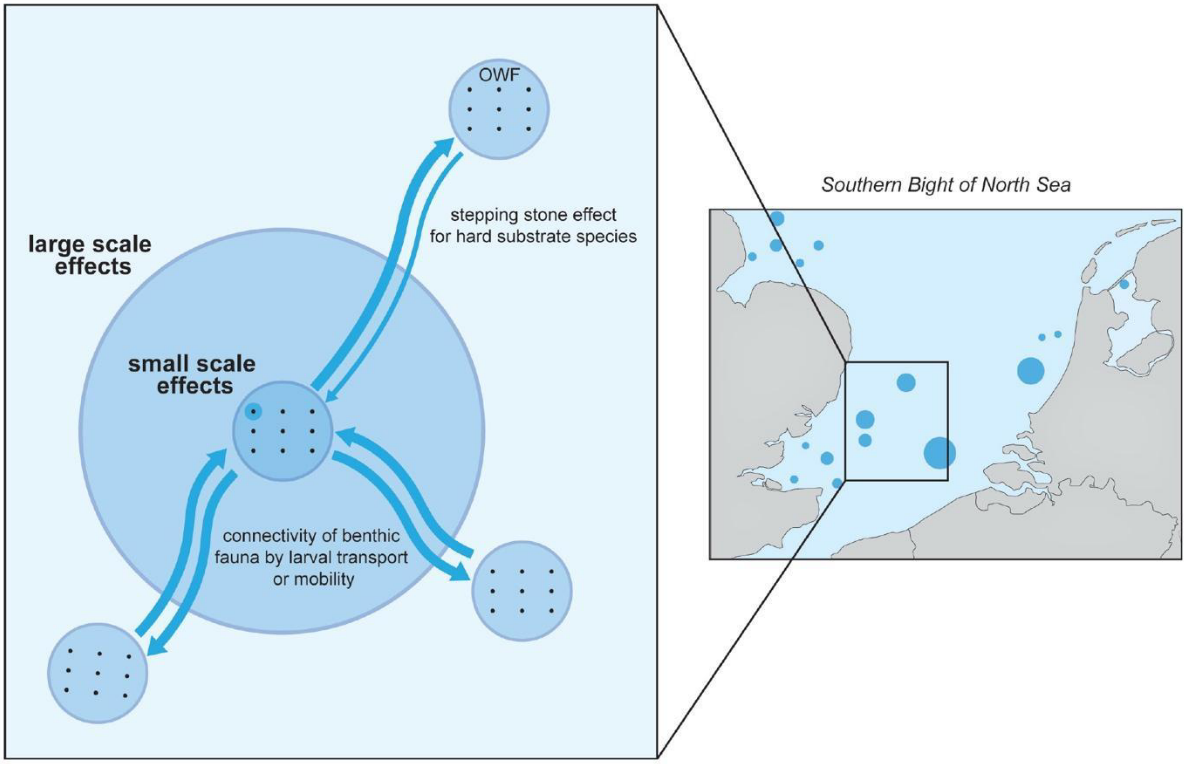

Figure 3. Illustration of how OWF artificial reefs create small- and large-scale effects by the connectivity of hard substrate species via the ‘stepping stone’ effect (Degraer et al., 2020).

3.3. A Dutch case study

Building on the theory of the ‘stepping stone’ effect, applied marine rewilding initiatives have occurred in Northwest Europe such as part of the Rich North Sea programme which prioritises restoring biogenic reefs within existing OWFs for biodiversity enhancement (Hermans, Bos and Prusina, 2020).

For instance, the Blauwwind consortium of OWF developers, constructors and operators are conducting field experiments within the Borssele III and IV OWFs in the Dutch North Sea to establish native oyster reefs and promote ecological development, with 2400 adult flat oysters deployed in 2020 (Reuchlin et al., 2021). Pilot restoration projects of the European flat oyster conducted by Bos et al. (2023) found successful growth and reproduction of translocated oysters from Ireland, Norway and other regions of the Netherlands in OWFs. Blauwwind (2023) provided updates on this project in that 88% of the oysters were ready to reproduce and there were 128 species in total identified at the wind farm encompassing the increase in species richness. Figure 4 summarises the general timeline of this restoration project.

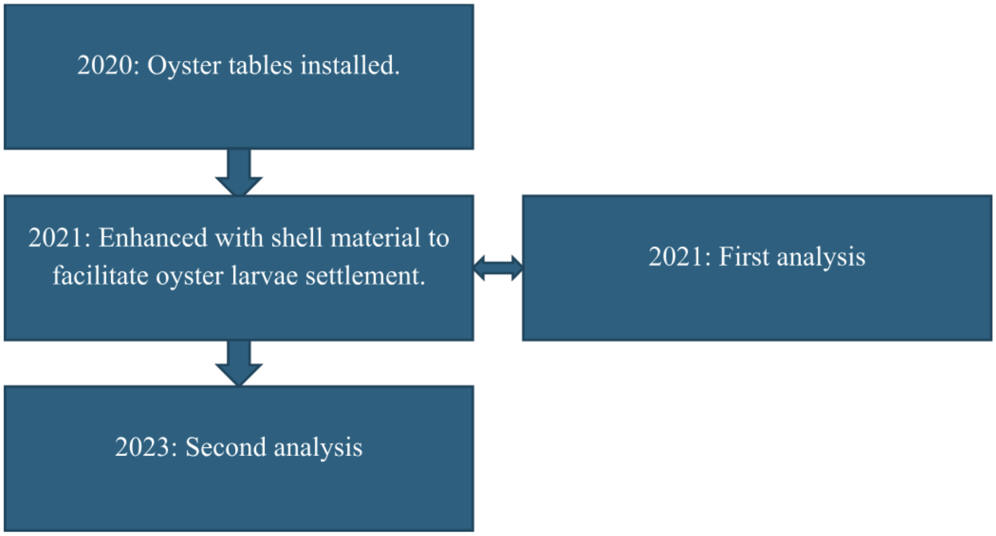

Figure 4. Research overview for the 2020 pilot restoration project at Borssele III and IV OWFs, conducted by Blauwwind and Eurofins Aquasense. Data used from (Blauwwind, 2023).

4. Policy integration and future directions

The success of this rewilding initiative can be attributed to the Dutch government's policy mandating OWF developers to incorporate ecological benefits into its tenders (Panny et al., 2023) and prove a net biodiversity gain. This led to developers such as Vattenfall (2022) aiming to make a net positive contribution to biodiversity by 2030. The Netherlands are pioneering efforts to incorporate ecological benefits such as through the North Sea Net Gain study in partnership with the Dutch-led Rich North Sea programme (Memija, 2022).

Conversely, the UK has no mandatory biodiversity offsetting for OWFs and although The Crown Estate (2024) Leasing Round 5 (Celtic Sea) introduces marine net gain principles, it lacks enforcement. Marine net gain (MNG) is voluntary as opposed to a legal requirement with biodiversity-positive criteria not integrated into OWF permitting. Therefore, policy recommendations could include evidence-backed initiatives such as requiring habitat restoration offsets in planning approval and incentivising these through tender scoring and government subsidies (Burney, 2023). Cross-border collaboration can further standardise these practices.

Further research should involve long-term monitoring of artificial reef developments (Ramm et al., 2021) alongside other less studied nature-inclusive design strategies or types of OREDs such as exploring the ecological opportunities of floating wind farms (Danovaro et al., 2024). Remote sensing and AI (Tang et al., 2024) alongside large-scale experimental trials can fill data gaps about the true effectiveness of MRIs to detect unforeseen ecological changes. Understanding species connectivity and population resilience will determine whether MRIs contribute to long-term population viability (Cowen and Sponaugle, 2009) or are short-term biodiversity hotspots.

While the potential ecosystem services that OWFs could provide are underexplored from a social science perspective (Haraldsson et al., 2020), there is a need for equitable interdisciplinary perspectives with how resource use and public engagement trade-offs influence governance (Jouffray et al., 2020). Evaluating these socio-economic dynamics can justify policy support and funding to align conservation goals like the SDGs and 30by30 with economic incentives.

5. Conclusion

Although OREDs align with the UK's Net Zero and sustainability goals, there is a lack of enforcement for biodiversity net gain with the decarbonisation of the energy sector. Marine rewilding is an under-researched field that can offset some of the ecological disruptions of OWFs through their life cycle, and nature-inclusive design is an emerging field with Northeastern European countries pioneering pilot projects.

OWFs contribute to anthropogenic noise pollution, alter hydrodynamics and cause seafloor and sediment disruptions yet targeted, large-scale efforts can recover positive conservation outputs. For instance, hard substrate species can benefit from scour protections in OREDs aiding connectivity and can replenish declining species populations such as at the Borssele III and IV OWFs. This aligns to the Rich North Sea programme being a trailblazer in the integration of MRIs with ORED development and the UK lacks this enforcement despite increasing demand for the OWF industry, risking missed opportunities for marine restoration. In conclusion, the UK government should consider a shift from ecological mitigation to adaptively managing proactive restoration and mandate nature-inclusive offshore development.

Acknowledgments

I would like to thank first and foremost all my family and loved ones for supporting me as this milestone could not have been possible without your individual inputs, especially my sister, Akash, Ayesha and Leo. My gratitude extends to the

Youngwilders team who have opened the door to many incredible opportunities for me and the Natural History Society of Northumbria who continue to inspire me and my closest peers and colleagues who fuel all my enthusiasm for the natural world and encourage me to stay optimistic and ambitious.

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Cite as: Balu, P. 2026. Blue rewilding and nature-inclusive design: Offshore wind farms as anchors for marine biodiversity recovery in the UK. *Routes*, 5(2): 87-100.