Review Article

Colocation of Seaweed Aquaculture at Offshore Windfarms: Policy Opportunities and Barriers in the UK

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The drive for net-zero, along with conflicts in fossil fuel producing regions of the world has driven interest and development in offshore wind as a renewable energy source. The UK's offshore wind capacity will need to increase significantly to meet government targets, and along with other commitments such as the 30by30 target for protected areas the area of water for other blue economy initiatives is crowded. The cultivation of seaweed can also contribute to net zero through carbon sequestration solutions, either directly, through natural sequestration processes or by using seaweed as a source for fertiliser (hence preventing further carbon emissions from production of synthetic fertilisers) and biochar (with the aim of 'locking in' carbon). Other benefits of seaweed cultivation can include potential increases of biodiversity and increased socio-economic activity by creating jobs in deprived coastal areas. Co-location of seaweed aquaculture within the space between turbines in offshore wind farms can help to achieve these targets, while at the same time reducing the impact on an already overcrowded marine environment, and these policy opportunities can apply to many Global North countries. However, in the UK, there are many leasing, regulatory, and motivational barriers to joint offshore wind and seaweed partnerships preventing these policy opportunities from being exploited, which appear to have been overcome in other countries such as the Netherlands. Just as the UK has become a leader in the development of offshore wind, it too needs to be a pioneer in sustainable seaweed aquaculture co-location activities or risks missing out on economic, societal, and environmental benefits.

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1. Introduction

The UK Government, along with many other governments worldwide, is committed to achieving net zero by 2050, by ‘ending our domestic contribution to climate change, and leading the world to a greener, more sustainable future’ [1]. It aims, in part, to do so by embarking on an ambitious commitment to increasing offshore wind-farm-generated energy to 50GW by 2030 (from ~21GW in 2022 [2]) mostly through installations across the North Sea, helping to ensure national energy security at a time of growing geopolitical turbulence [1], [3]. Also forming part of the UK’s net zero strategy is the aim for aquaculture to be a major contributor to seafood consumption, which could bring up to 40% growth in the blue economy, as part of the Seafood 2040 strategy by providing healthy food and employment opportunities [4]. The cultivation of seaweed as a marine crop can contribute to both strategies by helping to decarbonize the economy and contributing to the suite of carbon sequestration solutions needed to keep global temperatures below 1.5°C [5]. Both strategies also aim to support the UK Government’s overarching goals for levelling up to improve livelihoods and drive economic growth in all parts of the country, but especially in and around disadvantaged ex-fishing industry towns and villages and may also have benefits in terms of policies such as Marine Net Gain (of biodiversity).

Combining offshore wind farms and seaweed aquaculture as ‘co-location’ activities, therefore, can help support climate and social policy by generating cleaner energy while at the same time offsetting carbon emissions through a (hybrid) nature-based solution – cultivating seaweed with the aim of sequestering carbon. Nevertheless, within the UK, benefits from such co-location are difficult to achieve in practice because of numerous legislative and procedural barriers. This review outlines: the benefits of seaweed aquaculture; the carbon sequestration and emissions avoidance potential of seaweed and the biodiversity and marine net gain opportunities that could be provided through co-location. It will then review current barriers to co-location and potential solutions to encourage its expansion, before making recommendations for policy drivers in the UK. The themes explored here offer suggestions on how UK policy could be directed towards securing a sustainable and socio-economically viable future through offshore wind farms and seaweed aquaculture co-location.

2. Seaweed aquaculture and its benefits

2.1. Seaweed aquaculture

If there is sufficient water, sunlight, nutrients, oxygen, and carbon dioxide in seawater of required temperature and salinity, seaweeds can grow very well in the epipelagic zone, whether attached on lines or freely floating near the surface [6]. Large brown kelp species (e.g., *Saccharina latissimi*) are the main cultivated species in Europe. Their aquaculture production cycle (that is the seeding, harvesting, and production of seaweed as a crop) generally follows Chinese methods [7], which begin by inducing kelp reproductive material to release spores, before being cultured onto twine in a nursery. In the autumn, the seeded materials are suspended from a mooring grid or line, at an optimum depth where light stimulates growth, usually between 1-5 m from the surface. The mature plants are harvested and taken to shore in the spring and summer, where they are processed for use.

2.2. Uses of seaweed

Seaweed has been described as a form of 'charismatic carbon' for its numerous economic, ecological, and social benefits [5]. The use of seaweed is vast, and it has been shown to be utilised for human food, feed in aquaculture and livestock, biofertilsier in agricultural soils, biofuel, cosmetics, pharmaceuticals, nutraceuticals, construction, packaging, and textiles [8], [9]. Growth in demand for seaweed-based products and biotech is increasing through the development of eco-friendly packaging such as Notpla, the 2022 Earthshot Prize winner, and food and nutrition products such as Oceanium. Seaweed can also contribute to a net lifecycle benefit of CO_2 capture; a reduction in local ocean acidification and deoxygenation; and mitigation of greenhouse gas emissions through carbon sequestration [8].

2.3. Seaweed aquaculture and the blue economy

Economic benefits from seaweed are also potentially significant [10]. The European market for seaweed and seaweed by-products could represent a global industry worth up to €9.3 billion by 2030, of which European producers could capture around €2.7 billion, generating ~85,000 jobs across the continent through the production, harvesting, and sales of seaweed products [8]. Seaweed can be harvested through wild foraging for beach-cast seaweed or through managed aquaculture. Seaweed aquaculture can contribute to 13 of the UN Sustainable Development Goals, and it can generate localised socio-economic benefits by fostering inclusive economic development and jobs with fair wages, securing jobs and green economic stimulus and strengthening coastal communities through local development [8].

3. Carbon sequestration and avoided emissions

3.1. Natural carbon sequestration

Carbon sequestration can be defined as the "secure storage of carbon-containing molecules for >100 years" and blue carbon as that which is "stored by the oceans and coastal ecosystems" [11]. Seaweed is often considered one of the most scalable nature-based solutions for sequestering blue carbon because of its fast-growing nature and its ability to fix carbon through photosynthetic primary production at the surface of the ocean [12]. *Macrocystis pyrifera* (more commonly known as giant or bladder kelp) can grow up to 50 cm per day and in lengths of up to 60 m in optimal conditions [13], seaweed forests can absorb CO_2 at rates of up to ~3 $kg.m^{-2}.y^{-1}$ [14]. This means many seaweed species have considerably higher CO_2 uptake rates than tropical rainforests [15]. Despite high CO_2 uptake rates, natural sequestration from kelp is highly uncertain, but it is estimated that kelp and other seaweeds have an estimated sequestration rate of 5-10%, which if applicable to UK kelp forests, would equate to around 1.47 $t.CO_2.ha^{-1}.yr^{-1}$ [16]. If it is assumed that the exported carbon from farmed kelp is similar to that of wild algal forests then in 2018, global seaweed aquaculture could have naturally sequestered up to 0.7 $TgCO_2$ [17]. Based on such calculations, and assuming a maximum growth rate of 20% of the seaweed aquaculture industry per year, it is estimated that ~421 $TgCO_2$ could be sequestered per year by 2050, potentially even reaching 112 $PgCO_2$ per year if upper limits of farming are achieved [17].

3.2. Avoided emissions

When compared with many terrestrial agricultural sources of biomass and food, seaweed can be produced with a negative carbon footprint [18], [19]. For example, life-cycle analyses have projected that the production of 1 kg of green peas (nutritionally comparable to seaweeds) creates ~1 kg of CO_{2e} [20]. However, seaweed aquaculture absorbs carbon and does not require freshwater, fertilisers, or additional land or further land use change which most other land crops would require. In addition, seaweed can absorb a net uptake of nitrogen and phosphorous from the surrounding seawater [18], [21]. Benefits of seaweed in avoiding carbon emissions may also extend to livestock farming. Experimental lab studies show that simulated the digestion process of seaweed in ruminants have shown that methane emissions could be substantially reduced; by including just 2% of some species of seaweed in the diets of cattle, methane emissions could be reduced by 99% [17]. Consequently, as the demand for food and feed continues to rise, seaweeds could substitute many terrestrial foodstuffs, while increasing overall biomass production with fewer environmental impacts and greenhouse gas emissions [21]. However, the extent to which seaweed can realistically form a larger part of human diets and be swapped out for other terrestrial crops while also providing micronutrients is unclear, and extensive farm scale projects should confirm whether elements of seaweed in ruminant diets can reach the methane reductions seen in trials [17][21].

3.3. Algal biochar for carbon sequestration

Human and animal carbon cycles eventually return algal carbon from processed seaweed food and feed products back into the atmosphere as a mix of gases including CO_2 and methane [11]. Farming and harvesting algae can only significantly improve levels of carbon sequestration if the biomass is not allowed to degrade. Recent studies have shown that algal biochar could sequester a significant amount of the absorbed CO_2 in the seaweed for long periods, of at least 100 years. Seaweed is considered to have considerable potential as feedstock for biochar because of its wide distribution, rapid growth, and high fixation of CO_2 [22]. After naturally drying the seaweed, algal biochar can be produced through pyrolysis; the process of combusting biomass under restricted oxygen levels at a specific heating regime [23]. At a pyrolysis temperature of 500ºC, it has been found that 30% more CO_{2e} can be bound in the biochar than is released during production [23], comparable with other biochar feedstocks. In a lifecycle assessment study, it is estimated that if pyrolysis at 600ºC is performed and the algal biochar is subsequently used for electricity production, a saving of ~790 kg CO_{2e} could be made per 1 tonne of dry seaweed compared to liquid biofuel and syngas production [24]. Algal biochar could become a long-term form of carbon sequestration if it is buried underground or used as a soil amendment [23]. Further environmental and life cycle assessments are required to analyse the energy efficiency and viability of such projects while also accounting for any associated environmental or socioeconomic implications [25].

3.4. Seaweed as a fertiliser to reduce carbon emissions during production

Seaweed and its derivatives are proven as sustainable alternatives for fertilisers or soil supplements, especially in acidic soils, because of the high pH properties and nutrient content contained within it (low in bioavailable nitrogen and phosphorous, but high in potassium) which can aid plant growth, cell division, germination, and stress management [26]. In 2018, it was estimated that the global supply chain emissions from synthetic nitrogen fertilisers was ~1.13 $GtCO_{2e}$, and that the reduction in their use offers a significant and achievable opportunity to reduce emissions [27]. If seaweed is used as a soil fertiliser (in powdered, finely chopped, or aqueous extract form), then the demand for commercial fertilisers could decrease, in turn reducing greenhouse gas emissions from synthetic production [28]. Based on data in Cutress [26] and Menegat et al. [27], by substituting the commercial use of synthetic nitrogen fertilisers with natural seaweed fertiliser by up to 50%, a saving of ~0.5 tCO_{2e} per hectare of agricultural land per year in the UK could potentially be achieved, although only for specific crops, with others demonstrating lower carbon savings due to needing more synthetic fertiliser to grow at the same rate. Nevertheless, such savings are potentially huge when scaled up over land devoted to arable farming, and the savings per hectare are typical of carbon sequestration levels of habitat types such as natural grasslands (typically estimated in the range of 0.2 to 0.5 $t.CO_2e\ ha^{-1}.\ yr^{-1}$, [29]).

4. Biodiversity and marine net gain

4.1. Benefits of seaweed aquaculture for biodiversity

Seaweeds and kelp forests form the basis of many fundamental and complex habitats that provide a trophic and physical foundation for biodiverse ecosystems. Similarly, seaweed aquaculture may also create habitats through the provision of structure, attachment sites, and trophic subsidies which can also support biodiverse communities [30]. However, there are significant differences in function between kelp forests and kelp aquaculture; while forests form over many years in complex rocky substrates, farms are generally cultivated over a few months in waters with little or no benthic structure. Aquaculture does provide biomass and farming infrastructure, however, which increases the surface area and structural complexity available for colonisation of biota, as well as influence local patterns of carbon and nitrogen cycling, and the release and uptake of other nutrients [30]. Kelp farms, therefore, can provide ecosystem services such as refuge, nursery grounds, attachment sites, and foraging opportunities for prey and predators beyond the supply of biomass [31]. This novel environment can encourage some species over others but may be different from those ecosystems found in nearby kelp forests and adjacent communities. A study in Norway, for example, found that a kelp farm had lower biodiversity and taxa abundance than a wild kelp forest, but did host many associated species communities when compared with areas which had ropes but no kelp [32].

While seaweed aquaculture can benefit mobile communities through acting as nursery habitats which provide refuge to juvenile and adult fish [33], the effects on benthic communities have been found to be mixed. In south-west Ireland, cultivated *Alaria esculenta* (winged kelp) significantly increased sedimentation and nutrient enrichment during storms, but was not found to have a significant impact on benthic diversity or on the biomass of the nearby undisturbed sublittoral seagrass [31]. In contrast, cultivated *Saccharina latissimi* (sugar kelp) in Sweden was shown to increase benthic fauna diversity and had no impact on dissolved nutrient concentrations, indicating sedimentation rates and impact on biodiversity may be dependent on the species cultivated [34]. However, in this Swedish study, kelp aquaculture reduced light availability by 40% suggesting potential long-term impacts on surrounding light dependent habitats.

Another well-established biodiversity concern relates to the possible effects on seabirds, which could be attracted to increased numbers of mobile fish species [35][36]. However, evidence for this attraction is scarce. Some species of seabird are greater associated with floating seaweed patches than should occur by chance, although these are mainly, but not solely, in coastal locations of the North Sea, and naturally occurring seaweed, rather than seaweed aquaculture [37]. However, many of the species attracted to seaweed patches, such as divers, as also those which have been shown to avoid windfarms [35]. A risk assessment on offshore aquaculture's effects on seabirds in New Zealand suggest that attraction of seabirds to aquaculture locations or to enhanced food supply at these locations would be moderate to low, and low if situated well away from seabird colonies [38]. Clearly there is uncertainty on the effects on seabirds, with more research needed, but also a need to avoid co-location, and likely avoid windfarm construction altogether in areas near important seabird areas.

It should be noted that the majority of studies relating to biodiversity have been based on small-scale cultivation in onshore areas. The expansion of the industry increases the risk of introducing diseases and invasive species to neighbouring habitats, creating an overall loss of genetic diversity [39]. Emphasis should be on the cultivation of native species around the turbines which in turn could also mitigate noise pollution and improve connectivity of protected areas and other important habitats [40]. Consequently, kelp aquaculture should be recognized for its own ecosystem services, and efforts should be focused on sustainable biomass production at the same time as supporting restoration and conservation practices.

4.2. Artificial reefs and Nature-Inclusive Design of offshore wind infrastructure

To maximise biodiversity benefits of windfarms, it is possible to combine benthic artificial reefs and nature-inclusive design of windfarm foundations alongside seaweed aquaculture closer to the water surface. Artificial reefs are defined by the OSPAR Regional Sea Convention as:

> "A submerged structure placed on the seabed deliberately, to mimic some characteristics of a natural reef ... built for protecting, regenerating, concentrating and / or increasing the production of living marine resources, whether for fisheries or nature conservation" [41].

Scour protection layers placed around the foundations of offshore structures (which mitigate the removal of sea floor sediment by hydrodynamic forces) lead to an artificial reef effect that can support biodiversity through the creation of novel habitat [42], [43]. Biofouling communities (such as mussels, macroalgae, barnacles, arthropods, and anemones) quickly colonize the structure at various depths, which in turn attract larger crab and lobster species, predator fish, seabirds, and marine mammals [44]. Studies have shown that at the footprint level of a turbine, biomass can increase by 4000 times compared to the biomass present in the sediments originally [45]. Nevertheless, while some sites and species have shown increases in biomass and abundance within and near offshore wind farms, evidence of such positive effects is not universal across all sites or species [46].

In addition to the natural colonization of infrastructure, nature-inclusive design features (such as incorporating a rough surface texture, multiple entrances and hollow caves, tunnels and holes) can enhance the habitats provided by offshore wind farm installations and offer potential for marine net gain [47][48]. Anchoring infrastructure for seaweed aquaculture could also be nature inclusive. Prototypes of 'eco-anchors' that might attract organisms for habitat creation, for example, are currently being tested so that the industry can upscale sustainably [49].

4.3. Marine net gain

Marine development of offshore wind will increase significantly in the coming years if the UK is to meet its targets for renewable energy [2]. It is critical, therefore, that nature restoration and improvement is integrated with such development in the marine environment [50]. Marine net gain aims to improve the biodiversity value of a given marine area that has undergone modification, through the protection, restoration, or creation of environmental features that are of more ecological value to biodiversity, habitats and people than any losses associated with the development [51]. Net gain policies have their origin within the Convention on Biological Diversity framework [52], and while implementation varies between countries (and between England and the devolved nations in the UK), broadly the concept applies internationally. Marine net gain also supports the principles of the UK Government's 25 Year Environment Plan which aims to make environmental improvements and to reverse biodiversity loss [1].

However, extensive stakeholder engagement and co-production is necessary if marine net gain is to be successful [53]. A 2022 consultation with a variety of sectoral respondents across industry, academia, and other involved parties, the majority agreed that: (1) Marine net gain should assess impacts on species and habitats (89%), (2) Marine net gain should be a mandatory requirement of marine development (81%) and (3) Marine net gain will incentivise the delivery of strategic interventions alongside meaningful site-based interventions [54]. This consultation underlines the importance to most stakeholders that activity in the marine environment, therefore, needs to not only mitigate its environmental impact, but also seek to create and enhance habitats that offset those impacts. Co-location of seaweed aquaculture and offshore wind farms could help to fulfil this appetite by providing novel habitats in the areas around wind turbines. Such cross-sector stakeholder collaboration can already be seen in live projects such as ECOWind, which is bringing together experts from science, policy and industry to try to better recognize the impacts of offshore wind developments on ecosystems, species, and habitats with the aim of reducing the negative effects while also tackling climate change [55]. By investigating how current offshore wind farms have affected the marine environment, researchers will be able to model what impact future expansion in the industry will have, and how likely nature-based projects, which improve climate resilience and sequester carbon, are to succeed [55].

While co-location of windfarms, artificial reefs and seaweed aquaculture may have a positive influence on local biodiversity (although despite advances, the structures are likely to have a negative impact on birds [56] (section 4.1), it is necessary for metrics such as marine net gain to recognise and reflect these benefits. Within the English terrestrial and intertidal equivalent, (namely Biodiversity Net Gain), biodiversity is only estimated based on habitat and condition parameters. Crucially, artificial structures, including eco-enhancements, often score low on the 'distinctiveness' scale of the tool, resulting in low biodiversity scores for these areas, and disincentivising eco-engineering solutions to enhance biodiversity. Real changes in biodiversity need to be accounted for, in order for policy drivers such as marine net gain to be an incentive for colocation. Wind farm construction may change significant amounts, yet still the vast minority, of sand and mud benthic systems to hard substrate, and this could (given nature-inclusive designs as discussed in section 4.2) be ecologically beneficial. For example, small patches of hard substrate in the otherwise soft sediment of the North Sea have been shown to have great importance for biodiversity [57] and the importance of hard infrastructure, such as decommissioned oil platforms, for biodiversity is increasing being recognised [58]. While more research is required, a windfarm incorporating nature-inclusive design, alongside a well-managed seaweed aquaculture installation could qualify as an Other Effective Area-Based Conservation Measure (OECM), and even contribute to the 30by30 pledge for protected areas [59].

4.4. Compensatory measures

As part of the planning process, the UK Government is proposing that developers of new offshore wind farms are required to provide information which determines whether an offshore wind development will significantly harm protected habitats and species, and if so then developers must provide information on how 'impacts can be avoided, reduced, or mitigated' [60]. If the impacts cannot be mitigated, then strategic compensation is required, and developers and government should work together to identify such compensatory measures [60]. It is currently unclear, however, how negative environmental impacts might be mitigated through this process, although it is likely to be related to a biodiversity credit scheme, similar in approach to terrestrial developments [61]. However, compensatory measures may not be required if co-location activities including artificial reefs and aquaculture mitigated these possible biodiversity losses during construction.

5. Offshore wind farms and seaweed aquaculture co-location

Due to a lack of inshore sites, the visual impact of aquaculture farms nearer to coastal areas, and the competition in such areas for space, there is pressure for the seaweed industry should move offshore (beyond 12 nautical miles off the coast) [62]. Whilst there are difficulties associated with cultivating seaweed offshore, it has been found to be both biologically and technologically feasible [42]. There are also environmental benefits of moving aquaculture offshore: increased water flow in the deep-sea environment, superior water quality compared to inshore areas, less impact of diffuse pollution, fewer contaminants leading to better food safety and greater economies of scale for large farms [42]. However, potential new aquaculture initiatives present further demands on an overcrowded marine space off the coast of the British Isles [63]. The UK's Marine Management Organisation (MMO), therefore recommended giving adequate attention to co-location activities that can bring both social and environmental benefits [64]. Co-locating seaweed aquaculture within offshore wind farms would help to mitigate further spatial pressure on the marine environment and at the same time open access to extensive cultivation areas which are currently out of reach.

5.1. Benefits of offshore wind farm and aquaculture co-location

There are numerous benefits of offshore wind farm and aquaculture co-location. Firstly, high set-up and maintenance costs, and the risk of operating offshore can be shared across the two industries [65]. Studies show that as much as a 10% reduction in operation and maintenance costs can be achieved if aquaculture is combined with wind farm development [66] and such potential private cost savings could equal $50-100 per tonne of seaweed output [67]. Wind turbines and other offshore energy infrastructure can provide attachment points for mooring cages and longlines for mounting aquaculture systems providing an appropriately sized area which is free of commercial shipping [68]. Aquaculture and offshore wind farms can also share services such as power, monitoring equipment, supply vessels and costs, accommodation platforms and staff [69].

Employment for co-location projects could be provided for seaweed aquaculture by local inshore ex-fishing communities that have relevant skills, knowledge of local sea conditions, and have access to the necessary equipment [70]. Through collaboration, wind farm developers and aquaculture companies can learn from each other's expertise, experience, and perspectives [8]. One such example, is the new partnership between renewable energy company 'Ørsted' and offshore seaweed cultivators 'SeaGrown' to monitor the marine biodiversity benefits of seaweed cultivation [71]. There are also onshore benefits of co-location, as many shore-based skills are common across the industries – research and development, manufacturing, and engineering / maintenance – and shared facilities in port areas could become 'blue growth clusters' [69].

While co-location will not fundamentally change the economics of ocean use, it can, at the margins, make economic activities in the ocean more efficient [67]. Public benefits from co-location (that is the missed opportunity cost associated with ecosystem services which would have been foregone if the seaweed farm had not been co-located) are likely to be around $500-$3000 per year per hectare of area occupied by the aquaculture operation [67]. Co-location can be attractive to offshore energy companies who are keen to demonstrate their commitment to social good with aquaculture licensed as a secondary activity alongside their main business [69] which could contribute to the mitigation or offsetting of the

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environmental impacts of wind farm development [63], through carbon sequestration and the provision of artificial reef functions which can support biodiversity in ecosystems [42], [72].

Co-location is also potentially beneficial to other stakeholders: generating additional revenue for the Crown Estate through lease of the seabed; more efficient use of the marine space; and better food security [73]. For marine planners wishing to reduce conflicts in the use of the sea, co-location of marine activities is also attractive as only 3% of the total area leased for an offshore wind farm is occupied by the piles and foundations of the turbines [63]. Despite the benefits of seaweed aquaculture and co-location with offshore wind farms, there are, nevertheless, various leasing, legal, regulatory, and motivational challenges that remain for offshore co-location development [63] (section 5.3).

5.2. Negatives of co-location

The purpose of this article is to highlight benefits of co-location and to indicate the barriers present in terms of marine regulation to the activity in the UK. However, opposition to co-location does occur and a recent review by O'Shea et al. [74] outlines several perceived disadvantages of co-location of seaweed aquaculture at offshore wind. These perceived disadvantages were based on stakeholder opinion, rather than scientific studies, and range from of potential for invasive non-native species, especially if non-native seaweeds are cultivated, through to noise and pollution of the area through increased boat traffic. In some cases, perceived risks seem counterintuitive, for example, co-location should lead to reduced spatial competition with industries such as fishing. However, although fishing is typically reduced in areas of windfarms, it should be acknowledged that co-location of aquaculture would completely prevent fishing in these areas. In other cases, for example, whether kelp aquaculture has significant effects on marine primary production, either within the windfarm or in the wider area, and associated ecosystem impacts of such changes, do require more scientific evidence. However, existing evidence suggests that there is little effect on primary production and related ecosystem services [75], [76]. The effects of co-location on increased likelihood of bird collisions with windfarm turbine blades are discussed above (section 4.1) and are currently uncertain and in need of further research. However, co-location activities would be best avoided in close proximity to large bird colonies.

5.3. Barriers to co-location

While there are many regulatory frameworks which enable the development of offshore wind farms (the Electricity Act 1989, the Planning Act 2008, the Marine and Coastal Access Act 2009 and the Marine

(Scotland) Act 2010), the same does not apply for offshore aquaculture, where the legal and regulatory environment for such development is often considered an obstacle to industry expansion [77]. Offshore aquaculture will only reach its potential if governments create a supportive climate which allows investors to set up projects with a reasonable expectation that their investments are secure, and that the operation will be regulated [77]. The most important policy barriers are leasing, planning permission and regulation [63]. However, differences in devolved nation governance and lack of incentive for offshore wind developers add further complexities.

5.3.1. Leasing

Under current leasing policies, the most relevant concerns for aquaculture developers are the: (1) complexity and predictability of the leasing process, (2) legal security of a site in terms of exclusive use and property rights, (3) available length of lease and stability of the cost (in terms of rent and royalties) [77]. Currently the Crown Estate controls the lease of the seabed in UK waters (excluding Scotland, where Crown Estate Scotland have this control). They can lease to energy and aquaculture developments within 12nm of the coast (inshore waters), but can only lease to renewable energy companies in the remainder of UK waters (i.e. > 12nm from the coast), as per the Energy Act 2004 (i.e. they cannot lease to aquaculture developments outside of 12 nm). Christie et al. [63] state that leases from the Crown Estate are activity and specific, and energy companies are only allowed to profit from the sale of energy, additional co-location activities, such as seaweed aquaculture cannot be sub-leased from the energy company. They suggest separate leasing and assessment processes need to occur from scratch for co-location activities, or joint leases could be applied for during initial planning phases. However, it is unclear whether the Crown Estate have the option to grant such joint leases outside of inshore waters without a change in their powers.

5.3.2. Planning permission and regulation

If, and once, the lease for both wind and aquaculture development has been agreed with the Crown Estate, a separate statutory planning permission process starts, and a marine licence is applied for. Under MMO rules, any construction work associated with aquaculture that is required to support ropes or other structure for cultivation within the wind farm zone, requires a marine licence [63]. This application is then sent for review by all the government agencies with authority in the area, including: the MMO, Natural England, Environment Agency, Maritime and Coastguard Agency, Crown Estate, Trinity House, Fish

Health Inspectorate, Inshore Fisheries and Conservation Authority, and the Plant Health and Seeds Inspectorate (note, not all agencies have authority in all areas, for example Inshore Fisheries and Conservation Authority only are involved in aquaculture within 6nm of the coast). As a result, the aquaculture industry has many concerns around regulation which include: the number and complexity of the regulations; the number of agencies which grant approval; the unpredictability of the permit process; and costs of compliance [77].

5.3.3. Devolved nations

In the UK, England, Wales, and Scotland have slightly different processes for encouraging co-location of aquaculture and offshore energy development, adding further complication. At the time of writing, there are no offshore wind farms off the coast of Northern Ireland. The process for Wales is the same as England and is as described above. However, in Wales, the development of sustainable marine seaweed aquaculture is being supported through policy AQU-01b which promotes a collaborative approach between stakeholders [78]. In Scotland, no planning permission is needed for seaweed aquaculture as the 'marine construction' application process covers the marine licence for seaweed cultivation [79]. The process is likely to be further complicated across all nations in the coming years, in at least some of the devolved nations as the designation and implementation of Highly Protected Marine Areas (HPMAs) will limit the amount of marine space available for co-location activities, as fishing and aquaculture are banned within or close to HPMAs [80], [81]. At the time of writing, the future of HPMAs in Scotland is uncertain.

5.3.4. Wind farm developer and operator motivation

In England and Wales, the granting of a lease for offshore wind extends to the whole area encompassed by the wind turbines and does not allow the wind farm owners or third parties to carry out any aquaculture activities (or any other activity) within the farm boundary (unless additional or joint leases are applied for, see section 5.3.1). If the wind farm owners have any concern over the possible impact that co-location with aquaculture may have on their operations, then it is likely to be difficult to persuade them to participate in joint industry schemes [73]. The main advantage of wind farm co-location for aquaculture developers is the use of turbine foundations as anchor points in the high energy environment of the North Sea; without which it would not be economically viable [63]. However, establishing strong incentives for offshore wind farm developers is more difficult, and involves collaboration between wind farm developers and operators and the aquaculture sector. For future co-location on existing wind farms, dialogue between stakeholders on both sides to determine safe working practices is critical [63].

5.4. Learning from others in Europe

Although there are similar obstacles to the leasing and regulation of co-location in other European countries, there are some current trials and installations which could be used as leverage for future projects [8]. In Germany, legislation requires wind farm developers to consider and evidence co-location assessment during the application process, but it has not resulted in any projects to date [62]. In Belgium, legislative drivers insist on co-location, with some seaweed projects now planned [62]. Some European counterparts are encouraging research programmes to test co-location. Offshore wind farm developer, 'Vattenfall', for example, is working with Danish universities and other companies to test whether blue mussels, sugar kelp, sea lettuce, and dulse can be produced on lines at Scandinavia's largest wind farm, Kreigers Flak, off the coast of Denmark [82]. In the Netherlands, the North Sea Agreement put together by the Dutch Government consulted all Dutch users of the North Sea to propose that the authorisation of every new offshore wind farm is dependent on the combined use of the relevant area with other sustainable ocean activities [83], and a multi-use procedure has been set up to ensure a smooth legislative process for approval [84]. For example, North Sea Farmers are currently trialling the co-location of seaweed aquaculture and offshore wind farm in a test site 6.5 miles off the coast of the Netherlands, eventually aiming to develop and implement a co-location 10km^2 ocean seaweed farm with a yield of 1,000 tonnes of wet seaweed per annum [85].

6. Recommended policy drivers to encourage co-location

To meet net zero targets through carbon emissions reduction and renewable energy targets, the UK Government should encourage seaweed aquaculture development with offshore wind farms through the refinement of policy and planning processes. However, as has been documented in this paper, the current planning and leasing process is long-winded, bureaucratic and an obstacle to such multi-use development. Only significant regulatory reform alongside incentives for offshore wind developers will encourage joint industry projects and help to reduce redundant and complex permit requirements and processes [77]. Policy drivers that could encourage co-location can be split into the following areas: (1) Regulatory, planning, and leasing, (2) Research and piloting and (3) Partnership. In addition, all three areas must foster a sustainable and socio-economic approach which aims to reduce carbon emissions, increase marine net gain of biodiversity in both real and regulatory terms, and generate new blue economy growth while not detrimentally impacting the environment and local communities.

6.1. Regulatory, planning and leasing

In the first instance, and as in other North Sea nations, legislation should change to stipulate co-location as a condition for all new offshore developments [86], and, as a bare minimum, require offshore wind farm developers to carry out and evidence that co-location feasibility studies have been undertaken [73]. Co-location activities may not be appropriate in all sites, but a 'one-stop' agency could help with the management, promotion, and facilitation of aquaculture development to help link up farm owners with offshore wind developers [77]. Legislation should state that all new offshore developments (be they offshore wind or co-location activities) are developed from a nature-inclusive design perspective to help with habitat creation and overall marine net gain targets, as well as potentially contributing to 30by30 protected area targets.

Future co-location developments should be considered as dual ventures through an entirely new, and much smoother, leasing and assessment process which can grant joint seabed leases for the development, thus avoiding the need for multiple time-consuming and costly permissions applications [63]. By doing so, the whole development can be designed from the outset, providing financial and planning security for both parties, through a collaborative approach to fine-scale marine spatial planning [4]. The Crown Estate leasing rights beyond 12 nm that are enjoyed by offshore wind developers should be extended to aquaculture developers, providing tenure security for all involved parties [4]. Where possible, processes should be similar or the same across the devolved nations, so that developers can easily set up projects across the whole of the UK offshore area. A more streamlined approach could also help reduce fees for permits, leases, and rents for licences making joint ventures more attractive for private investment. Any collected fees could be used to support further offshore research and development [77]. Incentives, such as area passports, clearer licencing procedures, and clearer criteria for tender processes can encourage development of co-location activities [43].

6.2. Research and piloting

As evidenced by experimental projects off the coast of the Netherlands, research and piloting with ongoing monitoring and improvement are key to the development of co-location activities. Success of the

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North Sea Farmers pilot projects has been attributable to the open relationship between research, industry, government and agencies, which has enabled innovation and the sharing of expertise, supported by legislation and funding models. Similarly, piloting projects in the UK should be a partnership between industry and research supported by government [86], where adaptive management informs flexible decision making to determine whether co-location is commercially and scientifically practicable on existing and future joint activities [4].

6.3. Partnership

Significant co-design and co-production will be required if co-location and industry partnership is to be successful. Site selection criteria should be defined by collaboration between researchers and regulators, applying relevant operational, social, and ecological data against areas earmarked for offshore wind development [86]. Similar to the Seaweed Academy by SAMS Enterprise in Oban, government sponsored creation of seaweed innovation hubs and research centres of excellence which bring together skills and experience from research and industry should be encouraged to develop the full potential of seaweed and its uses. Cross-industry stakeholders need to share expertise to define the best available technology, best management operations and best environmental practices for the specific site and project [86]. For better marine environmental protection and a site-specific marine net gain approach, collaboration between maritime users, ecological agencies and regulation bodies should be encouraged to build the foundations for greater environmental protection [53]. Once projects are in operation, research activities and close monitoring of marine habitat creation should be carried out to assess benefits to biodiversity [30]. Cross-country collaboration across the North Sea nations should also be considered where there are similarities in the offshore marine space, especially between the Netherlands and the UK [87].

6.4. Fostering a sustainable and socio-economic approach

Rapid expansion of any industry can have unintended and unexpected consequences for ecology and society; ambitious expansion of seaweed farms co-located with offshore wind farms would be no different. Permitting seaweed aquaculture at scale without considered regulation risks harmful impacts on the marine environment and coastal economies. In the US, the Seaweed Commons [88] calls for a precautionary approach to the development of the seaweed aquaculture industry to protect wild seaweed cultivars, ecosystems, and the welfare of coastal communities. They advocate for ecological regulation around: limitations on farm size and location; restrictions on spore / seed distribution to preserve genetic diversity; biosecurity measures to reduce contamination of species; and Conditions of Licence to hold farm owners liable for marine debris and cross-contamination. Similarly, the United Nations University and SAMS recommend the setting up of national seaweed seed banks to make sure that there is a healthy standard of seed stock which farmers can rely on when a disease outbreak occurs, and for preventing the use of non-indigenous species [89].

Recommendations for socioeconomic regulations include: (1) limiting the size of sites for new growers until proof of concept has been demonstrated, (2) introducing inclusive licence application processes which take skills, education, and experience into consideration, and (3) ensuring that funding is allocated fairly across independent and corporate farm owners [88]. Long-term investment in the seaweed aquaculture industry and insurance schemes for smallholders should be encouraged by the UK Government [89]. The UK Government should also consider how co-location can benefit society and nearby coastal communities by working with industry and through supporting new job creation and blue economy initiatives. For example, blue growth clusters could be formed in coastal towns with independent ex-fishing smallholders to help support and develop new job creation in seaweed aquaculture and offshore development.

7. Conclusion

This study has set out to highlight the benefits of seaweed aquaculture, the current barriers to its co-location with offshore wind developments and recommendations for regulatory and legislative change in the UK. It is clear from this analysis that UK policy must transform if offshore wind farm owners and operators are to be persuaded to include seaweed aquaculture in their developments. Seaweed cultivation is not a silver bullet in the battle against climate change, but if it is encouraged in a sustainable and socio-economic manner, it has huge potential in its contribution towards UK Government net zero targets through carbon sequestration and avoided emissions, marine net gain of biodiversity, 30by30 targets for protected areas and levelling up in the coming decades. Its development as an industry will only be successful with sufficient supportive and legislative conditions to encourage investors and developers to set up regulated and financially secure co-location projects. Over the past few decades, the UK has become a leader in the establishment of offshore wind energy in the North Sea, but risks missing out on new multi-use opportunities in the marine space, unless it takes urgent and decisive, yet sustainable and socio-economically inclusive legislation to encourage the co-location of seaweed aquaculture with offshore wind farms.

Statements and Declarations

Conflicts of Interest

The authors have no competing interests.

Author Contributions

Conceptualisation: RS, FT, CB; Supervision: RS, FT, CB; Investigation: PD, ZB, KM, RS; Writing – original draft: PD, ZB, KM, RS; Writing – review and editing: PD, ZB, FT, CB, RS.

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