Scottish Wind Energy

SUMMARY DOCUMENT

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Executive Summary

This document summarises the outcomes from an investigation into the sustainability of Scottish onshore wind energy, describes the initial proposal for the more sustainable solution of an ‘Energy Island’ off the coast of Scotland in The North Sea. The energy island will be aligned with current wind energy and offshore infrastructure legislation, which aims to meet the Scottish Sustainability Targets.

The research undertaken to investigate the underlying issues with onshore wind energy production suggests that the future of onshore windfarms is limited, with both the planning and construction facing increased limitations and costly time delays. Current offshore wind farm designs are in no way perfect and have numerous issues, however, with adaption of the technology to utilise existing infrastructure such as oil and gas networks, an ‘Energy Island’ would provide a solution to many of the issues faced by both onshore and offshore wind farms and play a key part in meeting Scotland’s sustainability targets.

Figure 1- An Offshore Windfarm (Harvey, 2023), North Sea Oil Rig (World Atlas, 2023) and Offshore Wind Farm in The North Sea (Yale Environment, 2019)

1. Introduction

With global sustainability being a key topic in all political agendas, there is increased pressure for Scotland to meet its net zero and sustainability targets. One of the biggest contributors that is negatively impacting the ability to meet these targets is the Oil and Gas Industry. The reliant of finite fossil fuels to power the ever-growing population is one of the major concerns along with oil and gas processes being to blame for 15% of the global greenhouse gas emissions (MagellanX, 2023).

The Scottish wind energy industry is at a crucial point in development. With technology developing at a greater rate than before, the pressure for the industry to remain on top of design solutions in terms of energy output, is at a peak. However, this is restrained by the necessity to adhere to sustainability targets and outdated legislation and policies.

The Scottish Government is committed in developing the renewable energy in Scotland to reduce greenhouse gases emissions. The goal is to generate 50% of Scotland's total energy consumption from renewable sources by 2030, furthermore, to achieve full decarbonization in the energy system by 2050 (Scottish Government, 2023b). Plans have been made to reduce emissions, including to supply the energy for heating, transportation and electricity from onshore and offshore wind and bioenergy, with a potential explore in geothermal. In the year of 2022, Scotland has made up 35.7TWh of renewable electricity, which covers 26.4% of the UK's renewable electricity generation (Scottish Energy Statistics Hub, 2023).

Scotland has world-leading expertise in wind energy and shows a history of optimising its rich wind resources. As the lowest-cost electricity generation in the UK, onshore wind is one of the fastest growing renewables. It currently contributes the most to achieving the target for electricity demand of 21.9TWh in Scotland, responsible for more than 60% of renewable electricity generation in 2022 (Scottish Energy Statistics Hub, 2023).

This summary document will outline the identified issues found with the onshore wind energy sector in Scotland and detail the stakeholders involved in identifying these issues. Following this, the early-stage proposal for the final solution is described. This will include the design, construction and both the economic and carbon cost. Lastly, the plan and proposal for the final deliverable for this project is outlined.

1.1 Aims and Objectives

The aim of this project is to challenge the sustainability of windfarms in Scotland and provide an improved solution to remediate the identified problems surrounding wind energy production.

The objectives to achieve this aim are-

- Identify and connect with industry partners to act as 'clients' and 'stakeholders' for this project.
- Identify the main challenges and problems with Scottish windfarms.
- Develop a report of the identified problems within the wind energy industry in Scotland.
- Design a suitable solution to remediate numerous identified problems.
- Provide a suitable industry checker to advise on our solution.
- Align the proposed solutions to the Scottish sustainability targets and United Nations Sustainability Development Goals (SDGs) shown in Figure 2.

Figure 2- United Nations Sustainable Development Goals (United Nations, 2023)

2. Stakeholders and Case Studies

Through meetings and continuous communication with multiple industry stakeholders, numerous problems with current onshore windfarm developments have been identified. A summary of all the stakeholders engaged with throughout the initial project phase are detailed below.

Carrick Windfarm- Scottish Power Renewables

Initially investigated by Scottish Power Renewables in 2019, Carrick Windfarm is a controversial proposal which is currently pending an outcome following a Public Local Inquiry (PLI) (Scottish Power Renewables, 2023d). The proposal consists of thirteen, 200m tall wind turbines and an energy storage facility in the Carrick Forest, South Ayrshire (Scottish Power Renewables, 2023d). Project Manager, Kirsten Rae, followed up on the email sent (shown in APPENDIX 2) which led to a phone call to discuss the project. The problems identified through investigation of Carrick Windfarm are detailed in Section 3.

AnderShaw Windfarm- Statkraft

Andershaw Windfarm, situated in a similar location to the proposed Carrick Windfarm, is an operational windfarm with eleven Vestas Wind Systems – V117-3.3MW-IEC IIA turbines (Statkraft, 2023b). It is managed by Statkraft and has been operational since 2017 (Statkraft, 2023b). The operational Andershaw windfarm has an installed capacity of 36.5MW (Statkraft, 2023b), however, an extension to the wind farm, which is currently at design stage, faces many of the same issues as Carrick Windfarm (Statkraft, 2023e). The problems identified through researching both the operational and proposed extension to Andershaw Windfarm is detailed in Section 3.

Statkraft

Following identifying the Andershaw Windfarm as a potential case study, Statkraft, “Europe’s largest renewable energy producer and a global company in energy market operations,” (Statkraft, 2023a) were contacted and replied to the teams email willing to meet (APPENDIX 3). An initial meeting was held with Scott Valence, Principal Project Manager at Statkraft and Ciaran Black, Project Manager. Both employees at Statkarft provided much insight into the Wind Energy Sector, allowing the problems we had identified and many more to be explained from a technical perspective, as discussed in Section 3. Scott and Ciaran also suggested looking at the An Carr Dubh Windfarm, discussed in the following section.

An Carr Dubh Windfarm- Statkraft

An Carr Dubh Windfarm is currently at the Planning Application Submission and Decision stage (Statkraft, 2023c). The current windfarm proposal sees a reduction of half the wind turbines when compared to the initial design, and 20-meter reduction to the turbine height (Statkraft, 2023c). The problems identified through researching the An Carr Dubh Windfarm proposal are detailed in Section 3.

Beinn An Tuirc and Whitelee Windfarm

Whitelee, situated in central Scotland, is the biggest onshore windfarm in the UK (Scottish Power Renewables, 2023a). Whitelee has over 200 turbines and it has an expected operational output of 539MW. Beinn An Tuirc is an onshore windfarm on the West Coast of Scotland which has been in operation since 2001 (Scottish Power Renewables, 2023b). Beinn An Tuirc consists of three phases, with the third currently under construction (Scottish Power Renewables, 2023c).

Forestry and Land Scotland

Head of Renewables for Forestry and Land Scotland (FLS), Gavin Falconer, joined a meeting to discuss the issues that they face in terms of onshore wind farms following replying to an email sent to FLS (APPENDIX 4). Gavin highlighted that FLS is a land manager for the Sottish Ministers land. They act as a ‘landlord’ for the windfarm developers, which would be the ‘tenants’ of the land. Some interesting facts discussed by Gavin are- 25% of FLS income is from renewables, which is the second biggest behind timber. FLS are involved in the design phase, in which they ensure developers meet all FLS objectives. Outcomes may include scaling back the size of windfarms, increasing the turbine height for timber crops to be planted around or below the windfarm without disrupting operation for either. Gavin emphasised that peatland management and timber management are the two biggest concerns for FLS, which are discussed more in Section 3.

Gavin and Doherty Geosolutions

Through the LinkedIn post (APPENDIX 1), Daniel Clancy from Gavin and Doherty Geosolutions (GDG) reached out to us with the offer to help with this project (APPENDIX 5). Daniel is a Heriot-Watt Graduate and therefore not only could provide industry knowledge, but also had a greater understanding of the project than some other stakeholders may have. GDG Engineering are "experts at finding innovative engineering solutions to some of the most challenging wind, marine and infrastructure projects around the world" (GDG, 2023). Daniel echoed the issues that were identified through exploring the Carrick, Andershaw and An Carr Dubh Windfarm developments and managed to discuss some of the technical details behind these issues. GDG specialise in both onshore and offshore design and consultancy, therefore they are a key stakeholder going forward through the design phase of this project. The issues Daniel discussed are described more in Section 3.

Fiona Milligan

Through personal contacts, Fiona Milligan, Stakeholder Engagement for Boralex, was contacted to offer advice and act as a potential stakeholder for the project. She suggested multiple project Environmental Impact Assessments (EIA) to investigate the problems with onshore windfarms and give insight into the sustainability process. Fiona's advice on stakeholder engagements will be considered during the design choices in this project, to ensure chosen locations and environmental decisions can limit the time delays caused by a public enquiry. She has also agreed to consult on the project throughout its development to offer advice where needed. Fiona is a valuable stakeholder for the project with extensive experience. She also provided insight into the policies and legislations surrounding onshore windfarms which leads to much of the opposition to developments. The resulting research and problems identified from Fiona's suggestions are discussed through Section 3.

Dr Wolf-Gerrit Fruh and Dr Angus Creech

With knowledge of the Heriot-Watt University Orkney campus' research into renewable energy, Wolf-Gerrit Fruh and Angus Creech, two university lecturers/visiting academics were contacted. Dr Fruh met with the group at the beginning of the project to discuss his work and to understand the project aims. He advised us on many of the aspects associated with turbine design and suggested that we focus on developing specific aims in order to achieve an impactful design. His research is vast, and he understands that it is important to narrow down research and to concentrate on a certain area of development otherwise the span of problems is huge, and the solution is unattainable.

Craig Sinclair

Through personal contacts, Craig Sinclair, a power engineer for MES Power Engineering was contacted for guidance on the maintenance and possible failures of wind turbines. These are discussed in Section 3.

The stakeholders in order of date contacted are shown in Table 1 below.

Table 1- Stakeholders

Stakeholder Name	Company/Role	First Contact
Dr Wolf-Gerrit Fruh	Energy Engineering Lecturer	19/09/2023
Angus Creech	HWU- Visiting Academic	20/09/2023
Gavin Falconer	FLS- Head of Renewables	20/09/2023
Fiona Milligan	Boralex- Stakeholder Engagement	26/09/2023
Daniel Clancy	GDG- Graduate Engineer	27/09/2023
Scott Valence	Statkraft- Principal Project Manager	03/10/2023
Kirsten Rae	Carrick Windfarm-Senior Project Manager	05/10/2023
Ciaran Black	Statkraft- Project Manager	31/10/2023
Craig Sinclair	MES – Power Engineer	20/11/2023

3. Identified Issues with Onshore Wind Farms

This section features the major issues surrounding onshore windfarms in Scotland. All problems are backed up with stakeholder comments, windfarm case studies such as Carrick, Andershaw, Whitelee, Beinn An Tuirc and An Carr Dubh as well as references from external sources.

3.1 Efficiency of Turbines

A common issue in terms of the output from wind turbines is the proposed energy output when compared to the actual operational output. Due to low wind speed/no wind, mechanical failures, maintenance and extreme wind speeds, turbines often generate no energy, resulting in lower outputs than expected. The actual energy output can be predicted, known as forecasted load rate, and compared to the expected operational capacity which is the energy output expected from the windfarm. This was highlighted by Scott Valance from Statkraft and Daniel Clancy from GDG.

An example of this issue is when investigating the expected load of wind farms. Whitelee Wind Farm is the largest onshore wind farm in Scotland (Scottish Power Renewables, 2023a), however, the forecasted load rate for 14/11/2023 was 43.1% (The Wind Power, 2023b). This would result in an operation output for this day of 232MW, over 50% (307MW) lower than the expected operational capacity. Beinn An Tuirc Wind Farm is another operating wind farm situated on the West Coast of Scotland in Kintrye (Scottish Power Renewables, 2023b). The operating capacity is 68MW (Scottish Power Renewables, 2023b) but again the expected load rate for 14/11/2023 was only 34.3% (The Wind Power, 2023a). This highlights the major issue which is that the onshore windfarms being designed and constructed are continuously outputting a lesser energy rate than expected.

3.2 Land Use

The land cover type in Scotland is very varied as shown in Figure 3 (right). Wind turbines in Scotland can only be built on land which meets numerous requirements. Some of these requirements include a suitable wind speed, peat land and timber, as discussed in the following sections.

Additionally, Figure 3 illustrates that there is not a great quantity of unused land left in Scotland for expanding wind farm sites or developing new sites. Moorland, cliffs, built-up areas, woodland, bogs and peatland are all unsuitable for windfarm development. Daniel Clancy from GDG highlighted that despite there being no blanket answer for the land requirements for a wind farm, he did indicate that proximity to harbours, willingness to improve road routes for turbine transportation and proximity to residential areas also factor into the land suitability.

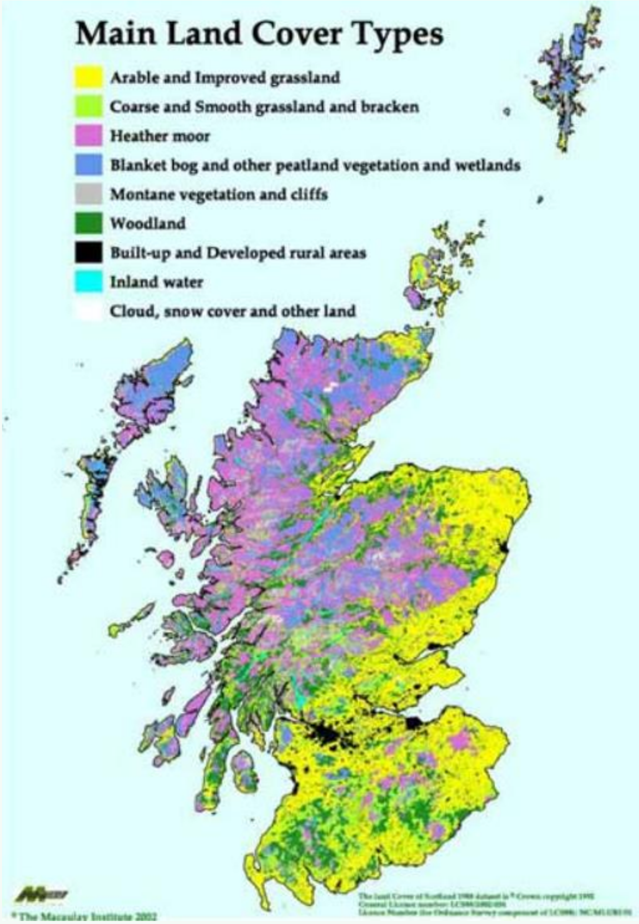


Figure 3- Scotland Main Land Cover Type (The James Hutton Institute, 2023)

3.3 Peat

Peatland protection is an increasing concern for developers of windfarms in Scotland, and for the construction industry as a whole. With improved knowledge and understanding of carbon capture and the benefits it has for the environment, the pressure to avoid constructing on peat is increasing. NatureScot state that over 20% of the land in Scotland is peat (NatureScot, 2023), as shown in Figure 4 below.

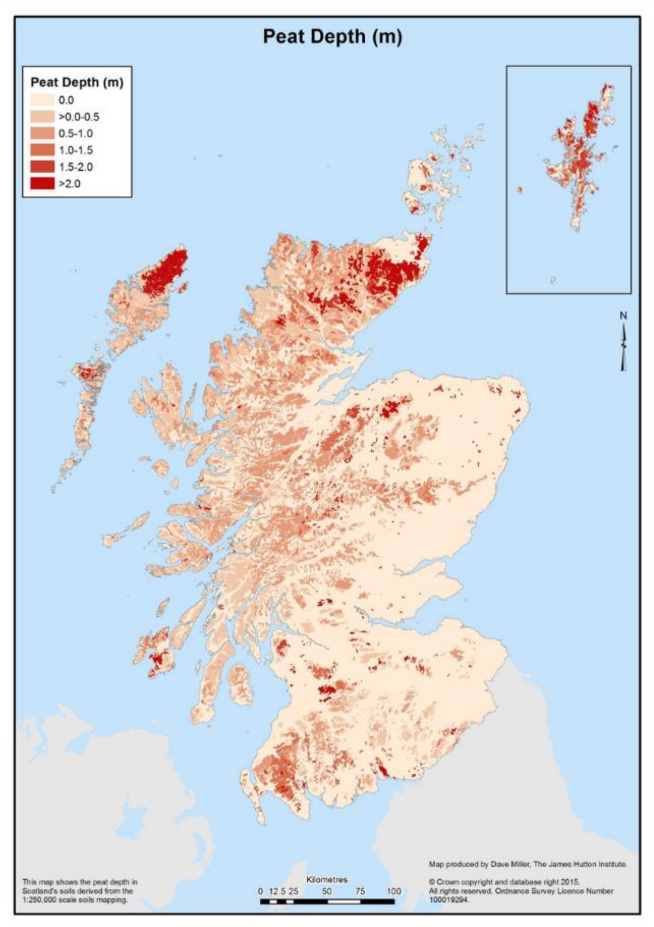


Figure 4- Peat Land Map Scotland (Waldron et al., 2015)

Not only does peat capture carbon and therefore reduce harmful effects to the environment, but there is also the advantage of peatlands reducing the risk of flooding, promoting rich biodiversity and keeping up the high quality of water in Scotland (NatureScot, 2023). NatureScot also states that not only do peatlands need to be protected, but also management plans and restoration must take place to achieve the highest contribution from peatlands in reaching Net Zero targets.

Therefore, windfarm developments, which are primarily situated in rural areas that are potentially peat filled land, must consider the depths of peat and the construction which will take place in terms of disruption or removal of peat bogs. When peat is removed, disturbed, or constructed on, the integrity of the peatland to capture carbon is destroyed, releasing carbon to the environment (NatureScot, 2023). Windfarm developments often are rejected or face numerous objections due to the harm to peatlands, such as Carrick Windfarm.

Carrick Windfarm Development was objected by the Scottish Environmental Protection Agency (SEPA) on the condition that more information on the excavation of deep peat was required (Scottish Power Renewables, 2023d). Carrick Windfarm would be situated on Class 5, Class 4 and Class 1 peat soil which are defined in Table 2.

Table 2 - Peatland Class Definition

Class	Definition
1	Peat soil; no peatland vegetation.
4	Predominantly mineral soil with some peat soil; health with some peatland
5	Nationally important carbon-rich soils, deep peat and priority peatland habitat

To propose the windfarm development on peatland, peat probing was undertaken, and the design was created around the deep peatland. However, due to visual and landscaping constraints numerous construction work sections would take place on peatland with depth greater than 2.5m- shown in Figure 5 (Scottish Power Renewables, 2021a). Carrick Windfarm development stated that “The ground condition constraints that were taken into account in the design of the Proposed Development have been: identification of peat depths in excess of 2.5m – to minimise incursion, protect from physical damage, minimise excavation and transportation of peat, reduce potential for peat instability and minimise potential soil carbon loss; and avoidance of areas where initial peat stability concern was identified, where possible to avoid areas with possible instability issues and associated indirect effects on surface water” (Scottish Power Renewables, 2021a).

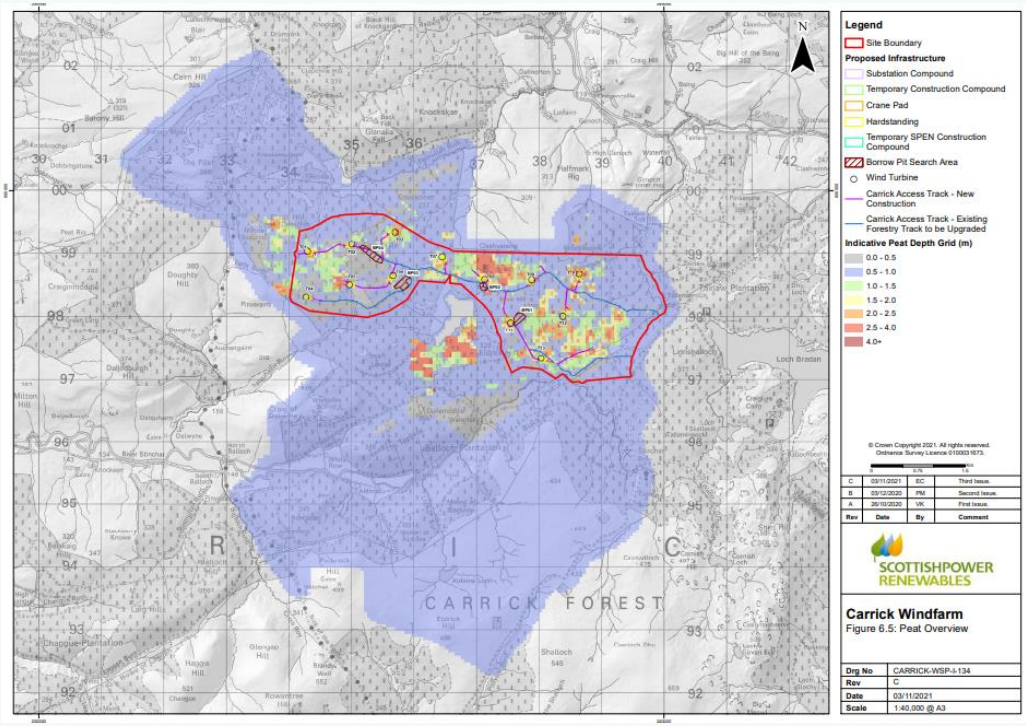


Figure 5- Carrick Windfarm Peatland Map (Scottish Power Renewables, 2021b)

Alongside Carrick Windfarm Development, the FLS Head of Renewables, Gavin Falconer, echoed the concerns with peatland as the land manager for a large number of windfarm developments in Scotland. He stated that “increasing peatland restoration is a focus for FLS, especially in new projects” and added that the struggle comes from the lack of knowledge on how to construct on peatland without realising the captured carbon or prohibiting the surrounding peatland’s ability to store carbon. The FLS website also highlights their involvement in the Scottish Governments Peatland Action initiative in restoring peatlands as part of land management (Forestry & Land Scotland, 2023a).

Carrick Windfarm and FLS are only two of the multiple stakeholders which have expressed that peat is a concern when it comes to onshore windfarm developments. The An Carr Dubh Windfarm site was selected by following the environmental limitation of avoiding peatland which is greater than 0.5m deep when possible (Statkraft, 2023d) and when the issue of peat was mentioned to Scott Valence and Ciaran Black from Statkraft, they both confirmed they have similar concerns and issues to those mentioned.

3.4 Wind

(Renewables First, 2023) explains the requirements for a windfarm, including a high average wind speed, noise separation distance, grid connection, site access and no unprotected land. Typically, any site with an average wind speed 7m/s or greater is a suitable site for a wind farm (Renewables First, 2023). Figure 6 displays the wind speed map for Scotland at 45m above ground level (Bright et al., 2008) This demonstrates that a large percentage of Scottish land would not be suitable for wind farm developments. Primarily this is cities and lowlands where other factors would also contribute to these sites not being suitable.

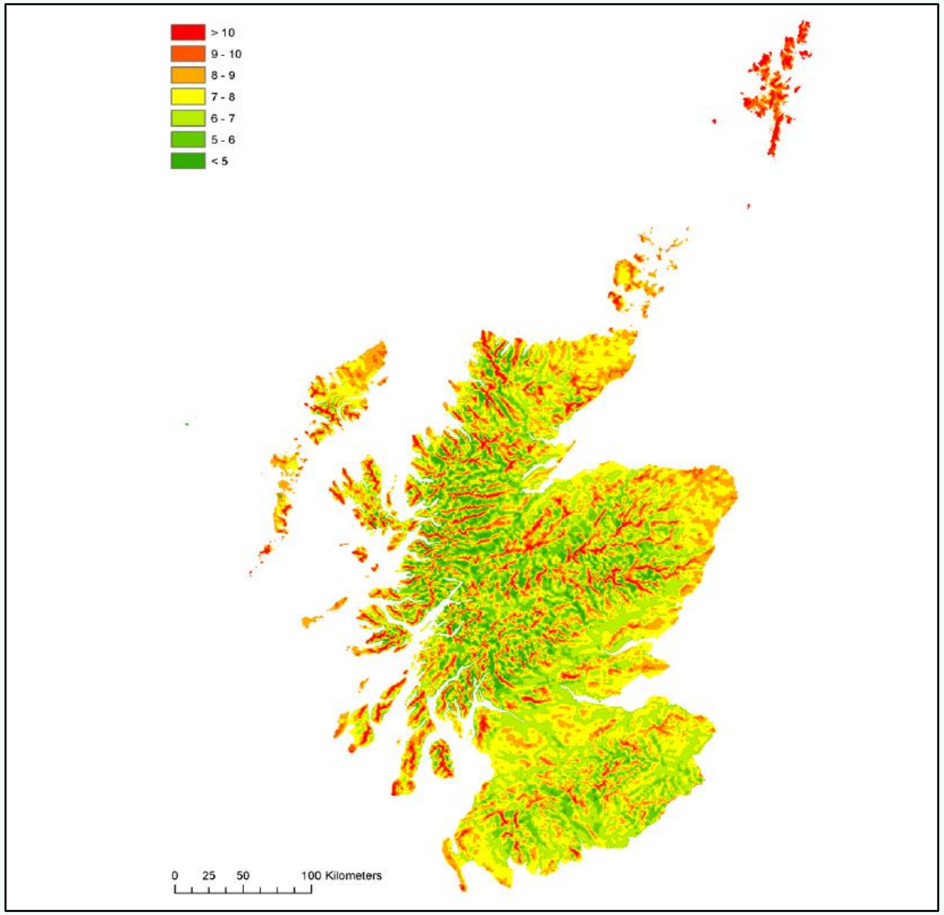


Figure 6- Scotland Wind Speed Map (Bright et al., 2008)

Not only must the turbines be in an area with a wind speed over 7m/s, but wind analysis must also be carried out to ensure the spacing of the turbines is suitable, so the upwind edge of the wind turbine array does not create turbulent air across the site, as detailed in (Scottish Power Renewables, 2021a). The Carrick Windfarm Site Selection document explains "A high wake effect is disadvantageous to the overall productivity of the site," as explained, however, "if wind turbines are located too far apart, the opportunity to maximise the capacity and thereby electricity generation from the site is reduced." The Carrick Windfarm development demonstrates the struggle surrounding wind as a factor in site selection, even when at first glance the site appears to be within a suitable area. The spacing requirement can lead to sites being ruled out or significantly decreased in size and therefore operational output due to the fact the land is not vast enough for the development intended.

In addition to Carrick, Statkraft's An Carr Dubh Windfarm also faced the issue of maximising energy output while relating well to existing landscapes and other developments. The scheme was reduced in size from 26 wind turbines with maximum tip height of 200m to 13 wind turbines with maximum tip height of 180m (Statkraft, 2021). This could be due to multiple factors; however, the wind turbine spacing-energy output ratio would have played a significant part in this decision.

3.5 Timber

Timber is one of the major contributors to the Scottish Economy with a £771 million Gross Value added per year (Forestry & Land Scotland, 2023b). Gavin Falconer confirmed this by stating "peat and timber" were his biggest concerns when it comes to implementing renewable projects on FLS managed land. He indicated that the timber industry is the main part of FLS, with land management being a smaller role for the organisation. Timber is a concern when it comes to implementing wind farm sites on land for a number of reasons. Gavin stated that three of these are-

- The land used for wind farms often involves removal of timber to allow for the wind turbines themselves and the access roads. This is not sustainable and will reduce the income from timber for Scotland.
- Coupes can often be left exposed close to the wind farm due to the construction of access roads which result in wind blow which will become an issue in terms of loss of financial value and potentially causing safety issues and prohibit access.
- Future planting is restricted by wind farm construction; the more trees felled for wind farms the less timber there is for export in the future.

Alongside financial value, timber has many environmental values including "carbon capture, biodiversity, human health and wellbeing and farming" (Woodland Trust, 2023).

Carrick Wind Farm has not received objection from FLS but there is concern regarding the 97.2 ha of trees which will be removed and as of yet, do not have an identified replanting location. This should be stated to comply with the Scottish Government's Control of Woodland Removal Policy, which will result in the replanting volume of woodland being more than the original 97.2ha (Scottish Power Renewables, 2021d).

When compared to the An Carr Dubh development led by Statkraft, the Carrick Wind Farm felling seems extreme. An Carr Dubh proposes that only 3.77ha of woodland would be felled for access and would be replanted on site (Statkraft, 2023d).

3.6 Foundations

The primary purpose of a wind turbine foundation is to distribute the vertical and horizontal loads from the turbine self weight and the applied wind loading. The foundations must distribute the loads into the soil to ensure that the soil pressure remains within the acceptable limits (C Lavanya and Nandyala Darga Kumar, 2020). Typical foundations include a spread foundation, piles, gravity foundations or jackets (in the case of offshore turbines) (C Lavanya and Nandyala Darga Kumar, 2020). All of which use a considerable volume of concrete and steel for their construction.

Although the purpose of wind turbines is to generate cleaner, greener energy that has minimal impact on the environment, there are a variety of environmental concerns regarding the foundations for the turbines. The use of large volumes of steel and concrete when constructing the foundation involves a substantial level of energy consumption and CO2 emissions (Moynihan, 2019)- not to mention the detriment to the environment caused by the production and extraction of the raw materials to create concrete.

The installation process of the foundations is another major CO2 contributor due to the plant used when transporting and constructing the component parts for both their installation and eventual decommissioning. The vast majority of vehicles used within the construction and decommissioning process run on diesel that contributes to greenhouse gas emissions. Additionally, these processes can disrupt local habitats and impact surrounding ecosystems.

Daniel Clancy, Graduate Engineer from GDG, had also highlighted several issues associated with decommissioning of the foundations. After 30-40 years of operation, wind turbines need to be decommissioned, although in some cases the foundation of the wind turbine can be kept in place and utilised for the newer turbine replacement. This ultimately saves time and money while eliminating the energy consumption and CO2 emissions which would be emitted during construction if replaced.

However, there can be significant challenges faced when planning to reuse and utilise old wind turbine foundations as typically, by the time a turbine is ready to be decommissioned, there will have been technological advancements within the industry. Wind turbines are becoming more efficient, meaning that they are significantly increasing in size and weight, therefore meaning that the greater turbine loading will exceed the original foundation design. Additionally, there is often an inability to reuse the concrete after decommissioning due to a large volume of steel reinforcement present in the hardened concrete, leading to mass concrete waste and contributing to environmental harm. Ongoing investigations and studies aim to improve the decommissioning process and improve the ability to recycle old materials (Unknown, 2020), however, if the design of wind turbine foundations does not change, the industry is far from achieving net-zero goals.

3.7 Nature

The installation of wind farms can cause many issues for the environment ranging from a loss in wildlife habitat and nesting areas to deaths of airborne animals due to direct collisions with the blades (Hogan, 2020). More specifically, bats experience responsive behaviour towards wind turbines, known as attraction and repulsion. Attraction is where the bat is 'attracted' by the turbine and flies towards it causing a direct collision and repulsion is where the bat 'rejects' the turbine and needs to flee from its habitat. As there has not been clear behavioural data identified, researchers are still unsure which circumstances cause attraction and which cause repulsion and have therefore not established any mitigation measures to combat this issue (Camille Leroux et al., 2022).

From reading the EIA it has become apparent that the Carrick windfarm application included a Habitat Management Plan which incorporated a land management strategy to ensure minimal harm to the natural environment during the site development as well as a more detailed plan on how to restore bog habitats. Although this plan was proposed, the development was still rejected by Nature Scot as they believed the application did not provide enough evidence to prove the site would cause no to minimal harm to the Merrick Wild Land Area, a nature reserve situated within close proximity to the development (Scottish Power Renewables, 2023d).

Stakraft then shared that from their experience, Naturescot and environmental issues always cause more of a timescale delay than community consultation and objections.

3.8 Decommissioning

At the end of a turbine's lifespan, it may be repowered with upgraded technology and repairs, however there will always be a stage when it must be decommissioned. The blades, tower and the foundations must be removed which requires heavy machinery and additional environmental impact. Sites are required to restore the land via plantation, peat restoration and removal of tracks and materials. Initial EIAs for Scottish wind farms have minimal content on the Decommissioning of turbines, showing a lack of forward planning at this stage. Although a decommissioning and Restoration plan (DRP) is required once operational lifespan is reached.

Decommissioning is an unavoidable challenge that should be a focus now as 5,600 wind turbines in the Scotland will reach their 25-30 years lifespan by 2050 (Scottish Government, 2022). Zero Waste Scotland published a report on wind turbine decommissioning stating the main issue is the recycling of materials, alongside a lack of accountable data from the industry showing recycling or disposing destinations. Data shows that over 90% of a turbine's materials can currently be recycled, as they are made from copper, steel, aluminium and plastic (National Grid, 2023). Recycling the blades directly is difficult due to their composite material construction, which is why the majority are dismantled and buried in landfill or incinerated at a high carbon cost, a growing issue (Strathclyde, 2021).

Reblade is a start-up specialising in diverting turbine blades from landfill by repurposing them as furniture and other products, shown in Figure 7, which has utilised 100 tonnes of waste material (Scottish Government, 2022). However the UK and Europe are predicted to produce 25,000 tonnes of blade waste by 2025 and up to 52,000 by 2030 (Biogradlija, 2023). This shows the need for further planning beyond small scale applications in order for windfarms to truly contribute to net zero carbon goals.

Figure 7- A Bench Made from Wind Turbine Blades by Reblade (ReBlade, 2023)

3.9 Noise Polution

Communities are primarily opposed to the development of new windfarm sites due to noise pollution during both the construction and operation stage. There are two main sources of noise, including the noise from mechanical and electrical components such as the gearbox and generator, and the noise of air motion around the blades, which is the aerodynamic voice (Teff-Seker et al., 2022). It is reported that these voices have severely impacted the local communities' quality of life as it affects their sleeping behaviours, psychological and physical health, causing sleeplessness, stress and anxiety (Mariano, 2019). Although there is no evidence showing direct physiological impacts on humans nor any statistically significant evidence associated with headaches or hearing loss from this noise pollution (Briggs, 2017), there is research that reports on the impact these noises have on wildlife, damaging their physical wellbeing, vital survival mechanisms, social and reproductive processes (Teff-Seker et al., 2022). Another noise produced by the wind turbines known as infrasound and low frequency voice, was mentioned to cause nausea and coordination problems (Briggs, 2017). Local communities quoted: "It's like being at a disco with a massive base driver type unit, you feel it rather than hear it" (Briggs, 2017). It is stated that they often suffer from dizziness, are unable to walk properly and feel like they are going to collapse to the ground constantly (Briggs, 2017).

3.10 Visual Pollution

Visual impact of windfarms has always been a subjective and debatable aspect in the renewables sector. Wind turbines are designed to be tall structures with large blades, allowing them to capture the wind for efficient wind energy generation. Its visibility in a great distance brings concerns to local communities as these large structures change the landscape and alter the visuals in natural beauty (UNESCO, 2023). Although some may see it as a symbol of clean energy, most local communities would argue that it is manmade infrastructure with industrial elements that disrupt the natural landscape (UNESCO, 2023). Furthermore, it's rotating blades will cause a 'disquieting' effect and attract people's attention away from the natural beauty (Unknown, 2005). Carrick Windfarm has gone through certain assessments indicating this issue in which the operation of wind turbines will cause constant significant impacts on the visuals and landscape in its surrounding foothills and certain residential areas (Scottish Power Renewables, 2021c)

The United Nations Educational, Scientific and Cultural Organization (UNESCO) has also pointed out its concerns on the construction of windfarms disrupting cultural and heritage properties. The large size of wind turbines and expanding areas of windfarms would influence the visual scale of natural beauty causing the surrounding historical buildings and natural landscape to look smaller in relative to the turbine, effecting its cultural and historical values (UNESCO, 2023). The local community also claimed that this would deter tourists from visiting these areas and this would affect the local economy (UNESCO, 2023). This has been one of the main focuses of the Carrick Windfarm as there were six potentially impacted heritage assets within the site (Scottish Power Renewables, 2021c).

Another visual impact is the night-time aviation lights that were installed on wind turbines to flash constantly for their aircraft warning and safety (Gregori, 2020). Furthermore, as wind turbine blades rotate when the sun is behind, a moving shadow will be casted, known as the shadow flickering effect (UK Government, 2011). This caused annoyance towards the residential areas when the shadows are casted through openings such as windows, causing an alternating light and dark periods indoors (UK Government, 2011). Furthermore, the reflection of sunlight off the blade surfaces will cause occasional glare (UK Government, 2015). This concerns the residents, especially when driving on days with frequent daylight, impacting their safety and comfort (UK Government, 2015).

3.11 Airport Radars

When placed in certain areas, turbine blades may interfere with large areas of airspace which are intended to be free from obstructions known as 'Obstacle Limitation Surfaces'. When rotating, the blades also disturb airport radars which leads to an inaccurate target placement and a loss of target detection. When a radar is transmitted from an airport, it is intending to reach a nearby aircraft, however if a turbine is in the way of the signal the radar may believe this is the aircraft and send a signal back. The 'radar returns', from both a turbine and aircraft, are interchangeable and therefore the radar cannot differentiate between the two, this leads to the aircraft being wrongly positioned on the radar display and can cause air traffic issues. The severity of these issues depends on the airspace available and the air traffic within the proximity of the windfarm (CYRRUS, 2020).

An example of this is the Carrick windfarm proposal which was rejected by Prestwick Airport as the site had potential to cause disruptions to the airport's primary surveillance radar, secondary surveillance radar and VHF/UHF Communications Equipment. There was no sufficient evidence to prove that the turbines would not interfere with the local radar and therefore planning permission could not be granted causing significant delays (South Ayrshire Council, 2022).

3.12 Timescales

From recent communication with Ciaran Black and Scott Valance from Stakraft it has become apparent that in many cases the onshore windfarm approval process takes longer than the construction of them due to objections from the community and professional bodies.

There were four main stages of development considered for the Andershaw West case study before the operation of the turbine:

Stage One is Site Selection; this process is also known as 'siting' and involves selecting the most suitable location for the project. Each site is reviewed against wind maps which highlight the windspeed and direction at the area. A windfarm site that combines high wind speed with few technical and environmental restrictions is ideal. This stage also involves acquiring land permits, following ordinance survey maps and guaranteeing optimal practices to accommodate for the size and proposed location of a project (WindExchange, 2023). During this period, no public involvement is conducted as there is a possibility that the site may not meet the requirements needed to be an acceptable development. This stage takes around 12 months (Statkraft, 2023e).

Stage Two is Pre-Planning, also known as scoping, which involves consulting with the Scottish Government and Local Councils on how much detail and research needs to be carried out on the proposal. A scoping report is created which summaries the information already obtained and the work that has been conducted up to that point. Each aspect detailed within the report includes a description of the method assessment as well as the limitations and assumptions related (Scottish Power Renewables, 2020). The scoping report is then forwarded to councils within the local area of the turbine development and consultees such as NatureScot, SEPA and Historic Environment Scotland. It is anticipated that at this point, the initial proposal will change and evolve based on the data collected from additional research and interactions with the community and statutory consultees (Statkraft, 2023e). This stage takes 6-12 months.

Stage Three is submission of planning application; this involves submitting a completed planning application to the Scottish Government along with an extensive Environmental Impact Assessment (EIA) that summarises the findings of all studies that were conducted. This information will be made available to the general public and will also be shown on the corresponding project/company website. Formal comments may be left on the application by anyone interested in the project, more specifically statutory consultees such as local councils and environmental stakeholders. This stage takes around 12 months (Statkraft, 2023e).

Stage Four is the construction stage; this usually begins at least one year after consent if the project is approved. The construction of the project involves building additional road networks to transport the materials to site, constructing the foundations and trenches for the cables, installing the turbines and cables, and connecting them to the grid. This stage takes 12-18 months (Statkraft, 2023e).

Therefore, in summary it takes around 3 years from the site selection stage to the approval of the application which is longer than the 12-18 months construction stage. Our research concluded a windfarm development takes 4-6 years in total from planning to operation stage depending on objections, however Stakraft, the owners of Andershaw West wind farm, informed us that from their experience the record time scale in Scotland was 10 years.

Stakraft have current involvement with windfarm projects in the planning and construction stage but cannot get grid connection for these turbines until the middle of 2030 due to the queue system that is in place. This means that once the windfarms are operational, they won't be providing any energy to the grid until they reach the front of the queue which in some cases could be many years after their construction.

3.13 Community Consultation

Through a meeting with a communications consultant – Fiona Mulligan- who works for Infinenergy, associated with large wind energy developers Boralex, more advice was gained on community consultation and stakeholder engagement. She explained her role within the company, working with communities, landowners, fisherman and anyone who acts as external, private, and public stakeholders for wind energy developments. She confirmed the problems that previous research identified with onshore community relations, mostly objections from the public to do with visual pollution. Fiona explained that most of the complaints she experiences come from an older demographic and younger generations tend to care less about the visual intrusion and better understand the necessity for wind farms. Fiona also noted that people with a negative opinion – objectors – speak a lot louder than supporters, so it is important to try and reach these positive stakeholders. Fiona mentioned that community consultants used to door knock, but they realised that this can be irritating to positive supporters and not very beneficial. Public enquiries held in evenings received better attention, but usually attract negative supporters. This gives companies a chance to persuade and inform objectors on the benefits and rewards that a wind farm can give to a community.

Public enquiries are a phase following an objection from a council of government body, to reassess the wind farm proposal. Fiona discussed how almost all wind farm developments experience at least 1 public enquiry phase, as turbines are now built larger and closer to built-up areas. Most public enquiries are due to councils objecting on grounds on visual pollution or agencies requiring better environmental protection efforts. Fiona experienced a project start in 2009, with community consultation in 2011, entered public enquiry in 2014, still received rejection in 2015 and entered a second public enquiry to finally be granted consent for the farm in 2021. This shows the extent that community consultation can affect a project.

3.14 Turbine Failures

Generally, wind turbines can fail either externally or internally. External factors causing failure are typically blade issues including bird strikes, extreme rainfall, lightening (Figure 8) – causing delamination and debonding, corrosion or cracking, and icing, which can cause the turbine to be unbalanced. Blades can be replaced or repaired; however, this has a high economic and carbon cost and creates waste (Troskie, 2023).

Figure 8- Image of Lightening Damage to a Turbine (Hall, 2021)

Internal failures can happen both mechanically and electrically, mechanically can mean the gear box, bearings, or the hub fail.

Gearbox failure happens due to high stress, it will often need repaired or replaced before a turbine's lifespan is up. "The gearbox is 13 percent of the overall cost of the turbine" (Mein, 2020) which means that replacing it is not only costly in itself, but the turbine will need turned off to be fixed, resulting in a loss of energy generated.

Bearings support the rotating components of a turbine, if bearing failure happens it is usually due to overloading, or general wear and tear. Bearing failures can cause a turbine to be down for a long time, again resulting in a loss of energy generated (Małgorzata Sikora and Tadeusz Bohdal, 2022).

The generator takes the mechanical energy generated through the turning of the blades, and converts it into electrical energy, it can fail due to electrical failures like overheating.

Wind farms have monitoring systems on their turbines which indicate when components need attention. This aligns with information provided by our stakeholder at Statkraft who informed us that their maintenance plan is mostly reactive, which focuses on fixing a part of the turbine after failure occurs.

Craig Sinclair, a turbine engineer for MES explained that most turbines are cleaned every five years, bearings and other moving parts are lubricated which are forms of preventative maintenance. Planned maintenance can be used to prevent failure, however if the maintenance is not needed then it could be a waste of time, resources, and money.

Failures in wind turbines can be detrimental, resulting in loss of efficiency in energy production over time and ultimately periods of no production. Turbines are designed to have a lifespan of 25-30 years, which is often shortened by failures, and after this period maintenance is not effective enough to ensure efficient energy production and they must be decommissioned.

4. Final Solution- Early-Stage Proposal

The problems with onshore windfarms were unanimous across all stakeholders and it was discovered there were so many problems with a lack of solutions. The energy targets are very ambitious, and it became clear that there wasn't enough viable land to build on due to peat land and space requirements. Following advice from industry experts who informed us they have been trying to find answers to these problems their whole career it would be better if we changed the scope of our project. This progressed to the decision of an offshore solution. The main issue with offshore wind is how expensive each individual farm is to set up and then directing the energy back to land efficiently. The North Sea has its own 2050 net zero target, and this will result in a large proportion of redundant oil and gas infrastructure that will be decommissioned in the future (North Sea Transition Authority, 2023a).

Therefore, the design of an energy island would incorporate these overriding issues whilst also achieving sustainability targets which the North Sea Transition Deal recognises will have to use emerging technologies.

Denmark has been consistent pioneers in offshore wind development, responsible for the world's first project and some of the most ambitious goals. They currently have preliminary designs for an energy island in the Baltic and North Sea (Danish Energy Agency, 2023). Part of their vision is to connect countries via intermediate islands so that an energy network can distribute the full potential of the North Sea. As the challenge of net zero is so great, it is essential that large scale cooperation is employed.

4.1 Energy Islands

Energy islands are hubs for offshore renewable energy connection and storage. They facilitate OSW to be constructed further away from the land, where wind is stronger, turbines can be bigger and more efficient and public nuisance is less.

Currently countries in Europe are producing plans and designs for energy islands but none are a reality yet. An energy island is an ambitious, large-scale project but would give the host country and connecting countries energy security and the ability to expand offshore wind power exponentially.

These hubs can be built on existing islands or manmade islands which connect to surrounding wind turbines and other renewable energy. On the island the energy can be processed and transmitted to countries on demand very efficiently.

As the North Sea is aiming to achieve net zero carbon, oil and gas infrastructure is becoming redundant. By utilising platforms, pipelines or connection routes, an energy island plan could help decarbonise the North Sea whilst reusing and reducing waste infrastructure.

This image (Figure 9) shows an example of an energy island design produced by Denmark (Royal HaskoningDHV, 2023).

Figure 9- Energy Island in Denmark (Royal HaskoningDHV, 2023)

4.2 Location Research

For the early-stage proposal three main areas of Scotland were researched as potential hosts for the energy island. Both Orkney and Shetland, were considered as existing islands that could be transformed into a potential energy island as there were many locations that were uninhabited and fulfilled the size requirements of a typical energy island. Areas off the North Sea off the coast of Aberdeen and Edinburgh were also researched as potential locations for a manmade energy island as there was existing oil and gas infrastructure in these locations and large pipe networks, both of which would be incorporated into the design.

4.2.1 Scottish Islands

Orkney

Orkney is situated in Northern Scotland, with islands covering a distance of 190km from the coast, as shown in Figure 10. However, the maximum distance from shore for an energy island to be situated in is 80-100km. Therefore, the distance from land to the energy island location is more likely to be within 100km from the coast in this area, see Figure 11.

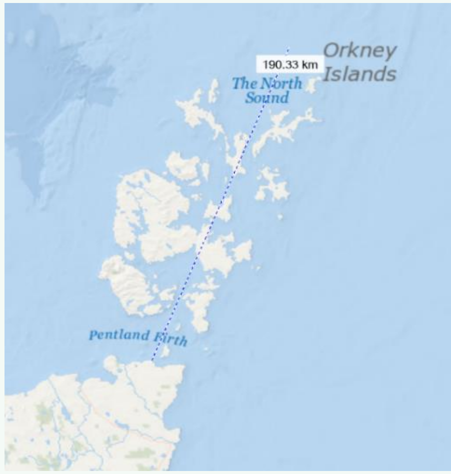


Figure 10- Distance from Land

Figure 11- 100km From the Coast

Following on from distance from the shore, the depth of seabed is also an essential factor to be considered when proposing a location for an energy island. Within this region, much like most of the North Sea around Scotland, the water depth surrounding the islands is around 50-100m, see figure 12 (Vledder et al., 2016).

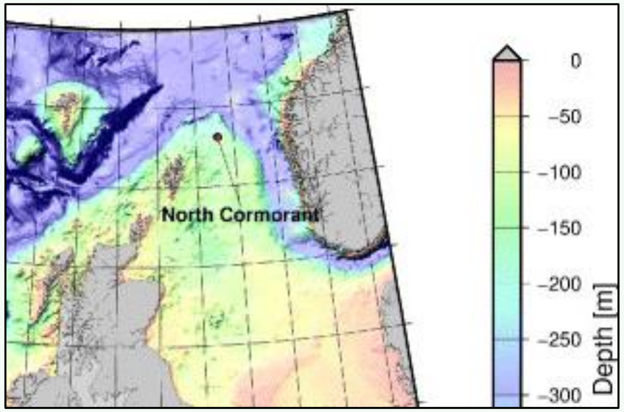


Figure 12- Depth of Seabed (Vledder et al., 2016)

The wind speeds appear to be higher the further north the location is, based on the average wind speed map shown in Figure 13 (Met Office, 2010). The islands have a noted average wind speed of 15-20 knots.

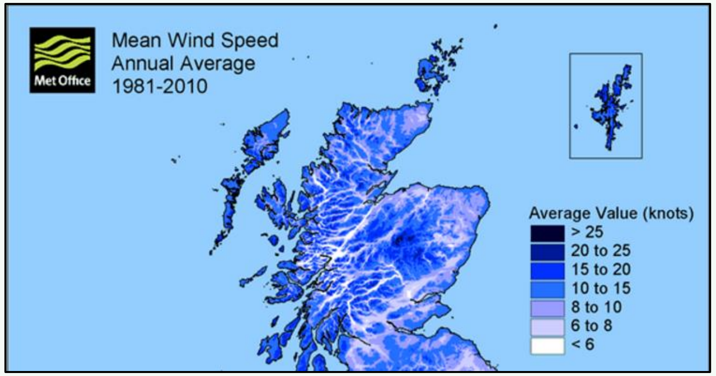


Figure 13- Wind Speeds (Met Office, 2010)

Another essential factor to consider is existing transport links in the area for construction and maintenance purposes. Personnel and materials/machinery must be able to easily be transported to the island in order for operation to be efficient. Figure 14 below shows the existing harbours on and around the islands (Open Sea Map, 2023). Airports are shown in Figure 15 (Aiports DK, 2023).

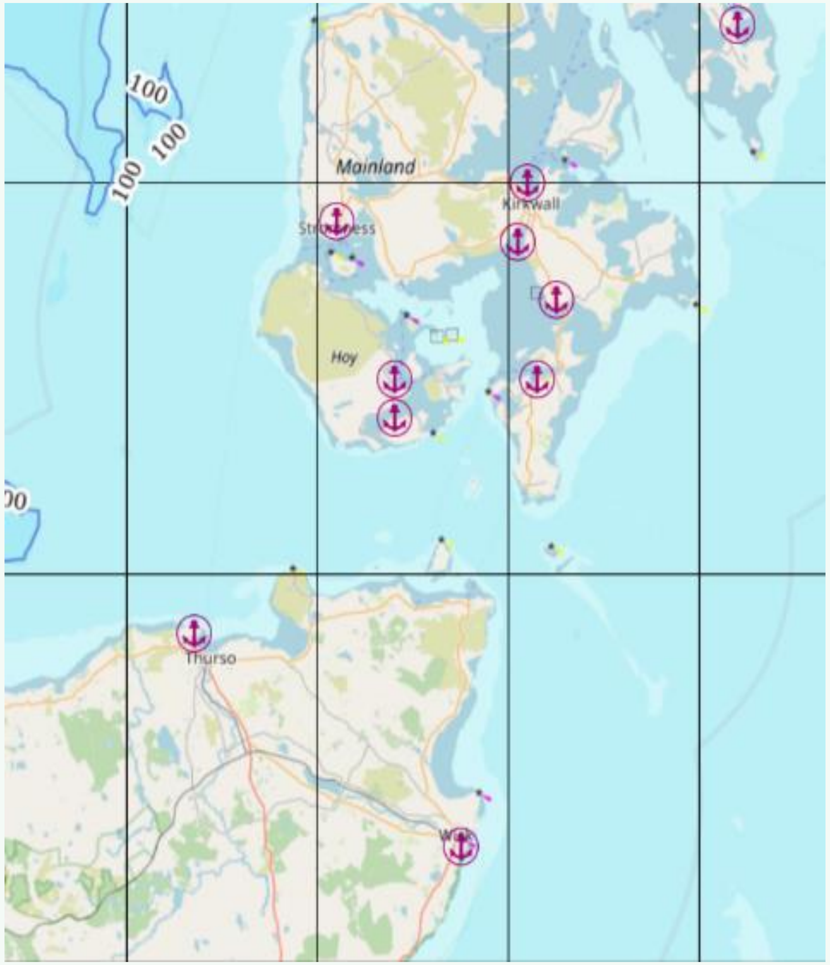


Figure 14- Existing Harbours in and around Orkney (Open Sea Map, 2023)

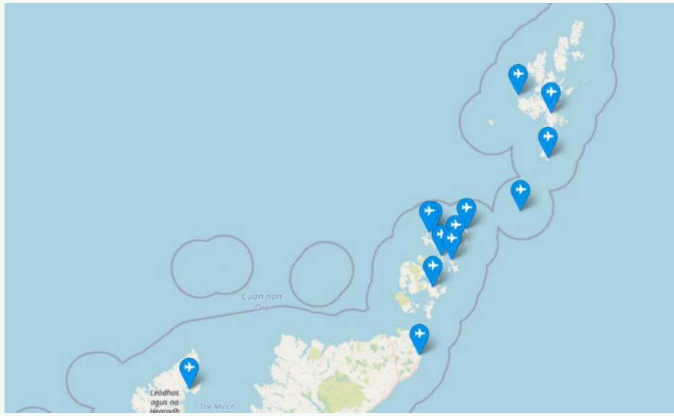


Figure 15- Airports in and around Orkney and Shetland (Aiports DK, 2023)

From Figure 16, it was noted that the sea surrounding the islands is predominately protected for marine wildlife (Scottish Government, 2023a). This may pose an issue when proposing the construction of an energy island and a large number of turbines in the area.

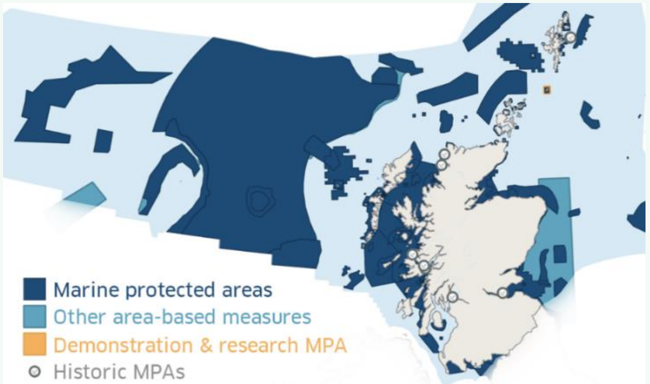


Figure 16- Marine Protected Areas (Scottish Government, 2023a)

There are existing offshore wind farms (shown in yellow in Figure 17 (Crown Estate Scotland, 2023b) around both the Orkney and Shetland Isles. Notably, there are more wind farms closer to mainland Scotland than there are close to the Shetland Isles.

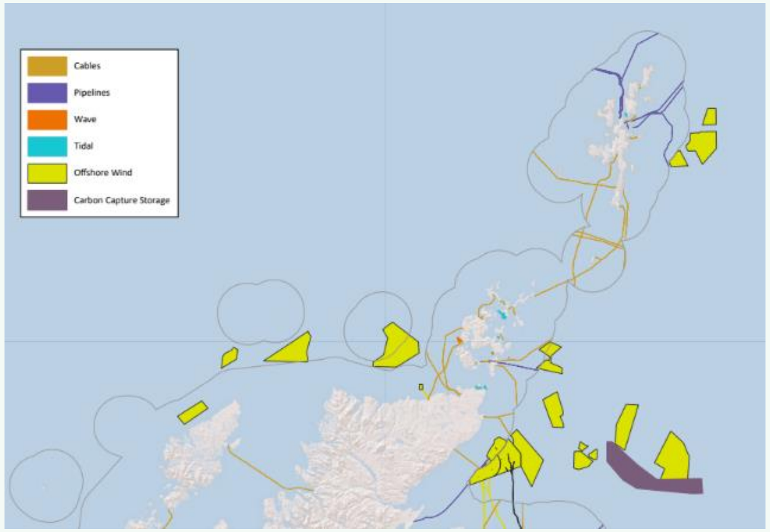
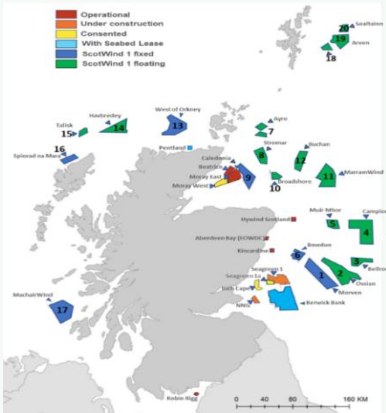


Figure 17- Existing Offshore Wind Farms (Crown Estate Scotland, 2023b)

Additionally, Figure 18 (Offshore Wind Scotland, 2023) below exhibits the operating, constructed, consented, and planned offshore developments around Scotland. This allows the potential future offshore wind map to be viewed and informs the likelihood of a new wind farm being in the proximity of the energy island.



ScotWind

SITE	DEVELOPER	CAPACITY
1	BP and EnBW	2907MW
2	SSE Renewables, CIP and Marubeni	3610MW
3	Renantis and BlueFloat Energy	1200MW
4	ScottishPower Renewables and Shell	2000MW
5	Vattenfall and Fred Olsen Renewables	798MW
6	Thistle Wind Partners	1008MW
7	Thistle Wind Partners	1008MW
8	Renantis, Orsted, BlueFloat Energy	1000MW
9	Ocean Winds	2000MW
10	Renantis and BlueFloat Energy	900MW
11	ScottishPower Renewables and Shell	3000MW
12	Floating Energy Allyance	960MW
13	RIDG, Corio Generation and TotalEnergies	2000MW
14	Northland Power	1500MW
15	Magnora ASA and Technip UK	495MW
16	Northland Power	840MW
17	ScottishPower Renewables	2000MW
18	Ocean Winds	500MW
19	Mainstream RP/Ocean Wind	1800MW
20	ESB Asset Development	500MW

Scottish current projects

SITE	DEVELOPER	CAPACITY
Robin Rigg	RWE Renewables	174MW
Hywind Scotland	Equinor	30MW
Aberdeen Bay	Vattenfall	93MW
Beatrice	SSE/Red Rock Power	588MW
Kincardine FOW	Cobra/Pilot Offshore	48MW
Moray East	Ocean Winds	950MW
NNG	EDF Renewables and ESB	448MW
Seagreen 1	SSE Renewables and TotalEnergies	1140MW
Seagreen 1a	SSE Renewables and TotalEnergies	420MW
Inch Cape	Red Rock Power	1080MW
Moray West	Ocean Winds	850MW
Berwick Bank	SSE Renewables	4150MW
Pentland FOW	Copenhagen Infrastructure Partners	100MW

Figure 18- Operation, Constructed, Consented and Planned Offshore Developments (Offshore Wind Scotland, 2023)

All existing oil and gas infrastructure is shown on the map in Figure 19; this can be compared with the pipelines in Figure 20 (North Sea Transition Authority, 2023b). There is little oil and gas infrastructure around Orkney or the North of Scotland coastline. Surrounding the Shetland Isles however, there is much more existing infrastructure.

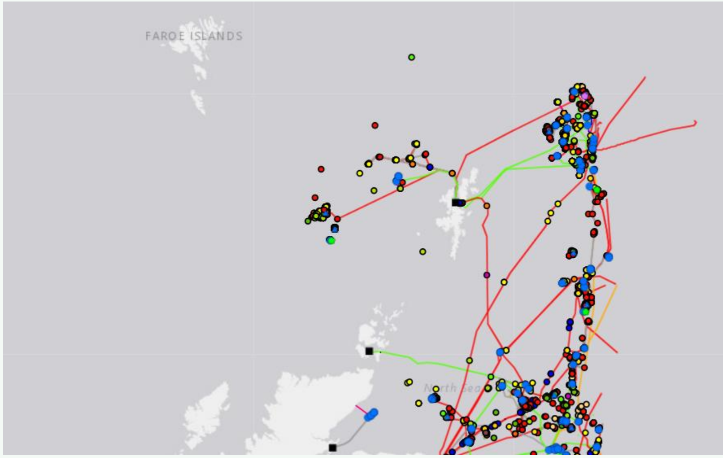


Figure 19- Oil and Gas Infrastructure (North Sea Transition Authority, 2023b)

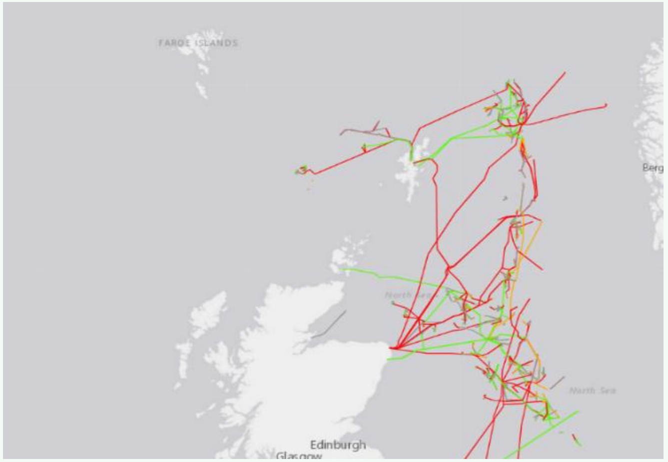


Figure 20- Oil and Gas Pipelines (North Sea Transition Authority, 2023b)

Figure 21 below shows the oil and gas infrastructure map overlayed with the offshore wind map in GIS. Along with the existing Crown state cables and pipelines maps shown above in Figure 20. This shows the existing connections to land.

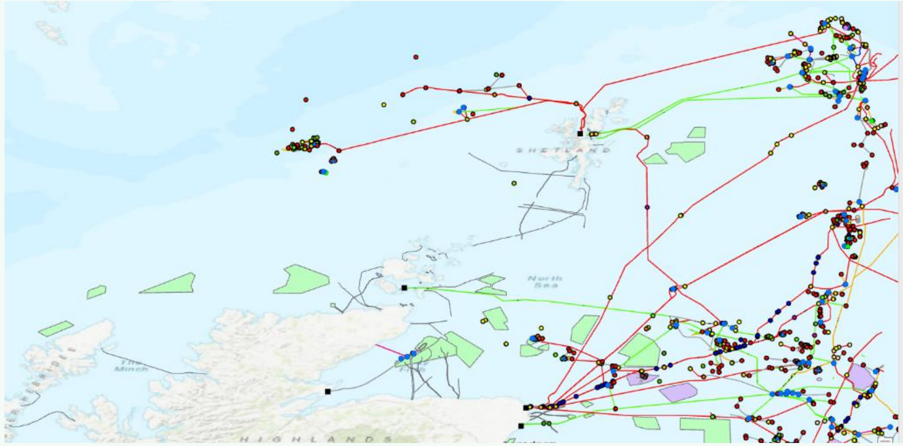


Figure 21- All offshore Infrastructure In GIS

Closer to the North Coast, there is one existing small island off the coast of Flotta in Orkney that has potential to be used as an energy island- shown in red circles in Figure 22. From the information available, it appears to be an uninhabited island, with an area of around 180,000m2, shown in Figure 23.

Figure 22- Uninhabited Island in Orkney

Figure 23- Area of Uninhabited Island

This would be suitable as it is the smallest piece of land that is close to existing infrastructure (Flotta Marine Oil Terminal and pipeline)- Figure 24.

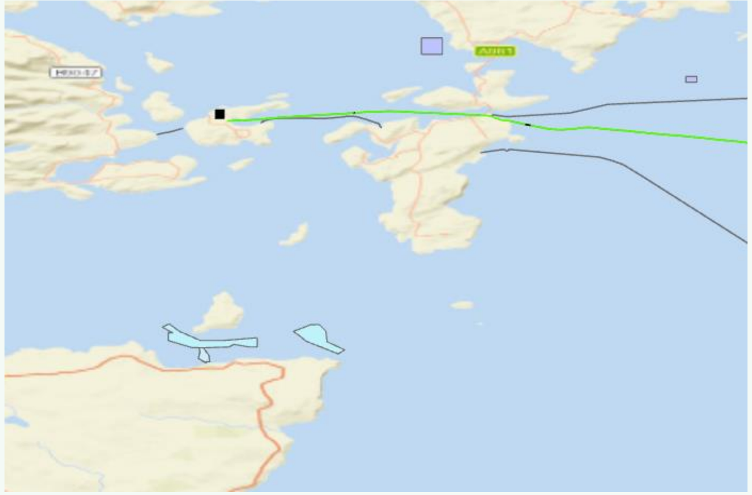


Figure 24- Flotta Marine Oil Terminal and Pipeline

Shetland

Situated 1.5 miles Northeast of Shetland there is a small island called Fish Holm near the village of Mossbank. The highest point on this island is 20m which means it is relatively flat to build on (Wikimedia, 2010). This island is uninhabited, with an area of around 190,000m^2. There is no online information provided about the island's usage and no online tourism rating (Scottish Places, 2007). Therefore, it is assumed the island is not a substantial area for tourism and wildlife, making this a good location in the Shetlands for an energy island. The findings regarding windspeed, seabed depth and transport links resembled that of Orkney.

This location is situated close to existing infrastructure like mains, cables, pipelines and also a proposed tidal energy project. There are also two offshore windfarm sites located 22km to the east of the island.

Approximately 74 out of 100 of the islands around Shetland are uninhabited for example Little Linga and Ladys Holm. These islands were also researched as potential locations for an energy island, however, both of which are known to home Atlantic grey seals with 500 pups born each Autumn. Furthermore, the island accommodates 200 pairs of fulmars and about 80 pairs of cormorants that rear their young on seaweed nests. Therefore, making them unsuitable sites for large infrastructure projects (Wikipedia, 2022b) (Wikipedia, 2022a).

There is potential to connect this energy island to North America, the Faroe Islands, Iceland and Greenland as there is an international network that passes North and South of Shetland which extends to these areas.

In this area there are also 88 operation cables totalling 1,100km of inshore and 3,500km of international cables (Scottish Government, 2019).

Figure 25 – Map of Shetland highlighting proposed location for the energy island.

4.2.2 Aberdeen

Aberdeen city and the coast of Aberdeen have a well-established energy production sector and core understanding of the energy industry, known as the 'Energy Capital of Europe' and home to Scotland's infamous oil and gas industry. This knowledge and established connection to the sector can help aid the energy transition and drive the achievement of sustainable development goals. Long known as a global energy hub, Aberdeen is of crucial importance to the energy security of the UK and therefore holds a unique supply chain capability that other regions in Scotland may not have. This will mean that transportation of resources and materials to the city will be well established and easy to utilise.

As illustrated in Figure 26, the majority area of the North Sea around Aberdeen sits between 40m, and 200m in depth. As discussed previously, wind turbines can be constructed in depths of up to 60m, therefore, there is a large percentage of area that can be used off the coast of Aberdeen for wind energy production.

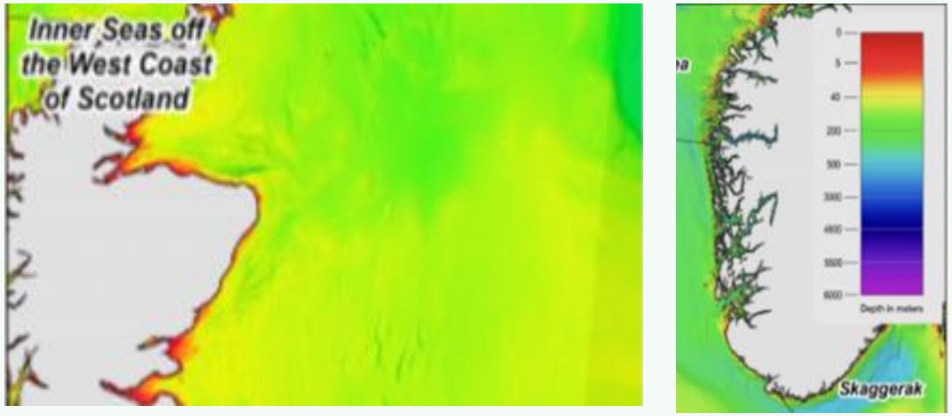


Figure 26-Map of Depth of Seabed (Marine Regions, 2016)

Aberdeen has an abundance of existing oil and gas infrastructure residing on its coastline and has the greatest access to offshore pipeline networks when comparing the city to other areas of Scotland. Figure 27 shows the map of the active hydrocarbon fields and pipelines in the North Sea, illustrating that the area has the potential to present an opportunity to exploit the existing infrastructure for offshore energy production and energy transportation to the UK Grid. Figure 28 shows the offshore wind.

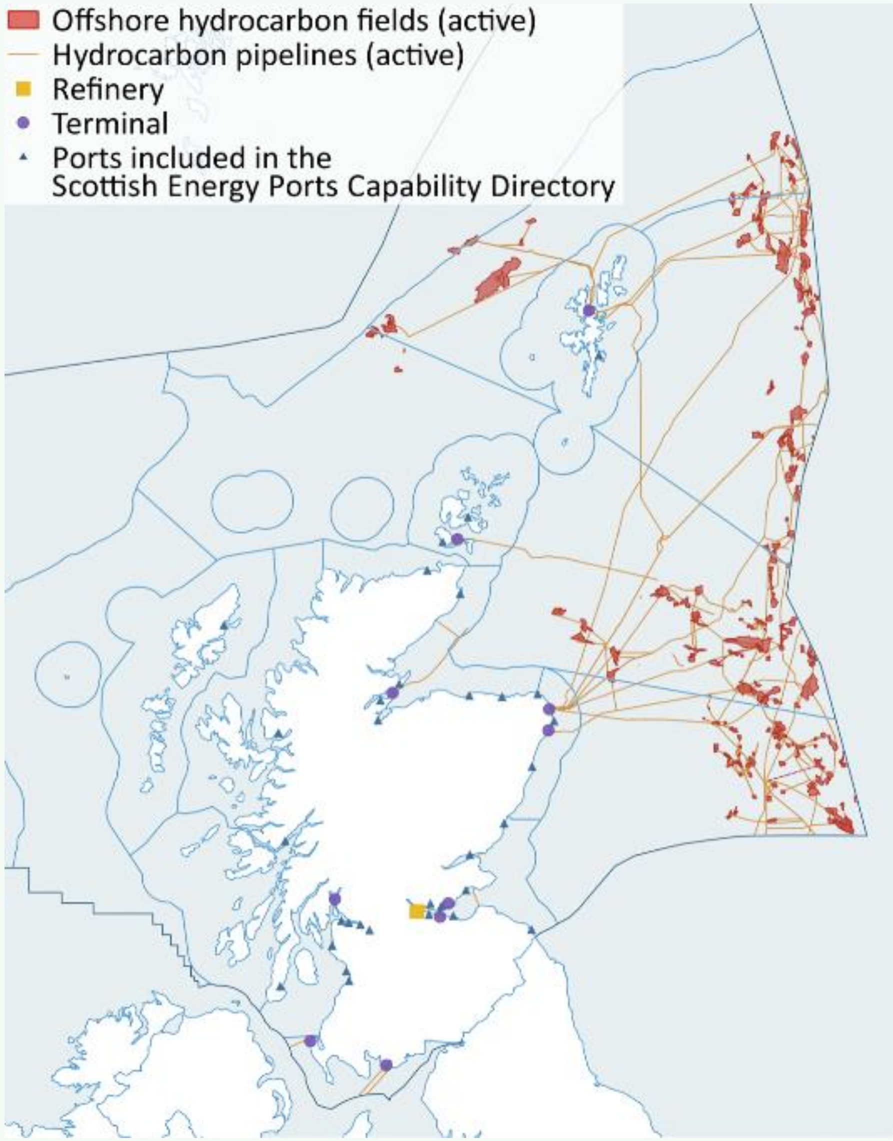


Figure 27- Map of Existing Scottish Offshore Energy Production (Marine Scotland Assessment, 2019)

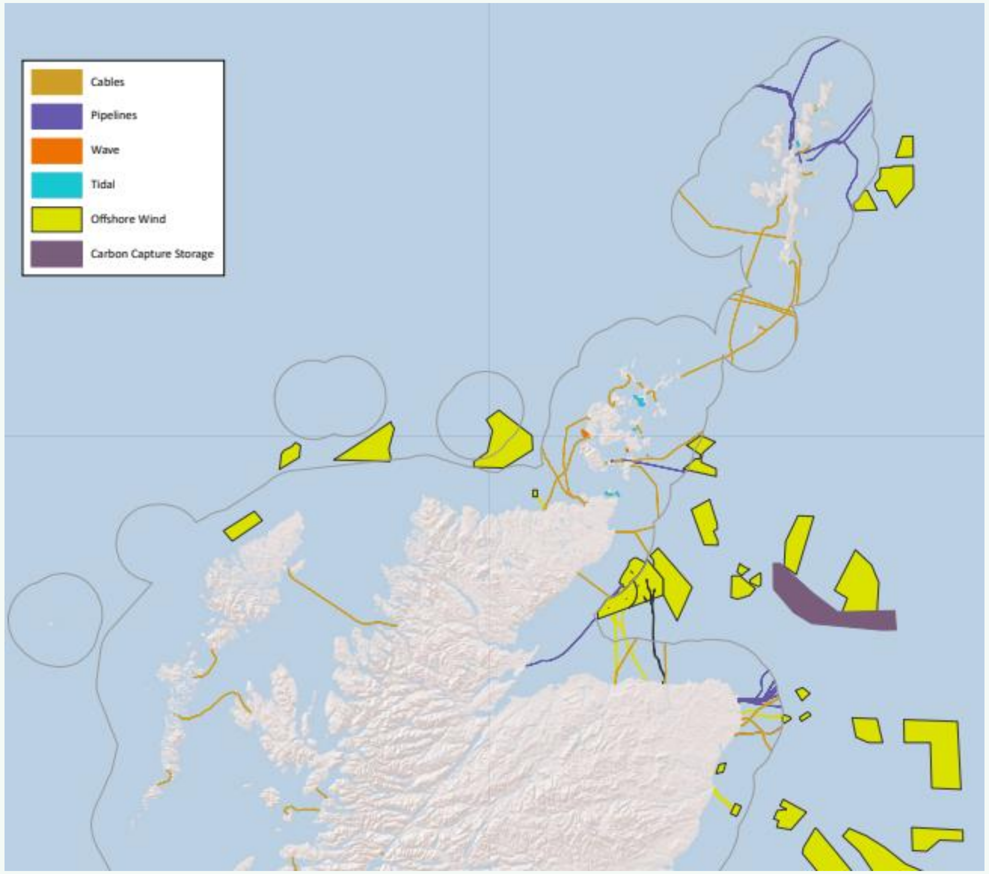


Figure 28- Offshore Wind Infrastructure Map (Crown Estate Scotland, 2023b)

Furthermore, statistical data gathered by the Scottish government identifies the number of active pipelines, platforms and FPSO (Floating Production, Storage, and Offloading) in the UK as of January 2019- Table 3.

Table 3 – Number of active pipelines, platforms and FPSO (Floating Production, Storage, and Offloading) in the UK as of January 2019 (Marine Scotland Assessment, 2019)

Scottish Marine Region	Pipeline length (kms)	Active platforms and FPSO*	Abandoned, Not in use, Removed platforms & FPSO*
Solway	94		
Clyde	10		
Argyll	3		
Outer Hebrides	1		
Orkney Islands	44		
Shetland Isles	596		
Moray Firth	115	4	
North East	268		
Forth and Tay	42		
Offshore Marine Region	Pipeline length (kms)	Active platforms and FPSO*	Abandoned, Not in use, Removed platforms & FPSO*
Faroe Shetland Channel	63		
North and West Shetland Shelf	1,880	10	2
East Shetland Shelf	3,347	28	6
North Scotland Shelf	128	2	
Fladen and Moray Firth Offshore	4,407	43	10
Long Forties	3,803	25	1
Total (2019)	14,801	112	19
Total (2011)	12,804	103	N/A

To illustrate this further, Figure 29 shows the various marine regions that surround the coasts of Scotland, identifying the Moray Firth area and the Northeast area are the two regions located off the coast of Aberdeen. These areas are confirmed by Table 3 to have the highest number of active platforms, FPSO, abandoned platforms and platforms that are no longer in use. Additionally, the Moray Firth and Northeast regions have some of the greatest lengths of pipelines in Scotland.

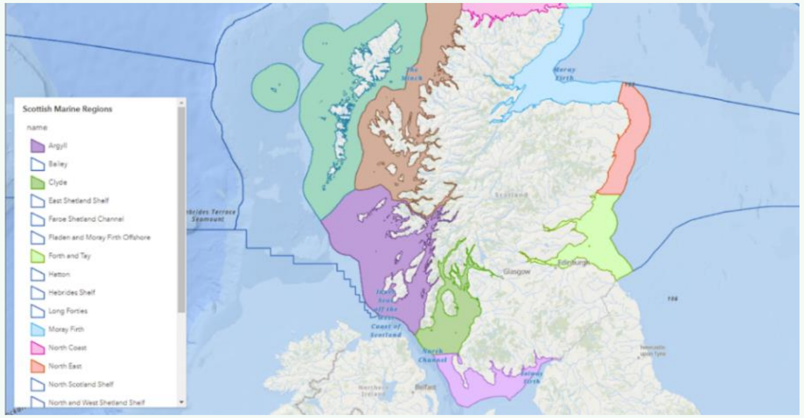


Figure 29- Marine Regions (Esri UK, 2022)

Around the coast of Aberdeen there are both MPAs (marine protected areas) and other area-based measures, these can be seen in Figure 30.

Figure 30- Map of Marine Protected Areas (Scottish Government, 2023a)

Using GIS, it was measured that the MPAs span to around 85-88km from shore, as seen in Figure 31. In terms of ecological permission, this means that anything over 88km from the shoreline would be applicable for the energy island. This has no impact on the energy island proposal as the ideal distance from shore is 80-100km.

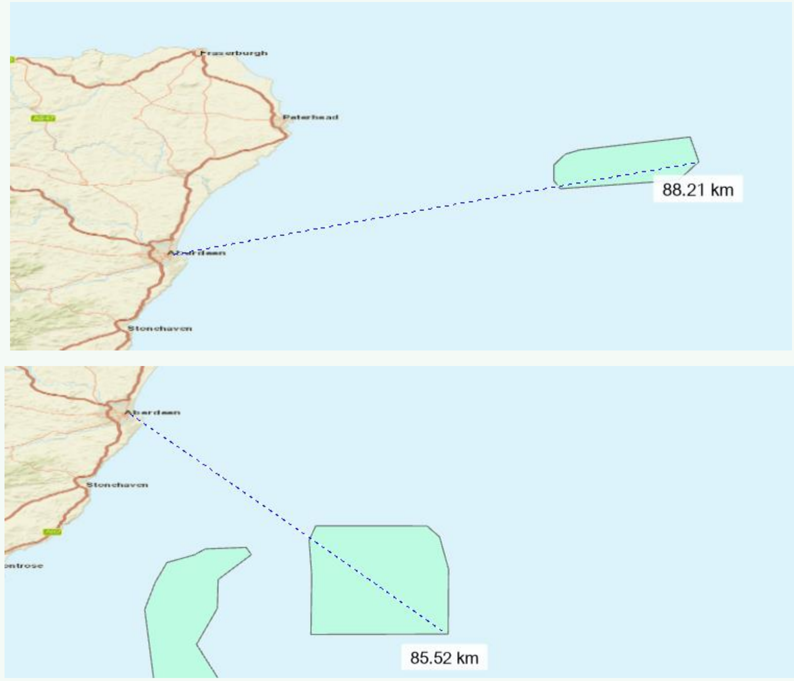


Figure 31- GIS Measurement to the Edge of the Marine Protected Area's

4.2.3 Edinburgh

Edinburgh is surrounded by Firth of Forth which connects to the North Sea (Figure 32). Several islands of varying distance and size are found in this area, including the Isle of May, Inchkeith, Inchcolm, Inchmickery and Cramond Island.

Figure 32- Map showing Edinburgh City and Surrounding Firth of Forth

Certain historical buildings were found on the islands, such as the Inchkeith Lighthouse, Inchcolm Abbey and the Beacon on Isle of May- see Figure 33.

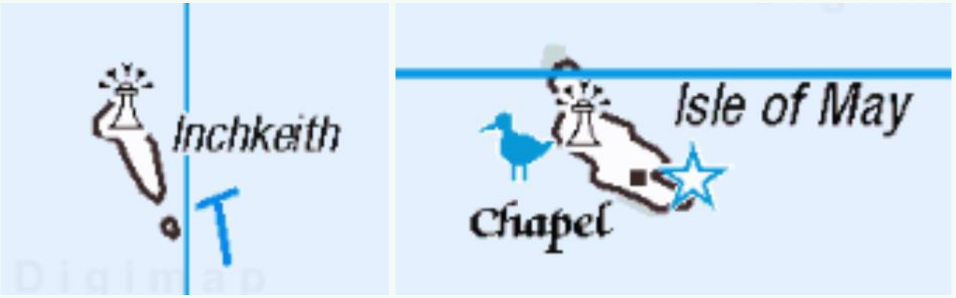


Figure 33- Map of Islands Near Edinburgh with Historical Buildings and Nature Zones (Digimap, 2023)

The Isle of May is the largest island the furthest from land, which would make it a potential candidate for energy use. However, it also acts as a National Nature Reserve and tourist attractions, especially famous for puffins viewing. An energy island should not interfere negatively with the environment or disturb current land use. Despite this area having several islands, a man made one would have the least impact to current habitats.

The geology of the area is as shown on the map (Figure 34) - rock (gold) is only seen near shore. Most of the bedrock is sandstone (light gold) with muddy sand (light gold and light green) as sediments. Mud (light blue) is found near the harbour with gravelly muddy sand (salmon) found around the shores of Edinburgh. Rock and hard substrate (grey) were found nearby the Isle of May and certain shore areas such as near East Lothian and Fife.

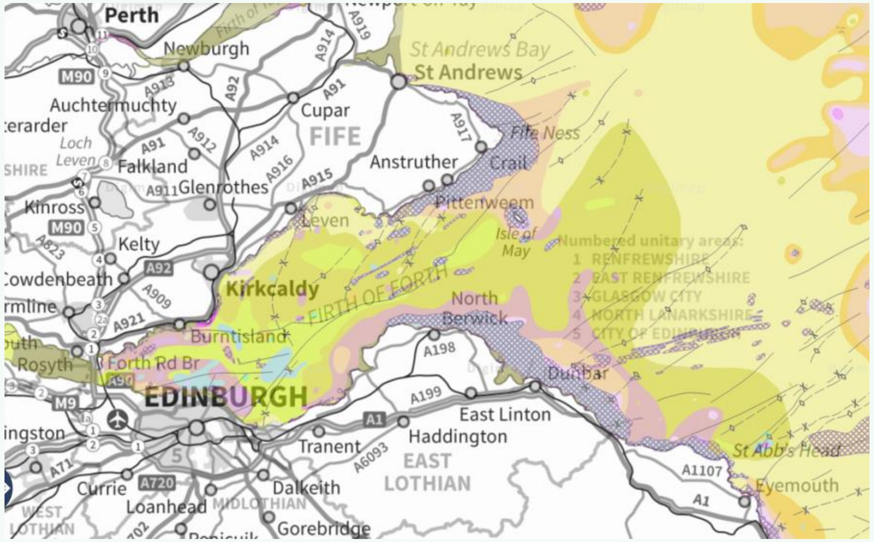


Figure 34- Geological Map of Seabed Around Edinburgh (Digimap, 2023)

The 2019 wind energy network map (Figure 35) shows several sites under planning, but none fully commissioned next to Edinburgh.

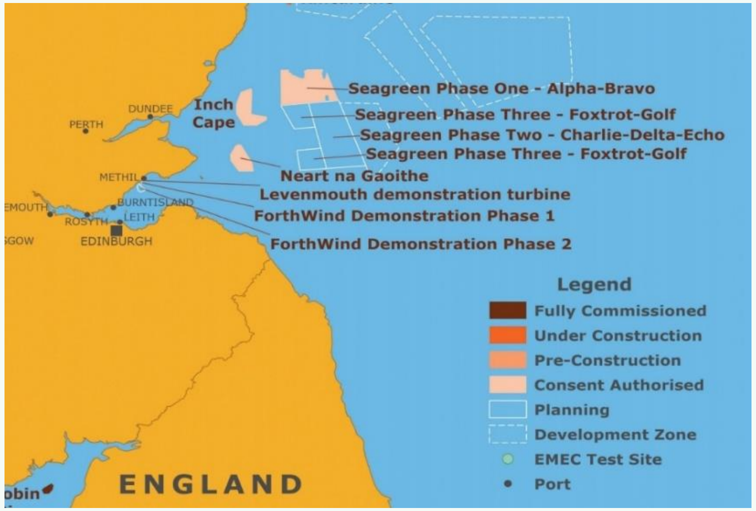


Figure 35- 2019 Map of Offshore Wind Projects Around Edinburgh (Wind Energy Network, 2019)

Crown Estate Scotland also show a map from 2022 (Figure 36) which shows offshore wind next to Edinburgh being developed further but still in constructing and planning.

Figure 36- 2022 Map of offshore wind projects near Edinburgh (Crown Estate Scotland, 2023a)

SSE currently has plans for their largest offshore wind project to be a super power off the coast of Edinburgh (Crow, 2023). These existing and planned sites may cause issues during the planning stage of energy island and prevent it from having best placement.

This map (Figure 37) shows subsea connection points to oil and gas infrastructure and the transmission network. Currently Edinburgh has no viable connections that could be utilised in this project.

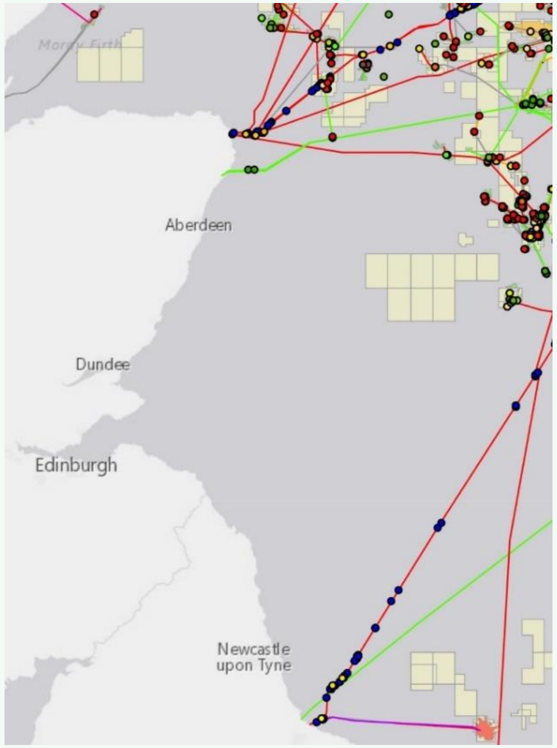


Figure 37- Map Showing the Lack of Undersea Cables from Existing Infrastructure to Land (North Sea Transition Authority, 2023b)

Marine Scotland shows maps of marine protected areas off Edinburgh, however the existing infrastructure and wind farms in these areas shows there is ways to build without breaking restrictions.

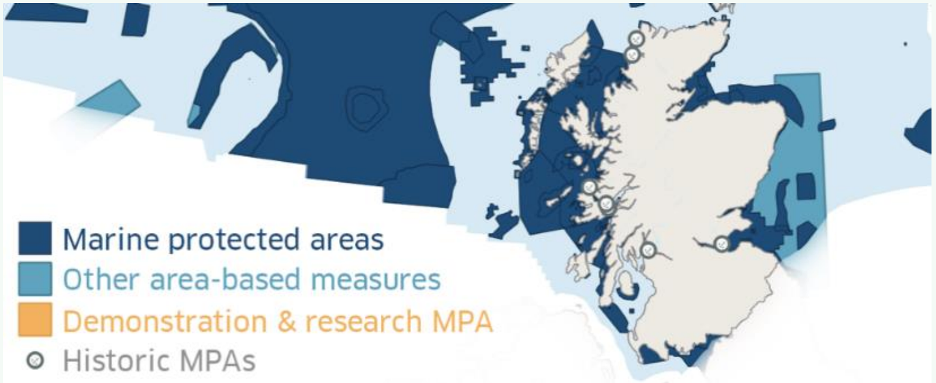


Figure 38- Map of the ecological zones next to Edinburgh – shown in dark blue (Scottish Government, 2023a)

This in additional map (Figure 39) shows a dense area of marine protected area near Edinburgh and less near Aberdeen (JNCC, 2023) .

Figure 39- Map highlighting the difference in marine protected areas between Edinburgh and Aberdeen areas (JNCC, 2023)

Edinburgh is a brilliant location with several major ports like Leith and Grangemouth to aid in the construction and connection of an energy island. Leith port (Figure 40) is currently constructing Scotland's largest renewable energy hub to accommodate offshore wind growth (Forth Ports Group, 2023b).

Grangemouth port is Scotland's largest shipping container handler and transports huge amounts of material (Forth Ports Group, 2023a). It is highly connected by main motorways to the central belt.

The transmission infrastructure in the city of Edinburgh is already at a high standard so needs fewer upgrades to be suitable to take energy from offshore and into the grid.

Figure 40- Photo of the port of Leith development in Edinburgh (Forth Ports Group, 2023b)

4.3 Options Appraisal

To determine the most suitable location between the Scottish Islands, Edinburgh and Aberdeen, a simple options appraisal was carried out. This is shown in Table 4. The research detailed in Section 4.2 has been split into ten categories and given a score from zero to five for each location. Table 3 explains the meaning of the given score- the location with the highest total score will be the chosen location for the energy island. This was chosen to determine the most suitable location as it is a fast and simple yet effective ranking method.

Table 3- Score Key

Score	Meaning In Terms of Suitability for An Energy Island
0	Not Applicable
1	Bad
2	Poor
3	Average
4	Good
5	Excellent

Table 4- Options Appraisal

Criteria	**Aberdeen**	**Edinburgh**	**Islands**
Depth of seabed	5	5	5
Proximity to existing windfarms	5	3	2
Proximity to existing oil/gas infrastructure	5	1	2
Proximity to ecological zones	2	2	1
Wind speed	5	5	5
Existing connections to land	5	1	2
Transport Links on Land	4	5	3
Existing Islands which could be utilised	0	0	5
Ability to utilise oil/gas infrastructure	5	1	1
Possibility of connection to multiple countries	4	2	4
TOTAL	**40**	**25**	**30**

4.4 Aberdeen

After reviewing all options, it has been decided that Aberdeen has the best potential for the energy island due to its established offshore network, land connections, transport, and existing infrastructure, as well as wind speeds, far proximity to protected areas, and seabed depths.

The depth of the seabed is much the same to that around Edinburgh and the islands, which is the same case with the wind speeds. The North Sea was chosen as it has suitable wind speeds (above 13 knots) and seabed depths (50-60m) for an energy island. Aberdeen has significantly better proximity to existing windfarms and oil/gas infrastructure when compared to the other areas which will reduce the economical and carbon costs. The ecological zones off the coast of Aberdeen are all within 90km from the shore, resulting in them having little effect on the location of the energy island as it should be ideally 80-100km from the shore. Due to the established offshore network, there are many existing connections to land, and despite being less central than Edinburgh, there are numerous transport links to the city including road, rail, sea and one international airport. Despite having no existing islands which can be used, there is plenty of opportunity to utilise existing oil and gas infrastructure to build the island on. Finally, the opportunity to connect the island to multiple countries from the coast of Aberdeen is high.

Aberdeen has ambitious energy targets for a 'Net Zero Vision' and plan to use the cities abundance of resources as a driver in becoming a world leader in the renewable energy sector. 'The Strategic Infrastructure Plan – Energy Transition' document describes Aberdeen cities infrastructure projects that will contribute to their energy transition from fossil fuels to net zero, further cementing idea that Aberdeen is looking for new and innovative ways to become more sustainable and likely to have full support of an energy island proposal.

4.5 Next steps- Design, Construction and Cost

4.5.1 Design

The next stage will include the design of the energy island which will involve detailing the chosen location,

- the island dimensions,
- the use of existing infrastructure and how this will be done,
- the materials/aesthetics for the island,
- connection details,
- type of energy which will be utilised and details for this,
- transport links,
- technology which will be used,
- the potential energy capacity and energy storage solutions.

4.5.2 Construction

The next stage will include determining the construction details including-

- The time scale for construction,
- processes involved,
- construction of the connection under sea and to grid on land,
- construction of the connections from surrounding wind turbines to islands,
- foundations,
- maintenance plan,
- flood / wave defence.

4.5.3 Economic and Carbon Cost

Economic

For the economic cost of the energy island design, it is intended that the Denmark energy island will be compared to the final solution and a Quantity Surveyor will be consulted.

Carbon

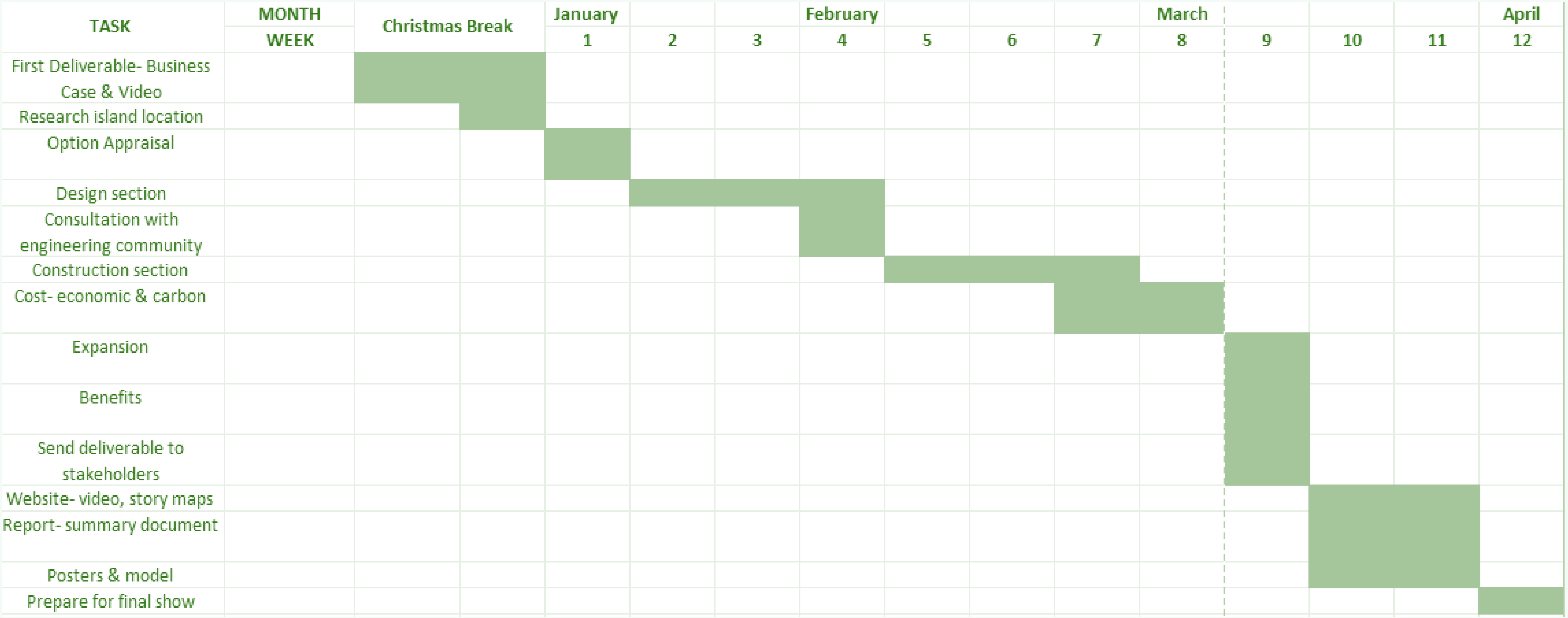
It is intended that the carbon cost for the solution will be calculated by using the Net Zero Scotland goals, SEPA and Scottish Government guidelines to ensure that our solution has the lowest embodied carbon.

5. Final Deliverable Proposal and Plan

The final deliverable for the project will be in the form of a website, consisting of:

- the initial summary document,
- the accompanying video,
- a final summary document with design details,
- sketches, photos, and GIS maps,
- photos of a physical model,
- posters which will be displayed at the final show.

Below is a proposed timeline for Semester Two which was shown to stakeholders at previous meetings.



Appendix 1- LinkedIn Post

Imogen Houston (She/Her) • You
MEng Civil Engineering student & Jacobs Intern
4mo • Edited •

How sustainable is the future of Scottish wind farms?

Alongside Annie Maclean, Elle Drummond, Brooke Stein, Abby Cruickshank and Yee Swen Ho, I have began undertaking my final year Master of Civil Engineering Design Project at Heriot-Watt University. This project is completely self-lead, with the topic, brief, aims, client and stakeholders being chosen by us. Examples of past projects, completed by Heriot-Watt University students which you may have heard of include involvement in the Friends of the Broadway - Prestwick restoration project and the 'submerged floating tube bridge' project aiming to establish a connection between Scotland and Northern Ireland https://lnkd.in/eeePDdiF.

We have chosen to investigate the sustainability of the design, construction, maintenance, transport, operation and decommissioning of both onshore and offshore wind farms/turbines in Scotland. This is a current global issue, which interests us all for a variety of reasons. We believe this is more than an environmental issue, we want to investigate all aspects of sustainability (social, economical and environmental) to support creating a sustainable future for Scotland.

As this is the beginning of our seven month long project journey, our brief is flexible. We are looking for potential stakeholders to work with us throughout, to provide insight into the above-mentioned aspects and more! If you are keen to speak with us further, please reach out or email me at ih37@hw.ac.uk

#sustainability #windenergy #nationalgrid #sustainabledevelopment #netzero #womeninengineering #renewables

Appendix 2- Kirsten Rae: Carrick Windfarm

CW Carrick Windfarm <carrickwindfarm@scottishpower.com>
To: Houston, Imogen E <ih37@hw.ac.uk>; Carrick Windfarm <carrickwindfarm@scottishpower.com> Thu 05/10/2023 08:52
Cc: Drummond, Elle; Cruickshank, Abby; Maclean, Annie; Stein, Brooke; Ho, Ricco

Caution: This email originated from a sender outside Heriot-Watt University.
Do not follow links or open attachments if you doubt the authenticity of the sender or the content.

Hi Imogen (and team!),

Thanks for getting in touch with us! Perhaps we could chat on the phone? My name is Kirsten Rae and I'm the Senior Project Manager for this project, my mobile number is 07850 943153.

Is there a particular stage of development that the suitable project should be at for your final design year project? Carrick Windfarm has a conceptual deign which was submitted (in 2021) alongside a Section 36 application for consent to construct and operate it. South Ayrshire Council objected to it alongside SEPA and we are therefore in the process of a Public Local Inquiry with he Scottish Government. Detailed design would follow if we receive planning consent which is unlikely to be before October 2024.

Kind Regards,

Carrick Windfarm Project Team
0141 614 9084
carrickwindfarm@scottishpower.com
www.scottishpowerrenewables.com/carrickwindfarm

Appendix 3- Scott Vallance: Statkraft

Sent: 30 October 2023 11:49
To: Ho, Ricco <yh2009@hw.ac.uk>
Subject: RE: : Heriot-Watt University MEng Design Project

Caution: This email originated from a sender outside Heriot-Watt University.
Do not follow links or open attachments if you doubt the authenticity of the sender or the content.

Good Morning Ricco,

Thank you for reaching out directly again to Alison and myself.

The below sounds like a really interesting overview. At Statkraft we have internal sustainability teams so definitely very valuable.

It would be beneficial to get a more in-depth understanding of your project so I would propose a Teams meeting so that we can have a discussion and get a greater understanding of your expectations and what we can offer as well.

If you can provide availability from your end that will be great and I'll endeavour to make one of the chosen slots.

I look forward to hearing from you.

Kind Regards,

Scott

Scott Vallance MRICS MRTPI
Principal Project Manager, UK
European Wind and Solar

Appendix 4- Gavin Falconer: Forestry & Land Scotland

G

Gavin.Falconer@forestryandland.gov.scot

To: enquiries@forestryandland.gov.scot; Houston, Imogen E <ih37@hw.ac.uk>

Wed 20/09/2023 10:34

Caution: This email originated from a sender outside Heriot-Watt University.
Do not follow links or open attachments if you doubt the authenticity of the sender or the content.

Hi Naomi

Thank you for your email. This sounds like an interesting study, and we would be happy to feed into it as resource allows.

Perhaps we can set up an initial teams call to discuss?

Gavin

Gavin Falconer FRICS | Head of Renewables
Forestry and Land Scotland, Upper Battleby, Redgorton, Perth PH1 3EN
t. 07557039255 **e:** gavin.falconer@forestryandland.gov.scot

Forestry and Land Scotland | Coilltearachd agus Fearann Alba

Appendix 5- Daniel Clancy: Gavin Doherty Geosolutions

DC

Daniel Clancy <dclancy@gdgeo.com>
To: Houston, Imogen E <ih37@hw.ac.uk>

Wed 27/09/2023 17:16

Caution: This email originated from a sender outside Heriot-Watt University.
Do not follow links or open attachments if you doubt the authenticity of the sender or the content.

Hi Imogen,
I saw your linkedIn post about your Civil Engineering Design Project on windfarms and thought I would reach out. I also went Heriot-Watt and completed the same course during my masters in 2021 so I have a good understanding of what it entails. I now work as a Civil Engineering Consultant and my company specialises in onshore and offshore wind farms as well as general renewables. Please let me know what sort of Information you are looking for and I will be happy to answer any questions you may have.

Regards,

Daniel Clancy
Graduate Engineer

GDG GAVIN & DOHERTY GEOSOLUTIONS

Gavin & Doherty Geosolutions
21 Young street, Edinburgh, EH2 4HU, Scotland
Tel: +447557228401
www.gdgeo.com

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