Renewable and Sustainable Energy Reviews 210 (2025) 115266

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Strategic seaweed farming to support protected seabirds impacted by offshore windfarms

Robert W. Furness [a,b,*], Euan N. Furness [c,d]

[a] MacArthur Green, Glasgow, UK
[b] School of Biodiversity, One Health and Veterinary Medicine, University of Glasgow, Glasgow, UK
[c] Department of Zoology, University of Cambridge, Cambridge, UK
[d] Sidney Sussex College, Cambridge, UK

ARTICLE INFO

Keywords:
Compensation
Northern gannet
Plastic pollution
Nest construction
Black-legged kittiwake
Larus gulls
Carbon sequestration
Renewable energy

ABSTRACT

Offshore wind farms generate electricity at relatively low cost and are regarded as a major contributor to net zero targets, supporting United Nations Sustainable Development Goals 7 and 13. However, some seabird species are at risk of colliding with turbine blades or being displaced by offshore wind farms. The European Union and the UK have legal requirements for wind farm developers to implement compensation measures if their developments are likely to have an adverse impact on the integrity of seabird populations in Special Protection Areas. Compensation measures that have been established have carbon costs and are applicable only to a restricted group of species, reducing the overall benefits. Here we make a novel suggestion that placement of seaweed farms close to selected seabird colonies could act as compensation for mortality associated with offshore wind farms. Many seabirds construct nests from seaweed that they collect at sea. These birds may also use plastic waste in nest construction. Plastic can kill seabirds by entanglement. Increasing availability of seaweed could reduce this mortality by reducing use of plastic in nest construction. This novel approach has multiple advantages over other forms of compensation. In particular it could benefit northern gannets *Morus bassanus*, a species considered especially at risk from impacts of offshore wind farms but not addressed by existing compensation measures. Seaweed farming as a compensation measure could also contribute to carbon sequestration and provide other environmental benefits as well as promoting the growth of an industry not yet well established in European seas.

1. Introduction

The planet is facing dual climate and biodiversity crises. The urgency of these twin crises requires “bold implementation of transformative policy interventions from local to global levels” [1]. Contributing to the United Nations Sustainable Development Goal (UNSDG) 13 (Climate Action), the United Kingdom (UK) is legally committed to reaching net zero emissions of greenhouse gasses by 2050 [2]. However, the UK’s independent Climate Change Committee has determined that meeting this target will require not just reducing emissions, but also the active removal of carbon dioxide from the atmosphere [3,4]. The rapid development of wind farms provides a means to reduce emissions and thus tackle the climate crisis. However, this may have adverse impacts on some aspects of biodiversity. There is an urgent need, therefore, to determine how best to prevent negative impacts of wind farms on biodiversity to allow for transition towards net zero targets. Developers of offshore wind farms are required to mitigate predicted impacts on seabirds by adjustments to the design, construction and operation of turbines that will be expected to reduce numbers of seabirds that are killed. Nevertheless, there will still be a residual impact after mitigation. That may produce a legal requirement for compensation (reductions of other existing pressures on seabirds) to offset the residual impact of offshore wind. Compensation addresses other threats to seabirds where actions could be taken to reduce the impacts of those threats, and therefore compensates for the residual and unavoidable impacts of offshore wind. Here, we draw together for the first time, evidence that commercial seaweed farming strategically located near selected seabird colonies could play a role in compensating for the impacts of offshore wind farms on some seabird species, while also contributing to carbon sequestration and providing a range of other environmental benefits. This could facilitate the expansion of offshore wind electricity

* Corresponding author. MacArthur Green, Glasgow, UK.
E-mail address: bob.furness@glasgow.ac.uk (R.W. Furness).

https://doi.org/10.1016/j.rser.2024.115266
Received 26 June 2024; Received in revised form 13 November 2024; Accepted 17 December 2024
Available online 20 December 2024
1364-0321/

List of abbreviations

BACI	Before-After-Control-Impact
EU	European Union
GW	Gigawatt
IPCC	International Panel on Climate Change
SAC	Special Area of Conservation (under the Habitats Directive)
SPA	Special Protection Area (under the Birds Directive)
SSE	Scottish and Southern Electricity
UK	United Kingdom
UNSDG	United Nations Sustainable Development Goals
US$	United States of America dollar

generation without adverse net impacts on protected seabird populations as well as providing wider benefits to the environment and marine economy.

The development of offshore wind farms represents a very effective approach to reducing the carbon dioxide emissions that are associated with electricity generation [5–7]. Wind farms provide electricity at relatively low cost and with a low carbon footprint [8,9] thus contributing to the UNSDG 7 (Affordable and Clean Energy). However, offshore wind turbines may harm some seabird species. Seabirds may be at risk of increased mortality caused by collision with rotating turbine blades [10, 11]. Some species may avoid offshore wind farms, thus increasing the time and effort that they need to spend foraging for food [12,13]. With the rapid development of this industry, UK waters now hold a particularly high concentration of offshore wind farms, especially off the east coast of England and Scotland, the cumulative effect of which, even after all feasible mitigation measures have been incorporated, may have significant impacts on the integrity of some seabird populations.

Many seabirds (such as auks) rarely fly at the height of the rotating turbine blades and are thus at low risk of collision [11]. In contrast, however, other species, such as black-legged kittiwakes *Rissa tridactyla*, northern gannets *Morus bassanus*, Sandwich terns *Thalasseus sandvicensis* and lesser black-backed gulls *Larus fuscus* often fly at heights that present a collision risk [11,14], and are thus considered to be key species at risk of collision mortality in European waters [10]. In addition, some seabirds, such as red-throated divers *Gavia stellata*, show strong avoidance of offshore wind farms [15–17]. Others, such as auks, show limited or inconsistent avoidance [12,18,19]. Avoidance of turbines and other structures may reduce the available feeding habitat and/or increase the energy expenditure for birds that choose to fly around, rather than through, offshore wind farms [20,21]. The resulting energy costs and loss of foraging habitat due to displacement and barrier effects might increase seabird mortality, although the extent to which that may happen is highly uncertain [20,22,23]. Because seabirds tend to be long-lived with deferred maturity and low reproductive rates (for example adult northern gannets have an annual survival rate of 92 %, but only start to breed when five years old and only lay one egg per year [24]), their populations are especially vulnerable to additional mortality [25]. Precautionary assessments of the possible impacts of offshore wind developments using simple population models have raised concerns about the sustainability of some seabird populations impacted by offshore wind farms [26].

The European Union (EU) and the UK have implemented the Birds and Habitats Directives in order to protect populations of birds and other wildlife, and their habitats. These directives require the long-term maintenance of the integrity of protected habitats and wildlife populations that are features of Special Protection Areas (SPAs) or Special Areas of Conservation (SACs). If, despite all feasible mitigation measures having been adopted, any development may threaten this integrity, there is a legally-binding requirement to compensate for the assessed impacts, with compensation measures expected to benefit populations by more than the assessed impact from a development. Britain and Ireland have internationally important breeding populations of many seabird species [27]. Accordingly, many seabird colonies have been designated as SPAs with breeding seabirds as their protected feature. For example, the 13 SPAs for breeding northern gannets in the UK and Republic of Ireland hold over 57 % of the entire world breeding population of that species [27]. There is therefore a tension between the rapid construction of offshore wind farms in order to achieve net zero and avoiding harm to seabird populations protected by the Birds and Habitats Directives. Potential impacts on protected seabirds pose the greatest risk to obtaining consent for construction of offshore wind farms in the UK [28]. This has led to substantial financial costs to developers with the surveys and data analysis required for planning applications costing around £12 million for a 1 GW offshore wind farm [28]. Docking Shoal failed to obtain planning consent due to perceived impacts on Sandwich terns [28] and a further planned development of offshore wind farms in the Outer Thames SPA was withdrawn because of perceived impacts on red-throated divers [28,29]. In German North Sea waters it has recently been concluded that offshore wind farms have displaced an important part of the red-throated diver population of the Eastern German Bight SPA [17].

Based on evidence presented by Natural England, the Secretary of State concluded that it was impossible to be certain that the predicted impacts of offshore wind farms could be held below levels that would risk damage to the integrity of some protected seabird populations in east England [26,30]. The same conclusion has been reached by NatureScot and by developers for several seabird populations in east Scotland [31,32]. There is therefore a legal requirement for further offshore wind farm developments in the UK and EU to compensate for the perceived negative effects on protected seabirds through targeted interventions that prevent any net reduction in the abundance of protected populations.

Compensation plans are generally targeted at individual protected species, and include measures such as the construction of bespoke nesting towers for black-legged kittiwakes [30,33], the eradication of invasive mammal predators such as rats from islands to enhance the breeding habitat for auks [30,31,33], the construction of protected nesting habitat for Sandwich terns [30], and reducing the fisheries by-catch of auks in set nets [30]. These compensation measures may cost millions of pounds per project [30–33], and the different ecologies of different protected seabird species mean that measures that provide appropriate compensation for one species are often inappropriate for others. For example, no obviously effective and practical compensation measures have yet been identified for northern gannets [34]. Following unprecedented mass mortality of breeding northern gannets and their chicks at many colonies around the North Atlantic in 2022 caused by High Pathogenicity Avian Influenza ("bird flu") [35], concern over the need to be able to compensate for the impacts of offshore wind farms on northern gannets has increased [32].

2. Seabirds, seaweed, and plastic pollution

Many seabirds, including northern gannets [36], actively build their nests using appropriately sized scraps of available material, traditionally seaweed (Table 1). Most seabirds are unable to dive to the seabed in search of seaweed and do not normally land in intertidal areas to pick up growing seaweed at low tide. Instead they collect scraps of detached floating seaweed from the sea surface. In addition, whereas some seabirds construct nests during a short period in spring, others continue to add nesting material to their structures throughout the breeding season (Table 1). The presence of floating plastic pollution around seabird colonies means that seabirds may also pick up plastic for use as nesting material (Table 1). O'Hanlon et al. [37] accordingly found anthropogenic debris (mostly plastic) incorporated into nests of 12 out of 16 examined species of seabirds across Europe, and Thompson et al. [38]

Table 1
Construction of nests including seaweed and plastic by European seabirds.

Species	Seaweed in nests	Plastic in nests	Period during which nest-building occurs
Northern gannet *Morus bassanus*	Principal nest material [51,52]	High prevalence [36,39]	April to August [51,52]
Great cormorant *Phalacrocorax carbo*	Principal nest material [51]	Moderate prevalence [38, 45]	March to August [51]
European shag *Phalacrocorax aristotelis*	Principal nest material [51]	High prevalence [38]	March to August [51]
Black-legged kittiwake *Rissa tridactyla*	Secondary nest material [53,54]	Moderate prevalence [40]	April to June [53, 54]
Great black-backed gull *Larus marinus*	Secondary nest material [53]	Moderate prevalence [38]	April to May [53]
Herring gull *Larus argentatus*	Minor nest material [53]	Moderate prevalence [38]	April to May [53]
Lesser black-backed gull *Larus fuscus*	Secondary nest material [53]	Moderate prevalence [38]	April to May [53]

found plastic incorporated into up to 80 % of nests of five seabird species on an island in west Scotland. Votier et al. [36] found plastic debris in 80 % of nests of northern gannets at a nesting colony in Wales and estimated that the colony as a whole held about 18.5 tonnes of plastic waste in northern gannet nests. Plastic has also been found extensively in northern gannet nests at colonies elsewhere throughout the North Atlantic, with plastic visible on the surface of an average of 49 % of individual nests [39]. At Helgoland, Germany, in 2005, 100 % of northern gannet nests contained plastic [40]. Although the prevalence of plastic in seabird nests has been the subject of study, very little is known about the extent to which seabirds may select particular colours or types of plastic, or whether they only collect plastic when they are unable to find natural material such as seaweed. However, it is evident that there is considerable competition among seabirds to collect nesting material; northern gannets often fight for fragments of seaweed and will steal material from unguarded nests of neighbouring gannets.

There are multiple global, national and regional initiatives to reduce the amount of plastic getting into the environment, and to remove plastic pollution. Nevertheless, the problem of plastic litter at sea has been increasing [41] and it is expected to increase further [42]. Presumably as a consequence of the increased abundance of plastic in the marine environment, the prevalence of plastic in black-legged kittiwake nests at a colony in Denmark increased by 46 % in the 13 years between 1992 and 2005 [40]. It is also a global problem; plastic has been found incorporated into seabird nests even in remote areas [43]. Thompson et al. [38] speculated that incorporating plastic into nest structures might alter the thermal and drainage properties of seabird nests which could in turn reduce the birds' breeding success. However, further studies are required to assess this possible impact. Plastic incorporated into nest structures certainly results in entanglement and death of seabirds [44]. Votier et al. [36] noted that a minimum average of 63 northern gannets died each summer at the colony on Grassholm, Wales, as a result of entanglement in plastic built into nests. Mortality of northern gannets trapped in plastic incorporated into nests has also been reported, but not quantified, at colonies in Scotland and Canada [36]. Entanglement mortality at nests has also been reported for cormorants [45] and gulls [46,47]. In addition to getting entangled with plastic in the nest structure, the act of collecting plastic at sea to use as nest material is also likely to increase the risk of entanglement of seabirds while at sea because this behaviour brings birds into close contact with floating plastic. Entanglement and subsequent drowning of seabirds at sea as a result of plastic waste has increased as amounts of plastic waste have increased [48]. These observations all point to the need to reduce plastic pollution at sea.

Substantially reducing the amount of plastic in the seas and oceans seems to be beyond current technological capabilities despite heightened awareness of this type of pollution, the animal welfare issues it causes and the potential impacts on marine animal populations [41]. It is to be hoped that in future there will be solutions applied to reduce plastic pollution. However, until then, it may be possible to introduce measures to reduce the extent to which seabirds make use of plastic as nesting material. Such an approach would be complementary to efforts to reduce plastic pollution. Brown boobies *Sula leucogaster* are close relatives of northern gannets and have been shown to use plastic more at colonies where there is a shortage of natural material in the surroundings [49,50]. The same relationship has also been reported for great cormorant *Phalacrocorax carbo* [45], indicating that the use of plastic could be diminished if the availability of natural nest material such as floating seaweed could be increased in the local environment where breeding seabirds are searching for nest construction material [40]. Implementation of measures that reduce the use of plastic as a nesting material by northern gannets and other seabirds would have quantifiable benefits in terms of survival and breeding success of the birds and therefore could provide compensation for some impacts of offshore wind farms.

3. Seaweed aquaculture

Despite its potential to float over long distances and to be aggregated by marine fronts and rotating ocean currents known as gyres, the amount of detached floating seaweed in coastal environments is primarily dependent upon the amount of seaweed growing locally [55–57]. Consequently, actively encouraging increased production of seaweed close to gannet colonies may be an appropriate compensation strategy for developers of offshore windfarms that are predicted to threaten those colonies. Given the current lack of established compensation measures for northern gannets, this alone would be a good reason to assess the viability of seaweed aquaculture as a compensation measure. Seaweed aquaculture, however, has numerous other benefits apart from as a potential compensation measure.

The global seaweed farming industry is highly developed, with annual production of 27.3 million tonnes globally in 2014 valued at 5.6 billion US$ [58]. Notably, the EU and UK contribute very little to this industry [59]. Seaweed use in the UK comes mostly from harvesting of natural wild seaweed stocks [60]. The Scottish Government lists 24 marine pressures that can be caused by harvesting natural seaweed stocks, including loss of seaweed habitat (change to another seabed type), opportunistic seaweed species replacing harvested species so reducing species diversity, a reduction in the availability or quality of prey that inhabit areas of seaweed, the removal of non-target species, and changes in wave exposure on harvested coastlines with consequent increases in coastal erosion [60]. Harvesting natural seaweed resources may also have impacts by disturbing coastal birds and by reducing the availability of seaweed for nest-building by species such as cormorants and gannets [61]. In contrast, seaweed farming in which seaweed is seeded onto long-lines that float close to the sea surface, has the potential to increase the area of seaweed habitat as well as supporting sustainable industry, and new organisations such as The Seaweed Alliance are currently forming to encourage and support the development of seaweed aquaculture in the UK [62]. Seaweed aquaculture can be commercially profitable, providing food, medicines, and bioplastics, and also a harvest of material for biofuels that can help to reduce fossil fuel consumption [58,63]. Seaweed farming results in an increase of sequestered carbon as some of the production sinks to the seabed and becomes incorporated into sediments. In addition, the UK's climate and extensive coastline makes it well-suited to host seaweed aquaculture projects [64].

Beyond their direct commercial potential, seaweeds provide a range of quantifiable and valuable ecosystem services. Kelp forests act as a nursery for economically important fish and shellfish, improve water quality, and can reduce coastal erosion by reducing wave height [65]. Furthermore, seaweeds can be important stores of blue carbon (i.e. carbon removed from the carbon dioxide pool in the atmosphere and stored in marine environments, where management of those ecosystems can influence the amount stored). Seaweeds hold short term carbon stores while alive, but carbon sequestered by kelp and other seaweeds can also be buried in sediments away from the site of growth over much longer timescales [59,66]. This long term storage means that seaweed farming in UK waters could contribute to carbon capture and storage and, in so doing, contribute to net zero emissions goals. Saltmarsh, seagrass and mangrove are the three best understood stores of blue carbon and are the only blue carbon habitats for which the Intergovernmental Panel on Climate Change has published guidelines for inclusion in national greenhouse gas inventories [67]. However, seaweeds are a candidate for future incorporation into such inventories [68] and have considerable potential as a carbon sink [65,69]. Some projects, such as the Yokohama Blue Carbon Project in Japan, have begun to issue carbon credits for seaweed aquaculture [70], and this approach is liable to expand in future as the carbon fluxes in seaweed systems become better understood. We conclude that long-line farming of seaweed at sea (away from the shore) has multiple benefits, including net biodiversity gain, increased local employment in remote areas, and carbon storage contributing to UNSDG 13 (Climate Action).

4. Seaweed farming as a compensation measure

Co-location of offshore wind farms and seaweed aquaculture sites has been proposed as an efficient use of marine space in spatial planning [71]. However, it should be noted that locating floating seaweed farms at offshore wind farms could potentially increase the collision risks for seabirds that might be attracted to collect seaweed from such sites to use as nesting material. Indeed, even in the absence of any such additional attraction of birds into the area, seabirds carrying seaweed are likely to be at higher risk of colliding with turbine blades because flight speed is a key factor determining collision risk [72]. Seabirds carrying seaweed will experience increased drag and so will therefore tend to fly more slowly than unencumbered birds [73], which increases collision risk for birds flying through the rotor swept area [72]. Consequently, while opportunistic seaweed farming around offshore wind farms is likely to provide a range of benefits but may have costs for seabirds, concentrating seaweed farming in areas close to protected colonies of seabirds, such as northern gannets and gulls, would have the potential to not only contribute to achieving net zero, but also compensate for the impacts of offshore wind farms on seabirds, as well as provide a profitable business, clean local seawater and reduce local coastal erosion.

5. The way forward

It is essential that compensation measures taken under the Birds and Habitats Directives are shown to be effective. Monitoring of the extent to which seabirds benefit from seaweed aquaculture could be achieved by aerial photography of colonies, which allows not only the amount of plastic visible in nests to be monitored [39] but can also quantify the numbers of dead northern gannets entangled at their nests [74]. An experimental approach needs to be taken, preferably using a before-after-control-impact (BACI) design. The best baseline data exist for northern gannets, which are known to build nests mainly from seaweed collected at sea, to add to the nest throughout the summer, to be killed by plastic entanglement at the nests and at sea, and are relatively easy to monitor [39,74]. This suggests that offshore wind farm developers should consider funding the creation of seaweed farms close to several northern gannet colonies, with the aim of establishing how management of the farms influences the use of seaweed and plastic in the construction of seabird nests. Such research would be practical and scientifically valuable. The extent to which seaweed farming close to seabird colonies will reduce the use of plastic in nest building is currently uncertain and will probably depend in part on the species of seaweed being farmed and the quantities that break off from the cultivation lines, but existing literature indicates that a reduction is highly likely, suggesting that seaweed farming may represent an effective method of compensation for offshore wind farm developers. To be effective in reducing the use of plastic in nest building, seaweed farming would need to provide scraps of floating seaweed in the area around the seaweed farm at the appropriate times of year for gannets to collect. Scraps of seaweed will break off from the long lines naturally, but it may be necessary to supplement that by deliberate release of seaweed from the long-line cultivation site to increase availability to gannets, which could reduce profitability of the farm. Such costs would represent compensation costs to the offshore wind farm industry as making material available for seabirds to build nests would need to be prioritized over other uses. The extent to which deliberate release would be required would need to be determined experimentally through adaptive management. Nevertheless, such development would come with a wide range of valuable co-benefits, not least being the stimulation of an industry that is currently underdeveloped in Europe but appears to have considerable economic potential [58,62–64]. The carbon sequestration associated with seaweed farming [59] would also help to support the climate goals of the wind farm industry and of governments, contributing directly to UNSDG 13 (Climate Action).

CRediT authorship contribution statement

Robert W. Furness: Conceptualization, Writing – original and review. **Euan N. Furness:** Conceptualization, Writing – original and review.

Funding

This work did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. E.N. Furness is funded through the Joint Collaborative Programme of the Leverhulme Centre for Life in the Universe.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

References

[1] Pörtner HO, Scholes RJ, Arneth A, Barnes DKA, Burrows MT, Diamond SE, et al. Overcoming the coupled climate and biodiversity crises and their societal impacts. Science 2023;380:eabl4881.
[2] UK Government. The climate change act 2008 (2050 target amendment) order 2019. UK Government; 2019.
[3] Climate Change Committee. The sixth carbon budget. The UK's path to net zero. Climate Change Committee; 2020.
[4] Climate Change Committee. Independent assessment of UK climate risk. Advice to government for the UK's third climate change risk assessment (CCRA3). Climate Change Committee 2021.
[5] Sadorsky P. Wind energy for sustainable development: driving factors and future outlook. J Clean Prod 2021;289:125779.
[6] Li C, Mogollon JM, Tukker A, Steubing B. Environmental impacts of global offshore wind energy development until 2040. Environ Sci Technol 2022;56:11567–77.
[7] Olabi AG, Obaideen K, Abdelkareem MA, AlMallahi MN, Shehata N, Alami AH, et al. Wind energy contribution to the sustainable development goals: case study on London Array. Sustainability 2023;15:4641.
[8] Yang JH, Chang Y, Zhang LX, Hao Y, Yan Q, Wang CB. The life-cycle energy and environmental emissions of a typical offshore wind farm in China. J Clean Prod 2018;180:316–24.

[9] Ruan ZW, Lu X, Yin ZH, Mobley SC, Zhang CY, Wang JX, et al. Spatiotemporal carbon footprint and associated costs of wind power toward China's carbon neutrality. Resour Conserv Recycl 2024;205:107593.
[10] Furness RW, Wade HM, Masden EA. Assessing vulnerability of marine bird populations to offshore wind farms. J Environ Manag 2013;119:56–66.
[11] Johnston A, Cook ASCP, Wright LJ, Humphreys EM, Burton NHK. Modelling flight heights of marine birds to more accurately assess collision risk with offshore wind turbines. J Appl Ecol 2014;51:31–41.
[12] Dierschke V, Furness RW, Garthe S. Seabirds and offshore wind farms in European waters: avoidance and attraction. Biol Conserv 2016;202:59–68.
[13] Bemmelen RSA van, Leemans JJ, Collier MP, Green RMW, Middelveld RP, Thaxter CB, Fijn RC. Avoidance of offshore wind farms by Sandwich terns increases with turbine density. Ornithological Applications 2024;126. https://doi.org/10.1093/ornithapp/duad055.
[14] Johnston DT, Thaxter CB, Boersch-Supan PH, Davies JG, Clewley GD, Green RMW, et al. Flight heights obtained from GPS versus altimeters influence estimates of collision risk with offshore wind turbines in lesser black-backed gulls *Larus fuscus*. Movement Ecology 2023;11:66.
[15] Mendel B, Schwemmer P, Peschko V, Müller S, Schwemmer H, Mercker M, Garthe S. Operational offshore wind farms and associated ship traffic cause profound changes in distribution patterns of loons (*Gavia* spp.). J Environ Manag 2019;231:429–38.
[16] Heinänen S, Zydelis R, Kleinschmidt B, Dorsch M, Burger C, Morkunas J, et al. Satellite telemetry and digital aerial surveys show strong displacement of red-throated divers (*Gavia stellata*) from offshore wind farms. Mar Environ Res 2020;160:104989.
[17] Garthe S, Schwemmer H, Peschko V, Markones N, Müller S, Schwemmer P, Mercker M. Large-scale effects of offshore wind farms on seabirds of high conservation concern. Sci Rep 2023;13. https://doi.org/10.1038/s41598-023-31601-z.
[18] Peschko V, Mendel B, Müller S, Markones N, Mercker M, Garthe S. Effects of offshore windfarms on seabird abundance: strong effects in spring and in the breeding season. Mar Environ Res 2020;162:105157.
[19] Trinder M, O'Brien SH, Deimel J. A new method for quantifying redistribution of seabirds within operational offshore wind farms finds no evidence of within-wind farm displacement. Front Mar Sci 2024;11:1235061.
[20] Masden EA, Reeve R, Desholm M, Fox AD, Furness RW, Haydon DT. Assessing the impact of marine wind farms on birds through movement modelling. J R Soc Interface 2012. https://doi.org/10.1098/rsif.2012.0121.
[21] Peschko V, Schwemmer H, Mercker M, Markones N, Borkenhagen K, Garthe S. Cumulative effects of offshore wind farms on common guillemots (*Uria aalge*) in the southern North Sea – climate versus biodiversity? Biodivers Conserv 2024;33:949–70.
[22] Searle KR, Mobbs DC, Butler A, Furness RW, Trinder MN, Daunt F. Finding out the fate of displaced birds. Scottish Marine and Freshwater Science 2018;9:8.
[23] Searle KR, O'Brien SH, Jones EL, Cook ASCP, Trinder MN, McGregor RM, et al. A framework for improving treatment of uncertainty in offshore wind assessments for protected marine birds. ICES (Int Counc Explor Sea) J Mar Sci 2023. https://doi.org/10.1093/icesjms/fsad025.
[24] Wanless S, Frederiksen M, Harris MP, Freeman SN. Survival of gannets *Morus bassanus* in britain and Ireland, 1959-2002. Hous Theor Soc 2006;53:79–85.
[25] Doherty PF, Schreiber EA, Nichols JD, Hines JE, Link WA, Schenk GA, Schreiber RW. Testing life history predictions in a long-lived seabird: a population matrix approach with improved parameter estimation. Oikos 2004;105:606–18.
[26] Department for Energy Security & Net Zero. Habitat regulations assessment for an application under the planning act 2008 sheringham shoal and dudgeon extensions offshore wind farm projects. Sheringham and Dudgeon Extension Projects - Project information (planninginspectorate.gov.uk 2024.
[27] Burnell D, Perkins AJ, Newton SF, Bolton M, Tierney TD, Dunn TE. Seabirds Count: a census of breeding seabirds in Britain and Ireland (2015-2021). Barcelona: Lynx; 2023.
[28] Nicholson S. Risk, regulation and offshore windfarms: ways to manage environmental uncertainty and over-precaution. Mar Pollut Bull 2024;202:116292.
[29] Allen S, Banks AN, Caldow RW, Frayling T, Kershaw M, Rowell H. Developments in understanding of red-throated diver responses to offshore wind farms in marine special protection areas. In: Marine protected areas. Elsevier; 2020. p. 573–86.
[30] Department for Energy Security & Net Zero. Planning act 2008 application for development consent for the sheringham shoal and dudgeon offshore wind farm extension project. 2024. EN010109-002340-SADEPS SOS LETTER DESNZ 170424.pdf (planninginspectorate.gov.uk).
[31] SSE Renewables. Berwick Bank Wind Farm Derogation Case. BERWICK BANK WIND FARM EIA documents. berwickbank-eia.com; 2022.
[32] SSE Renewables. Berwick Bank wind farm additional environmental information (AEI) submission AEI02: addendum to the derogation case section 2 gannet compensation (without prejudice). BERWICK BANK WIND FARM EIA Documents 2023. berwickbank-eia.com.
[33] Department for Energy Security & Net Zero. Habitat regulations assessment for an application under the planning act 2008 hornsea project four offshore wind farm. EN010098-002331-DESNZ HRA - Hornsea Four_Final.pdf 2023. planninginspectorate.gov.uk.
[34] Furness RW, Goodship N, Raveh S, Phillip E. Potential actions to support recovery of seabird populations in Scotland.NatureScot Research Report.
[35] Lane JV, Jeglinski JWE, Avery-Gomm S, Ballstaedt E, Banyard AC, Barychka T, et al. High pathogenicity avian influenza (H5N1) in northern gannets (*Morus bassanus*): global spread, clinical signs and demographic consequences. Ibis 2024;166:633–50.
[36] Votier SC, Archibald K, Morgan G, Morgan L. The use of plastic debris as nesting material by a colonial seabird and associated entanglement mortality. Mar Pollut Bull 2011;62:168–72.
[37] O'Hanlon NJ, Bond AL, Masden EA, Lavers JL, James NA. Measuring nest incorporation of anthropogenic debris by seabirds: an opportunistic approach increases geographic scope and reduces costs. Mar Pollut Bull 2021;171:112706.
[38] Thompson DL, Ovenden TS, Pennycott T, Nager RG. The prevalence and source of plastic incorporated into nests of five seabird species on a small offshore island. Mar Pollut Bull 2020;154:111076.
[39] O'Hanlon NJ, Bond AL, Lavers JL, Masden EA, James NA. Monitoring nest incorporation of anthropogenic debris by northern gannets across their range. Environ Pollut 2019;255:113152.
[40] Hartwig E, Clemens T, Heckroth M. Plastic debris as nesting material in a kittiwake (*Rissa tridactyla*) colony at Jammerbugt, northwest Denmark. Mar Pollut Bull 2007;54:595–7.
[41] Wilcox C, Sebille EV, Hardesty BD. Threat of plastic pollution to seabirds is global, pervasive, and increasing. Proc Natl Acad Sci USA 2015;112:11899–904.
[42] United Nations Environment Programme. From pollution to solution: a global assessment of marine litter and plastic pollution. Nairobi: United Nations Environment Programme; 2021.
[43] De Souza Petersen E, Krüger L, Dezevieski A, Petry M, Montone RC. Incidence of plastic debris in sooty tern nests: a preliminary study on Trindade Island, a remote area of Brazil. Mar Pollut Bull 2016;105:373–6.
[44] Montevecchi WA. Incidence and types of plastic in gannets' nests in the northwest Atlantic. Can J Zool 1991;69:295–7.
[45] Jylhä-Vuorio A. The use of plastic debris as nesting material by great cormorants (*Phalacrocorax carbo sinensis*) in the Gulf of Finland. Master's thesis. University of Helsinki; 2023.
[46] Wittiveen M, Brown M, Ryan PG. Anthropogenic debris in the nests of kelp gulls in South Africa. Mar Pollut Bull 2017;114:699–704.
[47] Tavares DC, Moura JF, Merico A. Anthropogenic debris accumulated in nests of seabirds in an uninhabited island in west Africa. Biol Conserv 2019;236:586–92.
[48] Ryan P. Entanglement of birds in plastics and other synthetic materials. Mar Pollut Bull 2018;135:159–64.
[49] Lavers JL, Hodgson JC, Clarke RH. Prevalence and composition of marine debris in brown booby (*Sula leucogaster*) nests at Ashmore Reef. Mar Pollut Bull 2013;77:320–4.
[50] Grant ML, Lavers JL, Stuckenbrock S, Sharp PB, Bond AL. The use of anthropogenic marine debris as a nesting material by brown boobies (*Sula leucogaster*). Mar Pollut Bull 2018;137:96–103.
[51] Cramp S, Simmons KEL. The birds of the western palearctic, vol. 1. Oxford: Oxford University Press; 1977.
[52] Nelson JB. The sulidae: gannets and boobies. Oxford: Oxford University Press; 1978.
[53] Cramp S, Simmons KEL. The birds of the western palearctic, vol. 3. Oxford: Oxford University Press; 1982.
[54] Coulson JC. The kittiwake. London: T & AD Poyser; 2011.
[55] Thiel M, Hinojosa IA, Joschko T, Gutow L. Spatio-temporal distribution of floating objects in the German Bight (North Sea). J Sea Res 2011;65:368–79.
[56] Filbee-Dexter K, Wernberg T, Norderhaug KM, Ramirez-Llodra E, Pedersen MF. Movement of pulsed resource subsidies from kelp forests to deep fjords. Oecologia 2018;187:291–304.
[57] MCS. Blue carbon: ocean-based solutions to fight the climate crisis. BlueCarbon_Report_cd4T2eP.pdf; 2021.
[58] Stévant P, Rebours C, Chapman A. Seaweed aquaculture in Norway: recent industrial developments and future perspectives. Aquacult Int 2017;25:1373–90. https://doi.org/10.1007/s10499-017-0120-7.
[59] Wentworth J, Furness EN. Blue carbon. UK parliament postnote, vol. 651. The Parliamentary Office of Science and Technology; 2021. Westminster.
[60] Scottish Government. Pressures caused by seaweed harvesting. https://marine.gov.scot; 2024.
[61] Goodship N, Furness RW. Seaweed hand-harvesting: literature review of disturbance distances and vulnerabilities of marine and coastal birds. Scottish Natural Heritage Research Report No. 2019;1096.
[62] Capuzzo E. Seaweed industries and products in the UK: a brief review. In: Ranga Rao A, Ravishankar GA, editors. Sustainable global resources of seaweeds volume 1. Cham: Springer; 2022.
[63] Chen H, Zhou D, Luo G, Zhang S, Chen J. Macroalgae for biofuels production: progress and perspectives. Renew Sustain Energy Rev 2015;47:427–37.
[64] MMO. Identification of areas of aquaculture potential in English waters, a report produced for the marine management organisation by Centre for environment fisheries and aquaculture science, MMO project No: 1184. May 2019. p. 107.
[65] Duarte CM, Wu J, Xiao X, Bruhn A, Krause-Jensen D. Can seaweed farming play a role in climate change mitigation and adaptation? Front Mar Sci 2017;4:100.
[66] Krause-Jensen D, Duarte CM. Substantial role of macroalgae in marine carbon sequestration. Nat Geosci 2016;9:737–42.
[67] Kuwae T, Hori M. Blue carbon in shallow coastal ecosystems. Carbon dynamics, policy, and implementation. Singapore: Springer; 2019.
[68] Burg S van den, Koch S, Raoult J, Tsvetkov B, Selnes T. Time to include blue carbon from seaweed in voluntary carbon removal certification. EuroChoices 2023;22:13–9.
[69] Fujita R, Augyte S, Bender J, Brittingham P, Buschmann AH, Chalfin M, et al. Seaweed blue carbon: ready? Or not? Mar Pol 2023;155:105747.
[70] Kuwae T, Watanabe A, Yoshihara S, Suehiro F, Sugimura Y. Implementation of blue carbon offset crediting for seagrass meadows, macroalgal beds, and macroalgae farming in Japan. Mar Pol 2022;138:104996.

[71] Gimpel A, Stelzenmüller V, Grote B, Buck BH, Floeter J, Núñez-Riboni I, et al. A GIS modelling framework to evaluate marine spatial planning scenarios: co-location of offshore wind farms and aquaculture in the German EEZ. Mar Pol 2015;55:102–15.
[72] Masden EA, Cook ASCP, McCluskie A, Bouten W, Burton NHK, Thaxter CB. When speed matters: the importance of flight speed in an avian collision risk model. Environ Impact Assess Rev 2021;90:106622.
[73] Pennycuick CJ, Fast PLF, Ballerstädt N, Rattenborg N. The effect of an external transmitter on the drag coefficient of a bird's body, and hence on migration range, and energy reserves after migration. J Ornithol 2012;153:633–44.
[74] Tyndall AA, Nichol CJ, Wade T, Pirrie S, Harris MP, Wanless S, Burton E. Quantifying the impact of avian influenza on the northern gannet colony of Bass Rock using ultra-high-resolution drone imagery and deep learning. Drones 2024;8:40.