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Tees Estuary Mariculture Co-location Feasibility Study

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Author: Charlotte Hebditch

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Photo: Kate Baxter, Tees Rivers Trust

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1 Introduction

The Tees Estuary holds a lot of ecological and socio-economic importance. It supports many different uses from commercial fisheries, heavy industry to recreational activities. Teesport is situated on the estuary edge and is currently the third largest port in the UK.

The Tees Estuary has historically had multiple water pollution issues derived from a diverse array of sources, including the industrial sector and the water industry.

Often the need to address water quality issues is negated by the economic benefits of pollution creating industries and the cost of water quality improvement. In order to solve this problem, it is proposed that a mariculture development be created co-located inside the Teesside Offshore Wind Farm to provide an economic stimulus for water quality improvement.

2 Background

The Tees Estuary is a dynamic and highly complex environment. This waterbody covers a 16km stretch from Teesmouth up to the tidal limit of the Tees barrage and includes seven immediate tributaries. The entire Tees Estuary catchment covers a 171-acre area.

The Tees has been an important trading river since the 1500s. At this time the small market town of Yarm was the main port, however, as ships grew in size and stops at ports became shorter due to increased demand and faster manufacture, most trade moved downstream. The industrialisation of the river led to many heavily polluting industries developing and saw a reduction in species once numerous in the area (Tees Valley Nature Partnership, 2022).

Historic industrialisation of the Tees Estuary has led to the natural estuary environment to be heavily modified. Over 90% of the estuary intertidal habitat has been reclaimed since the late 1800s, predominately from infill with waste slag from the steel industry. Throughout this industrialisation, pollutants were broadly discharged into the local environment. As a result, the natural estuary ecology has been negatively impacted.

In recent decades, laws preventing unwarranted environmental damage and necessitating environmental improvements have been introduced. This enhanced custodianship of the waterways has already led to substantial improvements in the health of the Tees Estuary waterbody. Despite this, some expected communities are either absent, reduced or in poor condition to what would be regarded as the assumed norm, primarily due to the remnants of past heavy pollution.

Pollutants within the Tees River system are still present resultant from past and current industry practices. Existing water quality levels have prevented the Tees Estuary from obtaining good Water Framework Directive (WFD) status. The Environment Agency (EA) Catchment Data Explorer lists 7 of the 14 issues preventing the Tees Coastal Water Body from reaching good status as being pollution related, with 4 listed under Industry and 3 under Water Industry (environment.data.gov.uk, 2021). Further improvements in estuary water quality remains necessary.

Despite recognised environmental concerns, the Tees Estuary contains a number of valuable habitats and communities of conservation importance and a high abundance of species resultant from the land-sea interface. The estuary currently possesses several protected designation areas, these being the Teesmouth and Cleveland Coast Special Protected Area (SPA) and RAMSAR site and the Teesmouth and Cleveland Coast Site of Special Scientific Interest (SSSI) (INCA, 2022). The intertidal estuary area holds particular value markedly for overwintering migratory waterbird assemblages. A broad range of habitats exist throughout the estuary, including saltmarsh, lagoons, sand dunes, intertidal mudflats, in addition to freshwater and coastal waters.

Historic evidence illustrates that several habitats of conservation importance, namely seagrass, native oyster and kelp beds, were once prevalent inside and around the Tees Estuary area. Multiple factors predominately disease, water pollution and over exploitation led to the rapid decline and loss of these three valuable habitats. Some marine species, specifically bivalve shellfish and macroalgae have the capacity to improve the quality of water through their biological function.

Bivalve shellfish are filters-feeders. They feed by sieving out organic and inorganic particles from the surrounding water column when pumping the water over their gills. These shellfish can thus improve water quality by removing pollutants present in their local environment and permanently store these toxins within their bodies. In North America, entire ecosystem services resulting from oyster reefs possess an economic value approximately US$106,000 ha^{-1} $year^{-1}$. Worldwide, bivalve habitat restoration inside estuaries is increasingly becoming a technique used to improve poor environmental conditions (McLeod et al., 2020). Macroalgae can also provide a range of services. Seaweeds absorb inorganic nutrients from the water column to fuel growth. Inadvertently this nutrient assimilation can reduce the level of inorganic pollutants present, improving the health of a water body (Stanley et al., 2019).

Mariculture is the technique of farming a fish stock as produce. Farming marine species acts to provision a service whilst preventing the exploitation of wild populations alone. In 2016, worldwide mariculture production increased to 28.65 million tons equating to 36% of all global aquaculture production (Carranza and zu Ermgassen, 2020). Aside from cultivating a stock, culturing marine species, principally bivalve molluscs and seaweed, can provide numerous ecosystem services like water quality improvements. Rearing, restoring and reintroducing these marine species within the estuary will support natural water quality enhancement, subsequently driving forward positive steps to the Tees Estuary achieving good Water Framework Directive status in the future.

The mariculture industry is set to continue expansion globally. An increase in offshore mariculture farm developments is predicted in conjunction with a rising global market demand (Marine Investment for the Blue Economy, 2016). As the quantity and scale of all offshore developments continues to rise in the coming years, opportunities to share marine space and co-locate multiple industries should be sort.

The UK currently accounts for nearly 35% of the global offshore wind capacity. The UK government has set the ambitious target of achieving 40 GW by 2030. This electricity, generated from offshore wind alone, will be enough to power every UK home. This target will significantly aid the process of accomplishing net zero emissions by 2050 and underpin a "green industrial revolution". The utilisation of marine renewable energy structures in combination with mariculture developments offer opportunity to jointly implement marine conservation, sustainable fisheries management and renewable energy initiatives (UK Government, 2020).

Achieving the planned net zero emissions goal by 2050 would equal a 13x increase in the current operational generating capacity of the offshore wind industry. Significant expansion of offshore renewable energy developments can be expected. Alongside an increasing blue economy, there is a drive to also designate a higher percentage of UK waters as Marine Protected Areas (MPAs). Currently 38% of UK seas are covered by a network of MPAs. Following Brexit, legislation is expected to harden over what activities will be permitted inside designated protected areas. Accommodating fisheries inside protected zones is anticipated to be denied if current conservation designations are altered to Highly Protected Marine Areas equating to No Take Zones. To avoid a mass displacement of fishing activities following conservation legislation change, in combination with offshore industry expansion, marine planning needs to become smarter and more resourceful (NFFO, 2021). The co-locating of mariculture developments in the vicinity of offshore renewable energy installations i.e., wind farms, would aid in supporting blue growth whilst enabling the effective use of marine space for compatible industries (Marine Investment for the Blue Economy, 2016).

In England, aquaculture production is predicted to double between the years 2020 to 2040. Revenue produced from this industry will rise to £60 million. In addition, a significant rise in jobs generated surrounding aquaculture production can be expected (Brown et al., 2020). The Seafish Report on aquaculture in England, Wales and Northern Ireland concluded that there was a strong potential for growth in shellfish aquaculture, but that constraints, such as marine planning and seed availability, are holding it back and must be addressed (Seafish, 2016). The demand for seaweed production outside Asia is limited. However, the seaweed aquaculture market demand is expected to increase by 50% by the early 2030s, due to its increasing international demand for use in pharmaceuticals, agriculture, biofuels and bioplastics (Racine et al., 2021).

Wind farms have been used in some European countries to be sites for mariculture and restoration trials of marine species, namely bivalve molluscs and seaweed. This scheme is particularly popular across the eastern North Sea with a number of wind farms within Dutch and Belgium waters being utilised in this way. Pilot studies are currently underway to test species survivability offshore and examine whether mariculture installations can successfully withstand harsh sea states. The operational viability of farming fish stock inside renewable energy developments must be determined and trialled (De Rijke Noordzee, 2022; Gemini Wind Park, 2020).

The Tees Offshore Wind Farm could potentially be a suitable place for a similar mariculture scheme.

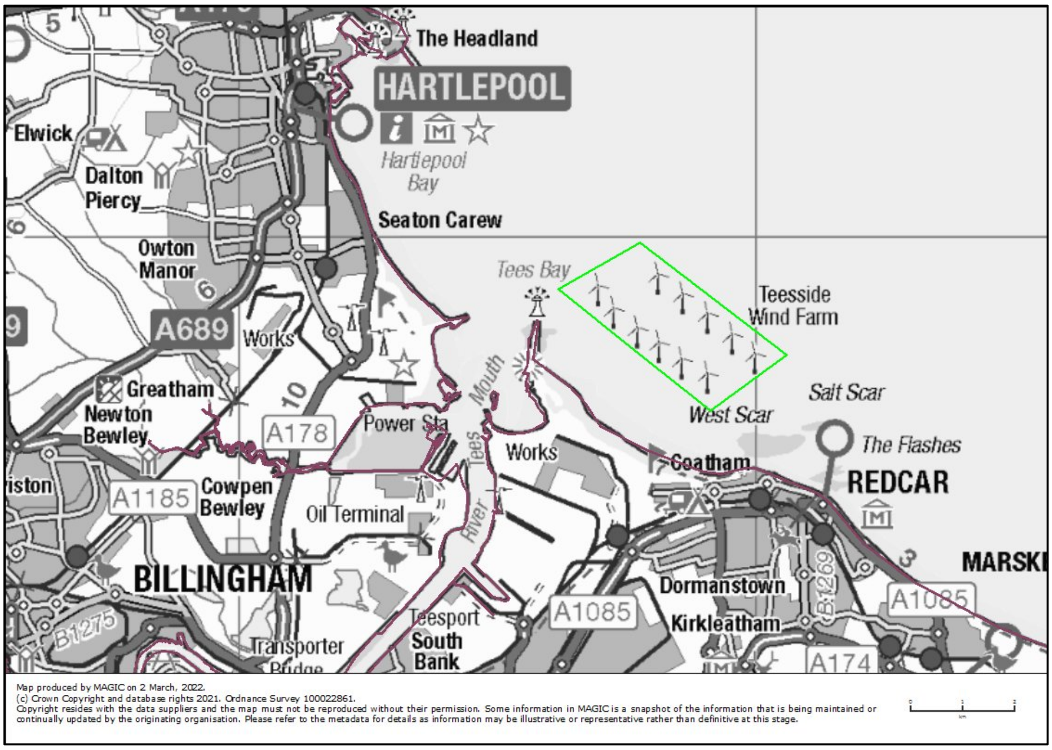


Figure 1: Map of Tees Inshore Wind Farm location inside Tees Estuary (MAGIC).

The building of the Teesside Wind Farm began in February 2011, with work completed by June 2013 and the first power being created in the same year. The wind farm consists of 27 turbines over an area of 10km², situated 1.5km off the shore of Redcar and in water depth ranging from 7-15m (figure 1) (4coffshore.com, 2022).

This report looks at the feasibility of implementing a mariculture development within the Teesside Offshore Wind Farm, to provide an economic stimulus to improve Tees Estuary water quality.

3 Requirements

The feasibility of this solution will be evaluated by assessing the environmental requirements for such a scheme compared to those present in the Tees Wind Farm, the costs and benefits of the scheme for the ecology and economy of the local area and any other additional considerations. Open communication with the wind farm site owners will be had throughout this study to ensure the effective appraisal of operational viability of this mariculture scheme.

4 Evaluation

Mariculture within offshore wind farms is an emerging industry. In Europe, there are a few examples to learn from, although those that exist have very little information available regarding their success, as they have not been in place for many years. A selection of schemes are currently being piloted. A number of different environmental and socio-economic factors need to be considered when determining the feasibility of mariculture co-location inside an offshore wind farm.

This feasibility study aims to address the main factors that determine the suitability of co-locating a mariculture enterprise inside the Tees Wind Farm as a combined socio-economic and water quality improvement driver.

4.1 Water Quality and Conditions for Mariculture

The Tees has historically had multiple issues with water quality with many of these issues leading to the Tees not achieving good Water Framework Directive (WFD) status. Despite recognised environmental concerns, the Tees Estuary contains a number of valuable habitats and communities of conservation importance and a high abundance of species resultant from the land-sea interface. The Environment Agency (EA) records water quality at various locations around the Tees, as well as the levels of pollutants within blue mussel (Mytilus edulis) populations inside the Tees Estuary.

Laws preventing the unwarranted release of pollutants and necessitating water quality improvements have been introduced in recent decades. Substantial improvements in the health of the Tees Estuary waterbody have resulted. Despite this, some expected communities are either absent, reduced or in poor condition to what would be regarded as the assumed norm, primarily due to the remnants of past heavy pollution.

The Tees Lower and Estuary TraC has 18 reasons for not achieving good WFD status (RNAGs) (Environment Agency, 2017a). Nine of those are to do with sources of pollution. Tributyltin compounds within river bed sediment, caused by diffuse pollution from the industry sector, is the only failing element. Dissolved inorganic nitrogen from industry, the water industry and farming was also listed as a key, albeit a moderate reason for the Tees Lower and Estuary TraC not achieving good WFD status. Positive steps must be taken to address these several key water quality issues to alleviate any negative environmental health impacts.

4.1.1 Water Quality Monitoring

Water Quality is monitored by the Environment Agency (EA) at various points around the Tees Estuary and coastal area. Unfortunately, water quality is not tested within the wind farm area itself, but five of the EA monitoring points are nearby, closer to the coast and will be included to give an impression of the water quality at the wind farm site.

4.1.1.1 Tees at the Gares (Surface)

Figure 2: A map showing the location of the Gares (Surface) EA monitoring point. This location lies just up the coast from the wind farm.

4.1.1.2 Redcar Coatham

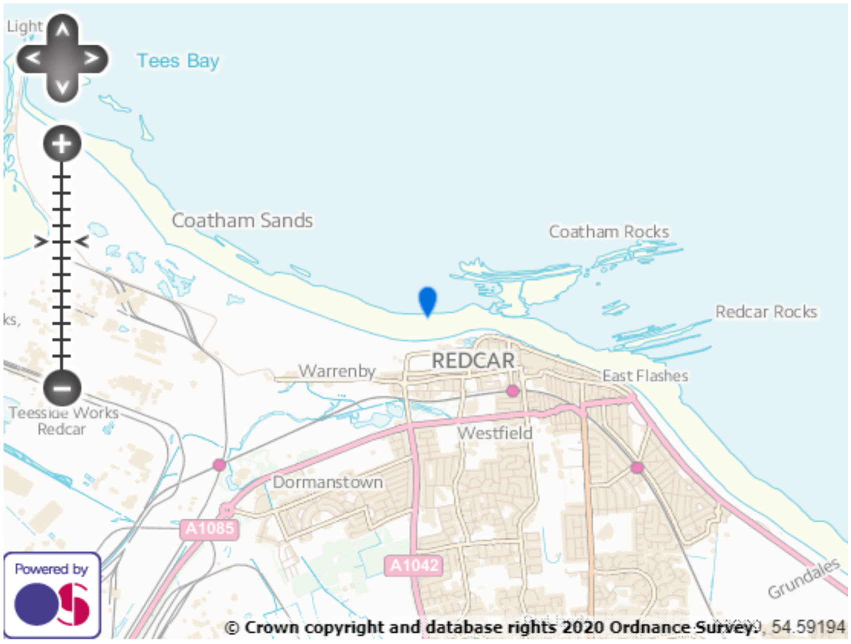


Figure 3: A map showing the location of the Redcar Coatham EA monitoring point.

4.1.1.3 Redcar Lifeboat Station

Figure 4: A map showing the location of the Redcar Lifeboat Station EA monitoring point.

4.1.1.4 Redcar Granville

Figure 5: A map showing the location of the Redcar Granville EA monitoring point.

4.1.1.5 Redcar Stray

Figure 6: A map showing the location of the Redcar Stray EA monitoring point. This is the most southern point of the five EA monitoring locations.

4.1.2 Blue Mussel Monitoring

Contaminants and current contaminant levels within the Tees Estuary are verified through the sampling of blue mussels (Mytilus edulis). The identified pollutants are shown in figures 7 to 11. Due to the number of pollutants tested for, some have been grouped; details of this can be seen in Annex 1. Samples of mussels are in batches of 60. Values quantified on the graphs are means taken from three batches of mussels per year.

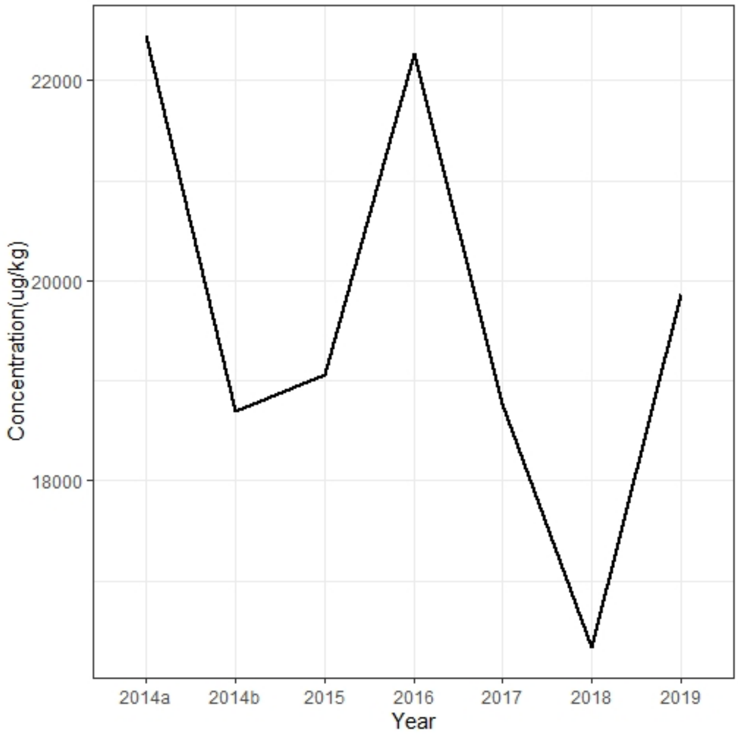


Figure 7: Mean level of Zinc (ug/kg) found in samples of blue mussels (Mytilus edulis) between the years 2014 to 2019 collected by the Environment Agency from the Tees Estuary (n.b., two samples collected in 2014).

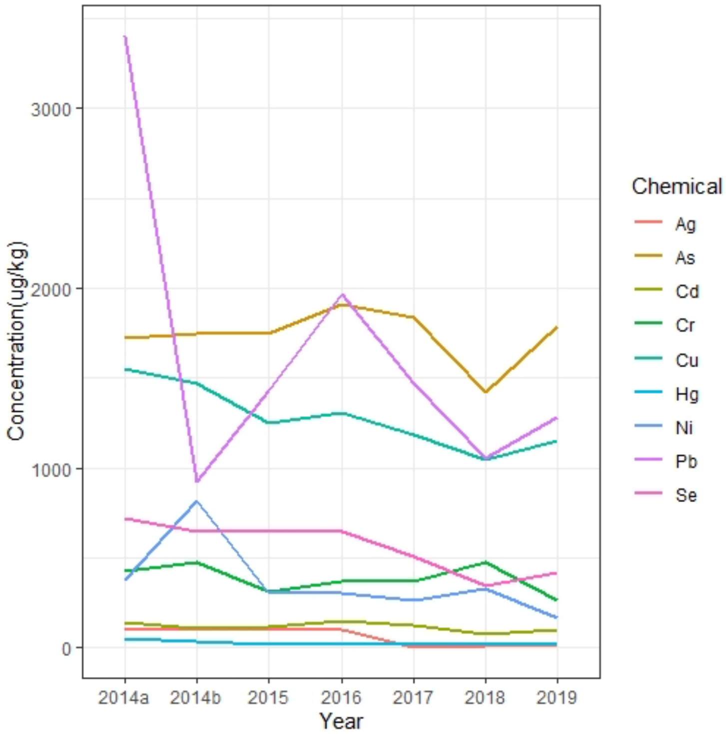


Figure 8: Mean level of heavy metals (ug/kg) found in samples of blue mussels (Mytilus edulis) between the years 2014 to 2019 collected by the Environment Agency from the Tees Estuary (n.b., two samples collected in 2014).

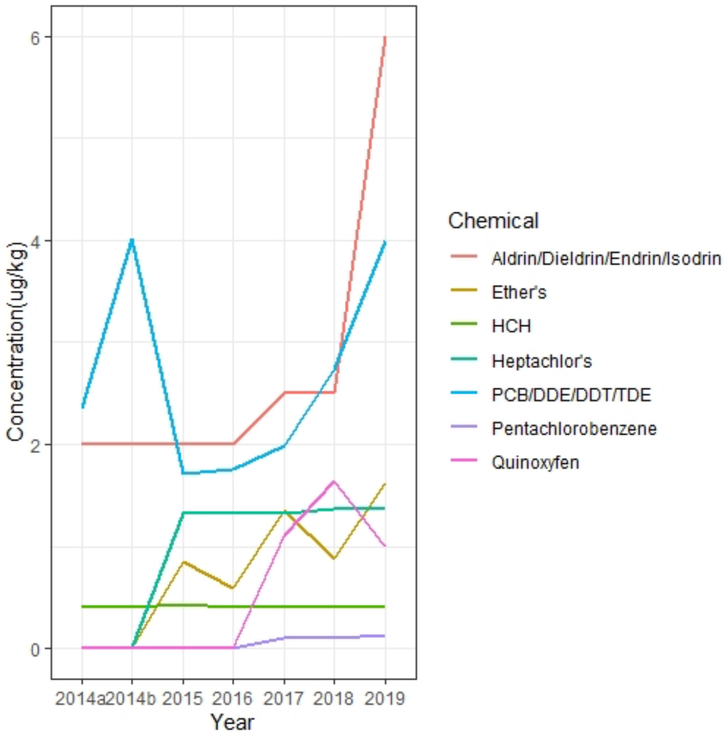
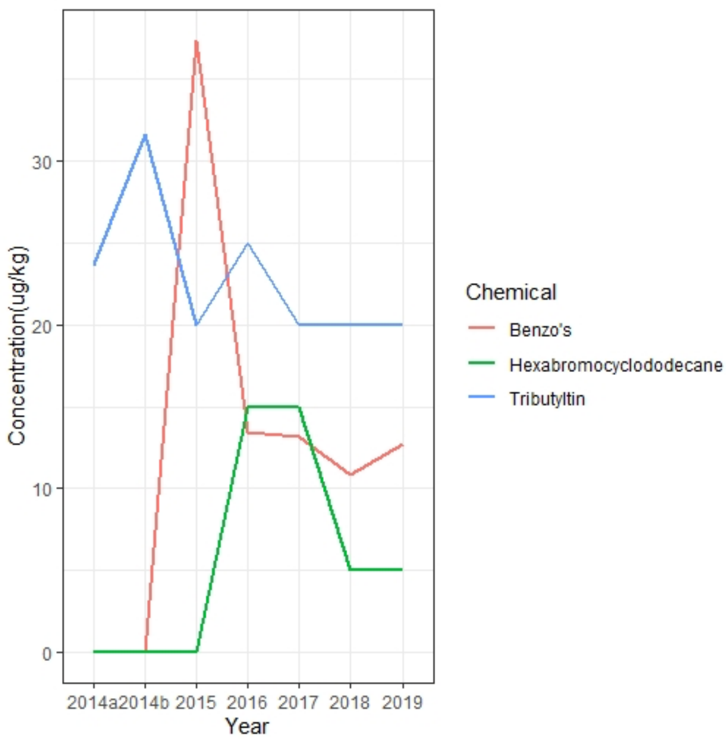


Figure 9: Mean levels of contaminants (ug/kg) found in samples of blue mussels (Mytilus edulis) between the years 2014 to 2019 collected by the Environment Agency from the Tees Estuary (n.b., two samples collected in 2014).

Figure 10: Mean levels of contaminants (ug/kg) found in samples of blue mussels (Mytilus edulis) between the years 2014 to 2019 collected by the Environment Agency from the Tees Estuary (n.b., two samples collected in 2014).



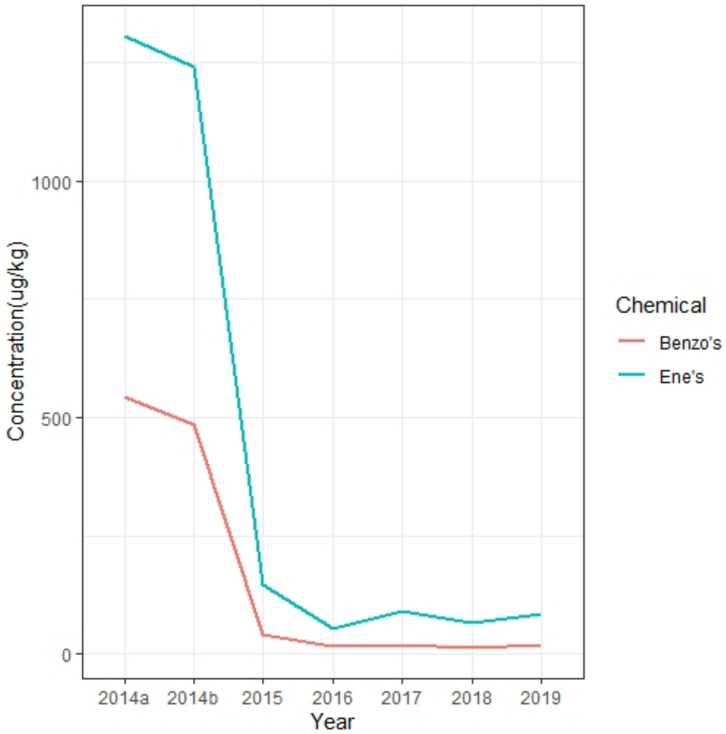


Figure 11: Mean levels of contaminants (ug/kg) found in samples of blue mussels (Mytilus edulis) between the years 2014 to 2019 collected by the Environment Agency from the Tees Estuary (n.b., two samples collected in 2014).

A number of different contaminants have been recorded inside blue mussels in the vicinity of the Tees Estuary. These results confirm that each contaminant displayed is present in the local environment to a degree. The concentration of contaminants verified varies between toxin to toxin. Following sampling, 10 heavy metals are known to be present inside the estuary. Zinc was shown to be the most concentrated of these (figure 7). A number of other organic and inorganic contaminants were identified (figures 8-11). The majority of these pollutants are however, shown to be decreasing in concentration, or remaining stable, across the sampling points around the Tees Estuary.

Much research has been conducted to understand the effects of different pollutants on bivalve physiology. Blue mussels (Mytilus edulis) are, however, the most researched species, with studies focussing on some of the pollutants known to be in the River Tees, such as flouranthene, heavy metals (Amiard et al., 1986; Roesijadi & Fellingham, 1987) DDT, dieldrin and PCBs (Hellou & Law, 2003; Sunila, 1988).

It has been found that although cobalt, iron and dieldrin have no effect on the gills of blue mussels, cadmium, copper, lead and silver do, causing an inflammatory response in the gills. After continued exposure to silver, cells of the gills became vacuolated. Continued exposure to copper caused the deformation of parts of the filaments. Exposure to lead caused a loss of lateral cilia and sloughing of the lateral cells within the gills. Exposure to organic pollutants (PCB and DDT) caused loosening of the intercellular connections in the epithelia and cell shrinkage (Sunila, 1988).

Culturing shellfish in industrialized estuaries may reduce the degree of shellfish growth and cause proper immune functionality to be suppressed. As a result, shellfish may be more suspectable to disease and cause stocks to have a higher mortality rate (Brown et al., 2020). Although there is a diversity of contaminants and high levels of some compounds and elements found inside the Tees Estuary, clearly mussels are able to tolerate these levels and can remove them from the water column, thus acting to improve water quality to some degree. It is therefore feasible that this species could be grown in this area. The amounts of pollutants found in their tissues, would, however, potentially cause issues using populations of shellfish in this area for human consumption. Cleaning of the shellfish to remove harmful substances before they would be fit for human consumption could be required. The large amounts of cleaning that would be needed to make these safe to eat would reduce the viability of such a fishery.

4.1.3 Wind farm Site Environmental Conditions

Environmental surveys were conducted both pre and post construction at the Teesside wind farm site, to review all environmental conditions present. Wind farm sites are selected due to their suitability for the construction of offshore renewable developments however, appropriate mariculture enterprises within these locations may be restricted by the offshore environmental conditions exhibited.

The offshore wave climate present at the Tees wind farm is highly dynamic. This site is exposed to high wave action. At the location of this wind farm, 90% of swell waves travel inshore from a northernly direction. Approximately 50% of swell waves are recorded at reaching heights of 0.5 meters or higher. Around 40% of offshore wind-sea waves are directed straight at the coastline. Any localized southernly wind-generated waves are likely to be overwhelmed by northernly swell, due to swell having a significantly longer wave period. The shallow depths found at the coastal adjacent side of the wind farm site, causes wave shoaling, which further increases wave height. The most north-eastern tip of the wind farm is most exposed to wave action, thus receives the severest inshore wave impact. Wave strength reduction will occur leading to the coastal facing proportion of the site due to the shallowing water depths. This region of the site however, will therefore face the most prominent wave breaking (Marine Data Exchange, 2022a).

The velocities of currents occurring within the Tees wind farm site are significantly lower than current velocities found offshore. The average sea-surface current velocity was recorded at <1.0 m/s at several sampling points within the windfarm development area. The ebbing tide from inside the Tees Estuary, together with the South Gare Peninsula causes reverse current circulation to occur. Tidal flow velocities inside the wind farm nevertheless are low. Tidal flow speeds ranged between 0.25 m/s to 0.5 m/s on spring tides during peak flood periods (Marine Data Exchange, 2022a)

The maximum sea surface water temperature reached at the Teesside wind farm site is 16.7°C, down to a minimum water temperature recording of 7°C (Marine Data Exchange, 2022b).

The seabed within the Tees wind farm area is virtually featureless and flat. The majority of the site is covered with silty sand. In the northern proportion of the site, there is a large area made up of exposed bedrock and gravely clay (Marine Data Exchange, 2022b).

The environmental conditions at an offshore wind farm site will dictate the feasibility of any proposed mariculture developments. The presented environmental perimeters at an individual wind farm should be used to determine if a), the selected mariculture species could survive in the offshore conditions displayed and b), if the mariculture installation type required to culture that selected species would be suitable for installation within the environmental conditions presented. Within the vicinity of the Tees wind farm, a variety of marine species could effectively be cultured from both surface-based and seafloor situated mariculture installations, given the known environmental conditions displayed at that location.

4.2 Shellfish Species & Tolerances

There are a number of different species that may be suitable to culture within the Teesside offshore wind farm, specifically scallop species, mussel species, oyster species and macroalgae. Evidence suggests that a multitrophic system with a diversity of marine species, such as seaweed and other reef-forming bivalve species, can improve yields than single-species culture alone (Michler-Cieluch et al., 2009).

The specific-species options identified for mariculture inside the Teesside offshore wind farm are the blue mussel (Mytilus edulis), king scallop (Pecten maximus), queen scallop (Acquipecten opercularis), European flat oyster (Ostrea edulis), pacific oyster (Crossostrea gigas), kumamoto oyster (Crassostrea sikamea) and macroalgae, namely kelp species.

Pacific oysters make up 98% of all farm-reared oysters (Simply Oysters, 2021), however, it is an invasive non-native species (INNS) to the UK. Kumamoto oysters represent a small proportion of cultured oysters and are also non-native species to the UK. As we aim to support native species throughout this work, we will not be including these two oyster species within this feasibility study.

Each identified species requires certain habitat characteristics to be met, within their specific environmental tolerance range, in order to survive and thrive. To ensure species survival, the selected mariculture site must provide the correct abiotic requirements, for example, salinity level, water temperature, oxygen concentration and provide a sufficient replenishable food source i.e., phytoplankton. The site must also be void of a significant number of predators and consist of a suitable benthic substrate (if applicable) (Smaal et al., 2017).

4.2.1 Blue Mussel (Mytilus edulis)

Blue mussels are a relatively adaptable species. They are capable of inhabiting a range of abiotic environments in cold water regions. For instance, the blue mussel can inhabit locations of varying wave exposure, from extremely sheltered to highly exposed. They are also proficient at residing in both strong to weak tidal currents. This species can thrive on a variety of different substratum; mud, sand, mixed sediment, pebbles and rocks. Blue mussels display a maximum biomass between a water depth of 5 to 8 metres deep (Westerbom et al.,2002), however they are able to withstand living in intertidal areas exposed during low tide, down to around 10 meters deep. They are particularly resilient against predators and competing species. They can survive in densities up to several thousand per meter squared (fromnorway.com, 2022). They are acclimated to a water temperature range between 5°C to 20°C, with a maximum tolerance up to 29°C for a limited time period (Animal Diversity Web, 2019).

Blue mussels are filter-feeders and thus require a sufficient replenishable food source of phytoplankton and other organic particles in order to grow (fromnorway.com, 2022). They are capable of filtering up to 5 litres of seawater per hour (Offshore Shellfish Ltd, 2021) and therefore would aid in improving water quality within the Tees Estuary, by filtering out pollutants and excess inorganic and organic nutrients.

The Teesside wind farm site provides suitable environmental conditions for blue mussels to survive. It can therefore be presumed that blue mussel mariculture in the vicinity of this area could be successful. As the wind farm lies between 7 to 15 metres deep, blue mussels could be cultivated best in the shallower parts of the site if using seafloor-based mariculture or in deeper areas of the wind farm if suspended at the water surface.

4.2.2 King Scallop (Pecten maximus)
The king scallop, also known as the great scallop, is one of two species of scallop found in the UK. In natural environments they live on the seabed. They are a semi-mobile species with the capability to move around short distances using the propulsion created when they open and close their valves. They reside only in soft substrate and have a preference for clean, firm sand or gravel. Fine sediment is unsuitable unless current speeds are low otherwise smothering could occur. The ideal water depth for king scallop settlement ranges between 15 to 30 meters, they are however capable of living up to depths of 200 meters (Laing, 2002).

King scallops are filter-feeders. They would be able to help improve water clarity and quality inside the Tees Estuary to a degree. However, other bivalves, specifically mussel species and oyster species, have a far superior water filtering capability compared to scallop species (Food.gov.uk. 2022).

King scallops could inhabit the wind farm site due to the availability of suitable soft substrate. The scallops would however, need to be cultivated inside fixed gear to avoid them freely moving out of the vicinity of the wind farm as they grow. Rearing the scallops in nets suspended at the water surface would be the alternatively option, although wave exposure at the wind farm site may be too high to make this technique viable.

4.2.3 Queen Scallop (Acquipecten opercularis)
The queen scallop is the other of the two species of scallop found in the UK. Queen scallops inhabit soft seafloor substrate and can live up to depths of 100m. The environmental tolerance parameters of queen scallops vastly match those of king scallops.

Equivalent to king scallops, as the wind farm site has a maximum depth of 15 meters, there should be multiple locations suitable to grow queen scallop in a suspended culture around the site. However, culturing scallops within the surface layers of the water column does negatively affect species growth rate. They are predominantly a species that likes to reside buried in soft sediment in low densities. Stress on the scallops equating to poor growth rates and increased vulnerability to disease otherwise could result (Laing, 2002).

4.2.4 European Flat Oyster (Ostrea edulis)

The European flat oyster, otherwise known as the native oyster, is a native species of the UK. The European flat oyster population has been in steep decline over the past centuries. Their popularity as a staple food stuff alongside detrimental environmental factors led to their decline in the majority of areas across Europe.

Oyster larvae require a hard substrate to settle. In natural environments flat oysters live on top of the shells of other oysters including empty shells, from this, they form oyster reefs. Flat oysters are regarded as ecosystem engineers as are capable of building their own reefs following spat settlement. Furthermore, they are capable of extending their existing reef habitat across soft substrate. A salinity range between 25 to 30‰ is optimal for flat oyster growth and spat survival. A salinity level below 20‰ would be unsuitable for survival. Flat oysters can live at depths of up to 80 meters deep. In intertidal zones, time between re-submersal in water limits survivability, nevertheless, flat oysters can be found present up until the low-tide limit. In theory, most water depths between these ranges are regarded as suitable for flat oyster growth and survival (Smaal et al., 2017).

Low velocity currents are crucial for larvae settlement. However, sufficient current speed is necessary for continual oxygen and organic nutrient supply i.e., their food source. Flat oysters are tolerant to high current speeds, particularly when inhabiting hard substrate. Low current speeds could result in an adverse sedimentation rate which could result in smothering. A current velocity between 0.25 and 0.6 m/s is optimal for flat oyster survival (Smaal., 2017). A single European flat oyster has the capacity to filter 200 litres of seawater per day (Zu Ermgassen et al., 2020b). This ability helps improve local water clarity and removes pollutants from the water column. Culturing native oysters or creating artificial native oyster reefs inside the Teesside wind farm could significantly help to improve local water quality within the Tees Estuary.

Research into Flat oyster growth suggests that oysters held in cages in the middle of the water column have an increased growth rate compared to those at the bottom and top of the water column (Zrnčić et al., 2007). However, both surface-based and seafloor-based mariculture would be regarded as suitable. There are many locations round the wind farm where cages could be placed at the water surface or on the seabed given the environmental perimeters present. Alternatively, depositing substrate for seafloor cultivation could be an option in some locations inside the site.

Of all bivalves mentioned in this study, European flat oysters that the greatest capacity to filter water, making them an ideal species to culture to generate water quality improvements whilst providing an economic stimulus.

4.2.5 Macroalgae Spp.

Seaweeds are divided into three separate groups; green seaweeds (Chlorophyta), red seaweeds (Rhodophyta) and brown seaweeds (Phaeophyta). These groups are based on the seaweeds photosynthetic pigment (Stanley et al., 2019).

Different seaweed species require different environmental conditions to grow. Brown seaweed, namely kelp species, are most widely used in commercial mariculture worldwide. Sugar kelp (Saccharina latissima) is the most cultured seaweed species in Europe. It is the fastest growing, making it ideally suited for mariculture purposes. It can live in water depths up to 30 meters and survives well in high wave-exposure sites. Winged kelp (or Dabberlocks) (Alaria esculenta), also naturally grows in exposed locations however, it can successfully be cultured in sheltered regions. This species is more sensitive to high water temperatures. It has a preference for colder water regions, thus is primarily grown in Northern Europe. Optimal growth occurs up to depths of 8 meters. Oarweed (Laminaria digitata) has a slower growth compared to sugar kelp, but it is found in the same geographic regions. Oarweed typically resides in shallower intertidal regions and characteristically forms kelp beds. This species is traditionally hand gathered and was the primary species used in the seaweed industry prior to the development of offshore seaweed cultivating practices. Cuvee (Laminaria hyperborea) is a related species to oarweed. It grows in semi-exposed locations and depending on water clarity, can grow up to depths of 30 meters. However, its growth rate is very slow making it less suitable for mariculture purposes (Stanley et al., 2019; Aberdeenshire Council Seaweed Cultivation, 2021).

Examples of red seaweeds species used in mariculture can be seen. Dulce (Palmaria palmata) is an intertidal seaweed species widely harvested across Ireland and Scotland. This species lifecycle is unpredictable making it challenging for using as a farmed species. Green seaweeds, specifically Ulva species, form very fine sheets therefore are only suitable for culture in very sheltered locations. They grow extremely quick in nutrient-rich conditions. Green seaweed species mariculture is extremely limited. No culturing of green seaweed currently takes place in Europe (Stanley et al., 2019).

Culturing seaweed would aid in water quality improvement. Seaweed absorbs inorganic nutrients from the water column for growth during photosynthesis. This uptake of inorganic nutrients will provide positive remedial benefits to the Tees Estuary, through helping to combat surplus nutrient loads within the localised water body (Aberdeenshire Council Seaweed Cultivation, 2021).

Kelp species require a hard, rocky substrate to attach to in order to establish. The benthic substrate inside the Teesside wind farm comprises of soft sediment, except for scour material placed around each individual turbine during wind farm construction. For kelp to be bottom cultivated in the wind farm vicinity, artificial structures or attachment to scour material would be required to stimulate growth. However, water clarity inside the Tees Estuary is relatively poor. The water depths present in combination with the reduced water clarity, would equate to the kelp receiving limited exposure to sunlight. It is consequently unlikely artificially placed kelp beds could grow inside the wind farm due to water turbidity levels present (H. Catherall, personal communication, November 25, 2021). Surface-based seaweed mariculture would still be suitable. All required environmental factors would be met for seaweed survival and effective culturing inside the wind farm area. However, the wind farm site is open to high wave action. Appropriate species selection must be considered.

4.3 Methods for Mariculture within Wind Farms

For the identified species to grow, at some point in their life cycle they require a hard surface to attach to or grow upon. In a natural environment this would be provided by rocky outcrops or the shells of other individuals. In the Tees Estuary these are not available. Structures must therefore be provided to cultivate such species and to make cultivation commercially viable. A number of options are available for attachment.

4.3.1 Ropes

Ropes can be used to provide a rough surface for spat and seeds to grow upon. Ropes are used for surface-based mariculture installations.

This method is particularly useful for blue mussels. It has been shown to work as the basis for mussel fisheries in numerous locations. Ropes hang vertically down in the water column. These ropes are soaked in seed laden water and left for the seed to settle onto the rope. Mesh covers the ropes to ensure spat attachment when placed into the sea. The mesh will degrade away after a few weeks. The approximate production of blue mussels cultivated via lines is around 24 tonnes per hectare. This production rate is 1.5x higher than bottom plot mussel cultivation (Offshore Shellfish Ltd, 2021).

The primary cultivation method for seaweed species also, is to attach seeds or spores to ropes. Attachment can be done through vegetative propagation, where fragments from a “mother plant” are attached directly to the growing rope. However, in seaweed farming the most common method of seed attachment is done through wrapping seeded-line around the main growing rope. As the seeds develop, the seaweed reattaches to the main growing line from this twine.

Seaweed ropes are traditionally suspended horizontally in the water column, held afloat and kept in place by a system of buoys and anchors attached to the seabed (Khan & Satam, 2003). Culturing seaweed by suspending it horizontally in the water column is the most cost-effective, simple and widely used technique however, it is only suitable for use within sheltered locations. Various other designs of cultivation structures are possible. Some techniques are more appropriate for exposed environmental conditions or are most space-efficient and therefore ideal for upscaling farms. Other methods include; adapted mussel longlines, i.e., vertical ropes, grid-based systems and offshore cultivation rigs. The suitability of particular types of cultivation structures are influenced by the environmental and socio-economic variables at each specific site.

4.3.2 Cages

The use of cages to cultivate shellfish is a well-known technique and has been shown to be successful for all bivalve species mentioned (Román et al., 1999; Laing, 2002). Cages prevents the need to search for individuals or catch those able to propel themselves through the water. Cages containing stock enables the shellfish to still be exposed to the correct environmental conditions, whilst being easily accessible. In particular, cages enable water movement between the shellfish for food and oxygen provisioning. Cages are typically suspended at the water surface either held afloat by a buoy or attached to a fixed structure. Using cages fastened to an inshore structure, such as a pier, is currently a popular technique used within native oyster restoration projects to create oyster nurseries (Native Oyster Network, 2022).

Placing cages on the seafloor is an alternative option, however, research has shown cages risk sinking into soft sediment. This outcome would result in potentially smothering the shellfish. Cages therefore left in-situ on the seafloor need to be placed onto hard substrate. Examples of placing cages on the scour material around individual wind turbines, as well sitting cages upon artificial reef structures have been trialled across Europe. This action raises the shellfish up off of the seabed to mitigate the risk of smothering. However, the shellfish are still vulnerable to predation and seabed hydrodynamics (Robertson et al., 2021; De Rijke Noordzee, 2022).

Divers would also be required to monitor and harvest the stock if cages containing shellfish are to be situated onto the seafloor. This makes this technique of mariculture more expensive and less commercially viable. Placing stock onto the seabed but not constrained inside a cage is an alternative option.

4.3.3 Reef structures

Reef balls are concrete structures that have textured surfaces, holes for different species to colonise and are hollow. This complexity of the structure maximises its surface area for colonisation and provides refuge for fish species within it. These structures would be permanent fixtures on the seabed as they are very heavy, which prevents movement of the structure. Movement may damage any growth on the reef ball.

Due to their weight, reef balls are not sold as pre-made units. Instead, their moulds are sold, ranging from US$690 to US$12,000 depending on the final structure size. The smallest units are 0.46m wide and 0.3m tall, and the largest units are 2m wide and 1m tall. These have been used in a number of locations around the world to create artificial reefs islands and have been shown to be able to withstand challenging conditions (The Reef Ball Foundation, 2017).

If this method was to be used, consideration must be given to the requirement of creating the reef balls using the moulds. This may require training and will require a concrete mix, both of which incur further cost. It is also certain that a number of reef balls would be required. The exact number would vary according to the size of reef ball and the area available. It is not clear how many reef balls one mould could be used to make, so this potential cost must be taken into account.

Reef cubes are eco-friendly concrete cube structures. They were developed to create individual artificial reef island units. Each cube is hollow with a circular hole on each cube side to permit crustaceans, fish and other marine life to take shelter inside. The surface of the cube encourages marine growth and reef building species to attach. Cubes can be coated with a shell veneer to attract certain bivalve species, principally native oysters.

Reef cubes are produced in a variety of different sizes. Cube size ranges from 150mm to 1500mm. Between these sizes, cost per cube ranges between £20 to £3000. Reef cubes can be used as individual units to form artificial reefs, alternatively, cubes can be collectively placed together and positioned in a pyramid form structure. Creating a pyramid provides a greater combined surface area and increases habitat complexity for species to take refuge and for natural marine growth, whilst also making the structure heavier and thus more stable in rough seas (Arc Marine, 2022).

Examples of other reef restoration projects using reef cubes inside wind farms can be found. The Rich North Sea project has placed several reef cube structures inside an offshore wind farm to allow for natural species recruitment, in combination with native oyster restoration trials (De Rijke Noordzee, 2022).

4.3.4 Depositing of Substrate

One method of mariculture is to provide substrate for growth, where natural materials that would create reefs in a natural setting are deposited on the seafloor to create an artificial reef. The provision of gravel and shells, otherwise referred to as "cultch", has been used previously in the creation of bivalve shellfish reefs such as blue mussels, although this method is predominately used for native oysters (Zu Ermgassen et al., 2020b). Artificial reef formation also provides a number of benefits to the local habitat aside from shellfish cultivation alone. Local net biodiversity richness will be improved.

In the correct conditions this has proven as a successful method, however, it is very labour intensive and expensive. It can also be a difficult process to source the cultch material, particularly shells, ready for deposition. Shells must be left outside and routinely turned in order for the material to dry out and any potential biological agents or invasive species to die before they can be dropped on site offshore. This biosecurity step can take up to 1 year before disposal is permitted (Zu Ermgassen et al., 2020a). This could potentially increase costs, as a storage area must be organised.

The collection of shellfish would also be more complicated on such a site if a fishery were developed. The use of dredging to remove shellfish would destroy the shell or gravel bed and all benthic marine life that has established. Subsequently, this fishing activity should therefore be avoided or be extremely well managed. Divers may be required for shellfish collection instead to mitigate reef damage, thus increasing exploitation costs.

4.3.5 Lantern nets

Lantern nets can be used to cultivate shellfish and are the primary culture method for scallop species. These nets form a circular tube with separate compartments that house a proportion of the stock. They hang vertically in the water column, held up and marked by buoys.

Rearing scallops via this method can be costly due to the large quantity of nets required to ensure that overcrowding and therefore potential for high mortality is minimized. Furthermore, evidence suggests that scallops reared in suspended cultivation can become stressed if subject to repetitive wave action resulting in movement of the nets. Growth rates of the scallops will be reduced or minimized.

Bio-fouling of shells, fouling of nets and predation on shellfish is an issue with suspended cultivation methods. As a result, when scallops reach a self-sustainable size (around 50-60 mm), farmers release the scallops from the nets and instead cultivate on the seabed where they are more protected from detrimental external factors (Laing, 2002). They are therefore then free in the local environment and not contained within a mariculture installation. Hand-diving or dredging for the scallops would then be necessary to exploit the stock. These techniques are either costly or highly damaging to the benthic marine environment.

Rearing stock via this method could be feasible inside the windfarm however, the additional cultivation challenges faced with this methodology might make this installation type less desirable than others previously mentioned.

4.4 Fishing Methods

Conversations with EDF Renewables have identified that there are areas (of undisclosed size) within the wind farm site that do not overlap wind farm cables or areas that are required for windfarm maintenance. These zones are the most suitable for the development of artificial reefs or other mariculture installations as they will not be disturbed, damaged or impact wind farm operational activities.

Fishing methods required will differ between mariculture techniques and species selected. If artificial reefs were used and left in-situ to rear bivalves, shellfish on these units would need to be harvested by divers. This would increase operational costs and reduce regularity in which produce could be supplied. This would also be the case if using divers to harvest shellfish growing on added substrate. However, significant benefits to the local ecosystem could result following the creation of an artificial reef habitat. Habitat enhancement could provide indirect economic revenues, as opposed to direct fishery development alone. If artificial reef units or substrate were used to establish new habitat within the windfarm, it could also lead to increased productivity outside of the bounds of the wind farm in the future.

Limitations would be expected surrounding where artificial reef positioning would be permitted inside a wind farm. It is strongly advised that artificial substrate or reef units are not placed on top of turbine cable routes. There is a risk that it would be necessary to dig up or remove any artificial reef present, in the event of a cable malfunction. Wind farm owners would deem this work vital over habitat enhancement. Receiving permission to situate artificial reefs above cable routes is assumed unlikely.

Scour material around the base of wind turbines acts as an artificial reef in itself. In addition, seafloor mariculture installations could be placed on top of scour material to further increase habitat complexity and support species restoration. Situating installations here would be an effective use of marine space, as they would be placed on top of pre-existing construction and utilise the same footprint. At present projects across Europe are piloting placing mariculture structures at the base of turbines. Project Blauwwind are conducting trials testing the survivability and recruitment of native oysters onto scour material inside Borsele III and IV wind farms (De Rijke Noordzee, 2022). However, in some cases placing mariculture installations on the scour material has been considered unviable. Wind farm vessels require free access to conduct routine or emergency work on individual turbines. Typically, vessels are anchors or fixed in place, mainly jack up vessels, in close proximity to the turbine. Objects placed on scour material could result in navigational issues or disrupt wind farm operations. Discussions over accepting mariculture installations to be situated on turbine scour material would have to be reviewed on an individual basis.

The cables and access points within the windfarm make it difficult for fishing practises such as dredging to be carried out within the site and could lead to expensive damage to wind farm assets. It is therefore typically deemed that this fishing method is entirely unsuitable for windfarm sites and would require considerable effort to avoid any cables that it would also be rendered unfeasible. This would create issues with using dredging as a method to collect shellfish growing on added substrate (NFFO, 2021). Furthermore, dredging causes adverse effects to benthic seafloor environments and consequently would not fall in line with conservation goals. Using alternative less-destructive fishing method would be advised.

The use of surface-based mariculture installations i.e., cages, ropes or nets, would make stock easy to monitor and harvest from the surface on a boat. The location of these mariculture ropes, nets or cages would be marked with buoys and securely anchored to the seabed to prevent them breaking loose in rough seas.

Suspended surface-based mariculture could be a suitable option in many areas around the wind farm to grow a variety of different species. The only contact to the seabed from the surface installation would be anchor points. This makes this mariculture type ideal for inside wind farms. They could easily be placed away from turbines, be relatively straightforward to move if necessary and no direct obstruction to subsea cables would occur. Deploying surface mariculture farms would be significantly cheaper and a faster process compared to depositing artificial reefs. Windfarm operations are therefore assumed to be less disrupted during initial set up. However, surface-based mariculture would result in a section of the wind farm becoming completely inaccessible to vessel traffic. Disturbance to pre-existing vessel navigational plans would result. Agreements with the wind farm owners would need to be arranged over designating suitable regions inside the wind farm to comprise surface-based mariculture farms.

An alternative to choosing one method would be to use a suite of methods in the vicinity of a wind farm. Combining a surface-based mariculture farm together with artificial reef placements will add additional value to a wind farm site footprint than farming alone. Evidence shows that surface-based mariculture installation types encourage marine species to aggregate as they provide shelter and protection (Michler-Cieluch et al., 2009). However, they are not permanent structures like artificial reefs. Surface-based farms increase local biodiversity through temporary habitat provisioning. Habitat complexity will be significantly improved by integrated muti-trophic mariculture, leading to increased net biodiversity. Direct economic benefits would be derived from farming at the sea surface.

The layout and spacing of turbines in wind farm design is the fundamental determent of whether a mariculture installation or fishing activity can function and co-exist within. Currently, wind turbine spacing is driven by technology not with the view to promote cross-industry coexistence (NFFO, 2021).

4.5 Ecosystem Services

Ecosystem services are defined as direct or indirect benefits that humans attain from nature. There are four separate categories of ecosystem services; supporting services, cultural, provisioning and regulating

(McLeod et al., 2020). It is generally accepted that the creation of habitat is positive for the natural world. These habitats can provide further benefits to humans, many of which address key environmental issues that we currently face.

4.5.1 Carbon Capture

The importance of locking away carbon within natural habitats is increasingly becoming more recognised. Carbon that is captured and stored by ocean ecosystems is referred to as "blue carbon". Blue carbon capture is important as our oceans take in at least 25% of the carbon that is released into the atmosphere (Macreadie et al., 2019). Worldwide, coastal ecosystems are highlighted as being highly valuable blue carbon sinks. Vegetated coastal habitats such as mangroves and saltmarsh only take up 2% of the global ocean area, but nonetheless are responsible for storing approximately 50% of organic carbon in the oceans (Lee & Sanderson, 2020).

It is well known that carbon is captured by bivalve shellfish. This carbon is stored in a solid mineral form. Bivalves sequester atmospheric carbon dioxide by feeding on carbon-fixing phytoplankton and deposit the carbon within their shells and soft tissue (Jansen & van den Bogaart, 2020). Carbon is removed from the ocean once it is stored within bivalve shells (Tang, Zhang and Fang, 2011). Net carbon storage in bivalves, such as in oysters, is determined through calculating the net deposition of carbon i.e., calcification, sedimentation and bio-deposition, minus the loss of carbon through resuspension, remineralization and respiration (Lee & Sanderson, 2020). Bivalve shellfish reefs act as important blue carbon sinks.

Bivalve mariculture offers significant potential in reducing the amount of carbon present in coastal waters. In China alone, 1.2 million tonnes of carbon is removed annually from coastal regions, through the culture of bivalves and seaweed species (Jansen & van den Bogaart, 2020). Farmed mussels have a high carbon sequestration rate of around 218kg $CO2^{-}$eq per tonne (Sheehan et al., 2019). Evidence shows that mussel farming produces the lowest carbon footprint of all global animal food production (Sheehan et al., 2019). Shellfish mariculture can therefore play a valuable role as a blue carbon sink (Tang, Zhang and Fang, 2011).

The role of macroalgae as a blue carbon sink has been a highly debated topic. Macroalgae grows on sandy or predominately hard substrate. The carbon burial potential from macroalgae growing on rocky substratum is limited. Nevertheless, detached macroalgae that has been transported to soft sediment regions can then contribute to long-term carbon sequestration following decomposition. The estimated global carbon burial rate of macroalgae into soft sediment is 6.2 Tg C year^{-}1 (Macreadie et al., 2019). The removal of carbon from the oceans by macroalgae is thus primarily restricted to during its lifecycle. Macroalgae acts as a good carbon sink due to it having a fairly long turnover time, around 1 year, plus a large biomass, compared to other marine primary producers (Tang, Zhang and Fang, 2011).

Culturing seaweed will enable carbon to be continually absorbed from the water column throughout its growth period. Macroalgae has the capacity to extract 120kg of carbon dioxide per tonne of wet seaweed (The Seaweed Company, 2022). Upon harvesting, this stored carbon will permanently be taken out of the marine environment. Seaweed mariculture therefore acts as a temporary blue carbon sink.

Persistently accumulating dissolved carbon dioxide in seawater is continually increasing the acidity of our oceans (Macreadie et al., 2019). The absorption and sequestering of carbon by marine primary producers and bivalve shellfish helps to alleviate ocean acidification.

Culturing bivalve shellfish or macroalgae inside the Teesside offshore wind farm, will positively contribute to removing a proportion of carbon from the water column throughout the duration of any mariculture enterprises, or unendingly following the development of artificial reef creation.

4.5.2 Water Quality Improvements

Filter-feeding organisms remove particulates from the water as they feed producing much clearer water. This performance of removing particulates from the water column reduced turbidity and can remove pollutants. This biological function of filter-feeders therefore improves water quality.

Bivalve shellfish have the capacity to significantly enhance the health of their local habitat. European flat oysters are able to filter and clean up to 240 litres of seawater per oyster per day (Native Oyster Network, 2022). This biological function works to improve water quality in close proximity to bivalve shellfish. Blue mussel aquaculture has proven to be an effective technique to reduce levels of eutrophication in the Baltic Sea (Kotta et al., 2020). Similar schemes utilizing bivalve mariculture elsewhere could prove effective.

Globally, around 221 species of seaweed are used for commercial purposes (Khan & Satam, 2003). Seaweeds absorb inorganic nutrients from the water column to fuel growth. This nutrient assimilation aids in reducing the level of inorganic nutrients in the vicinity of seaweed farms. It is worth noting that there are considerable differences in the nutrient assimilation capacity between seaweed species and amid differing environment conditions the seaweed is grown in (Racine et al., 2021). Despite this, culturing seaweed remains observed as a technique to reduce excess nutrients present in a water body. Seaweeds are widely used in combination with shellfish mariculture. Harvesting seaweed successfully removes the absorbed inorganic nutrients from the marine system.

Data from the Environment Agency provides evidence that blue mussels remove many elements and compounds from the river Tees, some of which are highly toxic (figures 7-11). This testing is however restricted to one species. Further testing on additional bivalve species would add extra value in gaining greater insight into the concentration of pollutants present inside the estuary and the effects pollutants have on the biological function of different species. It can be determined however, that current pollutant levels inside the Tees Estuary would not cause an offshore mariculture farm to be unviable, as shellfish already occur naturally within the estuary. Direct human consumption of bivalve shellfish may not be possible. Testing would be required to determine the status of this shellfish as a food product.

4.5.3 Supporting Marine Life

Offshore developments should ultimately aim to maximise the provision of beneficial ecosystem services and minimize associated detrimental effects to the marine environment. Sustainable mariculture developments should consider their overall effect on the local marine ecosystem.

Mariculture installations act as fish aggregation devices (FADS), encouraging marine species of all life stages to aggregate and utilize provisions created (Causon & Gill, 2018). Habitat provisioning from mariculture developments can improve ecosystem function, structure and spawning biomass in the local vicinity (Gentry et al., 2019). These developments provide a refuge for mobile marine species, as well as a surface for epibenthic fauna to attach to and permanently reside. This coming together of species enables a greater biodiversity to establish and helps populations to thrive (Kamermans et al., 2018). Areas with a high biodiversity also have more resistance to negative disturbance (Causon & Gill, 2018). Offshore mariculture farms thus increase local biodiversity through temporary habitat provisioning.

Offshore developments modify habitats. Combining mariculture together with artificial reef placements will add additional value to a site footprint than farming alone. Surface-based mariculture in combination with artificial reef creation will introduce new features to the seabed and water column. This action will increase habitat complexity, leading to amplified net biodiversity and biomass (Causon & Gill, 2018). Moreover, situating mariculture installations inside offshore wind farms, sites which alone have already been proven to attract marine species, will further add ecological value to the local area.

Mariculture can contribute to providing ecosystem services that extends beyond the direct production of a farmed resource. As well as the ecosystem and economic benefits of restoring a potential fishery, re-establishing native oyster beds around UK coastline would offer many indirect environmental benefits, like helping to stabilize sediment and dampen wave action, thus aiding in protecting shorelines from erosion. These intricate reef systems provide a hard substrate and a refuge for other species to colonise, improving the net biodiversity of the habitat (Fitzsimons, et al., 2019).

New habitat created by mariculture installations or artificial reef beds not only support the stationary species that are fixed to these structures, but also support a wider range of life. Evidence suggests that habitats with high species richness supports the recovery of commercially important fish stocks (Causon & Gill, 2018). Additionally, the footprint of mariculture farms can act as a protected area to these other marine species and commercial fisheries, as fishing vessels will be prohibited from entering the sea space directly around the circumference of any designated farm site. Fish populations will be allowed to recover in these “safe zones”. Stock sizes could then in time increase. Increased population sizes in these localized areas will eventually equate to fish “spilling out” into other areas of the sea surrounding these protected zones, where fish can be exploited. Designating areas of the sea where species populations are protected will allow stocks to constantly be replenished (Ashley et al., 2014).

Positive effects on local fisheries landings can be generated from establishing a mariculture farm. Moreover, fishing activity is already limited inside offshore windfarms. Fishing vessels avoid undertaking fishing activity in the vicinity of wind farms, to avoid damage to fishing gear occurring, such as snagging on cables or scour protection material. Windfarms can therefore provide a sanctuary to the marine ecosystem found within (Smaal., et al, 2017). The provisioning of a new habitat could lead to increased fish stocks within the local waters, generated from the ecosystem services provided (Gentry et al., 2019).

Principally edible crab and lobster are fished around the Tees Estuary. Installing a mariculture development inside the Teesside Wind Farm could indirectly lead to an increase in local crustacean stock sizes. This action would therefore support the local potting industry.

4.5.4 Supporting Species and Habitats of Conservation Importance

As well as conserving species and habitats for the benefit of humans, conservation is also completed for the good of the planet. Native species whose populations are struggling or habitats that are rare must be conserved to ensure their continued persistence on earth. Offshore mariculture developments can be valuable structures to aid in conserving threatened species and habitats.

The European eel is a critically endangered species on the IUCN Red List. Its numbers have declined rapidly over recent decades owing to negative anthropogenic influences, namely overexploitation and barriers to upstream migration. Only small numbers reach upstream river courses to live and grow before returning to their spawning grounds. Inshore habitats, like artificial reefs, encourage species to aggregate and provide refuge for small fish such as young eels, increasing survival rates at this life stage. Oyster cages inside estuaries have been found to be used by European eels at various sites around the UK coast (Zu Ermgassen et al., 2020b). It is evident that species of conservation importance can positively benefit from the inclusive of mariculture structures in the marine environment.

Direct mariculture enterprises can target the restoration of vulnerable marine species. More than 85% of European flat oyster (Ostrea edulis) beds have been lost globally. In the UK, European flat oyster populations have declined by 95% from previous levels. They are regarded as ecosystem engineers, where multiple generations of oysters will settle then grow on top of the mature oysters, creating an intricate three-dimensional reef structure. These native oyster beds are now regarded as one of the most threaten marine habitats worldwide.

Figure 12: Piscatorial Atlas Map on the distribution of the European oyster in the North Sea (Olsen 1883) (Pogoda, 2019).

Historically in the North Sea, the European flat oyster formed extensive beds in inshore coastal regions (figure 12) Native oyster populations suffered a significant collapse in the mid-20th century due to disease, water pollution, invasive non-native species (INNS) and unsustainable fishing pressure. Coastal communities and the health of marine ecosystems have since been negatively affected from the loss of these oyster beds (Robertson, et al., 2021).

Many estuary-focused native oyster restoration efforts across Europe have begun. The Native Oyster Restoration Alliance (NORA) and Native Oyster Network (UK & Ireland) were both established in 2017. These networks, in conjunction with each other, have brought together conservationist, scientists and fishers from a vast range of organisations across Europe, all with the shared goal of restoring the native oyster across the region (Wetlands International Europe, 2021). Several projects across Europe are currently focused at conducting native oyster restoration inside offshore wind farms (De Rijke Noordzee, 2022).

A large proportion of kelp forests around the UK coastline have been lost. These declines are largely due to adverse human impacts, particularly destructive fishing activity and pollution. Bottom-towed fishing gear, specifically trawling and dredging, tears kelp from the seabed. When these mobile fishing gears are repeatedly passed over the same patch of seabed, natural kelp regeneration is prevented leading to the permanent destruction of the forests (sussexwildlifetrust.org.uk, 2022). Around the Tees Estuary and local coastline, kelp abundance has reduced from its previous extent, mainly due to past heavy industry. Coal mining damaged the health of the local environment. Spoil heaps formed and left remnant from the coal mining industry led to a decline in coastal water quality (H. Catherall, personal communication, November 25, 2021). This poor water quality caused local kelp forests to be depleted. Direct rearing through mariculture development may be the only viable technique to enable the repopulation of these declining species.

Establishing mariculture installations comprised of species of conservation importance in the vicinity of the Tees wind farm, could provide numerous environmental and socio-economic benefits, alongside helping to restore highly threaten native species.

4.6 Economic Effects

There is opportunity for the aquaculture industry to play a large role in the wider blue economy. The need for its role to expand is driven by the current circumstances of wild fisheries, where the majority of commercially importance fish stocks are being exploited either close to or over their maximum sustainable yield (MSY) (Seafish, 2022). Over half of global mariculture food production comes from bivalve shellfish. These shellfish are amongst the most sustainable mariculture products, as they derive their own food from natural sources. No additional food supplements are required (Webber et al., 2021).

UK shellfish mariculture production has fluctuated in the past however, it is currently observed as a growing industry. In 2017, the industry generated a total worth of £27 million produced from 18,000 tonnes of produce. These figures increased in 2018 to a total worth of £28.3 million from around 21,000 tonnes. In the UK, mussels (*Mytilus spp*.) are the primary shellfish species produced through mariculture. In 2018, mussel mariculture farms generated around £16 million from 14,247 tonnes of shellfish. The second most cultivated species in the UK was the Pacific oyster (*Magallana gigas*) which produced 2,220 tonnes worth almost £7 million. The remaining UK shellfish production in made up of European flat oysters (*Ostrea edulis*) and king scallops (*Pecten maximus*), totalling 24 tonnes worth £172,756 combined (D&S IFCA Mariculture Strategy, 2021).

Scallops were the third most valuable UK fishery in 2018, worth £70 million and the fourth most valuable in the US worth $541 million (Stewart et al., 2020). Despite their high value, scallop mariculture in the UK remains extremely limited to a select few farms. This occurrence is primarily due to the difficulties around rearing scallops in enclosed installations.

Seaweed mariculture is rapidly expanding in the UK. A number of pilot seaweed farms began operation in 2020. This industry growth in expected to continue as an increase in market diversity and improved supply chains become viable. Annually, over 6 million tons of seaweed is consumed. The majority of this figure is comprised from Asian markets. The value of seaweed for human consumption generally ranges between US$18 to US$23.5 per kg. Notable some species achieve a considerably higher price. End product market also greatly dictates the economic value of cultured seaweed. In the North Sea region, it is currently expected that seaweed can be valued at US$950 per metric ton for use primarily by hydrocolloid producers (van den Burg et al., 2016).

Total economic outputs from a mariculture farm are dependent upon a number of factors, primarily; selected species, end product market, farm operational capacity and total economic inputs. Initial start-up costs differ between farm types. Setting up farms for certain species, such as native oysters and macroalgae, is generally deemed as requiring a higher financial input, compared to other species types. This factor is primarily due to the need to purchase initial seed stock from an external supplier. Challenges surrounding biosecurity and INNS make this process a necessity which adds initial input expenses. Some mariculture types however, allow for stock to be collected directly from the local marine environment. Blue mussel farms often incorporate spat collectors, where a continual supply of stock can be collected naturally from the surrounding water column (Offshore Shellfish, 2021).

The majority of mariculture species can be harvested at least on a yearly basis, although some species, mainly native oysters, have slow growth rates, taking several years to reach maturity. These slow growth rates have driven the pacific oyster to be the main oyster species cultured in the UK as a more effective industry alternate. However, the higher market value of native oysters could make this species a more desirable option, despite a slower stock turn-over rate (Long, Ffrench Constant and Witt, 2017).

Direct employment opportunities would be created following the establishment of a mariculture enterprise. Staff would be required to manage and maintain a farm. Number of staff required would be dependent on farm scale, installation set up structure and the required fishing method. A minimum number of two staff members would be required to complete harvesting per hectare (Menzies, Brook and Parker, 2021).

The total economic revenue of mariculture differs greatly between farms. A number of factors control this, principally; stock species, installation type, fishing methods, supply rate, target market and staff numbers. Cost-benefit analysis would be required on an individual basis to determine the profitability a selected mariculture farm following initial capital costs.

Aside from the direct economic benefits generated from rearing a fish stock, mariculture enterprises can also provide additional economic services secondary to farming. Culturing bivalve shellfish notably improves local water quality. Bivalve mariculture is an effective technique to mitigate eutrophication. In EU coastal waters, excess nitrate removal solely through bivalve farming is valued at US$20-30 million per year (Webber et al., 2021).

The ecosystem services that habitats provide can save local communities money. Many coastal habitats provide flood protection, removing the need to implement flood defences, as well as helping to protect against coastal erosion. Carbon capture provided by seagrass and saltmarsh, amongst other habitats, acts against climate change. Further indirect economic stimuluses could be generated from mariculture and wind farm colocation, as together, both developments would aid in increasing local marine biodiversity and support fish populations of commercial importance.

A mariculture development placed inside the Teesside Wind Farm would offer a direct commercial business opportunity, alongside providing ecosystem services to the local environment, that in turn could generate economic services to the local community.

4.7 Other Considerations

4.7.1 Licensing

The Teesside Wind Farm is located on an area of offshore seabed leased to EDF Renewables by the Crown Estate. The license for a wind farm development in this area, along with the associated set up, running and maintenance activities, is provided by the Marine Management Organisation (MMO). Activities outside of those agreed with the MMO are not permitted in the license area. Any proposed activity must not affect vessel navigation, conservation status or other legitimate users of the sea. Licensing and policy frameworks may differ in countries outside off the UK.

In order to implement a mariculture development within a wind farm, permission from the Crown Estate and EDF Renewables to complete this work, in addition to an MMO license that covers the initial works and any follow up works that may be required. If any substrate needs to be added to the seafloor in order to create a reef structure, a separate license will need to be obtained for this work from the MMO. It must be shown that whatever activities take place, they will not detrimentally impact the wind farm or local environment.

Consent from other local statutory agencies may need to be sort and approval granted depending on the proposed mariculture development. If a fishery was to become operational, additional licensing may be a requirement. Examples of potential further licensing bodies are Natural England, CEFAS and Inshore Fisheries & Conservation Authority (IFCA).

4.7.1.1 Bivalve Shellfish Testing

Bivalve shellfish pose a significant food safety risk. Bivalve's filter-feed organic and inorganic matter from the water column and can therefore potentially bioaccumulate harmful chemicals and microbiological contaminants present in their local environment. Shellfish containing high contaminant levels could be lethal to humans following consumption (CEFAS, 2021).

Official live bivalve mollusc (LBM) sanitary tests must be conducted regularly if mariculture produce is to be sold for direct human consumption. The relevant local authority must undertake these tests issued by the Food Standards Agency (FSA) and the Centre for Environment, Fisheries and Aquaculture Science (CEFAS). In the UK, classified shellfish harvesting areas are tested monthly. Prior to a new shellfish harvesting areas being classified, FSA sanitary surveys must be conducted. Shellfish are also principally tested for Escherichia coli levels. Wild harvesting sites are classified as A, B, C or prohibited, determined by E. coli test results.

Trace elements, heavy metals and toxins stored within shellfish flesh risks human health. Shellfish mariculture sites should be installed away from highly developed or industrialised areas. Harmful Algal Blooms (HABs) also threaten food safety as bivalves could consume these microalgae. If HABs are present, harmful toxins could be bioaccumulated inside the shellfish. HABs can form dependent on weather conditions and local coastal water circulation. Concern over HABs is comparatively low in the UK. However, testing of produce before sale should still be conducted. In the UK, the relevant authority must conduct monthly toxicity tests under official Regulation (EC) No 854/2004 of animal products intended for human consumption (D&S IFCA Mariculture Strategy, 2021).

4.7.2 Local, Regional and National Action Plans

As the environment is such an important topic and there is an increasing push to support nature and conservation, there are many local, regional and national plans that identify keys objectives at all levels. An overview of these plans and their potential links to mariculture colocation in Teesside Wind Farm follow.

4.7.2.1 Local

The Tees Valley Combined Authority covers 5 local authority areas (Darlington, Stockton-On-Tees, Middlesbrough, Hartlepool, and Redcar & Cleveland) and aims to maximise investment in the Tees Valley. Their ambitions to bring this to fruition are outlined in the Tees Valley Strategic Economic Plan. Within the plan there are multiple strategic priorities, one of which is research, development, innovation and energy. Within this priority, the combined authority mentions carbon capture and storage and low carbon advanced manufacturing including offshore wind. Coastal habitats are well known at providing good carbon capture opportunities, offering some of the highest levels of carbon capture of all UK habitats. Through this project we would be able to capitalise on the push for development of the offshore wind industry to integrate habitat creation with offshore wind farm development and develop plans for more environmentally friendly decommissioning.

The Tees Estuary Partnership formed in 2016 with a vision for the area to be a haven for wildlife, as well as an area of sustainable economic growth and business investment. This project is consistent with the vision of creating an artificial reef within the Teesside wind farm, creating a haven for wildlife within the thriving industrial landscape, enabling people and nature to co-exist.

The Tees Nature Partnership aims to support projects, and protect and enhance the natural environment in the Tees Valley. One of their objectives is to restore and deliver robust ecological networks that deliver environmental and economic outcomes. Coastal habitat creation and the development of a new fishing opportunity around Tees Bay would deliver on this objective.

The Tees estuary and coastal waters are categorised as heavily modified by the Environment Agency. The ecological status is moderate and the chemical status is failing. As the objective is to achieve good status, the ecological and chemical statuses of the Tees must be addressed. Through habitat creation and the provision of an economic stimulus for water quality improvements, the proposed habitat creation around the Teesside Wind Farm would help in addressing the current WFD status of the estuary and coastal waters.

4.7.2.2 Regional

The Environment Agency overall aims for the Northumbria Basin are to prevent deterioration of WFD status, achieve objectives and aim to reach good status. They also identify one of the outcomes for 2021 as the improvement of rivers and estuaries through a number of interventions including habitat enhancement and restoration work.

The Draft North East Inshore and North East Offshore Marine Plan outlines the main objectives for the area and the policies that will guide licensing. The proposed mariculture around the Teesside Wind Farm would support the objectives that the marine environment and its resources be used to maximise sustainable activity, prosperity and opportunities; the coast, seas, oceans and their resources are safe to use; biodiversity is protected, conserved and where appropriate, recovered; and that our oceans support viable populations of representative, rare, vulnerable and valued species. The proposal would also be supported by policies for co-existence, aquaculture, undersea cables, fishing, employment, biology and net gain (see policies NE-CO-1, NE-AQ-2, NE-CAB-3, NE-FISH-1, NE-EMP-1, NE-BIO-2, NE-BIO-3 and NE-NG-1 (Marine Management Organisation, 2020).

4.7.2.3 National

In their 2018 report (Environment Agency, 2018), the Environment Agency published their metrics for assessing success. Two of the eight metrics are the creation of 410 ha of habitat and 2000 km of healthier rivers, lakes and coastal waters. These aims would be directly supported by habitat creation around the Teesside Wind Farm.

Mariculture within the wind farm would supports the UK's vision of clean, healthy, safe, productive and biologically diverse oceans and seas under the Marine Policy Statement (HM Government, 2018). Creation of habitat supports marine productivity and biological diversity. This work would also support some of the High Level Marine Objectives within the Marine Policy Statement: biodiversity is protected, conserved and where appropriate, recovered and loss has been halted; healthy marine and coastal habitats occur across their natural range and are able to support strong, biodiverse biological communities and the functioning of healthy, resilient and adaptable marine ecosystems; our oceans support viable populations of representative, rare, vulnerable, and valued species; and our understanding of the marine environment continues to develop through new scientific and socio-economic research and data collection.

The government published their 25-year Environment Plan in 2018. It outlined the goals for the environment in the next 25 years and the policies that will support those goals. Some of the goals include having clean and plentiful water, thriving plants and wildlife and using resources from nature sources more sustainably and efficiently. These aims are all supportive of the proposed mariculture development in the Tees Estuary. These aims are supported by policies that are similarly supportive of the proposal. The government aims to reverse the loss of marine biodiversity and where practicable, restore it; ensure seafloor habitats are productive and sufficiently extensive to support healthy, sustainable ecosystems; maximise the value and benefits we get from our resources; and ensure that our food is produced sustainably.

4.7.3 Windfarm Decommissioning

The EDF Renewables Teesside Wind Farm is expected to be decommissioned in 2040. During the process of decommissioning planning, it will be decided how much of the wind farm is removed. The wind turbines and foundations will likely be completely removed however, the cables and base of the turbines may be left in situ if the environmental impact of removal is deemed too high.

To date, no offshore wind farms have been decommissioned. Renewable offshore wind still remains a relatively new industry. Following the decommissioning of offshore windfarms, the environmental impacts for full structure removal must be considered. Current legislation imposed by the Crown Estate, instructs that leased offshore sites must be fully vacated and left in its “pre-wind farm” state after decommissioning. A clear seafloor and verified clearance must be completed within a two-year period following lease termination (Smyth et al., 2015). However, positive environmental benefits could result from partially leaving wind turbine structures in situ. The full removal of turbine structures and attached transmission systems would incur high costs and result in significant environmental damage (Pakenham et al., 2021).

Wind turbines placed offshore in time create a new habitat for the ecosystem present. These artificial reefs can have numerous benefits to the marine environment and other industries. The economic benefits generated from wind farms, for example to commercial fisheries, could outweigh imposed decommissioning legislation. The challenges and costs of full wind farm removal would also be avoided (Pakenham et al., 2021). Following industry guidelines, the decommissioning i.e., removal or partial removal of windfarm structures, should not cause any significant negative effects on the marine ecosystem and living resources present. Threatened and endangered species hold particular value against permitting full structural removal. Decommissioning must also account for the potential that the windfarm acted as an artificial reef in itself following construction and during operational time (Smyth et al., 2015). When the Teesside offshore wind farm decommissioning works takes place, it’s likely that areas of artificial reef would be adversely affected by the work.

There is potential to leave sections of monopiles in place following decommission and subsequent blade removal. However, cracks are predicted to eventually form within the monopile structures due to excessive corrosion. Health and safety must be considered regarding the risk of monopile collapse at the point of extreme corrosion. Current industry standards dictate that the minimum uniform corrosion rate of submerged monopile exposed surface is 0.30mm/year (Pakenham et al., 2021). It is a requirement that all installation components left in situ be cut to an acceptable level below sea level to fulfil navigational safety obligations. To ensure cables and foundations remain buried continued monitoring would also be deemed necessary (Smyth et al., 2015). Only removing sections of cable that are exposed above the seabed has been proposed. Leaving scour material in situ has also been recommended due to difficulties that would occur to complete full removal. Scour material left behind will continue to create artificial reef habitats (Marine Data Exchange, 2022b).

Windfarms that become situated inside Special Areas of Conservation (SPAs) under the EU Habitats Directive during operation require an assessment to be conducted under Article 6(3) prior to decommissioning. This assessment must determine whether structure removal would adversely affect conservation objectives at the wind farm site (Smyth et al., 2015).

Any decommissioning works are sure to stop mariculture operations for part or all of the decommissioning time, on part or all of the windfarm site. This will impact any mariculture farm that develops in this area and must be planned for well in advance. A formal review is conducted 5, 12 and 15 years following initial wind farm start up. The final review is conducted 2 years before wind farm shut down to determine wind farm decommissioning or repowering plans (Marine Data Exchange, 2022b).

Having contacted EDF Renewables regarding this work, they have identified that the decommissioning plan is yet to be finalised and that they may be able to work with the Tees Rivers Trust to determine the best way forward to plan for wind farm decommissioning, if mariculture is installed.

4.7.4 Biosecurity

When undertaking restorative mariculture organisms will be translocated from one location to a new location. A suite of risks is associated with this human-mediated movement. Primary risks include the introduction of invasive non-native species (INNS) and disease transfer. INNS pose a risk as they competent for food and space, act as pests or predators or alter the local habitat to the detriment of native species. When conducting translocation activity risk of these inductions can never be fully eliminated. The movement of equipment, material and people also threaten biosecurity, not just stock transfer alone. The potential of disease and INNS transfer are major barriers to new mariculture enterprises. Both signify a significant threat. Rigorous biosecurity protocols must be adopted to reduce the risk that an intended positive action might have on the local environment (Zu Ermgassen et al., 2020a).

In an open marine environment, fully eradicating invasive species and disease is not possible. To effectively manage mariculture enterprises, the reality of where INNS and diseases are presently found in the natural environment needs to be accepted. Considering alternatives to translocation is an initial step i.e., using locally sourced stock and materials alone. If unavailable, recognising what appropriate biosecurity measures and legislative responsibilities are required is the second step. This includes international legislation and disease control if applicable. Biosecurity risk associated with moving shellfish through a hatchery supply chain must be minimized. Once a donor site has been identified, testing must be undertaken to confirm current disease status at that location. Strong biosecurity measures need to be incorporated into the project planning and the project implementation stage to ensure existing shellfish and macroalgae stocks remain disease and INNS free (Zu Ermgassen et al., 2020a).

Disease and invasive species are major drivers for the mass decline of European flat oyster populations. Flat oysters are particularly vulnerable to diseases such as Oyster Herpes Virus OsHV-1 and Bonamiosis, caused by the parasite Bonamia ostreae. Predation from INNS is also a contributing factor to the decline of native oyster stocks. The American slipper limpet (Crepidula fornicate) and American oyster drill (Urosalpinx cinerea) are two main predators (Zu Ermgassen et al., 2020a). When relocating mariculture stock, it is important to confirm donor stock is initially disease and INNS free and that the transfer location is free of these elements also.

Biosecurity considerations also need to be taken into account regarding the addition of reef-building materials to a site. Artificial reef creation using marine-derived cultch i.e., bivalve shells and gravel, creates potential biosecurity hazards. It is a requirement that all collected cultch material either be exposed to high intensity heat or left to weather before dumping, to ensure that all biological residue is removed from the shells. The minimum legal time period for weathering is 12 months. If depositing shell in <15 meters depth, turning the shells every two months is mandatory (Zu Ermgassen et al., 2020a).

Biosecurity measures and connecting legislation needs to be carefully considered during the project planning phase of any mariculture development.

4.7.5 Marine Traffic

Teesside is currently the third largest port in the UK. A significant number of large vessels transit through the Tees Estuary on a daily basis. Marine traffic levels area expected to continue to rise in the area, following the completed construction and establishment of the newly developing Freeport. In addition to this heavy industry, commercial fishing fleets are also present within the estuary vicinity. Hartlepool and South Gare are located at the estuary mouth and are the two principal landing ports in the Tees Estuary area.

The Teesside Offshore Wind Farm lies only 1.5km off the coast of Redcar, in close proximity to the Tees Estuary mouth and consequently the main shipping lane. Any mariculture development would have to be mindful of shipping traffic when carrying out maintenance, monitoring or harvesting offshore. It will be at the discretion of any mariculture farm owner, to plan and avoid both wind farm vessel traffic and vessels transiting the estuary.

A mariculture development situated inside the Tees Wind Farm may pose a risk to marine traffic, in the possible scenario any mariculture equipment brakes free and drifts into the main shipping lane. Following conservations with EDF Renewables, this conceivable situation is a notable concern. Any mariculture development placed offshore must be designed to withstand high wave exposure, to limit the possibility of mariculture infrastructure being damaged and set adrift, thus posing a significant risk to marine vessels.

5 Conclusions

This report aims at determining the feasibility of co-locating a mariculture enterprise within the Teesside Offshore Wind Farm, as a socio-economic driver to implement water quality improvement inside the Tees Estuary.

The water quality of the Tees Estuary is currently listed as "Moderate" under the Water Framework Directive (WFD). At present there are 18 reasons, all pollution derived, as to why good WFD status has not been achieved. It is well known that certain marine species biological functions, aid in water quality improvement inside estuaries and beyond. Culturing these marine species i.e., bivalve shellfish and macroalgae inside the Tees Wind Farm would be a valuable technique to drive forward improving the quality of water in the Tees Estuary area.

Such a practice would bring forth economic benefits to the region, both through direct fishery creation and through indirect environmental and socio-economic services that in turn would be provided.

Mariculture offers financial gain to any individual farm owner. Many environmental benefits generated from mariculture, such as carbon capture, net biodiversity gain and coastal protection, additionally will equate to generating indirect economic gains to local communities, industries and the natural environment, through a single offshore mariculture development. Co-locating inside a renewable energy development will provide additionally socio-economic benefits, principally from efficiently utilising valuable offshore marine space.

Following a review of the abiotic environmental factors present inside the Tees Wind Farm site, all species mentioned (in section 4.2) could theoretically survive in this given location. Species survivability may be reduced if reared via a technique which causes exposure to negative environmental factors to be increased. The most appropriate installation type should be selected on an individual basis, following a review upon the distinct site environmental conditions presented, against the known targeted culture species. Seafloor based mariculture is deemed feasible inside the Tees Wind Farm for all reviewed bivalve shellfish species considered (in section 4.2). Seafloor based mariculture is considered unfeasible for macroalgae culture inside this wind farm, given site water depth and water clarity levels. Surface-based mariculture is deemed feasible for all study species mentioned however, wave action would limit appropriate installation set up design, could cause stress to the stock and risks loss and damage to equipment and loss of stock through mortality and subsequent removal from the installation. With regards to rope-based mariculture, a vertical rope system set-up would be required to protect against high wave action. Horizontal rope set-up would be unrecommended in this given site location.

The operational requirements of an offshore wind farm site, is a main factor to considered when determining if such a site could effectively be used for multiple industry purposes. As wind farm sites are specifically constructed by an energy company to serve a single-use, focused on offshore energy production, any other industry wishing to co-locate within such a site would be under the discretion of the original site owners and limited to pre-agreed upon practices. The size and location of any mariculture farm installed inside an offshore wind farm is expected to be limited. Certain areas for these installation types can be assumed unviable inside wind farms. Seafloor-based mariculture techniques or artificial reef creations should not be situated above subsea cable routes. In the event of cable malfunction, access requirements would be deemed a priority over seafloor installations. Mass destruction or disturbance to a farm or reef could then result. Surface-based mariculture would affect vessel navigation around a wind farm site. Following mariculture installation, full site access would be impossible. Plans regarding the location of such an installation set up inside a wind farm would be under the decision of the wind farm site owners and reviewed on an individual basis, in conjunction with specific wind farm site navigational plans and operational practices.

Discussions with the owner of the Tees Wind Farm, EDF Renewables, have been positive. It has been made clear that there are a number of areas between the wind turbines that could be suitable for mariculture installations, In addition to an area outside the wind farm itself, but still within the wind farms designated footprint. It has been determined that preference would be given for locating surface-based mariculture at a distance from individual turbines. Situating this new industry in close proximity to turbines, could disrupt assess to turbines and therefore the functional operational needs at the site. It is important to note, that installations would be prohibited from being situated in areas required for access during routine maintenance of the wind farm. Installations placed in locations needed in the case of emergency maintenance requirements arising, would be situated at your own risk and thus would likely be prohibited.

Situating a mariculture enterprise inside the Tees Wind Farm will support an emerging industry and provide a vast range of research and learning opportunities. Many associated environmental and socio-economic benefits would be derived from such multi-industry co-location initiatives.

6 Recommendations

The feasibility of co-locating mariculture within the Teesside Offshore Wind Farm is currently deemed viable to some extent. In order for this mariculture scheme to be feasible, certain scenarios would be acceptable, whilst others unsuitable, with regards to this specific Tees wind farm site. Continuation with the proposal of a mariculture development would be viable under certain constraints.

It is strongly advised that all environmental factors are reviewed in full at a given offshore wind farm site, prior to planning a mariculture enterprise. Individual site conditions will ultimately dictate which marine species could be cultured. Moreover, specific site conditions presented will determine which installation techniques would be suitable. Effective selection of farm set up will help to ensure the successful rearing of a mariculture stock.

Any co-location development plans first need to be permitted by the original offshore wind farm site owner. Any additional development plans desired within a pre-owned site will be completely up to the discretion of the site owners. As the offshore mariculture industry emerges, a rise in co-location strategies is being seen. In many circumstances, co-locating developments inside offshore wind farms are being welcomed and accommodated, however, this is never a given. If mariculture co-location plans are agreed, it can still be assumed farm arrangement will be restricted. Allowing for unimpaired wind farm full operational function will remain the main priority. Prior to offshore mariculture developments commencing inside wind farms, appropriate discussions, permissions and planning must be sort with the relevant wind farm owner.

The success of establishing mariculture farms offshore in the vicinity of wind farms remains undetermined. Many examples of such schemes remain at the pilot stage or have only been operational for a limited number of years. Conducting a small-scale pilot study for a proposed mariculture enterprise is highly recommended prior to scaling up to designated full farm size. Conducting an initial pilot study will allow species survivability and growth rate to be tested. This will aid in ensuring an effective commercial practice is functional. Adjustments to mariculture installation types can also be made, if necessary, to further ensure best farming practices, in terms of operational functionality and high yield achievement of stock. Establishing a pilot-scale mariculture farm for at least one stock growth cycle is highly advisable.

7 References

4coffshore.com. (2022). Teesside Offshore Wind Farm - Fully Commissioned - United Kingdom | 4C Offshore. [online] Available at: https://www.4coffshore.com/windfarms/unied-kingdom/teesside-united-kingdom-uk28.html [Accessed 24 Feb. 2022].

Aad Smaal, Pauline Kamermans, Frank Kleissen, Luca van Duren & Tom van der Have. 2017. Flat oysters on offshore wind farms, Wageningen, Wageningen Marine Research rapport C052/17.

Aberdeenshire Council Seaweed Cultivation -A new opportunity for Aberdeenshire. (2021). [online] Available at: http://publications.aberdeenshire.gov.uk/dataset/0964f372-1a23-447a-bf2c-828da1ed78a1/resource/fe54ef76-d2f4-467c-912f-c2ad9e82e74e/download/aberdeenshire-council---cids-seaweed-cultivation-feasibility-study-july-2021-13092021.pdf.

Amiard, Jean-Claude & Amiard-Triquet, C. & Berthet, Brigitte & Métayer, C.. (1986). Contribution to the ecotoxicological study of cadmium, lead, copper and zinc in the mussel Mytilus edulis - I. Field study. Marine Biology. 90. 425-431. 10.1007/BF00428566.

Animal Diversity Web. (2019). Mytilus edulis. [online] Available at: https://animaldiversity.org/accounts/Mytilus_edulis/.

Arc Marine. (2022.). ARC Marine | Reef Cubes® | Marine Ecology | Sub Sea Protection. [online] Available at: https://www.arcmarine.co.uk/ [Accessed 24 Feb. 2022].

Ashley, M.C., Mangi, S.C. and Rodwell, L.D. (2014). The potential of offshore windfarms to act as marine protected areas – A systematic review of current evidence. Marine Policy, 45, pp.301–309.

Brown, A., Webber, J., Zonneveld, S., Carless, D., Jackson, B., Artioli, Y., Miller, P., Holmyard, J., Baker-Austin, C., Kershaw, S., Bateman, I. and Tyler, C., 2020. Stakeholder perspectives on the importance of water quality and other constraints for sustainable mariculture. Environmental Science & Policy, 114, pp.506-518.

Carranza, A. and zu Ermgassen, P.S.E. (2020). A Global Overview of Restorative Shellfish Mariculture. Frontiers in Marine Science, 7.

Causon, P. and Gill, A., 2018. Linking ecosystem services with epibenthic biodiversity change following installation of offshore wind farms. Environmental Science & Policy, 89, pp.340-347.

Cefas.co.uk. 2021. Seafood safety - Cefas (Centre for Environment, Fisheries and Aquaculture Science). [online] Available at: <https://www.cefas.co.uk/science/food-safety/> [Accessed 26 August 2021].

D&S IFCA Mariculture Strategy, 2021. [ebook] Available at: <http://Annex+1+to+Agenda+Item+8+Final+Draft+D&S+IFCA+Mariculture+Strategy+2020+v2%20(5).pdf> [Accessed 26 August 2021].

De Rijke Noordzee. (2022). Eneco Luchterduinen. [online] Available at: https://www.derijkenoordzee.nl/locaties/eneco-luchterduinen [Accessed 24 Feb. 2022].

Environment Agency, 2017a. Tees Lower and Estuary TraC, Environment Agency, viewed 6 January 2020, <https://environment.data.gov.uk/catchment-planning/OperationalCatchment/3446>.

Environment Agency. (2018) Creating a Better Place Our Ambition to 2020. UK: Environment Agency. Available at: https://www.gov.uk/government/publications/environment-agency-our-ambition-to-2020. (Accessed: 25/03/2020).

Environment.data.gov.uk. 2021. Tees Coastal | Catchment Data Explorer | Catchment Data Explorer. [online] Available at: <https://environment.data.gov.uk/catchment-planning/WaterBody/GB650301500005> [Accessed 22 October 2021].

Fitzsimons, J., Branigan, S., Brumbaugh, R.D., McDonald, T. and zu Ermgassen, P.S.E. (eds) (2019). Restoration Guidelines for Shellfish Reefs. The Nature Conservancy, Arlington VA, USA.

Food.gov.uk. 2022. [online] Available at: <https://www.food.gov.uk/sites/default/files/media/document/Indicator%20shellfish%20species%20report.pdf> [Accessed 25 February 2022].

fromnorway.com. (2022). Blue mussel. [online] Available at: https://fromnorway.com/seafood-from-norway/blue-mussel/#:~:text=If%20left%20to%20their%20own%20devices%2C%20blue%20mussels [Accessed 24 Feb. 2022].

geminiwindpark.nl. (2022). Now at Gemini Wind Park. [online] Available at: https://geminiwindpark.nl/now-at-gemini-wind-park.html [Accessed 24 Feb. 2022].

Gentry, R., Alleway, H., Bishop, M., Gillies, C., Waters, T. and Jones, R., 2019. Exploring the potential for marine aquaculture to contribute to ecosystem services. Reviews in Aquaculture, 12(2), pp.499-512.

Hannah Z. L. Lee & William G. Sanderson (2020). Real-time carbon budgets and the native oyster: carbon sink or source? – NORA. [online] Available at: https://noraeurope.eu/real-time-carbon-budgets-and-the-native-oyster-carbon-sink-or-source-2/ [Accessed 24 Feb. 2022]

Hellou, J. and Law, R.J. (2003). Stress on stress response of wild mussels, Mytilus edulis and Mytilus trossulus, as an indicator of ecosystem health. Environmental Pollution, 126(3), pp.407–416.

Henrice Jansen & Lisanne van den Bogaart, 2020. Blue carbon by marine bivalves. [ebook] Available at: <https://library.wur.nl/WebQuery/wurpubs/fulltext/537188> [Accessed 31 August 2021].

HM Government. (2018) A Green Future: Our 25 Year Plan to Improve the Environment. [Online] London: The Crown. Available from: <http://www.gov.uk/government/publications>. [Accessed: 25th March 2020].

Inca.uk.com. 2022. INCA - Industry Nature Conservation Association. [online] Available at: <http://www.inca.uk.com/> [Accessed 25 February 2022].

Kamermans, P., Walles, B., Kraan, M., van Duren, L., Kleissen, F., van der Have, T., Smaal, A. and Poelman, M. (2018). Offshore Wind Farms as Potential Locations for Flat Oyster (Ostrea edulis) Restoration in the Dutch North Sea. Sustainability, 10(11), p.3942.

Kotta, J., Futter, M., Kaasik, A., Liversage, K., Rätsep, M., Barboza, F.R., Bergström, L., Bergström, P., Bobsien, I., Díaz, E., Herkül, K., Jonsson, P.R., Korpinen, S., Kraufvelin, P., Krost, P., Lindahl, O., Lindegarth, M., Lyngsgaard, M.M., Mühl, M. and Sandman, A.N. (2020). Cleaning up seas using blue growth initiatives: Mussel farming for eutrophication control in the Baltic Sea. Science of The Total Environment, 709, p.136144.

Laing, I. (2002) Scallop Cultivation in the UK: A Guide to Site Selection. The Centre for Environment, Fisheries and Aquaculture Science. [Online] Available at: <https://www.cefas.co.uk/publications/files/scallop_cultivation.pdf>. (Accessed on: 29/01/2021)

Long, S., Ffrench Constant, R. and Witt, M.J. (2017). Have Centuries of Inefficient Fishing Sustained a Wild Oyster Fishery: a Case Study. Fisheries and Aquaculture Journal, [online] 08(02). Available at: https://www.longdom.org/open-access/have-centuries-of-inefficient-fishing-sustained-a-wild-oyster-fishery-a-case-study-2150-3508-1000198.pdf.

Macreadie, P.I., Anton, A., Raven, J.A. et al. The future of Blue Carbon science. Nat Commun 10, 3998 (2019). https://doi.org/10.1038/s41467-019-11693-w

Marine Data Exchange. (2022a). 2008, ABP Mer, Teesside Offshore Wind Farm, Metocean Study. [online] Available at: https://www.marinedataexchange.co.uk/details/2056/2008-abp-mer-teesside-offshore-wind-farm-metocean-study/summary [Accessed 24 Feb. 2022].

Marine Data Exchange. (2022b). 2011, PMSS, Teesside Offshore Windfarm, Offshore Decommissioning Plan. [online] Available at: https://www.marinedataexchange.co.uk/details/2049/2011-pmss-teesside-offshore-windfarm-offshore-decommissioning-plan/summary [Accessed 24 Feb. 2022].

Marine Investment for the Blue Economy. (2016). D5.1 Review of multi-use of space and multi-use platform projects. [online] Available at: http://maribe.eu/blue-growth-deliverables/blue-growth-work-packages/d5-1-review-of-multi-use-of-space-and-multi-use-platform-projects-2/.

Marine Management Organisation. (2020) North East Inshore and North East Offshore Marine Plan Draft for Consultation. UK: Marine Management Organisation. Available at: https://www.gov.uk/government/publications/draft-north-east-marine-plans-documents. (Accessed: 01/10/2019).

McLeod, I.M., Heller-Wagner, G., Gillies, C., Boström-Einarsson, L. and Dwyer, P.G. (2020). Hitching a ride on Hercules: fatal epibiosis drives ecosystem change from mud banks to oyster reefs. Ecology, 101(6).

Menzies, B., Brook, T. and Parker, A. (2021). CROWN ESTATE SCOTLAND Economic Feasibility Study on Seaweed (Cultivation and Supply Scenario). [online] Available at: https://www.crownestatescotland.com/resources/documents/economic-feasibility-study-on-seaweed [Accessed 25 Feb. 2022].

Michler-Cieluch, Tanja & Krause, Gesche & Buck, Bela. (2009). Marine Aquaculture within Offshore Wind Farms: Social Aspects of Multiple-Use Planning. GAIA - Ecological Perspectives for Science and Society. 18. 158-162. 10.14512/gaia.18.2.14.

Native Oyster Network, (2022). Native Oyster Network – Facilitating the restoration of Native Oysters across the UK and Ireland. [online] Available at: https://nativeoysternetwork.org/.

NFFO. (2021). Can Fisheries Co-exist with Offshore Wind in the Race to Carbon Net Zero? [online] Available at: https://www.nffo.org.uk/can-fisheries-co-exist-with-offshore-wind-in-the-race-to-carbon-net-zero/.

Offshore Shellfish, 2021. Cultured Mussel Farm In Brixham I Offshore Shellfish Ltd. [online] Available at: <https://offshoreshellfish.com/> [Accessed 21 October 2021].

Pakenham, B., Ermakova, A. and Mehmanparast, A., 2021. A Review of Life Extension Strategies for Offshore Wind Farms Using Techno-Economic Assessments. Energies, 14(7), p.1936.

Pogoda, Bernadette. (2019). Current Status of European Oyster Decline and Restoration in Germany. Humanities. 8. 9. 10.3390/h8010009.

Racine, P., Marley, A., Froehlich, H., Gaines, S., Ladner, I., MacAdam-Somer, I. and Bradley, D., 2021. A case for seaweed aquaculture inclusion in U.S. nutrient pollution management. Marine Policy, 129, p.104506.

Robertson, M & Locke, S & Uttley, Matthew & Kean-Hammerson, & Helmer, Luke. (2021). Exploring the role of offshore wind in restoring priority marine habitats Case Study: Opportunities for native oyster (Ostrea edulis) restoration at the Gunfleet Sands Offshore Wind Farm.

Roesijadi, Guritno & Fellingham, Gilbert. (1987). Influence of Cu, Cd, and Zn Preexposure on Hg Toxicity in the Mussel Mytilus edulis. Canadian Journal of Fisheries and Aquatic Sciences. 44. 680-684. 10.1139/f87-082.

Román, G., Campos, M.J., Acosta, C.P. and Cano, J. (1999) Growth of the Queen Scallop (Aequipecten opercularis) in suspended culture: influence of density and depth. Aquaculture. 178(1-2): 43-62.

Scallop Cultivation in the UK: a guide to site selection I. Laing CENTRE FOR ENVIRONMENT, FISHERIES AND AQUACULTURE SCIENCE LOWESTOFT 2002. (n.d.). [online] Available at: https://www.cefas.co.uk/publications/files/scallop_cultivation.pdf [Accessed 24 Feb. 2022].

Seafish. (2016). Aquaculture in England, Wales and Northern Ireland: An Analysis of the Economic Contribution and Value of the Major Sub-Sectors and the Most Important Farmed Species. [online] Available at: https://www.seafish.org/document?id=4382b7aa-ffce-448b-850d-46a8f7959115 [Accessed 24 Feb. 2022].

Seafish. (2022.). Seafood 2040. [online] Available at: https://www.seafish.org/about-us/working-locally-in-the-uk/working-with-the-seafood-industry-in-england/seafood-2040/ [Accessed 24 Feb. 2022].

Sheehan, EV, Bridger D, Mascorda Cabre L, Cartwright, A, Cox D, Rees S, Holmes L, Pittman SJ. 2019. Bivalves boost biodiversity. Food Science and Technology 33 https://fstjournal.org/features/33-2/offshore-bivalve-farming.

Simply Oysters, 2021. Farmed & Wild Oysters, Simply Oysters, viewed 14 January 2021, <https://simplyoysters.com/farmed-and-wild-oysters#:~:text=The%20Pacific%20Oyster%20(sometimes%20referred,oysters%20in%20the%20world%20today.>.

Smyth, K., Christie, N., Burdon, D., Atkins, J., Barnes, R. and Elliott, M., 2015. Renewables-to-reefs? – Decommissioning options for the offshore wind power industry. Marine Pollution Bulletin, 90(1-2), pp.247-258.

Smyth, K., Christie, N., Burdon, D., Atkins, J.P., Barnes, R. and Elliott, M. (2015). Renewables-to-reefs? – Decommissioning options for the offshore wind power industry. Marine Pollution Bulletin, [online] 90(1), pp.247–258. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0025326X14007292 [Accessed 6 Dec. 2020].

Stanley, M.S., Kerrison, P.K., Macleod, A.M., Rolin, C., Farley, I., Parker, A., Billing, S-L., Burrows, M. & Allen, C. (2019). Seaweed Farming Feasibility Study for Argyll & Bute. A report by SRSL for Argyll & Bute Council. pp. 190

Stewart, B.D., Jenkins, S.R., Boig, C., Sinfield, C., Kennington, K., Brand, A.R., Lart, W. and Kröger, R. (2020). Metal pollution as a potential threat to shell strength and survival in marine bivalves. Science of The Total Environment, p.143019.

Sunila, Inke. (1988). Sunila, I. 1988: Histopathology of mussels (Mytilus edulis L.) from the Tvärminne area, the Gulf of Finland (Baltic Sea). -Ann.Zool.Fennici 24: 55 - 69.

sussexwildlifetrust.org.uk. (2022). Help Our Kelp | Sussex Wildlife Trust. [online] Available at: https://sussexwildlifetrust.org.uk/helpourkelp.

Tang, Q., Zhang, J. and Fang, J. (2011). Shellfish and seaweed mariculture increase atmospheric CO2 absorption by coastal ecosystems. Marine Ecology Progress Series, 424, pp.97–104.

teesvalleynaturepartnership.org.uk. (2022). Tees Valley Nature Partnership. [online] Available at: https://teesvalleynaturepartnership.org.uk/ [Accessed 25 Feb. 2022].

The Reef Ball Foundation, 2017. Reef Ball Brochure & Key Features Page. [Online] Available at: <https://www.reefball.org/brochure.htm>. (Accessed: 25th January 2021).

Theseaweedcompany.com. 2022. The Seaweed Company | Capturing the value of seaweed. [online] Available at: <https://www.theseaweedcompany.com/> [Accessed 24 February 2022].

UK Government (2020). New plans to make UK world leader in green energy. [online] GOV.UK. Available at: https://www.gov.uk/government/news/new-plans-to-make-uk-world-leader-in-green-energy.

van den Burg, S.W.K., van Duijn, A.P., Bartelings, H., van Krimpen, M.M. and Poelman, M. (2016). The economic feasibility of seaweed production in the North Sea. Aquaculture Economics & Management, 20(3), pp.235–252.

Webber, J.L., Tyler, C.R., Carless, D., Jackson, B., Tingley, D., Stewart-Sinclair, P., Artioli, Y., Torres, R., Galli, G., Miller, P.I., Land, P., Zonneveld, S., Austen, M.C. and Brown, A.R. (2021). Impacts of land use on water quality and the viability of bivalve shellfish mariculture in the UK: A case study and review for SW England. Environmental Science & Policy, 126, pp.122–131.

Westerbom, M., Kilpi, M. and Mustonen, O. (2002) Blue mussels, Mytilus edulis, at the edge of the range: population structure, growth and biomass along a salinity gradient in the north-eastern Baltic Sea. Marine Biology. 140: 991-999.

Wetlands International Europe. 2021. Native Oyster experts agree on monitoring methods for oyster habitat restoration. [online] Available at: <https://europe.wetlands.org/news/native-oyster-experts-agree-on-monitoring-methods-for-oyster-habitat-restoration/> [Accessed 22 October 2021].

Yusufzai, Sajid Khan & Satam, Sachin. (2003). Seaweed Mariculture: Scope And Potential In India. 8. 26-29.

Zrnčić, S., Oraić, D., Mihaljević, Ž. And Zanella, D. (2007) Impact of varying cultivation depths on growth rate and survival of the European flat oyster Ostrea edulis, L. Aquaculture Research. 38: 1305-1310.

Zu Ermgassen, P., Gamble, C., Debney, A., Colsoul, B., Fabra, M., Sanderson, W. and Strand, Å. (2020a). EUROPEAN GUIDELINES ON BIOSECURITY IN NATIVE OYSTER RESTORATION NOVEMBER 2020. [online] . Available at: https://noraeurope.eu/wp-content/uploads/other-publications/European-Guidelines-on-Biosecurity-in-Native-Oyster-Restoration.pdf [Accessed 25 Aug. 2021].

Zu Ermgassen, P.S.E., Bonačić, K., Boudry, P., Bromley, C.A., Cameron, T.C., Colsoul, B., Coolen, J.W.P., Frankić, A., Hancock, B., Have, T.M., Holbrook, Z., Kamermans, P., Laugen, A.T., Nevejan, N., Pogoda, B., Pouvreau, S., Preston, J., Ranger, C.J., Sanderson, W.G. and Sas, H. (2020b). Forty questions of importance to the policy and practice of native oyster reef restoration in Europe. Aquatic Conservation: Marine and Freshwater Ecosystems, 30(11), pp.2038–2049.

Annex 1

Details on data from Figure 7 to 11. All data shown was the wet weight (Wet Wt., ug/kg) of each contaminant.

Figure 7:

- Zinc

Figure 8:

- Arsenic, Cadmium, Chromium, Copper, Lead, Mercury, Nickel, Selenium, Silver.

Figure 9:

- PCB/DDE/DDT/TDE: DDE -pp, DDT -op, DDT -pp, TDE -pp, PCB –028, PCB –052, PCB –101, PCB –118, PCB –138, PCB –153, PCB –180.
- HCH: HCH -alpha, HCH -beta, HCH -delta, HCH -gamma {Lindane}.
- Aldrin, Dieldrin, Endrin, Isodrin
- Ether's: 2,2,4,4 Tetrabromodiphenyl ether, 2,2,4,4,5 Pentabromodiphenyl ether, 2,2,4,4,5,5 Hexabromodiphenyl ether, 2,2,4,4,5,6 Hexabromodiphenyl ether, 2,2,4,4,6 Pentabromodiphenyl ether, 2,4,4 Tribromodiphenyl ether.
- Heptachlor's: Heptachlor, cis-Heptachlor epoxide, trans-Heptachlor epoxide.
- Quinoxyfen.

- Pentachlorobenzene.

Figure 10:

- Benzo (b) Fluoranthene, Benzo (k) Fluoranthene.
- Tributyltin.
- Hexabromocyclododecane.

Figure 11:

- Benzo (a) Anthracene, Benzo (a) Pyrene, Benzo (g,h,i) Perylene.
- Ene's: Anthracene, Chrysene, Fluoranthene, Hexachlorobenzene, Hexachlorobutadiene, Indeno(1,2,3-cd)pyrene, Naphthalene, Phenanthrene, Pyrene.