Energy Island

Feasibility Study and Options Appraisal

SHE ENGINEERING | Heriot-Watt University

FEASIBILITY STUDY/OPTIONS APPRAISAL

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Introduction

SHE Engineering offers two options for the design and construction of an energy island in the North Sea. The project aims to deliver many benefits including generating income, creating employment and improving energy security, all whilst ensuring a sustainable future for Scotland. The energy islands are proposed to be located either on a Shetland Isle, or off the coast of Aberdeen utilising oil and gas infrastructure, where significant offshore wind infrastructure is nearby and readily available. This supports SHE Engineering's overall aim to challenge the sustainability credentials of windfarms in Scotland and provide an improved solution to remediate the identified problems surrounding wind energy production. The energy island proposals both remediate several of the identified problems whilst aligning with the Scottish sustainability targets and United Nations Sustainability Development Goals (SDGs) (Figure 1).

By developing an energy island in the North Sea, the offshore oil and gas sector will be transitioned to net zero through electrification, utilising renewable energy sources to sustain current employment levels and security of energy supply. An energy island will address Scotland's current dependency on fossil fuels and create a value-added asset through a green hydrogen industry by utilising renewable power and creating new job opportunities.

The success of the project will depend on the Scottish and UK governments' willingness to include SHE Engineering's proposal in national energy policies, along with key stakeholder engagement and collaboration.

Figure 1- United Nations Sustainable Development Goals (United Nations, 2023)

1. Background

Function of an Energy Island

Energy islands are hubs for offshore renewable energy connection and storage. They allow offshore wind (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. An energy island is an ambitious, large-scale project that would give the host country - and connecting countries - energy security, in addition to the ability to expand offshore wind power exponentially. These hubs can either be built on existing land islands or manmade structures which can both connect to surrounding wind turbines and other renewable energy sources. On the island, energy can be processed and transmitted to countries on demand very efficiently.

Current Situation

Energy Islands are at the forefront of innovation, none have been constructed and few have been designed. Many of these installations will grow the green energy network vastly, but each should be designed to suit its unique location, to be minimally invasive on the environment, and make the best use of available resources.

Currently Denmark has concept designs for two energy islands (Danish Energy Agency, 2023). The first is an artificial island in the North Sea, around 100km from shore. It plans to feed wind energy back to shore and eventually connect neighbouring countries. The total estimated investment for the project is DKK 210 billion (£24 bn) (North Sea Energy Island, 2024). The construction of the island will only use 5% of the cost, with the rest being used for connections to countries, new offshore wind farms and infrastructure. The figures below show plans and variations of the design.

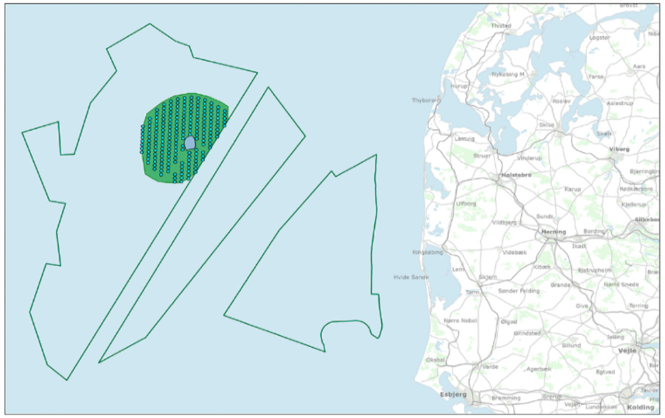


Figure 2- Map showing location of Danish energy island in North Sea (Danish Energy Agency, 2023)

Figure 3- Concept image of Danish Energy Island (BBC News, 2021)

Figure 4- additional concept image of Danish energy Island (GoTechies, 2021)

The second is the conversion of an existing island, Bornholm, in the Baltic Sea. This island will house the necessary equipment to connect surrounding offshore wind farms and distribute the energy to nearby countries. The figures below show the location and position of turbines and the island.

Figure 5- Schematic of the Bornholm energy island with wind farms marked in green. (Urland, 2020)

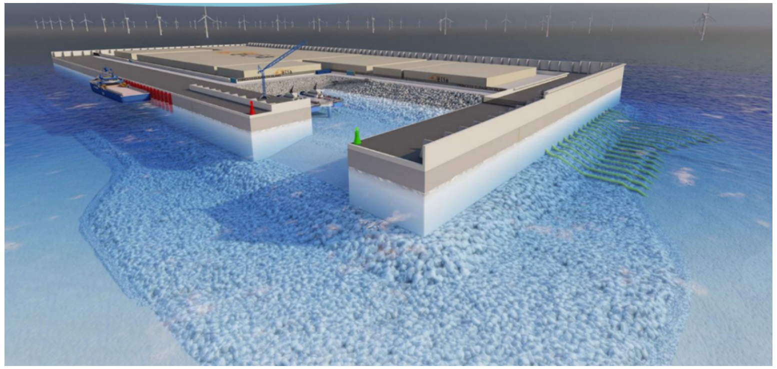


Figure 6 - Detailed design concept for Princess Elisabeth Island with nearby wind turbines. (Royal HaskoningDHV, 2023)

Figure 7 - Map showing location of the 2 Danish energy islands. (BBC News, 2021)

Belgium has also began designing an energy island 45km from their shore – "The Princess Elisabeth Island" (Elia Group, 2023). This development has been granted an environmental permit and is planned to be fully commissioned by 2030. However, the island is planned to be within a marine protected zone, making construction a challenge (Euractiv, 2023). Similar to the Denmark designs, the island will connect wind farms and distribute energy to Belgium, England and Denmark. The Island will be 6ha in size and be constructed from concrete caissons (Offshore Magazine, 2023). The completed island is estimated to cost more than €2 billion, not including the price of additional wind farms and connections to countries. The figure below shows the location and design concept.

Figure 8- Location of Energy Island off the coast of Belgium and the UK (Elia Group, 2023)

Aim of an Energy Island

The fight against climate change requires new sustainable energy solutions as individual sources such as onshore wind, solar, wave etc. will not be sufficient. The aim of an energy island in the proposed locations would be to facilitate SDG 7, 9 and 11, and by expanding Scotland's current and future production of renewable energy, an energy island would help achieve net zero emissions of all greenhouse gases by 2045; a goal defined by the Scottish Government (Scottish Government, 2024b). Additionally, this design would increase energy security in Scotland, making the country more economically resilient against energy blackmail by reducing dependence on imported fossil fuels. The North Sea also has sustainability goals in place – "The North Sea Transition deal", which strives for decarbonisation of the oil and gas industry to aid net zero goals. This hopes to transform the North Sea to net zero carbon status by 2050 (Maritime Spatial Planning, 2024). An energy island would be a significant step towards harnessing the large-scale green energy production capabilities of the North Sea. "New and emerging technologies" are recognised by the North Sea Transition Authority as being crucial for decarbonisation (North Sea Transition Authority, 2023a). The Scottish Government has also set a specific goal of increasing the countries offshore wind capacity to 11GW by 2030 (Scottish Government, 2020). Currently, Scotland has only 1GW of operational offshore wind, with an increase to 5.6GW when consented farms are completed. These goals are summarised in the graphic below.

Figure 9- United nations SDGs targeted by an energy island (United Nations, 2023)

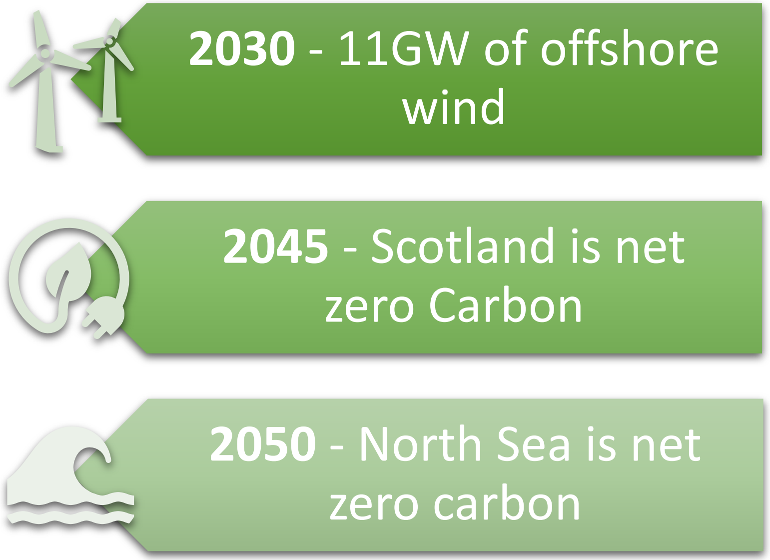


Figure 10- Sustainability Goals

Benefits of an Energy Island

Energy islands show innovation in sustainable infrastructure by providing clean, affordable and reliable energy that is accessible to all, while accelerating the transition to a net-zero carbon society. The following addresses the benefits of an energy island.

Renewable energy generation and transmission: Energy islands act as a connector between various renewable energy sources, energy storage facilities and onshore platforms for grid connections. This arrangement optimises the usage of renewable energy resources and reduces the reliance on fossil fuels or other environmentally harmful energy sources. The variety in energy sources also allows the utilisation of these energy assets according to their availability which depends on weather conditions or geographical location. Additionally, the presence of energy storage and direct connections to grid transmissions also enhance energy stability and reliability as it reduces the risk of power outages.

Potential for expansion: As energy islands mainly focus on offshore renewables, it reduces the issue of land shortage and increases the potential for expansion significantly. Offshore technology is not as advanced as onshore, hence, there is opportunity for the development of offshore technology and expansion of current renewable facilities to further increase the efficiency in renewable energy generation.

International connections: Energy islands encourage the collaboration among different countries. Additional energy generated can be exported to neighbouring countries where demand is higher and renewable resources are less abundant. The connection is not limited to the North Sea region only, showing potential for future expansion. This helps to foster international collaborations such as joint investments or standardising on energy policy or regulations, connecting countries to work together towards the sustainability goals.

Wind farms: Issues associated with onshore wind farms, such as visual and noise impact, as well as land shortages or restrictions, will be resolved by placing the wind turbines further offshore. The carbon cost is reduced significantly as offshore wind power paired with an energy island can utilise hydrogen production which is an alternative to fossil-based hydrogen.

Green hydrogen production: Energy islands allow the large-scale production of green hydrogen using electricity generated from wind turbines. With no carbon emissions throughout the manufacture chain, the green hydrogen that is produced will be significantly more sustainable compared to traditional fossil-based hydrogen production. The use of electricity-based fuels, such as green hydrogen, contributes to the nation’s decarbonisation effort and helps to promote a more sustainable environment.

Mitigation of Current Wind Energy Issues

Following on from the accompanying Summary Document which identified the issues with onshore wind, it is noted that the implementation of an offshore energy island will significantly reduce these known challenges. The solution can provide mitigation measures to onshore issues including:

Land Use Restrictions: An energy island is situated in one area of the sea, with renewable energy sources surrounding it. The connections from the surrounding sources all go back to the island which reduces the land take if there were to be multiple cables back to the mainland and substations in many different locations. Therefore, the land use for an energy island is less than that which would be needed for multiple onshore windfarms.

Peat: Challenges with peat disturbance that often occur with onshore wind farm developments is not applicable to offshore windfarms/the energy island.

Timber: Implementing an energy island mitigates concerns about the loss of land and disruptions caused by wind farms to timber production. This protects Scotland's land and economy.

Wind Speed: Generally, the wind speeds are higher and more consistent at sea when compared to on land. Therefore, an energy island mitigates the issue of inconsistent wind speeds as it utilises offshore wind energy.

Public Objection/Timescales: Although there may still be public objection and long timescales, the chance of objection is reduced as there are fewer public groups that would be affected by offshore construction. Potential issues may include nuisance to fishermen. Additionally, the timescales are expected to decrease with a single connection to the grid, removing the long waiting times associated with connecting multiple wind farms.

Decommissioning: Utilising oil and gas infrastructure within an energy island provides the benefit of not having to fully decommission the infrastructure without a repurposing plan. Additionally, there is a lesser risk of decommissioning wind turbines offshore without reuse of foundations or other components.

Noise: There is no nuisance caused by noise pollution in the sea as there are no residents or communities nearby, like there is on land.

Visual Pollution: The energy island will be far enough into the North Sea that there will be no visual pollution from the shoreline.

Airport Radars: The energy island is not situated near any airport radars therefore they will not be affected.

Grid Connections: As mentioned, there is only a single connection to the National Grid which will reduce the risk of long waiting times and cost.

Consultation: The consultation for the energy island will be focused on professional bodies and industry partners, alongside fishermen and other people who may have an interest in the North Sea. This should reduce the risk of public objection as there will be less parties involved compared to onshore windfarms.

However, not all issues can be mitigated such as wind turbine efficiency, mechanical failure of turbines and risk of harm caused to birds or wildlife. With the progression of the wind energy industry, it is expected that the efficiency of wind turbines will be improved to reduce the probability of mechanical failures and efficiency. Although there is still a risk to birds, the energy island is proposed to avoid marine protected areas to help safeguard marine wildlife. More significantly than the risk of harm caused by a wind turbine blade, the use of fossil fuels and their contribution to climate change poses a much bigger threat to bird life, however, it is hoped that advances in technology will provide a solution to reduce the immediate risk of wind turbines to birds in the future.

Stakeholders

Following on from the semester one stakeholder list shown in the initial Summary Document, there are both continuing and new stakeholders that have showed a keen interest and have engaged with the project throughout semester two, these stakeholders are shown below in Table 1. Unfortunately, despite all the initial stakeholders being contacted after Christmas, not all have responded or were willing to be part of the project going forward. Those shown in Table 1 are the dynamic list of passionate industry professionals, representing the projects 'Engineering Community' in Semester Two. The project stakeholders have had frequent meetings with the team to directly inform on the structural integrity of the oil and gas platforms, the potential of reusing pipelines, overall design considerations, to offer their opinion from the initial proposal or to answer the questionnaire. The presentation slides delivered to all stakeholders during meetings can be found in the Appendix.

Table 1- Stakeholder List (Semester Two)

Name	Company	Position
Colin Wilson	Repsol Resources	Structural Authority/Technical Assurance
Stuart Smith	Altrad Sparrows	Head of Engineering
Mehdi Zaidi	TAQA Group	Structural Integrity Engineer
Morteza Haghighat Sefat	HWU	Associate Professor
Daniel Clancy	GDG	Civil Engineering Consultant
Campbell Keir	Energy Industry Council	President
Fiona Milligan	Milligan Communications	Stakeholder Management
Kirsten Rae	Scottish Power Renewables	Project Manager
Eamonn Cullen	Shell	Commercial Manager
James Saunderson	Jacobs	Graduate Civil Engineer
Am Noimon	Jacobs	Graduate Civil Engineer
Hannah Bewley	Jacobs	Environmental Scientist
Ethan C	Jacobs	Graduate Civil Engineer
Teo Wee	HWUM	Associate Professor
Ross Davidson	BP	Production Technician
Rachel Buttilana	SSE	Civil Engineer (Hydro)

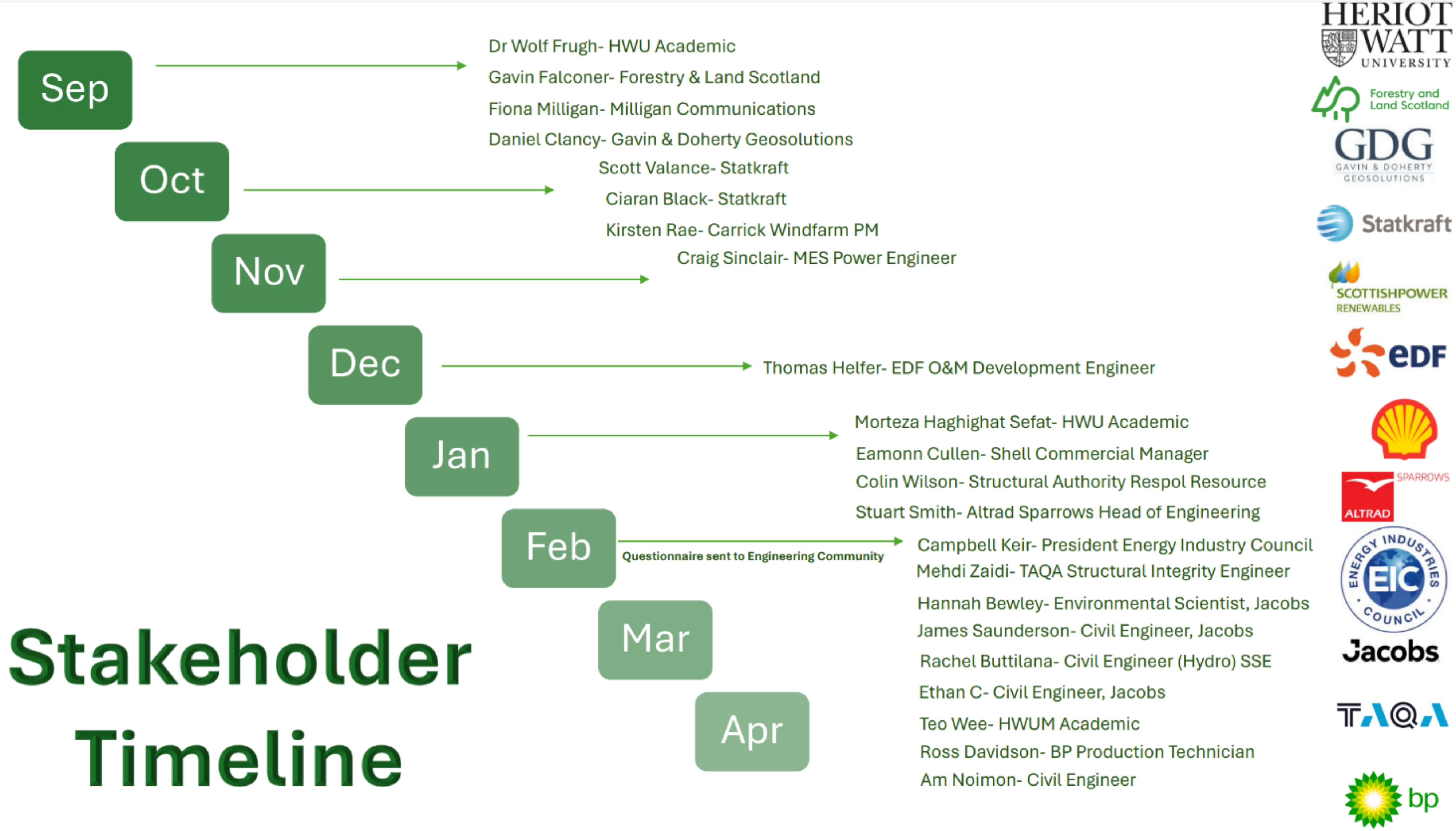


Figure 11- Stakeholder Timeline (Semester 1 and Semester 2)

Questionnaire Results

A questionnaire was posted on LinkedIn and sent to the 'Engineering Community', comprising of stakeholders, engineers, and lecturers to gather a range of opinions on the proposal. In total, thirteen responses were collated which informed the proposal going forward. The range of response givers included Graduate Civil Engineers, Civil Engineers, a lecturer from Heriot-Watt Malaysia, a Production Technician, Commercial and Communications Managers, the Head of Engineering at Altred Sparrows, and the President of the Energy Industry Council.

The first question asked was whether our Engineering Community believed that the Net Zero by 2045 target for Scotland was achievable, to which around half believed that it is (Figure 12).

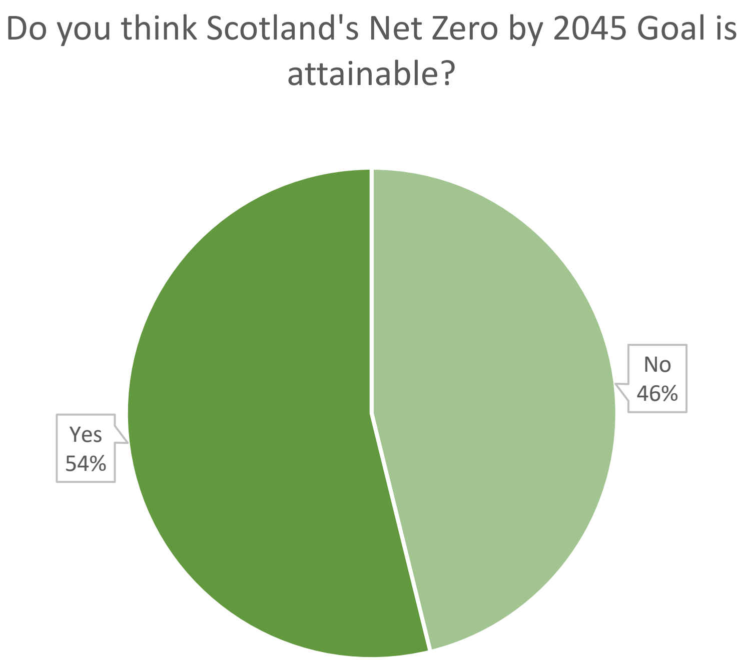


Figure 12- Opinion on Scotland's Net Zero Targets

The questions then centred around wind energy and energy islands, where the audience was asked what they perceived the biggest challenge with offshore wind was. The results of this are displayed in the word map below (Figure 13). Cost/funding, maintenance and environmental concerns were shown to be the biggest challenge perceived by the response givers.

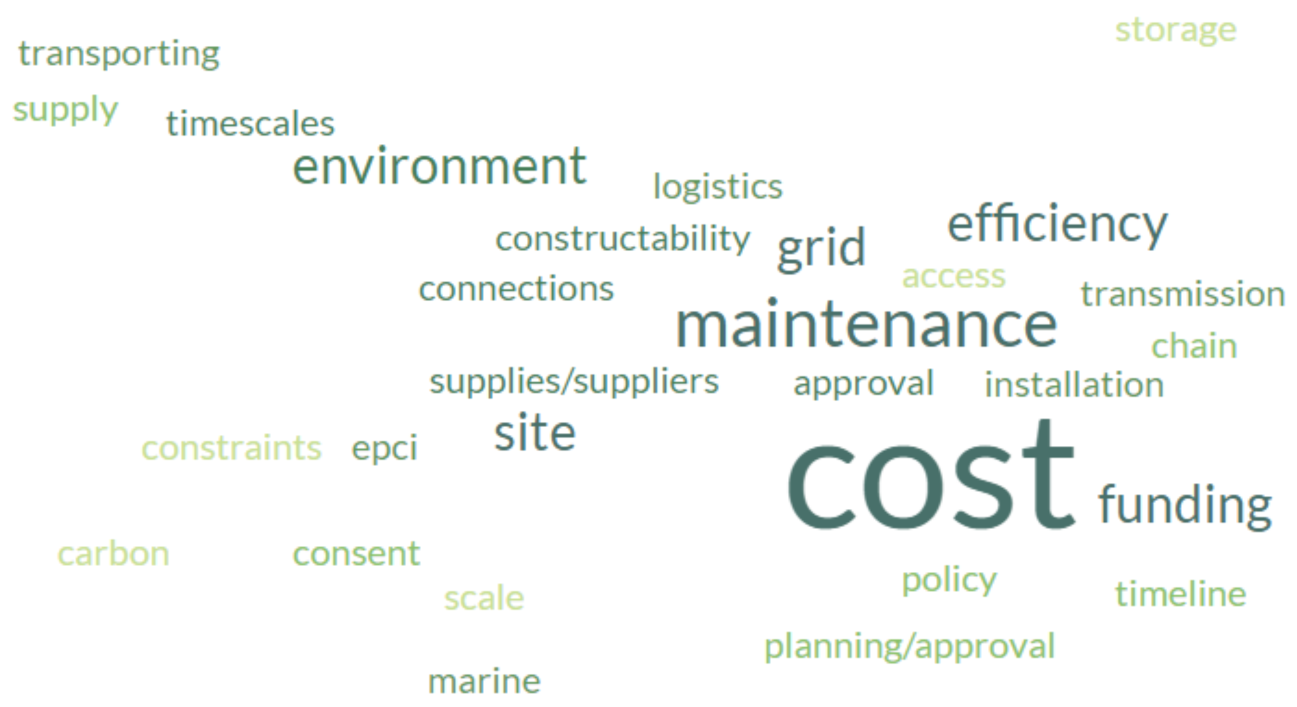


Figure 13- Biggest Challenge with Offshore Wind Opinion

Following this, the stakeholders were asked if they were familiar with the concept of an energy island, to which seven people answered yes, although two went on to say that they had only heard of the concept from this project. Therefore, this realistically results in only 31% of stakeholders being aware of the energy island concept prior to contact with SHE Engineering.

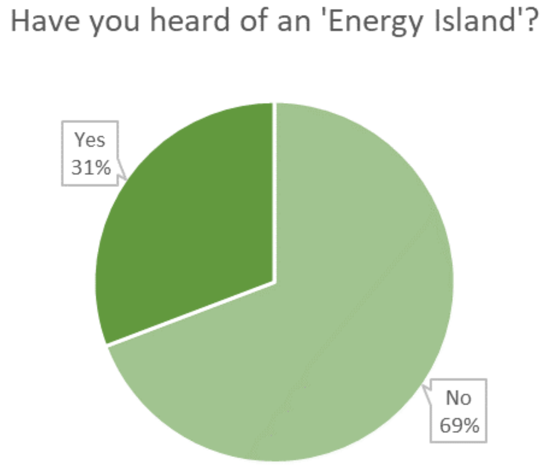


Figure 14- Energy Island Concept Response

The four who had heard of an energy island stated they had heard of this from “HWU while researching for the offshore wind foundation project”, “while in university”, “conference where presentations have been made on the European plan for the island hubs” and “Industry press articles”. Their understanding of this was-

- “A hub for electricity generation from surrounding offshore wind farms, that will be connected and distribute power between neighbouring countries.”
- “Multiple energy assets located around offshore wind turbines.”
- “An electricity generation hub located out at sea allowing for bigger more remote windfarms and supplying energy to multiple nations to meet demand changes.”

The 69% which had not heard of this before gave their understanding of what an energy island may be. The responses are as follows-

- “An island or offshore location where energy transfer takes place.”
- “Above sea-level man-made structure housing an energy source.”
- “Artificial Island solely used to produce energy.”
- “A self-contained facility to generate or process energy.”
- “My first thought is a floating island. But based on your recommendation of using the recommissioned old platform, it is close to my initial thought.”
- “Similar idea to an offshore platform, an island with connections to mainland Scotland to transport energy produced along with means of getting personnel to and from to carry out maintenance and operations.”
- “I had assumed it would be a large cluster of generation units, e.g. offshore wind turbines.”

The stakeholders were then asked what their biggest concern would be if Scotland were to approve the construction of an energy island in The North Sea? The results of this (Figure 15) show that economic cost is the biggest concern for the audience.

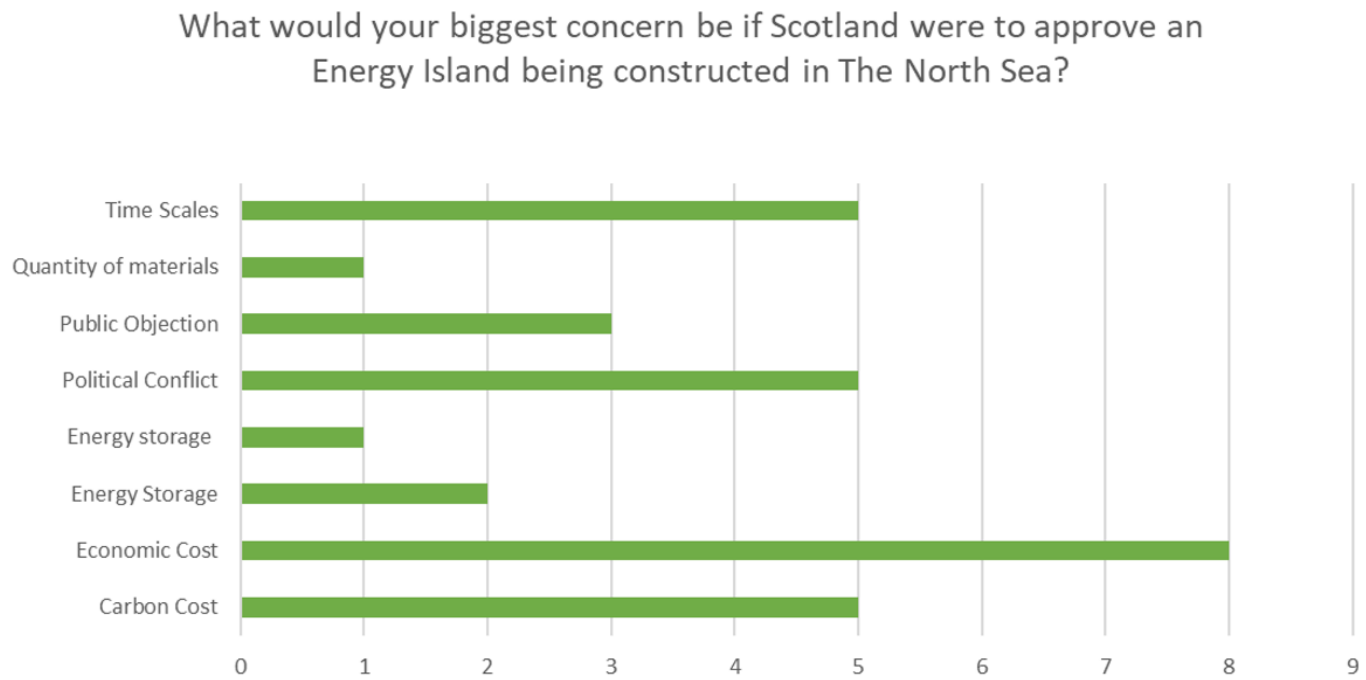


Figure 15- Biggest Concern

The questionnaire then focused on the proposal, asking what the strongest aspect was, their main concerns based on the proposal and what they might change. The responses are shown in Table 2 below.

Table 2- Questionnaire Responses

What is the strongest aspect of our proposal, in your opinion?	From our proposal, what would be your main concern?	What, if anything, would you change about our proposal?
Security of energy supply for Scotland, aids in establishing self sufficiency	Objections from the general public and other countries. Myths and disinformation impacting the project.	Mention what the scale of the energy provided by this island will roughly be, would the proposed islands supply enough energy to service the entirety of Scotland? Is there potential to supply other countries such as England and Wales?
N/A	The man-made island would only work in shallow water, while the offshore wind energy is now moving to deeper water.	N/A
Using repurposed oil and gas infrastructure is a really good concept. Decommissioning and conversion may be more amenable to stakeholders than building from scratch.	Environmental impacts / compliance, economic costs and getting the general public on board	Maybe include more information on benefits to the economy, climate, environment etc.
Reusing decommissioned oil and gas infrastructure	Converting an existing island - will this impact wildlife or the local environment? e.g. migration of birds	Talk more about the UNSDGs and how your solution can tackle specific SDGs
location - infrastructure planned or in place already to aid delivery	Grid timelines and fishermen!	nothing currently, but always be open to change and innovation down the line.
Allows for larger more remote wind farms generating more energy than in shore windfarms.	Economic and Carbon cost of building an entire Island	More Clarity on carbon emissions.
In my opinion. I like the idea of converting an existing island. Would be	Getting approval to even start concept design of this project even before prefeed, feed and detailed design.	Rather than making an island you can use preexisting vessels for energy and hydrogen storage.

significantly more cost effective and possibly much easier to get approved.		
The UK grid has severe limitations on how new power generation can be plugged in - there aren't enough nodes. With multiple big OSW projects in the pipeline - the projects are challenge to access the grid. Offshore island would help manage the problem.	N/A	Nothing. Worth going for.
Utilization of offshore structures due for decommissioning; deferring decommissioning & restoration (D&R) expenditures and sustainably utilizing existing infrastructure for longer	Approval would be needed from - local government, North Sea authorities, maybe SEPA, cross border agreements (Norway, Denmark and Netherlands)	Do not have a proposal dependent on Government investment; seek Joint Venture Participants such as: turbine or electrolysis equipment manufacturers, other similar investors to SHE Engineering. then plan to dilute or sell out to Pension or Infrastructure funds.
Using old existing or abandoned platforms certainly has the lowest carbon/environmental impact compared to other options such as existing islands or man-made islands.	I think it is a good project to consider. 1) I would not exclude the reuse of oil and gas facilities but many of them are old, and it could be expensive to repurpose them. You also get into the complex tax and legal issue of who decommissions the facilities at the end of the day and how (remember Brent spar and the huge row with Greenpeace). 2) I think that there would be a real concern about using a remote island in terms of wildlife. Probably many of the remote islands in North Sea are home to unique/rare/endangered wildlife. Worth engaging one of the NGO's. 3) you would need to do some thorough mapping of all the issues and the impact on your project.	Nothing, but it will be good to explore (if you have time) the option of floating island. Is it sensible in Scotland?
the two shortlisted options of Shetland and Aberdeen seem worth investigating.	Cost of the Value Chain to produce Green Hydrogen vis-a-vis the price, market and hence	Nothing, I see this proposal as being a worthwhile feasibility study.

	margin for such Green Hydrogen. A high cost, technically challenging, unproven Value Chain.	
The energy island (man-made or constructed on an existing island) is a strong proposal because it would be custom built for the requirements of the energy production to be carried out. Using an existing platform structure would mean significant modification being required as well as being restricted by weight, footprint etc.	Nothing I can think of. But since you have the option to use recommissioning of the old platform. You may need to find out what existing standards or codes are available to deal with these kinds of matters.	I wouldn't change anything about the proposal.
Looks good. Well worth considering all 3 (existing / new / ex-O&G) options	If this is a completely new man-made island (excluding the repurposing O&G platform jackets), the quantity of materials, and where these will source from.	Energy storage is key for our future power supplies. But you are addressing this.

Finally, the respondents were asked to give their opinion on which option out of repurposing an existing land island, utilizing existing oil and gas infrastructure, or constructing a man-made island was the strongest proposal.

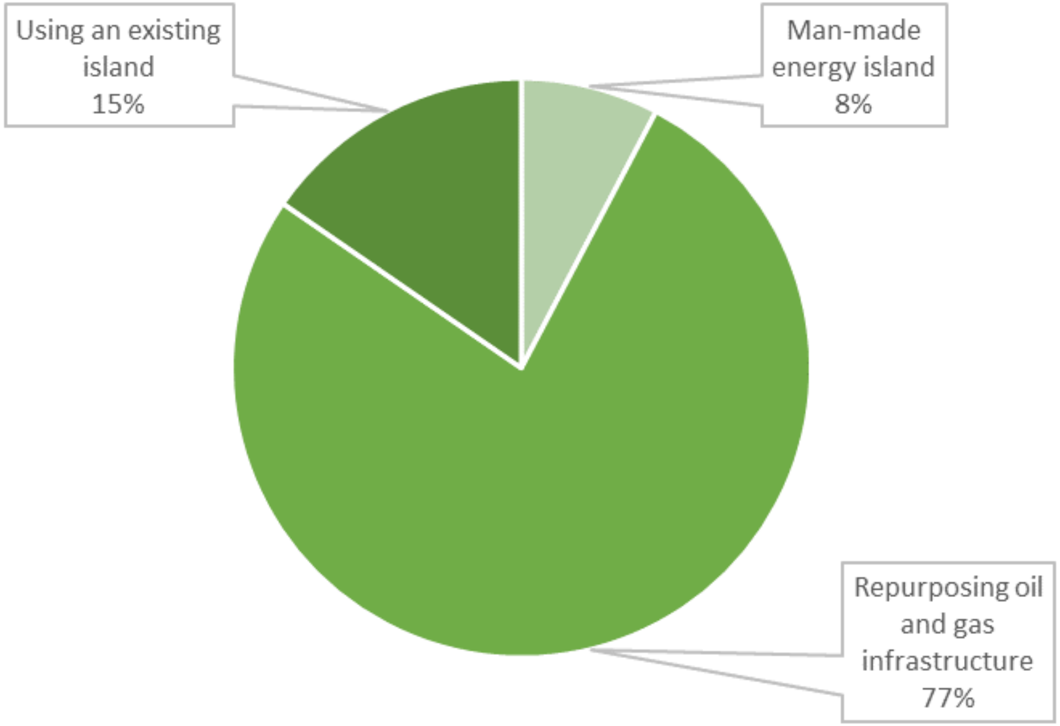


Figure 16- Strongest Proposal

The results clearly indicated that repurposing oil and gas infrastructure or using an existing island was the most favored solution. The justification for the responses suggested that this is mainly due to the economic and carbon cost which will be significantly reduced by not constructing a man-made island. Additionally, some believed this would be more environmentally friendly to avoid more habitats being destroyed and reduce stakeholder objection.

From our questionnaire, it was evident that conducting a feasibility study for the construction of a man-made island was not going to be effective if the stakeholders had already suggested their concerns for this. Therefore, the options appraisal and feasibility study will focus on an island made by repurposing oil and gas infrastructure and using an existing island.

2. Proposal of Energy Island

Conceptual Design

The following sections detail the key components of an energy island design constructed on an existing island in Shetland, and an energy island that's constructed by utilising oil and gas infrastructure off the coast of Aberdeen. General arrangement diagrams of both proposals are shown in Figure 17 and Figure 18.

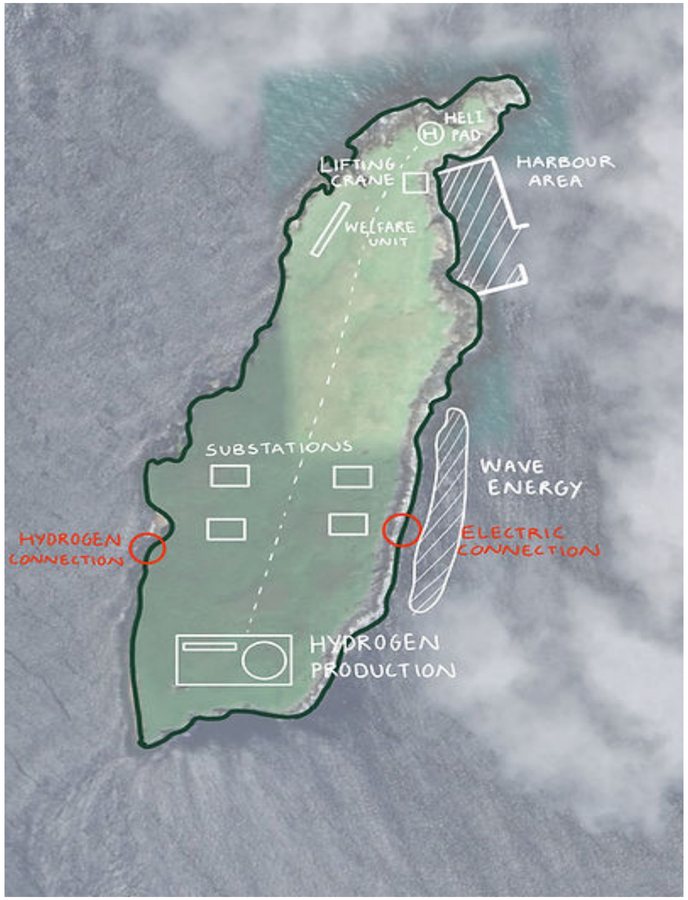


Figure 17- Shetland General Description Diagram

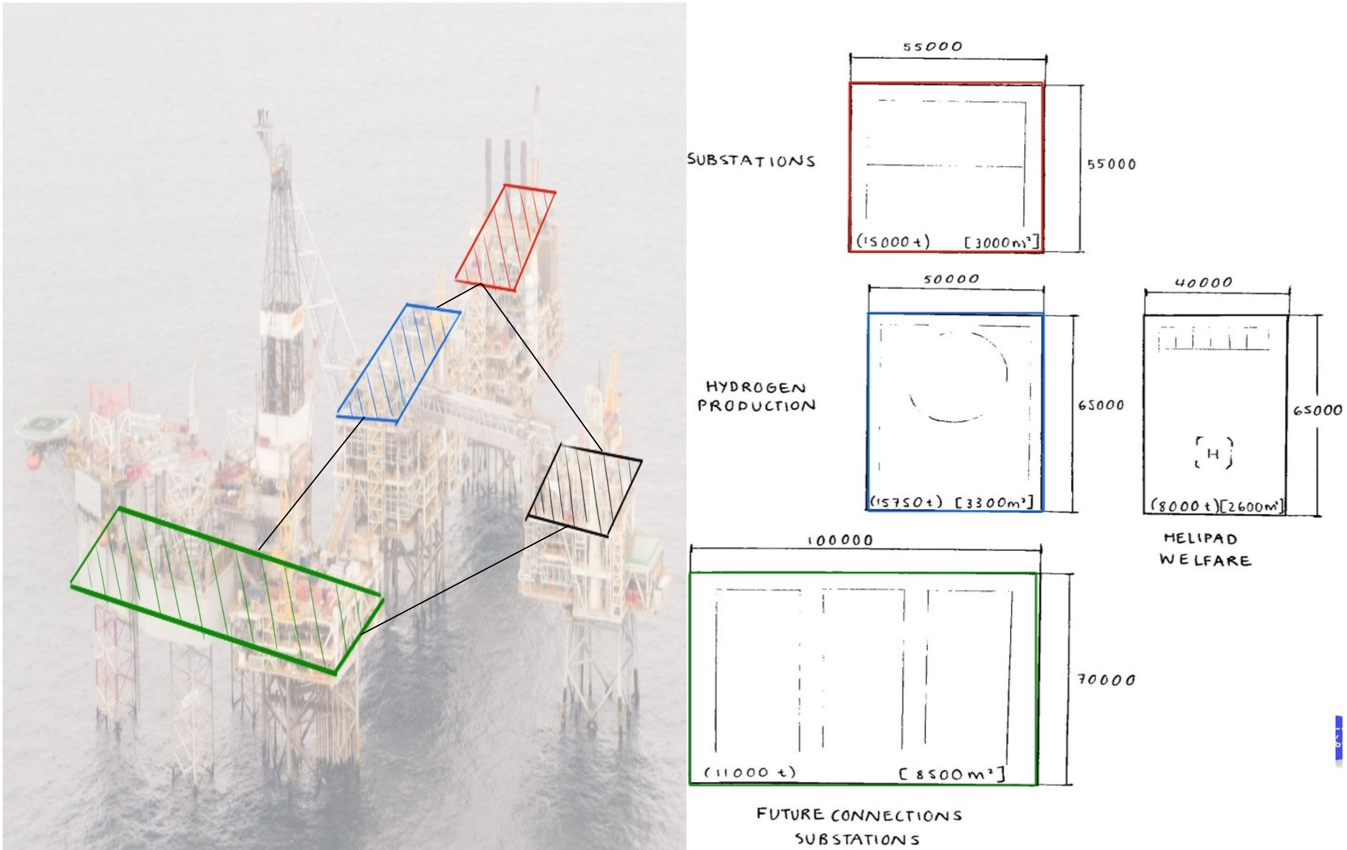


Figure 18- Aberdeen General Description Diagram

Location

Shetland

The island of Fish Holm, situated 1.5 miles Northeast of Shetland and near the village of Mossbank, features all the essential assets to host an energy island. The island's peak elevation reaches 20 meters, indicating its relatively flat terrain, suitable for construction (Wikimedia, 2010). Spanning approximately 190,000 square meters, this uninhabited island lacks available online data regarding its utilisation or tourist attractions (Scottish Places, 2007). It is therefore assumed the island is not a substantial area for tourism and wildlife, making this a good location in the Shetland Isles for an energy hub. The island is also located within close proximity to an abundance of wind and tidal resources, significant existing and potential hydrocarbon resources, existing infrastructure ready for use and redevelopment, and a knowledgeable and skilled local workforce (Orion, 2021).

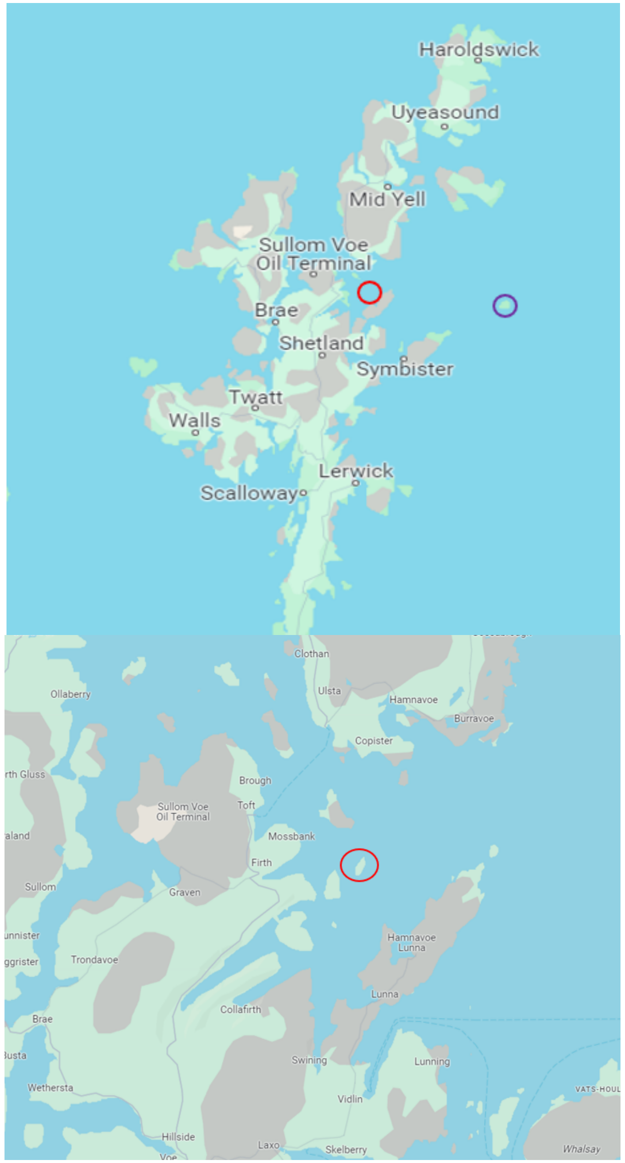


Figure 19- Shetland Island Location (Red circle = chosen island, purple circle = more ideal location)

Approximately 74 out of 100 of the islands around Shetland are uninhabited however many are protected for rare wildlife species, grey seals or have high slopes/rocky terrain which aren't suitable for building on. For the purpose of this proposal, the island of Fish Holm will be selected to represent the energy hub in Shetland as it meets all the essential requirements. However, with further investigation and advanced surveying equipment, ideally an island further out off the coast of Shetland would be selected. Figure 19 shows the location of Fish Holm (circled in red), as well as a different island that was considered for the project (circled in purple). The island circled in purple is in a better location than Fish Holm to hold the energy island infrastructure and connections, however, the terrain on the island made it much less suitable for construction and therefore was not chosen for the study.

Aberdeen

In terms of repurposing oil and gas infrastructure, the most appropriate place to begin is in the planning for decommissioning stage. As the UK moves closer to its sustainable energy goals, decommissioning is essential for all oil and gas platforms in the North Sea. The NTSA revealed that the industry spent around £8bn on decommissioning the North Sea between 2017-2022 and plans to spend £21bn in the next decade. For the purpose of this project, CNOOC platforms Buzzard and Golden Eagle were chosen for repurposing, with a particular focus on Buzzard - these can be seen in Figure 20. The Buzzard platform (Figure 21) is located around 97km from the coast of Aberdeen at 0.9764599°W 57.8145632°N, with Golden Eagle (Figure 22) being slightly further away at 112km at 0.9067128°W 57.9540575°N. The platforms are located just 17km apart, as seen in Figure 23, which means they could both be used in connection with the island. Both platforms have connections back to Aberdeen, going to both St Fergus and Cruden Bay.

Buzzard oil field was discovered in 2001, with production starting in 2007. Golden Eagle was discovered slightly later; in 2007, with production starting in 2014.

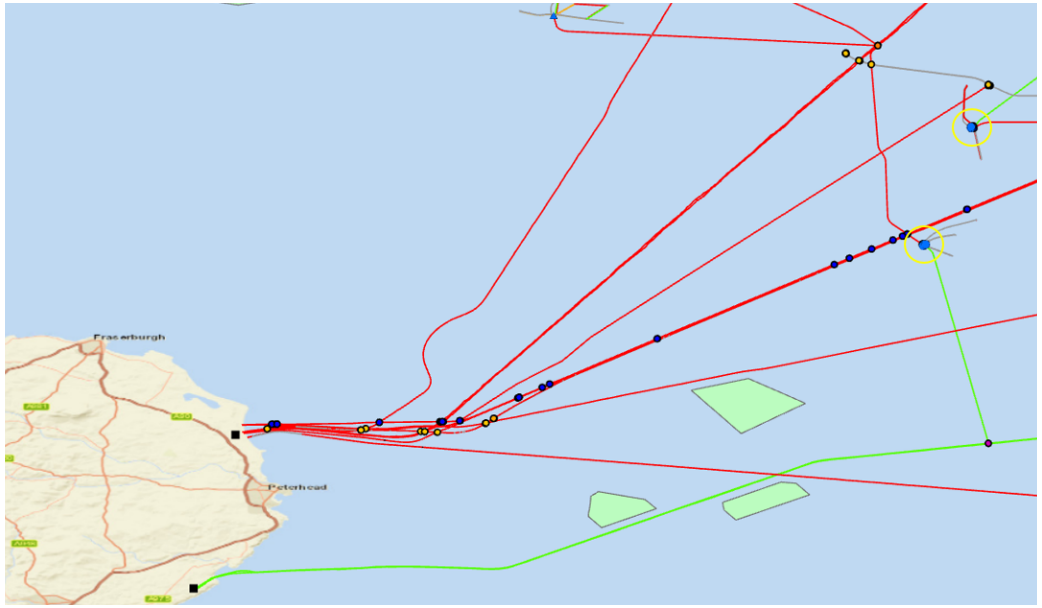


Figure 20- Locations of Golden Eagle (North) and Buzzard (South)

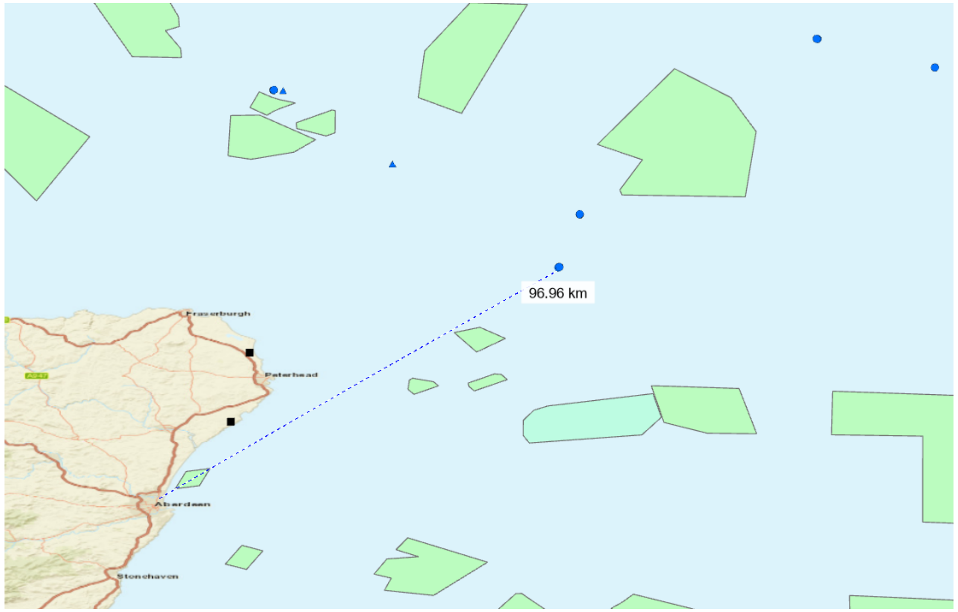


Figure 21- Distance from Shore to Buzzard platform from GIS

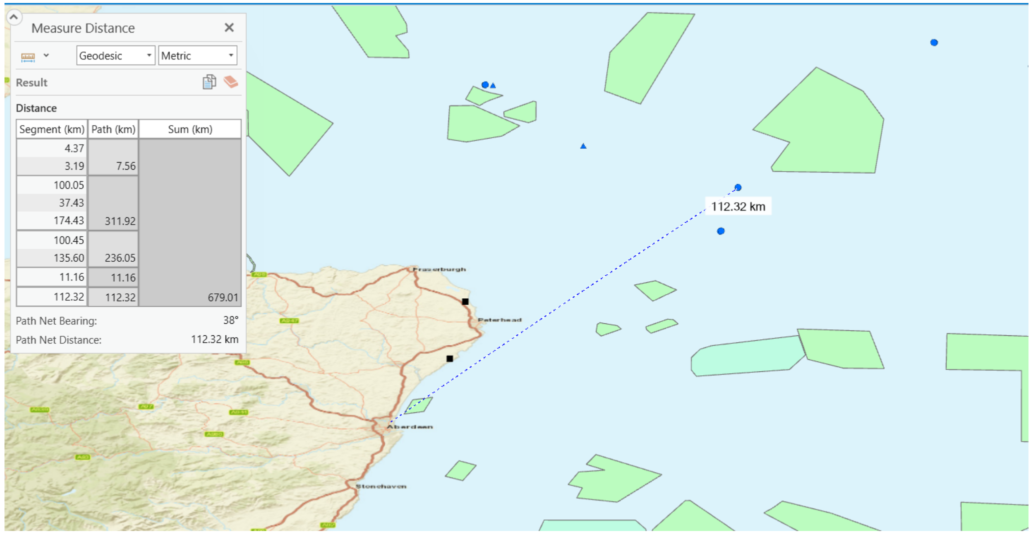


Figure 22- Distance from shore to Golden Eagle platform

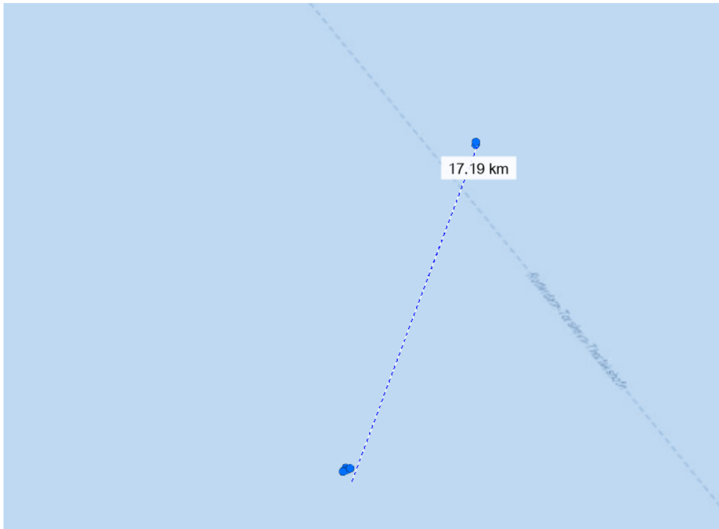


Figure 23- distance between Buzzard and Golden Eagle platforms, from GIS

Island Dimensions

Shetland

The area of the proposed island is 190,000m^2.

Figure 24- Size of Shetland Island

Aberdeen

Buzzard (Figure 25) sits in around 97m of water and is made up of four platforms, each on top of a steel jacket (Offshore Technology, 2004), and connected with bridges, as can be seen in Figure 25. The rig has 4 main platforms these include the production, wellhead, production sweetening, and utilities decks. From Buzzard's ICOP, the load capacities for each deck are stated as 15,750te, 8,000te, 11,000te, 15,000te, respective to the listing above. This would mean the combined load capacity of the jackets is around 50,000 tonnes (CNOOC, 2019).

Golden Eagle sits in around 112m of water (North Sea Transition Authority, 2023b). Similar to Buzzard, the rig comprises of wellhead, production and utility platforms, each sitting on top of steel jackets and connected with 70m bridges.

Figure 25- Buzzard Platform

Energy Supply

Wind Energy

Scotland's world-leading expertise in wind energy is evident in its history of effectively optimising its rich wind resources. Offshore wind, recognised as one of the lowest-cost electricity generation methods in the UK, has experienced rapid growth as a renewable energy source. It successfully met the target for electricity demand of 5.8TWh in Scotland, contributing to 16.2% of renewable electricity generation in 2022 (Scottish Energy Statistics Hub, 2023). The UK aims to achieve 80GW of potential energy by 2050 and, recently, both the UK and Scottish governments have provided further clarity on this ambition by establishing a target to deliver 5GW of floating offshore wind by 2030 (Department for Energy Security and Net Zero HM Government, 2023). Crown Estate Scotland's Offshore Wind report further indicates that the floating offshore wind market in the UK has the capacity to sustain 17,000 jobs and generate £33.6 billion of Gross Value Added (GVA) with potential in Scotland to place turbines within an area of 462,000 km^2 where most water depths are more than 60m (Crown Estate Scotland, 2018).

Shetland

Current iInfrastructure

There are currently no operational windfarm developments in Shetland, however, a recent proposal known as the Stoura Wind Farm has been accepted in the NE1 region (Mainstream Renewable Power, 2024). Situated approximately 40km from Shetland, the site will cover a total area of 776 km^2, with water depths ranging between 100m-130m. The floating wind farm intends to generate 500MW of energy which is equivalent to powering around 350,000 homes (Energy Voice, 2024). There are also two other floating windfarms in the development stage known as the Arwen wind farms that aim to produce a combined 2300MW of energy, enough to power an additional two million homes. These two sites are located 22km east of Shetland and slightly south of Stoura (Mainstream Renewable Power, 2024). There is significant potential for offshore wind around Shetland beyond the NE1 area. There is also over 10GW of additional potential in these areas, all currently unlicensed (Orion, 2021).

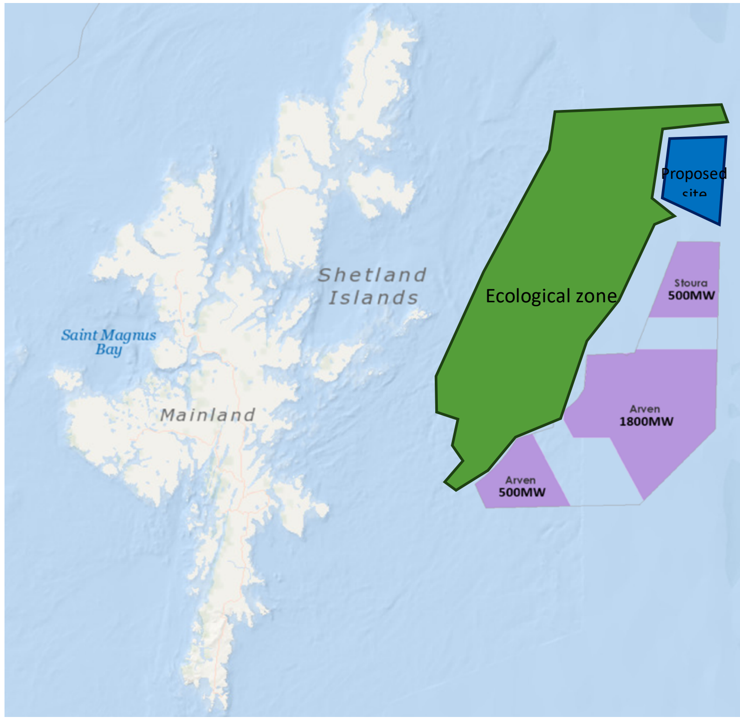


Figure 26- Proposed site (Blue), Developing wind farms in Shetland (purple) (TGS, 2024), Ecological zone (Green)

Proposal

The proposed location for additional wind farms is East of the Shetland Islands, above the Stoura Wind Farm, shown in Figure 26. Several factors have been considered when choosing the location, such as wind speeds, water depth, ecological zone and distance from the mainland and energy island. The proposed site is at a distance of approximately 22km from the mainland, with a water depth of around 100m, making it ideal for floating offshore wind farms (Mainstream Renewable Power, 2024). The distance from shore also helps to reduce certain negative impacts of wind farms such as noise and visual pollution for the Shetland residents. Additionally, ecological zones have been avoided to prevent disturbance of wildlife during turbine construction or operation. Figure 27 indicates the wind speeds around the proposed location to be 13m/s to 15m/s, which is the optimal wind speed range for energy maximisation (Windy, 2024b). Additionally, the wind speeds around the location are always above 4 m/s, achieving the minimum threshold required for the turbine to generate electricity (Windy, 2024b).

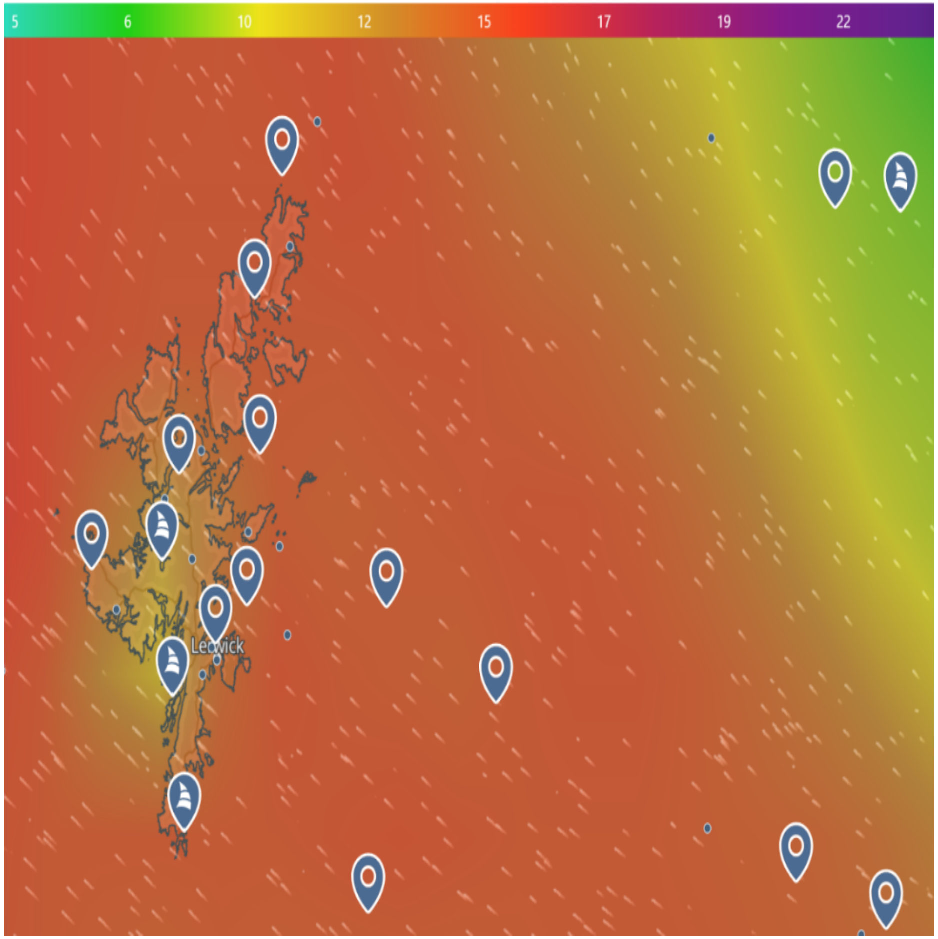


Figure 27- Wind speeds around Shetland islands (Windy, 2024b)

Comparisons have been made with the proposed wind farms and nearby existing wind farms to further understand the potential of the project. The proposed wind farms share similar sizes and characteristics as the Stoura Wind Farm and the second phase of Arven Wind Farm, which both have a capacity of 0.5GW each. However, additional data collection and analysis will be necessary to further optimize wind energy generation. The energy generated from new wind farm developments will be connected to the energy island at Fish Holm where it can be stored and then transported to Fergus gas terminal for further integration into the national grid transmission.

Golden Eagle and Buzzard

<u>Current Infrastructure</u>

There are operational wind farms around the Golden Eagle and Buzzard platforms, with the nearest ones being Hywind Scotland Pilot Park Moray East, and the Beatrice Wind Farm. Figure 28 shows the location of these wind farms and the proposed development site in relation to Golden Eagle and Buzzard.

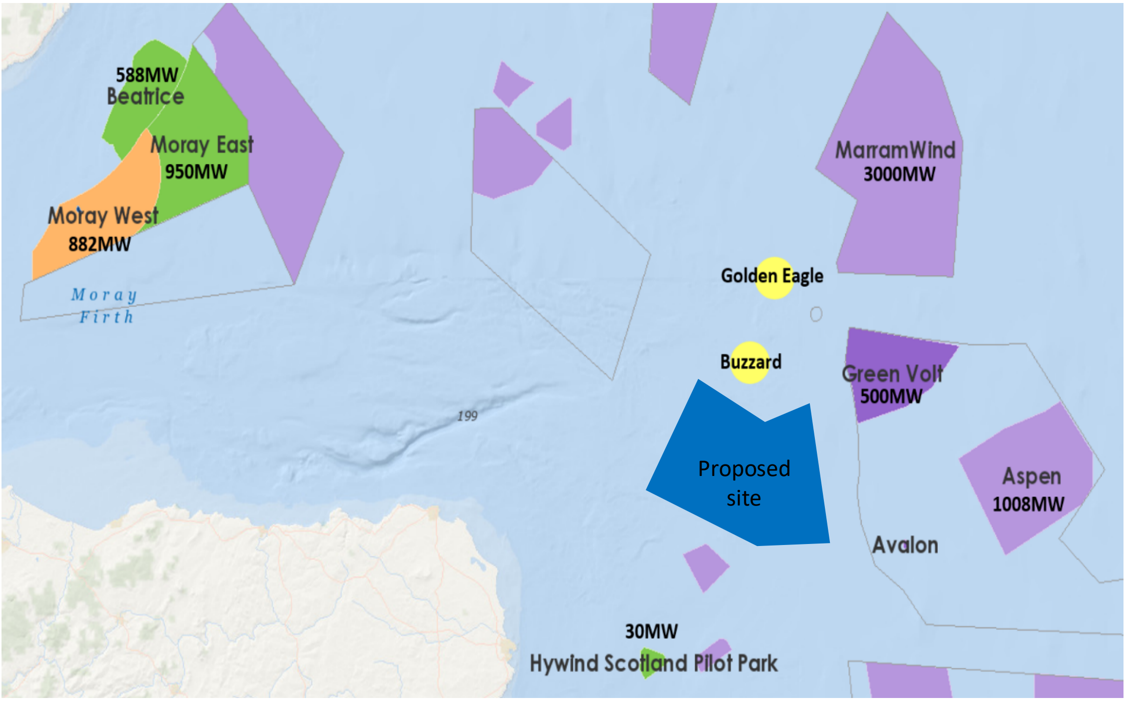


Figure 28- Proposed site (blue), Operational (green), under construction (orange) and developing (purple) wind farms around Golden Eagle and Buzzard (TGS, 2024)

As the world's first floating wind farm, the Hywind Scotland Pilot Park has been in operation since 2017 (Equinor, 2024). With investments from Equinor and Masdar, the wind farm has generated the highest average capacity factor of all UK offshore windfarms, producing an electricity generation of 30MW since its operation (Equinor, 2024). This has built a foundation for further expansion and development for offshore windfarms in the North Sea.

In 2019, the Beatrice Wind Farm became operational after seven years of development and three years of construction (Beatrice Wind, 2024). The 84 Siemens Gamesa turbines have a total capacity of 588MW, enable to power 450,000 homes (Beatrice Wind, 2024). This achievement is the result of a joint venture between SSE Renewables and other renewable energy companies that are dedicated to developing offshore wind farm technology.

Following that, Ocean Winds, a 50/50 joint venture by EDP Renewables and ENGIE, oversees the Moray East Wind Farm (OW, 2024). This wind farm, with an area of 295km^2, has 100 9.5MW turbines installed, reaching a total of 950MW capacity (OW, 2024). Three offshore substation platforms were located around these wind turbines for further process of the energy generation in voltage step-up and onshore export (OW, 2024). The voltage is then further regulated to transmission level and is transported into the national grid network to power households (OW, 2024). Additionally, the Moray West Wind Farm was proposed with a capacity of 882MW using 60 turbines (OW, 2024). The wind farm is currently under construction and is expected to provide the first source of green energy in 2024 (OW, 2024).

With Scotland aiming to derive 50% of its total energy consumption from renewable sources, renewable energy companies have intensified their focus on developing offshore wind farms. Several wind farm development ideas have been proposed such as the MarramWind, the Green Volt Wind Farm and the Aspen Wind Farm. As one of the largest proposed wind farms, MarramWind is expected to be able to deliver 3GW of power to Scotland, powering more than 3.5 million households (Marram Wind, 2024). The project is under a 50/50 joint venture with Scottish Power Renewables and Shell New Energies UK with the aim to support Scotland and the UK in achieving net-zero targets (Marram Wind, 2024). Although still in early stages, high hopes were given to the two partners employing their experience in offshore technologies, specifically in the North Sea, to deliver the world's first large scale floating offshore wind project.

Proposal

The proposed location for additional floating wind farms is along the north-east coast of Scotland, under the Buzzard platform as shown in Figure 28. The site is located at a distance of 35km from mainland and is in a water depth of around 110m (Marram Wind, 2024). Ecological zones were investigated, and it was found the proposal did not interfere with this.

Figure 29 highlights the wind map, indicating wind speeds ranging from 11 to 13 m/s (Windy, 2024a). The wind speed is lower compared to Shetland; however, this has minimal impact on the energy generation. It is also indicated that wind speed throughout the year is above the minimum required wind speed.

To gain further insight into the project's potential, comparisons were drawn with nearby existing wind farms. The proposed wind farms exhibit similar sizes and characteristics to those of the Moray East Wind Farm and the MarramWind. It is suggested that the proposed wind farm will have a potential capacity of around 2.5GW. Energy generated will then be fed to the energy island for further transmission.

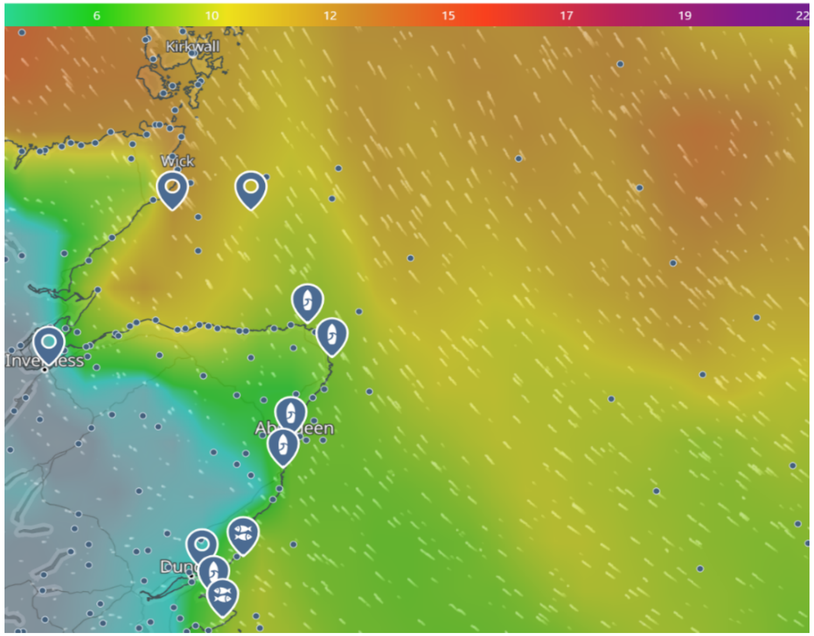


Figure 29- Wind speeds at the North Sea (Windy, 2024a)

Tidal and wave energy

Orkney consists of the world's largest tidal stream array and the world's most powerful tidal stream turbine under The European Marine Energy Centre (EMEC). Since established in 2003, EMEC has been committing to develop the technology in electricity generation through wave and tidal energy. Tidal energy is considered a more reliable energy source due to its high predictability and consistency when compared to other renewables. With two high and two low tides every day, the maximum amount of energy can be generated every twelve hours. This helps to substitute the energy generation gap from other renewables such as wind and solar. Furthermore, water can be stored with pumps to be released during low energy generation period for a consistent energy generation and supply.

Research by (Neill et al., 2017) has reported the tidal and wave resources in Scotland, showing the mean wave power in Scottish waters as well as the simulated peak spring tidal current amplitude. The information is used for further analysis of the feasibility of wave and tidal energy in each region.

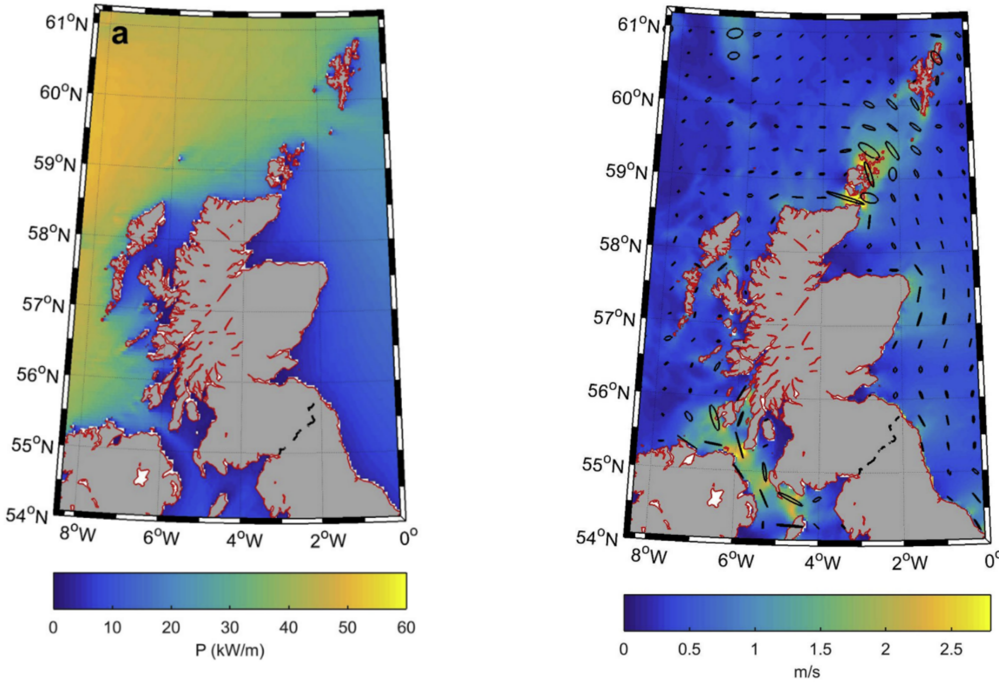


Figure 30: (a) Simulated peak spring tidal current amplitude (b) mean wave power (kW/m) in Scottish waters (Neill et al., 2017)

Shetland

Current Infrastructure

In 2014, Nova Innovation installed the first tidal turbine in the Shetland Islands. Located within close proximity to the energy island, the tidal turbine is located in Bluemull Sound, situated in water between 30-40m between the islands of Yell and Uns (IER, 2023). The Nova 30 turbine has successfully generated 30kW capacity to power 30 households, building a foundation for future developments of tidal technology in Shetland (IER, 2023). Two years later, the world's first offshore tidal array was installed in the Shetland Isles at the same location (IER, 2023). The array consists of three Nova M100 turbines with a capacity of 300kW installed (IER, 2023). It was then extended to an array of six turbines with an increased capacity of 600kW in 2018 (IER, 2023). In the same year, Nova Innovation worked with Tesla to incorporate energy storage into the tidal turbines, creating the world's first grid connected tidal power station to supply constant and steady power (IER, 2023). Further usage of the tidal energy has also proved Shetland's potential in wave and tidal energy by powering households and supporting infrastructures such as electric vehicle charging points. Hence, more tidal plants were planned to be develop around the Shetland Isle, for example, the Yell Sound project which is set to generate an electricity capacity of 15 MW to provide one-third of the household electricity demand in Shetland (Shetland News, 2022).

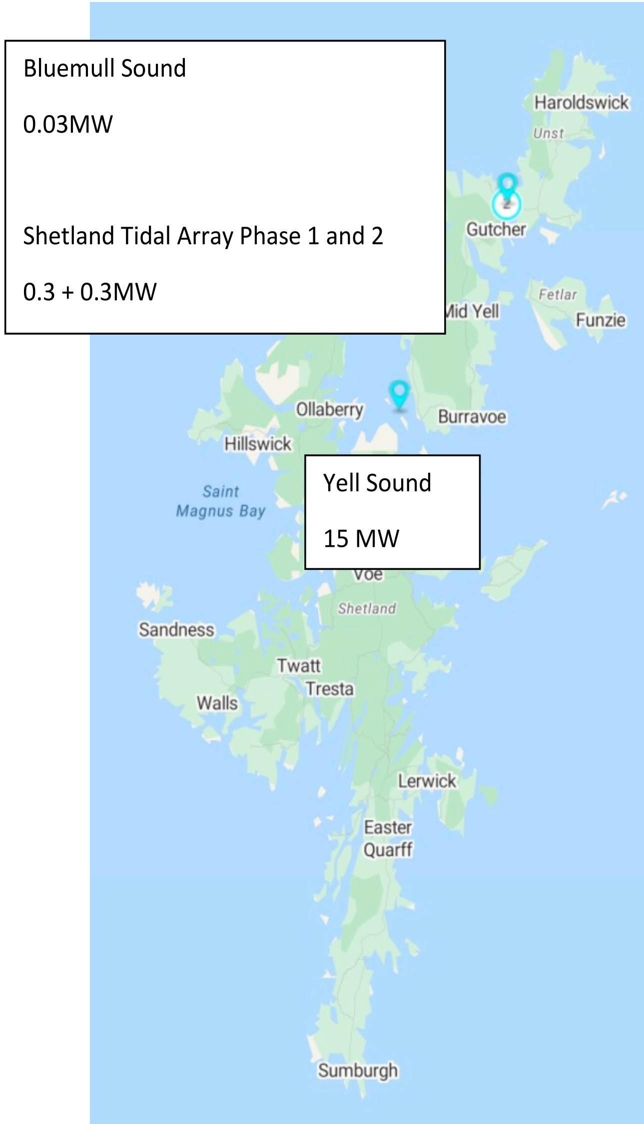


Figure 31: Tidal energy in Shetland

Proposal

As Fish Holm is located in a coastal area, tidal plants can be installed along the coastlines. The coast of Fish Holm is rich with wave and tidal energy resources as it has a peak current speed of over 2.4 m/s (Halliday, 2011)/ (Neill et al., 2017) and an average wave height ranging from 1.5m to 3.5m. Furthermore, the regions present peak wave periods of 6-7 seconds from Southwest to Southeast. It also provides favourable conditions for the installation of wave and tidal energy plants with a water depth of more than seven meters and a seabed depth of more than 15 meters, providing sufficient water head for turbines.

There are three types of tidal plants that can be considered – tidal barrages, tidal fences, and tidal turbines. After comparison of Fish Holm's conditions with the region of Yell Sound where the energy plant is located, both regions share similar sizes and characteristics. Hence, it's estimated that tidal turbines could be installed to maximize the island's energy capacity to approximately 10 MW which is 5MW lesser than Yell Sound as Fish Holm has a smaller area for plant installation. However, more information such as geological topography, coastal range and weather patterns are needed to make further judgements to optimise the implementation of tidal energy in the area.

There is potential to construct more tidal energy plants like the one identified above, that can be connected to the energy island. The tidal plants must be constructed around the ecological zones highlighted in Figure 32 and 33.

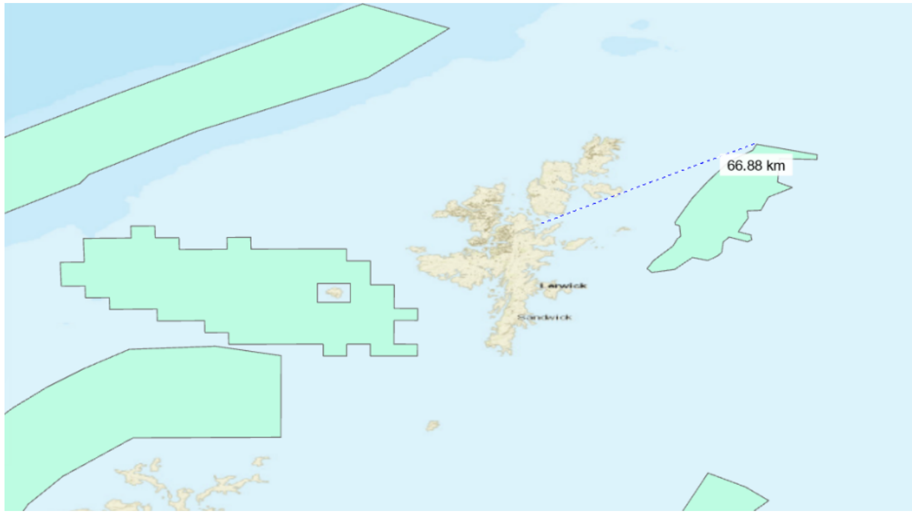


Figure 32- Distance to Ecological Zone from GIS

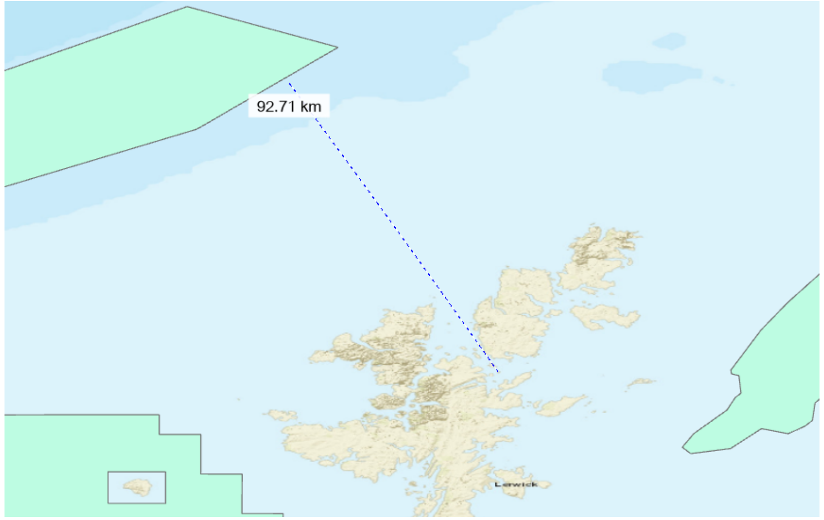


Figure 33- Distance to Ecological Zone from GIS

Golden Eagle & Buzzard

Current Infrastructure

Over many years, Scotland has been focusing on the development of wave and tidal energy on the Northern Isles and the West Coast. Due to a lack of significant tidal and wave resources on the east coast, the development of tidal and wave energy technologies has been less common in these areas. As shown in Figure 34, there has not been any tidal or wave turbines around the east coast due to the limited tidal and wave resources.

Proposal

Locations like the Golden Eagle and Buzzard platforms in the North Sea experience weaker tidal currents compared to regions like Shetland and the West Coast, with peak current speeds less than 1m/s (Neill et al., 2017). This lower current speed can be due to more gradual coastlines and fewer narrow channels along the east coast, which result in weaker tidal currents. As there is lower kinetic energy available for electricity generation, tidal and wave energy projects in these areas are less economically viable. The lack of resource potential has limited the future development of tidal and wave energy in this region.

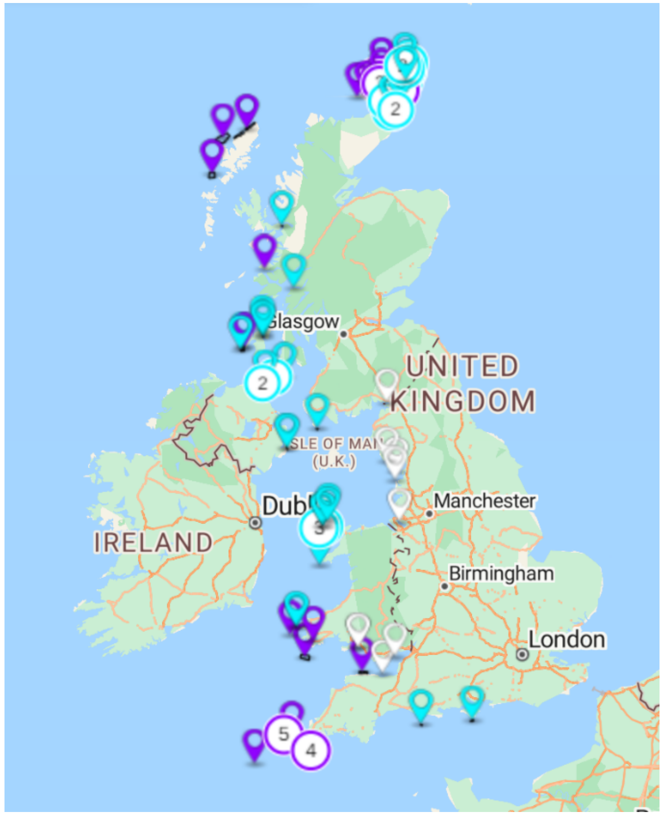


Figure 34: Tidal and wave energy in Scotland (RenewableUK, 2024)

Solar Energy

Scotland has a relatively lesser solar irradiance when compared to other regions due to its location up North. However, solar energy still plays a vital role in the country's renewable energy generation. To achieve the goal of generating 50% of Scotland's total energy consumption from renewable sources by 2030, the Scottish government have been implementing efforts in promoting the usage of solar energy. Recently, the government has provided a Home Energy Grant Funding – ECO4 Scheme, to provide homeowners with installation of solar photovoltaic (PV) panels at no cost (Scotland Energy Grants, 2024). This has further popularised the usage of solar panels among the public while accelerating the transition of Scotland to a renewable energy future.

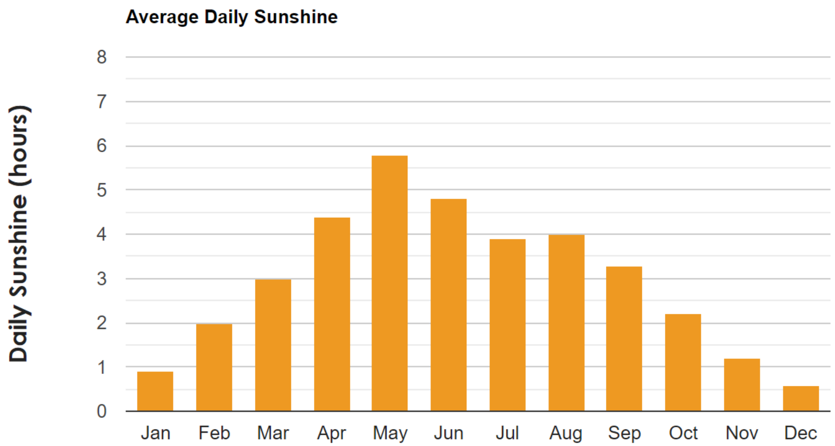
Shetland

Current Infrastructure

The usage of solar power in Shetland is relatively low due to its limited sunlight when compared to other regions in Scotland. As Shetland is located in the most northern area of Scotland, it experiences shorter days with lesser sunlight during winter. This has significantly reduced its potential for solar energy generation. Despite these challenges, the use of solar panels within households is increasing in the Shetland islands. This is to mitigate power blackouts, especially during the night from 11.30pm to 7.30am on certain islands that rely solely on wind turbines for electricity supply (Solar Kinetics, 2024). Photovoltaic (PV) arrays and inverter systems have been installed to integrate both wind energy and solar power into charging battery storage systems (Solar Kinetics, 2024).

Proposal

Shetland has shown high inconsistency in daylight hours and sunlight conditions throughout the year, especially during winter months when sunlight is the least while electricity demand is the highest. Data collected from a coastal area near Fish Holm - Mossbank, has shown the inconsistency of average daily sunlight throughout the year. For example, during peak months like May, the average daily sunshine can be up to 5.5 hours, while during winter months such as December and January, it decreases significantly to less than one hour per day (Scottish Places, 2024)(Figure 35a). Furthermore, it shows relatively low sunshine totals than other regions, with only 1104 hours of sunshine recorded in a year (Scottish Places, 2024). Further analysis was done using the European Commission Photovoltaic Geographical Information System to estimate the monthly energy output from a fix-angle PV system (European Commission, 2024). The graph matches the amount of sunlight each month which shows high inconsistencies with a less total energy output (Figure 33b). This is further confirmed by the data from Global Solar Atlas which mentioned that the photovoltaic power output at Fish Holm will be around 800 kWh per year (Scotland Energy Grants, 2024).



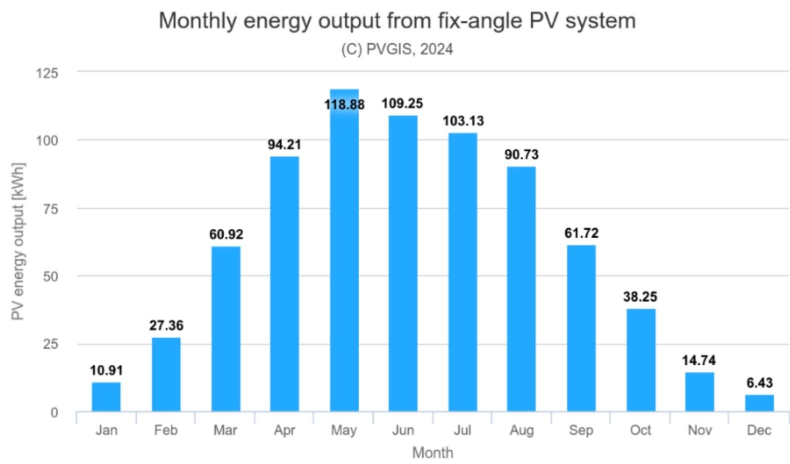


Figure 35- (a) Average daily sunshine at Mossbank (Scottish Places, 2024) (b) Monthly energy output at Fish Holm (European Commission, 2024)

This inconsistency in sunlight conditions greatly reduces the potential of solar energy in Fish Holm. While solar energy can contribute to a more stable energy system, it may not be the best choice given the island's conditions on sunlight and weather when focusing on the economic considerations which has a low benefit-to-cost ratio. Therefore, it may be best viewed as a supplementary option which can be incorporated with other renewable sources, such as wind and tidal energy to ensure a more stable energy supply.

Golden Eagle & Buzzard

Current Infrastructure:

In comparison to Shetland, the usage of solar power around the area of Golden Eagle and Buzzard is relatively high. With several solar farms in the region, an average of 250kW solar panels were installed at each site with a power generation of minimum 200,000 kWh per year (Scottish Water, 2024) (Figure 36a and Figure 36b).

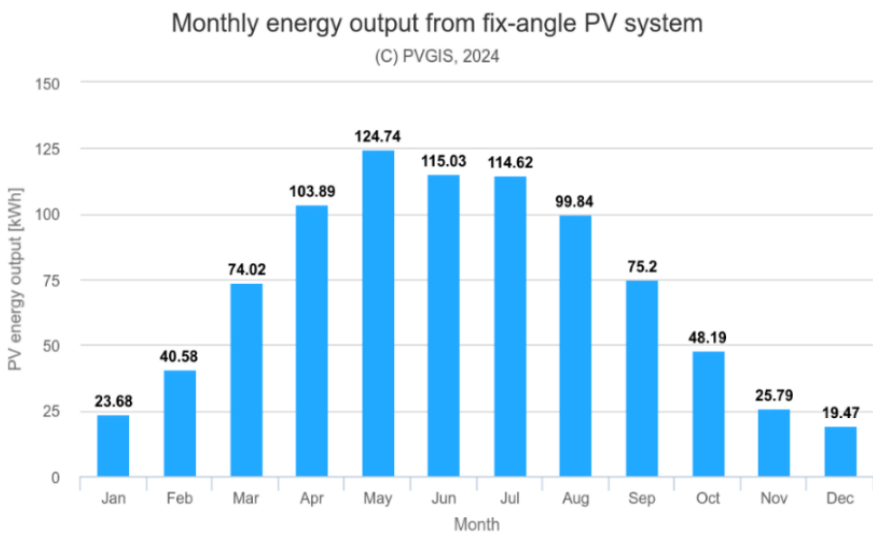


Figure 36- (a) Solar map in Aberdeen (operational) (Scottish Water, 2024) (b)Monthly energy output at Golden Eagle and Buzzard platform (Global Solar Atlas, 2024)

Proposal:

Similar analysis was conducted at the Golden Eagle and Buzzard platform showing the estimated monthly solar energy output at that area. In comparison, the region shows a higher total energy output with a minimum of 950kWh per annum with 770kWh being direct normal irradiation (Global Solar Atlas, 2024). Despite showing similar trends in inconsistency of energy output as Fish Holm, the difference within various months is significantly lower, showing a more feasible usage of solar energy. The energy output can be maximised with the correct arrangement of solar panel facing south where sunlight is greater. Arrangements facing other directions should be avoided as it is estimated that an energy generation reduction of 15% will occur for arrangements facing East and West whereas the arrangement towards north will not be feasible at all (Scotland Energy Grants, 2024).

A new technology of floating solar panels has recently been introduced and it represents an optimal choice for this region as it eliminates the need for land space on the platforms. This approach not only increases the energy generation around the energy island, it also enhances the electricity generation yield from the solar panels as the water proximity leads to a cooling effect that benefits the panels (Ciel & Terre, 2024). It is estimated that with one hector of a water body, 1MW can be generated by floating PV plants (Ciel & Terre, 2024). This shows high potential for the installation at water bodies around the Golden Eagle and Buzzard platform where there is no limit on the space that can be used for plant installation. However, the current technology of floating solar panels is limited to only be used on lakes or other still water bodies. This is because the usage of floating solar panels on oceans often come with challenges such as strong winds and salt corrosion, causing high maintenance or damage towards the solar panels.

The industry has been putting efforts in to find a solution for the problems. At the Amer power station by RWE, the solar plants were anchored to concrete blocks which was then placed at the bottom of a lake to avoid drifting from strong wind (RWE, 2024). Currently, RWE is collaborating with SolarDuck to build the Merganser, an offshore floating solar (OFS) demonstrator plant in the North Sea. The plant consists of six interconnected platforms with an installed capacity of 520kWp and is designed to withstand the extreme storm conditions of the North Sea. This technology can be taken into consideration for future expansion of the solar energy around the energy island at the Golden Eagle and Buzzard platform.

<u>Geothermal energy</u>

Geothermal energy is not commonly used in Scotland as compared to other renewable sources, mainly due to the lack of enthalpy resources and limitation on power plant's locations. The Scottish Government has been investigating the opportunities in geothermal energy as low-carbon heat. Studies from AECOM and the British Geological Survey (BGS), supported by the government, has identified three potential energy sources in Scotland, including abandoned mineworking's, hot sedimentary aquifers, and hot dry rocks that exist in high heat production granites (Scottish Government, 2023).

Shetland

The geothermal energy in Shetland is not as commonly discussed as other renewable sources, however, it shows potential for providing heat and electricity generation to the island. The two common geological features associated with geothermal potential are hot sedimentary aquifers and radio thermal granites. The former is unlikely to be feasible in Shetland due to the absence of substantial hot aquifers beneath the region, which lacks notable deep sedimentary basins (Cluff Geothermal, 2013). On the other hand, research conducted by Shetland Heat Energy and Power (SHEAP) has identified the potential for utilising geothermal energy for heating systems in Shetland. Various igneous rocks were found scattered around the island which shows the potential of using this as resource (Cluff Geothermal, 2013). However, none of these resources have been found nearby Fish Holm, which denies the potential of utilizing geothermal energy in that specific area (Cluff Geothermal, 2013).

<u>Ocean Thermal Energy Conversion (OTEC)</u>

OTEC is a new renewable energy technology that converts solar heat energy stored in the ocean into power. The concept is similar to geothermal energy, where warm surface water is used to evaporate a fluid which produces a vapour that spins the turbine for electricity generation. The vapour is then condensed to water due to lower temperatures of the sea (up to 800 meters) to continue the cycle (Global Otec, 2024). This renewable resource is generally more effective than the others as it is able to generate energy every second and it takes up less space – only 1/10th of the space needed for a solar plant to generate the same amount of energy (Global Otec, 2024). Additionally, it does not require high levels of investigative drilling, unlike geothermal energy.

Golden Eagle and Buzzard

The OTEC technology is more feasible in tropical and equatorial regions of the world as the year-round ocean temperature difference is more stable with a higher consistency (Global Otec, 2024) (Figure 37).

As the Golden Eagle and Buzzard is located far North, the surface temperature varies often due to weather changes, causing inconsistency in the temperature difference. This causes challenges to the OTEC system as it relies on a consistent temperature gradient to maximise the energy generation. Furthermore, the fluctuating surface water temperatures have limited the utilisation of solar thermal energy in the ocean, further reducing the efficiency of OTEC in this region.

Nevertheless, as technology continues to improve, it is possible that a more advanced OTEC system could be developed in the future, making it feasible in other regions rather than just equatorial areas. Hence, while OTEC is not currently practical around the Golden Eagle and Buzzard platform, it can be considered in future plans when technology is more advanced.

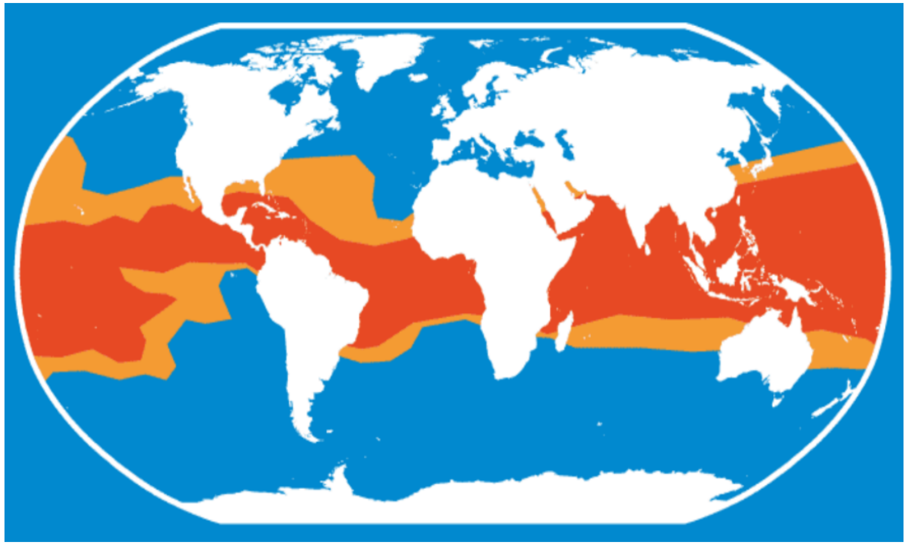


Figure 37- Current developing plans for OTEC (Global Otec, 2024)

Storage

Energy storage systems for wind turbines have a vital role to play in effectively optimising the efficiency and reliability of wind energy. Often, wind turbines capture and produce significantly more energy than is required at that immediate point in time (Ampowr, 2024). Therefore, an energy storage system is crucial when considering the varying scales of supply and demand. If excess energy from long periods of high wind can be stored and readily available for use at a time in the future when the wind may be limited, or during periods of abnormally high demand, it maximises the capability of wind energy and helps to ensure a stable and dependable energy supply. There are several different types of energy storage systems (ESS) that have been considered for the storage of excess wind energy including battery storage, flywheel storage, air energy storage and hydrogen storage.

Battery Energy Storage

Battery storage systems (BSS) are widely used for wind energy because of their scalability - especially in large-scale commercial production. They can be conveniently placed on offshore platforms within containers, requiring no modifications (Yessica Arellano-Prieto et al., 2022). Energy is stored in charged batteries and discharged when needed, providing reliable support for wind energy production. BSS offer rapid response times, high efficiency, and adaptable scaling to meet varying requirements (Ampowr, 2024). They come in compact sizes and can be optimized for backup power during peak demand. Lithium-Ion batteries and Vaanadium Redox Flow batteries are commonly studied for the purpose of large-scale energy storage systems (Kim et al., 2021).

The Lithium-Ion Battery (LIB) offers the flexibility to be combined across different energy sources such as solar photovoltaics' to store excess generated power. Various studies have evaluated the feasibility of an economically viable LIB system for hybrid wind and photovoltaic energy and suggesting that there is short term profitability potential, but highlighted limitations due to their relatively short life cycle (Kim et al., 2021). Despite the LIB being widely used and mass produced, it can be a much more expensive route for energy storage than other options (MIT Technology Review, 2018). Additionally, lithium-ion batteries can be very sensitive to high temperatures during rapid charging, therefore, when used for wind energy storage, lithium-ion batteries are usually buried in the ground which would come at a considerable economic cost when considering their offshore potential.

One of the greatest concerns regarding the use of LIBs for the purpose of storing renewable energy, is their sustainability. Not only is the mining, processing and manufacturing of their raw and rare materials for the batteries tremendously energy intensive, but the disposal of used lithium-ion batteries is extremely environmentally damaging (IER, 2023). When lithium-ion batteries are disposed of in landfill, their cells can release harmful toxins, like the heavy metals, that can leak into the landfill and groundwater. This can also increase the risk of landfill fires that can burn for years on end.

The Vanadium Redox Flow Battery (VFB) is another type of rechargeable flow battery that uses four different oxidation state vanadium ions to store energy in the form of chemical potential (Kim et al., 2021). Different to a lithium-ion battery, a VFB has a long cycle life and can be scaled up with substantial flexibility, showing the potential of the VFB for seasonal energy storage in the power grid. However, VFB can come at a high technological cost, limited energy density and can exhibit degradation within the cell due to the harsh environment caused by the chemicals in the battery (Lourenssen et al., 2019). Nevertheless, VFB components are assumed to be around 95-100% recyclable compared to that of the lithium-ion batteries that are only 80-90% recyclable (Onu, 2021).

Flywheel Energy Storage

Flywheel energy storage works by rotating a rotor at high speeds, essentially converting the excess electricity into kinetic energy as a way of storage. To obtain the stored energy again, the rotor is decelerated, and the kinetic energy is converted back to electrical energy (Yessica Arellano-Prieto et al., 2022). However, flywheel energy storage comes with a variety of challenges as they generally have a lower energy density than the likes of compressed air energy storage or battery storage, in addition to short duration times for storing the kinetic energy (State of Green, 2017). This would make flywheel energy storage less feasible for large, commercial scale energy production.

Air Energy Storage

Liquified air energy storage (LAES) and compressed air energy storage (CAES) are efficient ways to utilise the air for storing excess energy (Ondřej Burian and Dančová, 2023). Like their names describe LAES stores energy in the form of liquified air and CAES in the form of compressed air, both of which utilise the thermal cycle for energy discharge.

Both CAES and LAES share the same storage options and working cycle, i.e., utilising a charge period for storage of energy and then a discharge period for releasing energy, however, both have different energy charge storage systems. LAES stores energy in thermal form at extremely low temperatures, below air boiling point (-195 degrees C), whereas CAES stores highly pressurised air at ambient temperatures (Ondřej Burian and Dančová, 2023). Due to the system in LAES store energy, the process of air cooling can reduce efficiency and lead to energy losses as well as requiring large amounts storage space (Khatana, 2023), therefore, for the purposes of our energy island design, CAES will only be considered.

Compressed air energy storage systems can be stored in naturally occurring underground salt caverns and when power is needed for electricity, the air is released which then propels turbines and generates energy. Studies have found that adiabatic CAES (CAES that are based on air compression and storage in underground geological voids) can be profitable when combined with a wind farm (Zhang et al., 2019). Figure 38 illustrates how compressed air energy storage can utilise underground salt caverns (naturally found in the ground around the UK) for storage purposes (Colthorpe, 2017).

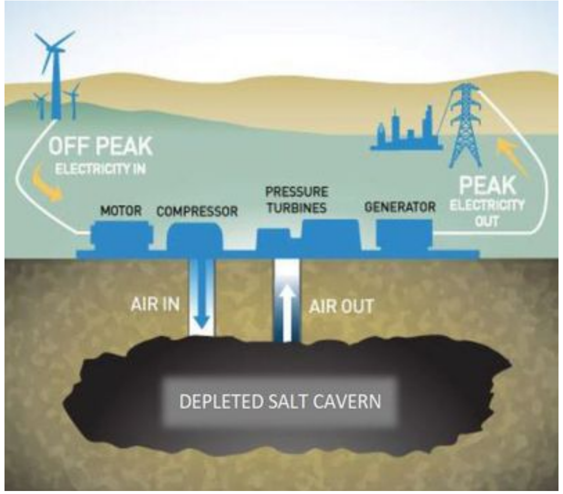


Figure 38- Naturally occurring salt cavern for compressed air energy storage (Colthorpe, 2017)

CAES are more environmentally friendly than batteries as they don’t rely on rare or hazardous materials. Additionally, CAES have longer duration energy storage, with a lifespan of 20-40 years and a typical capacity of 500MWh- 2.5GWh (Energy Systems and Energy Storage Lab, 2024). Companies such as Corre Energy are making huge strides in the development of CAES and Hydrogen storage for offshore wind energy (Corre Energy, 2024). Their extensive research has proven that salt resources, excellent grid connections, existing infrastructure, and gas and hydrogen supply are ideally situated to serve as storage platforms for offshore wind, providing a roadmap of additional CAES and hydrogen storage projects on a global scale.

Hydrogen Energy Storage

Offshore wind farms offer a distinctive opportunity for large-scale production of green hydrogen utilizing desalinated seawater. Hydrogen is produced sustainably through electrolysis, using electricity to split the hydrogen and oxygen molecules in water. Excess electricity generated from the wind turbines can be used to power this process, making the entire hydrogen production chain carbon free, unlike alternatives like grey or blue hydrogen. Producing and storing hydrogen can enhance overall energy production efficiency by optimizing wind farm sites and minimizing transmission losses (Ramboll, 2024). Furthermore, repurposing existing assets in the North Sea that face future decommissioning for hydrogen production and storage, offers a value-added product to investors that are obligated to decommission rigs once their operation has ceased. Not only is this approach modular and scalable, but the option for geological hydrogen storage in porous rocks both within the North Sea and on land, has the capability to offer large-scale storage across diverse timescales.

To utilise seasonal storage of hydrogen, the capacity required is much larger than the typical storage tanks used above ground. Subsurface hydrogen storage, however, can meet the significantly larger scale required while providing an economically viable energy storage solution in both seasonal and short-term timescales (Energy Technologies Institute, 2018). Types of subsurface hydrogen storage options include, saline aquifers, depleted hydrogen reservoirs, or salt caverns. Thus far, commercial hydrogen storage has only utilised salt cavern systems. An example of this is the SABIC H2 facility at Teesside where the facility has three shallow caverns that can store up to 30 GWh of working gas (Cline, 2022). Although utilising salt caverns is influenced by geological considerations, the geotechnical requirements for hydrogen storage are similar to that of natural gas and is well known to be successful.

Expanding upon the potential of wind energy by utilising green hydrogen production with offshore or onshore hydrogen storage has the capability to accelerate the UK's transition to Net Zero by providing a solution to storage issues while also aligning with the interests of investors.

Case Study: Shell's Cross Wind Consortium with Holland Hydrogen 1 Plant

A 200 MW electrolyser is planned to be constructed on the Tweede Maasvlakte in the port of Rotterdam and will produce up to 60,000 kilograms of renewable hydrogen per day (Shell, 2022). In electrical terms, the energy density of hydrogen is equal to 33.6 kWh of useable energy per kg. Comparing this to diesel, which only holds around 12-14 kWh per kg (RMI, 2019)

The electrolyser will be powered by renewable energy sources from an offshore windfarm partly owned by Shell called Hollandse Kust (Noord). The green hydrogen will be transported by the HyTransPort pipeline to the Shell Energy and Chemicals Park in Rotterdam.

Shell acknowledges that offshore wind projects produce intermittent electricity, and that balancing the highs and lows of supply and demand will require a variety of new technologies to support the energy supply (Shell, 2020). This is why the offshore wind farm is also including a floating solar park; short term battery storage; turbines that are optimised and tuned to the network to minimise the negative 'wake' effects that the turbines have on each other; as well as the green hydrogen made by electrolysis.

<u>Cavern Storage Capabilities</u>

Underwater compressed gas energy storage (UWCGES) is one of the most viable solutions to large-scale offshore energy storage as it can make up for the shortages that come with more traditional energy storage and supply systems offshore (Hu Wang et al., 2022). However, there are many challenges that come with large scale UWCGES such as structural stability under cyclic loads, vortex-induced vibration, local scouring near foundations, biofouling of marine organisms and gas escape from the storage system. Despite these challenges, the large demand for clean energy will likely help to accelerate the development of offshore compressed gas storage alongside the advance in offshore energy production technologies. Figure 39 shows how UWCGES can be used in various applications, in both the short and the long term.

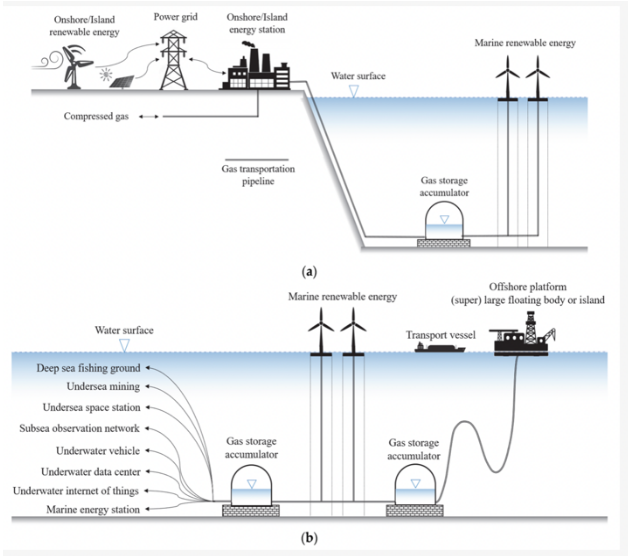


Figure 39- UWCGES (Hu Wang et al., 2022)

For the scope of this report, compressed air energy storage and hydrogen energy storage have been considered. Presently, CAES shows merit due to its predicted reliability with service life and low environmental impact, however, can show relatively low efficiency, energy density and variable economics. Despite the variable economics, CAES still has a lower cost than battery energy storage for large-scale applications.

Hydrogen energy storage (HES) shows a promising future in terms of application in industry, likely to play a huge role in the energy transition, however, presents various challenges when comparing the technology to CAES as there can be issues during production, transportation and utilisation (Hu Wang et al., 2022). When considering using hydrogen energy storage or compressed air energy storage, generally, underground storage facilities are utilised. For offshore underground storage systems, there are three options to consider: a newly drilled cavern which is made specifically for the new storage purpose; repurposing old oil or gas wells for the new energy storage system; or the use of existing, naturally occurring salt caverns within the earth geology.

<u>Salt Caverns</u>

Solution-mined caverns in salt structures are already being widely used as onshore subsurface energy storage for natural gas in the UK. This technology can be easily utilised for subsurface hydrogen energy storage (HES) or compressed air energy storage (CAES) due to the impermeable, inert and self-healing nature of the salt (Prof. Jürgen Adam et al., 2020). Research has found that in the Southern North Sea there is an abundance of salt structures that are located near current and future offshore wind projects, with the capacity to support a huge economic potential of CAES and HES up to 290 GWh of wind energy storage (Prof. Jürgen Adam et al., 2020). Studies from Shell, NAM and Store Electric in the Dutch sectors are well underway and should provide reliable data on the potential of offshore CAES and HES.

Similar to offshore, storing green hydrogen in onshore salt caverns has proven to be one of the most efficient and economical ways to store large volumes of hydrogen. The technology of using onshore salt caverns to store compressed gas is a mature technology as it has been done within the UK since the 70's

(Storage Working Group, 2022). Salt caverns have a low temperature naturally and their leakproof nature make the solution low risk to unwanted microbial or chemical reactions affecting the quality of the hydrogen that is stored. This low temperature also allows hydrogen to be compressed more efficiently than in above ground scenarios with low land and operational costs associated. These factors, alongside the strong geomechanical structure of hydrogen salt caverns, leads to the option having approximately a 100x higher volumetric energy density than CAES of the same size as well as being cheaper than battery storage options by a factor of 100 (costing less than £0.50 per kgH2) (Storage Working Group, 2022).

However, there are challenges associated with utilising salt caverns for compressed gas storage such as hydrogen as they aren't always widespread geographically and can have a limited size. Constructing new salt caverns can be done, however the high economical cost can often discourage investors, as well as the 7–10-year timescale that it can take to build new facilities. To construct a new salt cavern facility, a process called leaching is necessary and can take well over a year to complete, often requiring additional infrastructure to prevent environmental damage to freshwater from the brine that needs to be disposed of safely.

Rock Caverns

With significant geological adaptability, the use of rock cavern storage can present a viable alternative where other options aren't possible such as salt caverns. As an emerging technology, rock caverns are created through rock excavation in underground rock formations. After rocks have been excavated, a layer that seals the cavern is applied to prevent leakage of the gas (Department for Energy Security and Net Zero, 2024). The construction process for rock cavern storage is more intricate and expensive when comparing to other forms of storage as the excavation process is expensive, requiring significant drilling and blasting before the additional lining costs. However, despite these extra costs, rock cavern storage may offer a viable alternative if other options aren't available. Lined rock caverns for hydrogen storage is currently being piloted in Sweeden (Department for Energy Security and Net Zero, 2024) that may provide an insight into the potential of using the technology in the UK.

Depleted Oil and Gas Reservoirs

Depleted hydrocarbon reservoirs that were once utilised for the offshore oil and gas industry has been studied to propose a very suitable option for offshore compressed gas energy storage like HES (Storage Working Group, 2022). Not only are they sufficient in size, but they can seal natural gas and oil well, with 74% of natural gas already being stored within these depleted fields globally (Amid et al., 2016). Data and research for these fields are readily available as they have been utilised for the extraction of oil and gas for years, allowing an adequate understanding of the nature of the reservoir before construction begins. Repurposing the depleted wells minimises environmental impact and land usage as there would be reduced need for drilling and constructing new reservoirs or connections, minimising CO_2 output from large plant and construction methodologies, and reducing impact on the marine environment.

Additionally, the existing pipelines and infrastructure connecting to these reservoirs will considerably reduce capital costs of the gas transport. The H21 report describes the process as more cost effective than creating new salt caverns when comparing cost per unit volume of storage (Amid et al., 2016). However, there are still several challenges to overcome that are associated with the planning processes, as each case will have site specific circumstances. This includes understanding the differences between repurposing an oil reservoir rather than a gas reservoir as oil reservoirs will require a much more complex process of repurposing due to the nature of the leftover oil residues. There are also issues associated with the physical, chemical and microbial processes as sulphate reducing bacteria have the potential to contaminate the oil and gas reservoirs. Furthermore, the risk of hydrogen diffusion into the porous media is an issue that is raised frequently in the engineering community as compressed gas molecules like hydrogen are much smaller than methane molecules, however, recent findings suggest that the losses from diffusion and dissolutions can be minimised to 0.1% (Amid et al., 2016).

Despite the challenges, new modelling technologies allow the prediction of multicomponent flow behaviours, allowing design to limit base gas and working gas from mixing, mitigating risks that have previously been a concern within the industry such as 'viscous fingering' and 'gravity override' (Hassanpouryouzband et al., 2021). Research projects such as the HYStorPor and HyUSPRe investigated this issue and found no significant losses during laboratory testing. Additionally, recent studies suggest that the risk of geochemical reactions between hydrogen and the minerals in the storage reservoirs is unlikely within the timespan of hydrogen that is seasonally stored.

Various feasibility studies and reports by the groups such as the Oil and Gas Technology Centre, have identified that by completely repurposing a typical large offshore asset, circa 20,000kg of hydrogen could be produced per day (Marram Wind, 2024) (equivalent to 0.0006666 TWh a day and thus, 0.243309 TWh a year (Idealhy, 2024)). Additionally, HyUSPRe (Hydrogen underground Storage in Pourus Reservoirs) have indicated that the average depleted gas field converted for hydrogen storage will have a capacity of 1-5 TWH (HyUSPRe, 2023).

Shetland Proposal:

From the research outlined, compressed air energy storage (CAES) and hydrogen energy storage (HES) were considered the most suitable storage options for the Shetland energy island, with both options utilising onshore underground salt caverns for storage. Although CAES was carefully considered for a variety of reasons above other technologies such as battery storage, there were several factors that highlighted why HES would be the preferred option.

Hydrogen stored in salt caverns can provide around 100 times higher volumetric energy density than CAES systems of the same size, with a low economic cost of less than £0.50 per kgH_2. The technology that utilises onshore salt caverns for compressed gas like hydrogen is a mature technology that has a reliable track record in the UK, meaning that the system is reliable and low risk. As salt caverns have a naturally low temperature, they reduce the risk of unwanted chemical or microbial reactions in the cavern, ensuring that the hydrogen maintains a good quality standard and reducing the risk of contamination. This low temperature also allows the hydrogen to be compressed much more efficiently than in above ground storage facilities which will reduce its operational cost, alongside the natural geological strength of their structure. Furthermore, geological salt caverns have an inert nature as well as being naturally leakproof, making them a suitable option for hydrogen storage.

Utilising the existing caverns minimises the need to construct new storage facilities, therefore further reducing the economic cost associated with creating the facility. Additionally, the environmental impact will be lessened as CO_2 emissions from heavy plant will be reduced and land use will be minimal. However, despite these advantages, there are challenges associated with planning to utilise existing geological salt caverns for hydrogen storage as there is little information available or mapping of the abundance of salt caverns both on and around the Shetland islands. New caverns can be constructed; however, they take around 7-10 years, with the leeching process alone taking at least a year. Furthermore, constructing new salt caverns comes at a high capital cost and the leeching process must be carefully monitored to ensure there is no environmental damage to surrounding ecosystems. Alternatively, rock cavern storage may be utilised where salt caverns aren't possible, following a more comprehensive understanding of their challenges and benefits.

There are several studies currently researching the capability of above ground hydrogen storage technologies, many funded by the Long Duration Energy Storage Competition. The studies focus on a variety of innovative technologies or processes, such as the utilisation of nuclear waste products for hydrogen storage, metal hydride technologies, Corres's patented Carbon280 Hydrilyte hydrogen carrier system, and a practice known as linepacking where hydrogen can also be stored within the gas transmission and distribution network. Additionally, there is active research into the use of ammonia for not only carrying hydrogen but as a fuel itself.

The SHyLo (Solid Hydrogen at Low Pressures) project has just secured £4.3 million from the governments Low Carbon Hydrogen Supply Competition to develop their storage system in the Orkney Islands. This aims to surpass the limitations of compressed gas storage systems as they can have efficiency limitations and high compression costs. Storage savings can be increased by 55% by removing the need for compression, reducing operational costs to an estimated £0.20 per kg by 2028. The research is relatively new but promising when considering the limitations of underground storage options.

Overall, hydrogen storage in salt caverns is the most robust and viable option for long-term energy storage needs on the Shetland energy island, offering both economic and environmental advantages. If there are little or no available options for the utilisation of a natural salt cavern on Shetland, the construction of a new salt cavern or rock cavern storage options should be considered. Additionally, with continued research and innovation, above surface onshore hydrogen storage technologies have the capability to play a crucial role in the energy transition and should be kept as an open discussion throughout the development of the Shetland energy island.

There is already a considerably good understanding of the green hydrogen production process on the Shetland islands due to the presence of the Pure Energy Centre that manufactures hydrogen systems in a variety of scalable sizes. This would be significant for the Shetland based production as the local knowledge could be utilised for the hydrogen plant on the nearby energy island. Furthermore, Pure Energy is involved in the development of a variety of renewable energy schemes, including green energy storage technologies that would be beneficial to the energy island project throughout its life cycle (Scottish Government, 2024a).

Aberdeen Proposal:

Considering the research discussed, the capacity for offshore energy storage and the storage needs of an energy island constructed off the coast of Aberdeen, both hydrogen energy storage (HES) and compressed air energy storage (CAES) present viable options, each with their own considerations.

CAES, particularly adiabatic CAES has been shown to be profitable when combined with wind technology, offering efficient energy storage solutions that are environmentally friendly and avoid reliance on rare of hazardous materials. The CAES systems have long duration energy storage, with lifespans ranging from around 20-40 years and capacities of around 500 MWh to 2.5 GWh.

However, HES offers a unique potential for mass production of offshore green hydrogen, utilising excess offshore wind energy to produce green hydrogen through electrolysis. Prospects for offshore HES can offer large scale hydrogen energy production and storage that may present as an investment opportunity for current owners of offshore assets in a UK climate that is preparing to switch their industries from the burning of fossil fuels to a carbon neutral alternative.

Tractbel and partner companies have designed one of the first offshore infrastructure and processing facilities for the storage of offshore hydrogen (Durakovic, 2021). The development outlines a scalable large-scale offshore hydrogen storage solution that facilitates the compression and storage of 1.2 million cubic meters of hydrogen. The design features a platform and underground salt caverns that can be used for storage and buffer for the hydrogen produced before transporting the gas via a pipeline network to the onshore grid. In response to predicted future mass H2 energy demands, Tractebel believe that offshore sites are key to industrial scale hydrogen production and from that developed the offshore hydrogen platform concept in 2019, followed by an improved and scalable version in 2020 and now developments into its design, Figure 40 shows this representation (Durakovic, 2021).

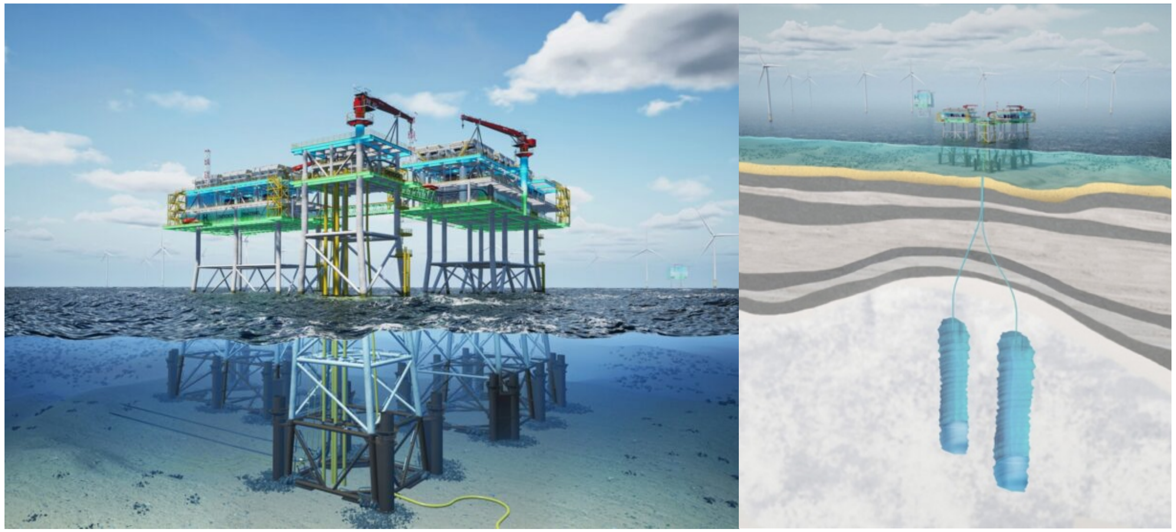

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Figure 40- Offshore Hydrogen Platform (Durakovic, 2021)

The concept is based on converting 2GW of green offshore wind power into hydrogen, however, allows for extensions or individual adaptations. Tractbell designed storage and compressor platforms that would process 400,000 Nm3/h of hydrogen that is stored within underground salt caverns at a pressure of up to 180bar. The salt cavern storage systems buffer the production peaks while optimising the flow rates so that the export pipeline is efficiently and economically designed. Furthermore, the geological nature of the North Sea is well suited for the solution as there are underground rock salt formations that could facilitate the large storage volume needed for hydrogen storage.

However, when considering under water compressed gas energy storage (UWCGES), there is debate over the utilisation of naturally occurring salt caverns compared to repurposing depleted hydrocarbon reservoirs. By utilising depleted hydrocarbon reservoirs for offshore compressed gas storage, particularly when considering HES, there are numerous advantages compared to the use of natural salt caverns, such as the established knowledge that these wells have sufficient capacity for gas storage. Their appropriate volume and the availability of existing infrastructure will significantly reduce capital costs for hydrogen transport and need for capacity expansion. The locations of these reservoirs are known, with existing rigs in nearby proximity for transport of personnel, equipment and maintenance support to potential storage facilities.

Additionally, there is readily available, accessible data and research of the hydrocarbon fields in the North Sea from years of oil and gas extraction, providing a comprehensive understanding of the reservoir characteristics before construction begins and therefore minimising uncertainties in design.
One option within the scope of this project would be the oil and gas reservoirs underneath and nearby the Buzzard Platform. Figure 41 shows the buzzard platform, with the module to the right (circled in red), positioned directly above an oil reservoir.

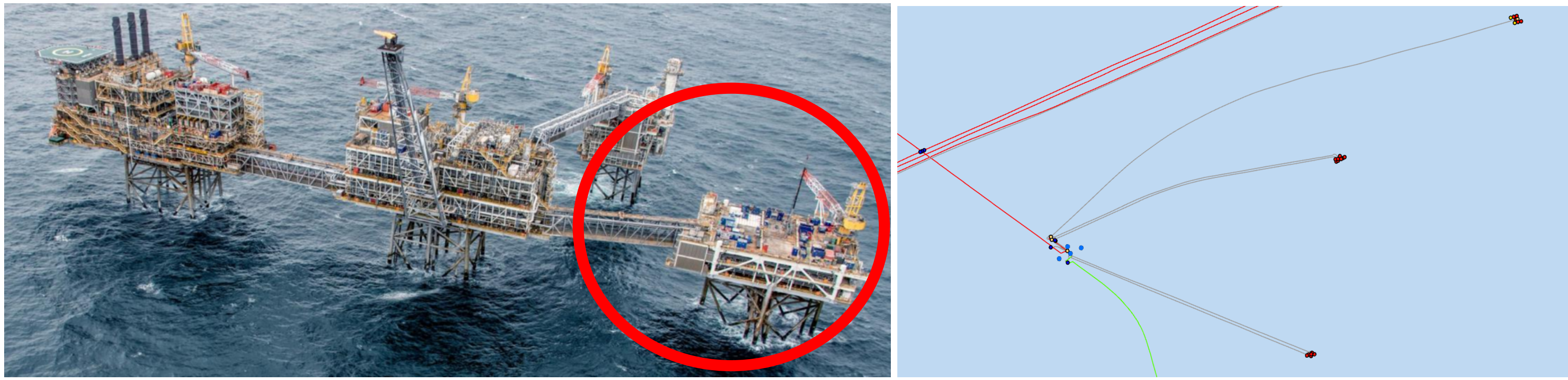


Figure 41- Buzzard Platform and GIS Distance to Oil Wells

Figure 41 shows the GIS map of additional oil/gas wells nearby, all with connections to the Buzzard platform. The red clusters show the location of oil/gas wells, the grey lines are the pipeline connections (all within 5km of the platform), and the blue dots show the location of existing platforms. This provides an opportunity for future expansion of offshore hydrogen storage within the scope of the energy island and the potential to increase renewable energy production significantly.

Similarly, at the Golden Eagle platform, there is an oil well located underneath one of the modules on the rig. Figures 42 and 43 show the Golden Eagle platform and the GIS image that identifies the reservoirs and pipeline infrastructure that are near the Golden Eagle platform, respectively.

Figure 42- Golden Eagle Platform

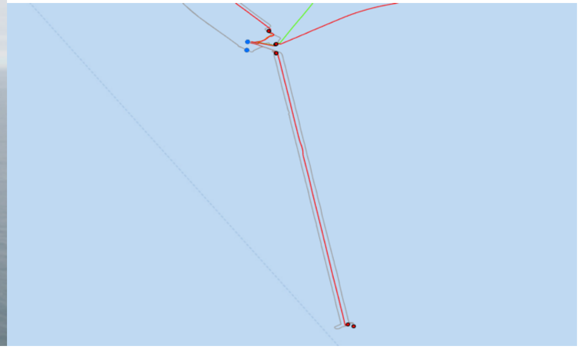


Figure 43- Oil Wells around Golden Eagle shown on GIS

Edinburgh University have identified through their accessible ArcGIS mapping database the Hydrogen storage potential in geocryological formations across the UK (including salt caverns, rock caverns and depleted gas fields). The map shows an approximate capacity of 158 TWh of hydrogen energy storage in depleted reservoirs (The University of Edinburgh, 2024) in a region relatively close to the Buzzard and Golden Eagle platform in the North Sea (Figure 44).

Repurposing the depleted reservoirs minimises environmental impact and land usage as there would be reduced need for drilling and constructing new reservoirs or connections, minimising CO2 output from large plant and construction methods, therefore reducing impact on the marine environment. Challenges presented associated with the physical, chemical and microbial processes when repurposing existing oil and gas wells such as the contamination due to sulphate reducing bacteria are currently being researched, alongside mitigation measures for these issues. Recent findings suggest that losses due to hydrogen diffusion and dissolution can be minimised with the aid of new technologies that have the capacity to predict multicomponent flow behaviours so to prevent these hydrogen losses.

Overall, the repurposing of depleted hydrocarbon reservoirs in the proximity of the Buzzard and Golden Eagle platforms for the purpose of offshore hydrogen energy storage, offers a unique combination of appropriate storage capacity, existing infrastructure, accessible data and continuing technological advancements in the industry that make this a highly favourable option. Providing that the potential challenges can be effectively mitigated with careful planning, using underwater green hydrogen storage within depleted hydrocarbon reservoirs provides a cost-effective solution for offshore energy storage that minimises environmental impact and surpasses the limitations of compressed air energy storage or the utilisation of salt caverns.

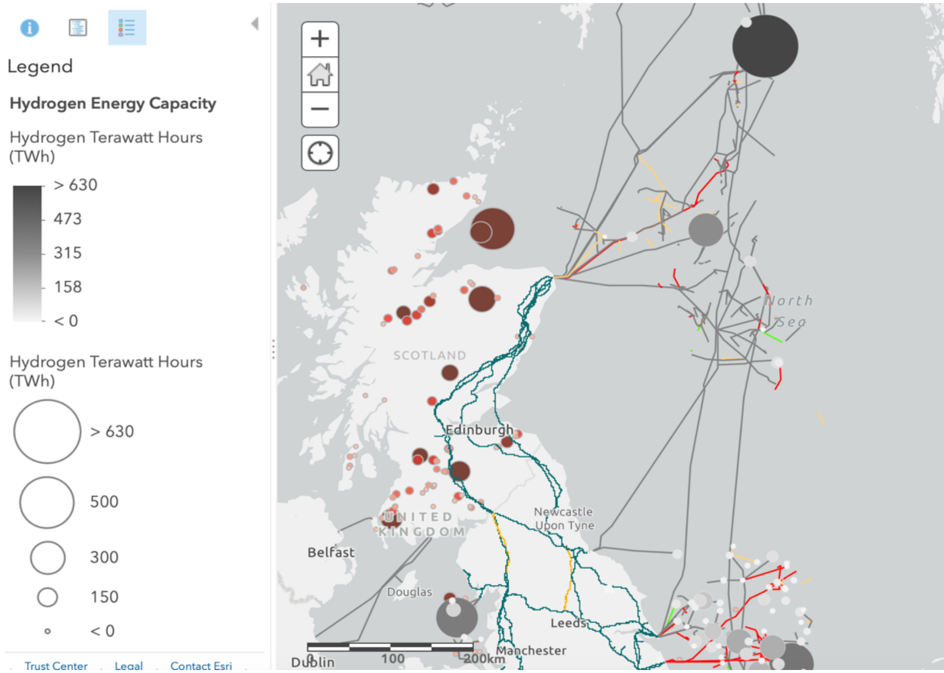


Figure 44- UK Hydrogen Storage Database: Map of North Sea (The University of Edinburgh, 2024)

Cable Connections

To transport the energy created from the island back to shore through a subsea cable, no greater than a 3.5 GW cable can be used, and thus multiple cables would be needed to take any significant amount of energy to the mainland, however, the use of hydrogen pipelines for energy storage and transport presents a promising solution to maximising the quantity of energy transported back to the mainland. By converting the offshore wind energy to hydrogen there are fewer transmission losses than if the energy were to be transported through HVAC current cables to shore (Klaudia Ligęza et al., 2023), meaning that there would be greater efficiency transporting the energy through hydrogen pipelines than through electricity cables. The increased energy density is because electricity cables loose some of their power due to the Joule effect (Department for Business, 2023). Additionally, by transporting the energy back to shore using hydrogen pipelines rather than HVDC cables (generally for distances greater than 100 meters) there are significant reductions in capital expenditure as a hydrogen pipeline is 55.6% cheaper than using a HVCD export cable. Furthermore, if you consider the option to retrofit oil and gas pipelines, the cost will further decrease (Department for Business, 2023).

<u>Connecting the energy island substation to the onshore substation</u>

The electricity produced by the renewable sources surrounding the energy island will be transported through cables to the substation on the energy island, where a single cable will transport the electricity to mainland Scotland. This cable will connect to an onshore substation at the location of the current St Fergus Gas Terminal, much like the cables from offshore windfarms (Guide to Floating Offshore Wind, 2024), to transmit energy to the National Grid and supplying Scotland with renewable energy.

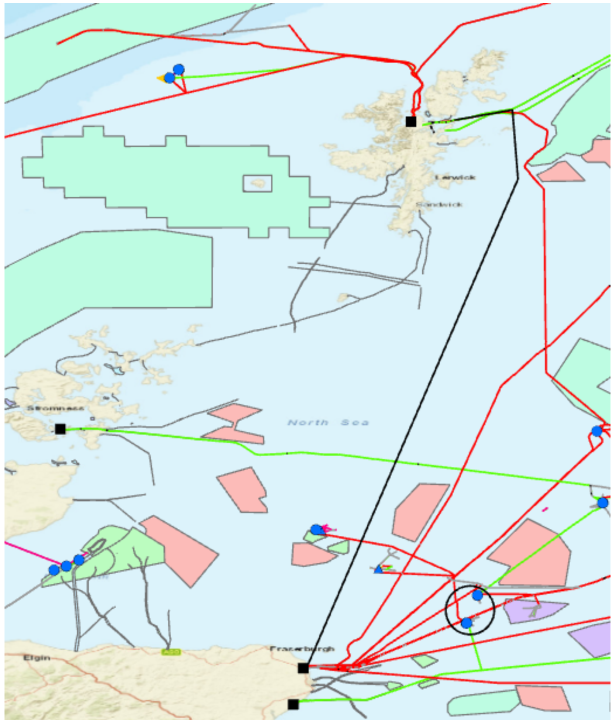


Figure 45- Cable Connections from Shetland Island shown on GIS

Shetland

For electricity transmission, a direct cable from Shetland to Mainland Scotland is desirable due to the reduced loss of energy when compared to using a longer alignment, such as the existing pipelines. In Figure 45, the black line shows the proposed alignment from the existing island to Peterhead, measuring approximately 350km, which is plausible for an undersea cable. This cable alignment does not cross any marine protected areas, however, there is the possible negative effect to marine wildlife and seabed habitat during the construction of this.

Aberdeen

The electricity cables will be constructed along the alignment of an existing pipeline which has been decommissioned, to ensure there is minimal disruption to marine life and that the proposed location is plausible. The cable alignments which follow the existing pipeline alignments are shown in Figure 46. From Golden Eagle Platform, the cable measures 70km and from Buzzard Platform the cable measures 57km, both pipelines terminate at the St Fergus gas terminal. Details of the pipelines around these platforms are found in the following section.

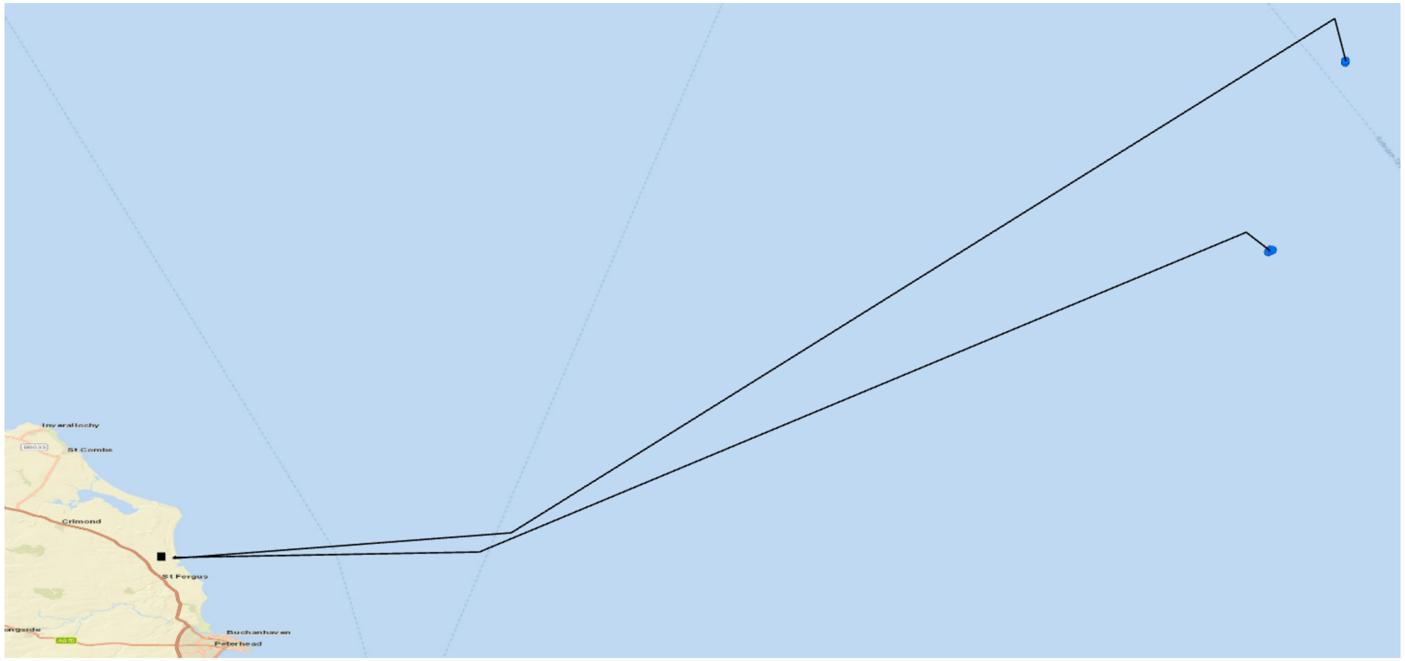


Figure 46- Cable connections from Buzzard or Golden Eagle shown on GIS

Hydrogen Pipelines

To transport the stored hydrogen from the energy island, pipelines will be required. From extensive research, it has been discovered that there are conflicting opinions and methods for the conversion of natural gas pipelines to hydrogen pipelines. Repurposing current infrastructure, including offshore gas pipelines, for hydrogen transport can be a wise strategic decision since hydrogen is becoming increasingly recognised as a promising sustainable energy source. Many in industry believe this is possible (KNF, 2022), while others say that the hazards and economic costs are too high to outweigh the carbon saving (St.John, 2022).

(Wilcoxa et al., 2023) states that it is possible to repurpose gas pipelines to transport hydrogen, which is proven by numerous studies carried out in Europe and the proposed plans to transport disposed CO_2 from land through the pipelines at the St Fergus Gas Terminal. (Vysus Group, 2021) echoes the possibility of existing pipelines being utilised for hydrogen export. However, the pipelines cannot be used as they are currently, retrofitting must be carried out for the pipelines to be suitable for exporting hydrogen.

The first point to note is that gas pipelines are more suitable for conversion to hydrogen export than oil pipelines (Wilcoxa et al., 2023). This is because the gas pipelines require less cleaning and preparation prior to usage for hydrogen, and that the transport energy density of hydrogen is not a great deal lower than the that of natural gas (Peter Adam et al., 2020). Thus, the ability of a pipeline to transmit energy is not significantly affected by the conversion from natural gas to hydrogen (Peter Adam et al., 2020). Secondly, the upper calorific value of natural gas is around 11 kWh/Nm3 and hydrogen is 3.5 kWh/Nm3, demonstrating that hydrogen is almost three times lower (Peter Adam et al., 2020). Therefore, in order to maintain the same content at the same pressure, given that hydrogen has a density nine times lower and three times the flow rate of natural gas, three times the volume of hydrogen is needed (Peter Adam et al., 2020). This results in the ability to transport greater volumes of hydrogen at the same time as it would to transport natural gas in the same pipelines.

Overall, the loss of hydrogen through cracks in the pipelines or other reasons during transportation, or the development of atomic hydrogen in the pipeline walls is a possibility. If atomic hydrogen is to develop in the pipelines the fracture toughness of the pipeline will be reduced (Peter Adam et al., 2020). Based on exposure to atomic hydrogen, the pipeline's service life may be shortened by 20–50% due to embrittlement, dependent on the steel grade, which can speed up the spread of cracks (Findlay, 2020). However, the likelihood of this occurring is only if the pipeline has existing fractures and is subjected to dynamic stresses because of fluctuating internal pressure while also being exposed to atomic hydrogen (Findlay, 2020).

To determine whether the operating parameters for specific steel kinds and operating situations need to be modified, more research is required; the suitability of the membranes and seals for hydrogen is not known (Peter Adam et al., 2020). Additionally, before deciding whether the pipelines are adequate, the existing infrastructure would need to be examined, evaluated, and the appropriate laws and regulations reviewed (Peter Adam et al., 2020).

Maintenance prior to conversion and post conversion to hydrogen will use the “pigging technique.” Currently the "pigging technique" is a crucial tool for assessing the upkeep and state of natural gas pipes. This "pigging" enables the pipe wall to be inspected for any anomalies that might be present. With few modifications, the current maintenance concepts and instruments may be tailored to the needs of hydrogen transport, ensuring the long-term, safe, and dependable operation of the hydrogen transport lines (Peter Adam et al., 2020).

Once the hydrogen is transported through either the retrofitted pipeline or the new pipeline from the energy island, it will reach land at the St Fergus Gas Terminal (Wilcoxa et al., 2023) St Fergus Gas Terminal is situated 65km North of Aberdeen and is used to manage gas exported from the North Sea (Wilcoxa et al., 2023) It is assumed that this will become redundant as oil and gas is no longer used, therefore, can be repurposed for this proposal. The land in which St Fergus Gas Terminal currently operates on will be converted to manage the hydrogen which is exported from the energy island. The hydrogen will then be used as fuel source or converted back to electricity and supplied to the National Grid.

Pipeline Capacity

Buzzard Pipeline Capacity (Natural gas) (CNOOC, 2019)	Buzzard Pipeline Capacity (Hydrogen)	Maximum Buzzard Pipeline Capacity (Hydrogen)
47220m3/hr (40MMscfd)	141600m3/hr	10GWh Per day

Shetland

To transport stored hydrogen from the energy island, retrofitting existing pipelines would be the preferred option. Surrounding Shetland there are numerous pipeline connections (Figure 47); however, none go directly from Shetland to mainland Scotland (Figure 47). The pipeline shown in red connects Shetland to a point in the North Sea, which then connects to St Fergus Gas Terminal in Peterhead. Table 3 summarises the details of both the pipeline from Shetland (No.1) and to mainland Scotland (No.2).

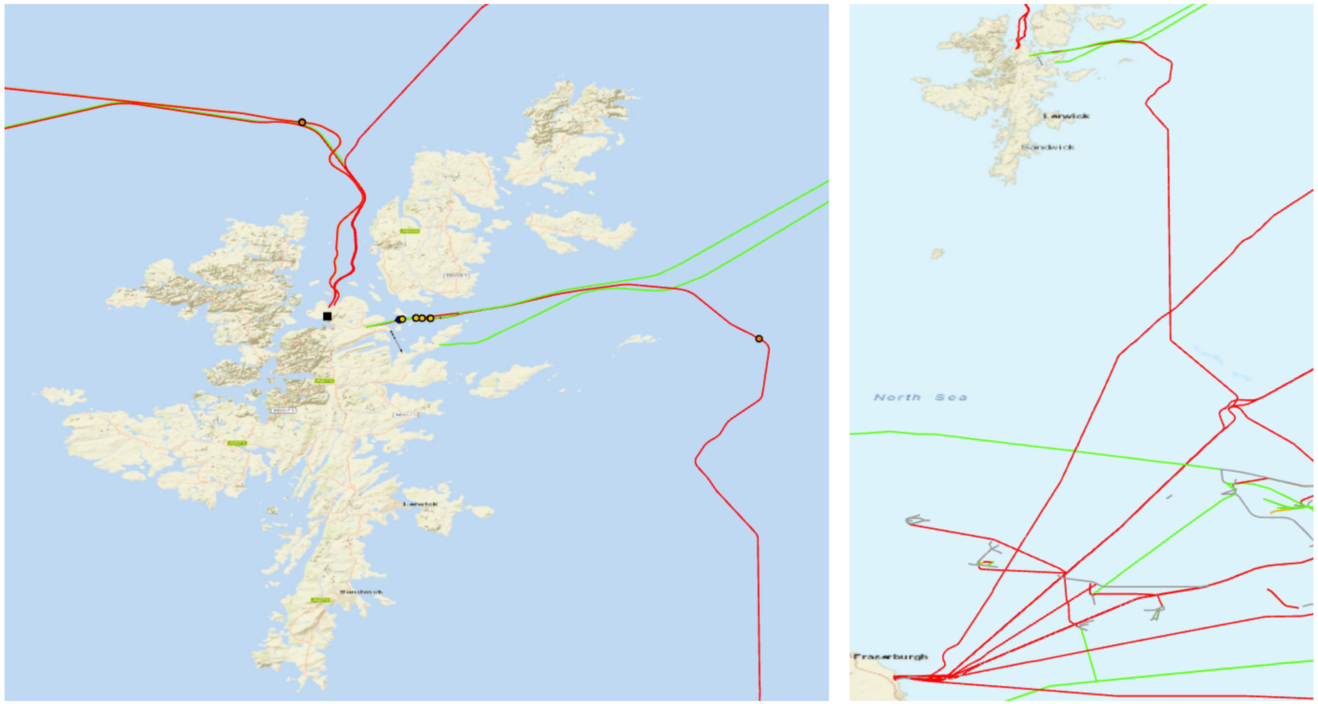


Figure 47- Pipeline Connections shown on GIS

Table 3- Pipelines

	Pipeline Name	Description	Length (m)	Diameter (mm)	Status	Fluid
1	30 IN SIRGE GAS EXPORT	30 IN SIRGE GAS EXPORT (SIRGE) FIRTHS VOE TO MCP01. THE LENGTH INCLUDES ONSHORE SECTION OF 6KM FROM SGP GAS PLANT TO FIRTH VOE. COMMISSIONED IN 2014	233000	762	Active	Gas
2	32 IN MCP01 BYPASS BUNDLE TO ST FERGUS GAS PLANT	32 IN MCP01 BYPASS BUNDLE TO ST FERGUS GAS PLANT	186000	812	Active	Gas

The pipelines shown in green in Figure 48 connects from Shetland to a wider pipeline network, which spans into the North Sea off the coast of Norway. The gas pipeline connections for the rest of the North Sea are shown in Figure 48.

Figure 48- Pipelines further out to sea shown on GIS

To connect the energy island to the existing pipe network, there are two possible options. The first option is for an approximate 800m long pipeline (shown in Figure 49) to be constructed. This will tie in with the network at an existing point in the alignment by cutting and connecting the pipes, creating a new pipeline junction.

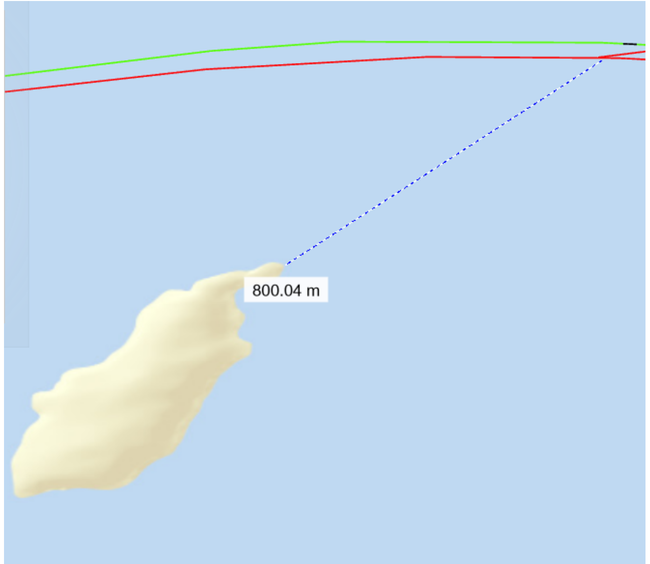


Figure 49- Required length of additional pipeline

The second option would be to construct a new pipeline to the closest existing pipeline junction (Figure 50) or a proposed future pipeline tie-in point (Figure 51).

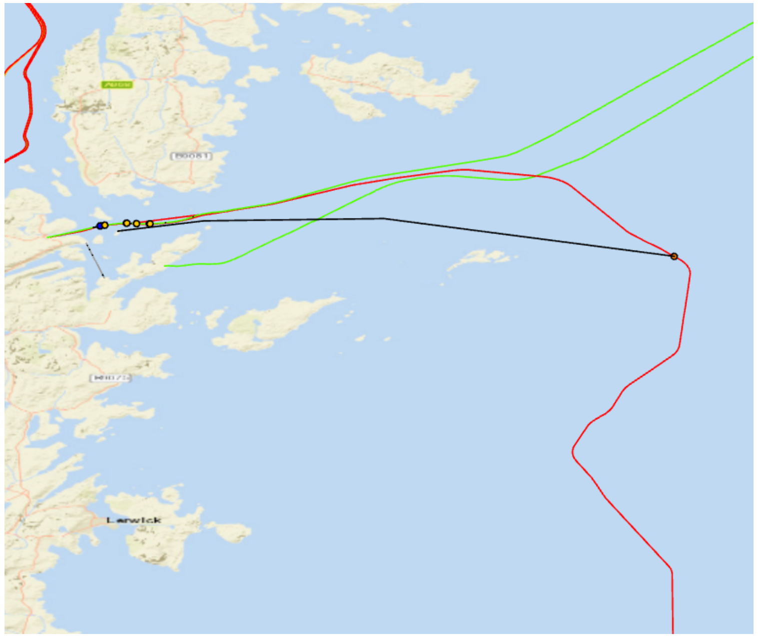


Figure 50- Closest Existing Pipeline Junction

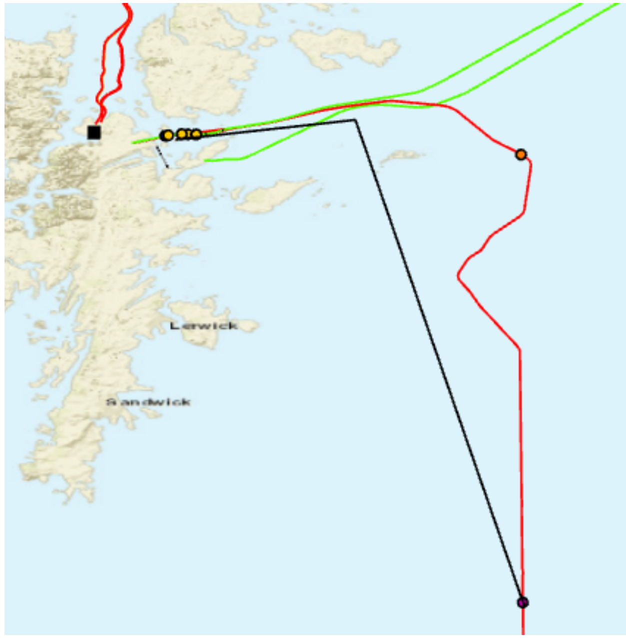


Figure 51- Proposed Future Tie-In Point

A similar alignment to the electricity cable alignment (below) will be used for the hydrogen pipeline if it is determined that the existing gas pipe network from Shetland to the North Sea to Peterhead is not plausible for the transmission of hydrogen.

For the proposed energy island to be constructed on an existing island, it would be preferred that the existing pipelines are used for hydrogen transportation. If this is not possible or found to require extensive retrofitting, both the hydrogen and electricity will be transported on a new, direct alignment, as shown in the Cables Section.

Aberdeen

To transport hydrogen from the energy island, retrofitting existing pipelines would be the preferred option. Golden Eagle and Buzzard oil and gas production platforms in the North Sea are circled in Figure 52. From the existing network from these platforms to St Fergus Gas Terminal in Peterhead, numerous pipelines and pipeline assignments have been identified as potential links for the energy island to connect to land. Additionally, numerous pipelines from these platforms connect to other platforms and pipe networks further out to sea, allowing for potential expansion and multi-island connections in the future- see Figure 53.

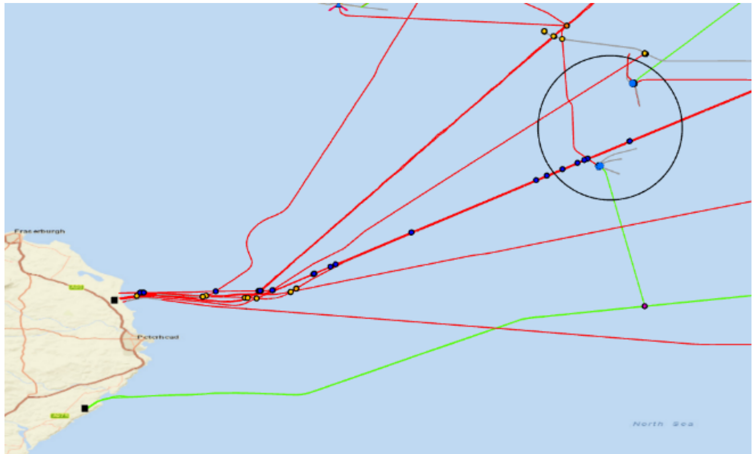


Figure 52- Golden Eagle and Buzzard oil and gas production platforms in the North Sea

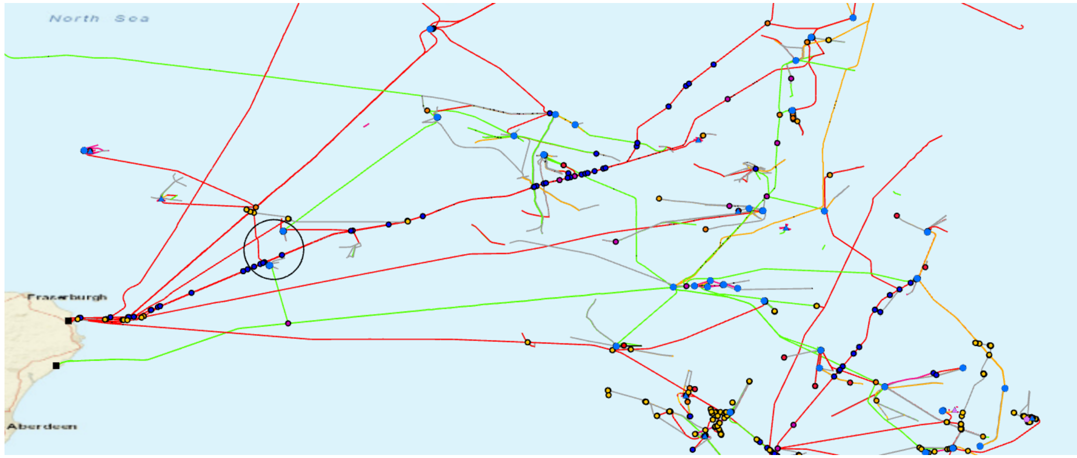


Figure 53- numerous pipelines from these platforms connect to other platforms and pipe networks further out to sea

Figure 54 shows two pipelines running closest to the Golden Eagle platform to land (highlighted in blue), while three pipelines which are close to the Buzzard platform are shown highlighted in blue in Figure 55.

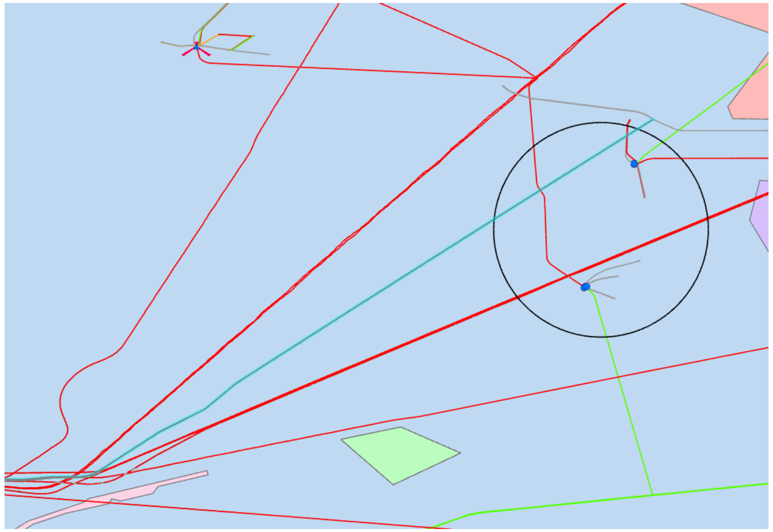


Figure 54- two pipelines running closest to the Golden Eagle platform to land

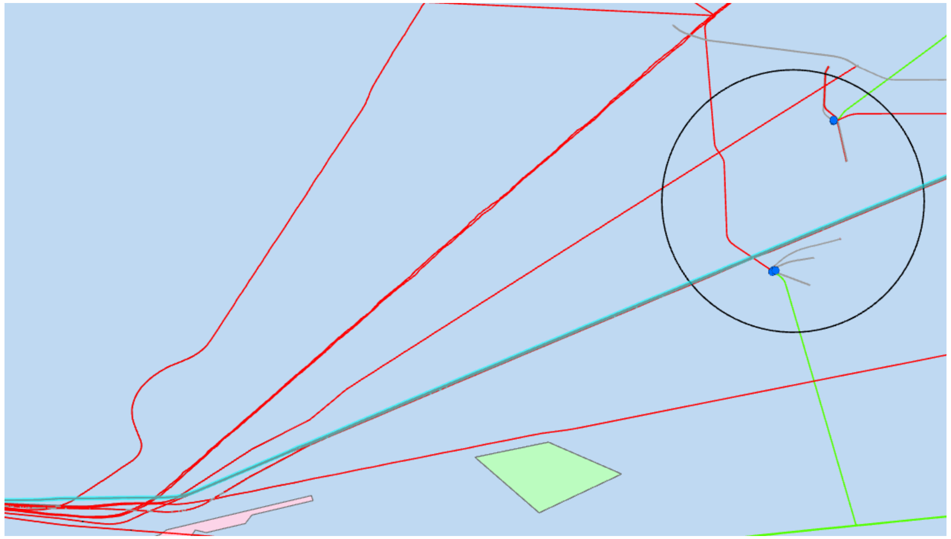


Figure 55- three pipelines which are close to the Buzzard platform

These pipeline details are shown below in Table 4.

Table 4- Pipelines near Aberdeen

	Pipeline Name	Description	Nearby Platform	Diameter (mm)	Length (m, from platform to land)	Status	Fluid
1	4" MEG ST. FERGUS - ATLANTIC MANIFOLD	4" MEG ST. FERGUS - ATLANTIC MANIFOLD	GE	102	70000	Abandoned	Chemical
2	16" GAS ATLANTIC MANIFOLD - ST. FERGUS	16" GAS ATLANTIC MANIFOLD - ST. FERGUS	GE	406	70000	Abandoned	Gas
3	SAGE PIPELINE	BERYL ALPHA TO ST FERGUS 30IN GAS EXPORT	B	762	57000	Active	Gas
4	MILLER TO ST. FERGUS	MILLER TO ST. FERGUS 30IN GAS LINE	B	762	57000	Not in use	Gas
5	20" GAS GOLDENEYE - ST. FERGUS	20" GAS GOLDENEYE - ST. FERGUS	B	508	57000	Not in use	Gas

Golden Eagle-

It should be noted that Pipeline 1 and 2, which are closest to the Golden Eagle Platform have been abandoned and therefore may not be suitable for retrofitting for the energy island. However, the existing alignment could be utilised to run a new pipeline or cable to land. It should also be noted that Pipeline 1 was used for the transportation of chemicals and therefore, if it was to be used, would require flushing and/or significant protection to transport hydrogen. Therefore, it will likely be only Pipeline 2 which will be used from Golden Eagle for transporting hydrogen; Pipeline 2 alignment could be used for the cable alignment.

Buzzard-

There are three gas pipelines which run from the Buzzard Production Platform to land, two of which are not in use. Gas pipelines have been determined to be the most common and simplest pipeline to convert for the transportation of hydrogen, therefore would be suitable for transporting the hydrogen from the island to land. Consequentially, one of the other pipeline alignments could then be used to run a cable from the island to land for the transportation of electrical energy. This would save on maintenance and construction costs as the work would take place in one area, rather than being spread across different locations.

3. Construction- Shetland

Firstly, the island will be surveyed, and the structural stability of the soil will be assessed. Areas of steep terrain will be levelled for the installation of roads and foundations; however, works will be kept to a minimum to preserve habitat. Each unit on the island will require carefully selected and constructed foundations that can withstand the determined load capacity.

Foundations

For the buildings, substations and hydrogen production infrastructure, a foundation will be required. The foundations will likely be concrete pad foundations unless suggested otherwise following ground investigations on the island. Ideally, all material will be sourced from mainland Scotland, with minimal transportation required from manufacturer to site. A low carbon concrete will be utilised and recycled materials will be used as far as possible.

Roads

It is assumed there are no access roads on the island and therefore the construction of roads will be essential for moving personnel and materials/equipment round the island. For this, a typical single carriageway road will be constructed using the generic construction as shown in Figure 56. This will require earth foundations, a gravel subbase, base course, surface course and asphalt road layer (Engineering Feed, 2024). An embankment will also be required alongside the road, so surface water runoff does not gather at the roadside; this will be constructed using reuse earth excavated for the road. The road length is expected to be 800m in length, spanning from one side of the island to the other, branching off to each of the components that make up the island.

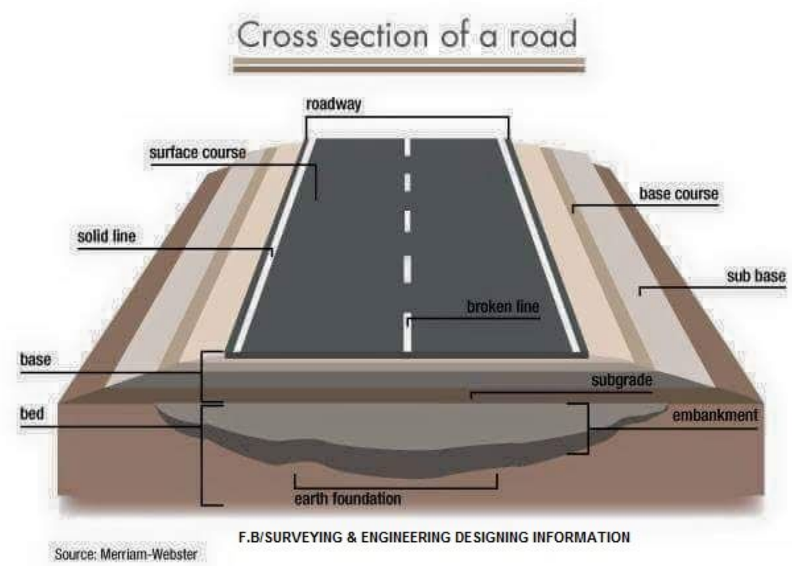


Figure 56- General Road Construction (Engineering Feed, 2024)

Welfare Facility

The island will home approximately 100m^2 of welfare facility that will be prefabricated off site. This facility will comprise of a bathroom(s), staff room area with sink, office room and small medical room. The offsite fabrication will further reduce the carbon by ensuring strong performance, quality, productivity, reduced risk and minimisation of buildability issues arising on site, which are more likely to occur on a remote island.

Wind Energy Infrastructure

The island will have a 2GW HVDC cable that connects onshore at Peterhead. Therefore, on the island it will be essential to have a transformer and convertor. Array cables connect the turbines to the island, where the voltage needs transformed, and the current needs converted from direct (DC) to alternating (AC).

The brand of this technology will depend on the leading design available at the time of construction. DC converter stations are considerably heavier than AC equipment however there are currently large developments being made in this sector. Figure 57 shows the HVDC substations that are being installed at dogger bank wind farm. They measure 65 x 36 x 39 metres and are 70% lighter in weight than previous designs. The number of substations required is dependent upon the number and size of wind farms connected.

Figure 57 - HVDC substations being installed at Dogger Bank (SSE Renewables, 2023)

Offshore Wind Farms

100 5MW wind turbines with a horizontal three-bladed design are proposed to be installed initially with a total capacity of 0.5GW. The turbines foundation is referenced from other wind farms nearby and are chosen to be floating. Inter-array cabling running between each turbine is installed with 20MW capacity, connecting four turbines. The power generated is then transmitted to one offshore substation platform on the island with an AC to DC converter.

Tidal Energy Infrastructure

Wave turbines are assembled onshore before the installation offshore. Chains and cables are used to anchor the turbines onto the seabed to prevent drifting. The turbines are connected to a generator and all power is transmitted through underwater cables to one substation on the island where an AC to DC converter is located. The electricity generated is then transmitted to the grid for further usage.

Transport Routes

There are existing transport links near the energy island location including harbours and airports on mainland Shetland that link to major facilities. There are four airports (Figure 59), two harbours (Figure 58) and one port. All personnel will be brought in via these routes. On the island, a helipad will be required for health and safety purposes and a small dock would be essential for transporting materials and personnel for maintenance. The small dock will feature a 400m^2 concrete harbour wall.

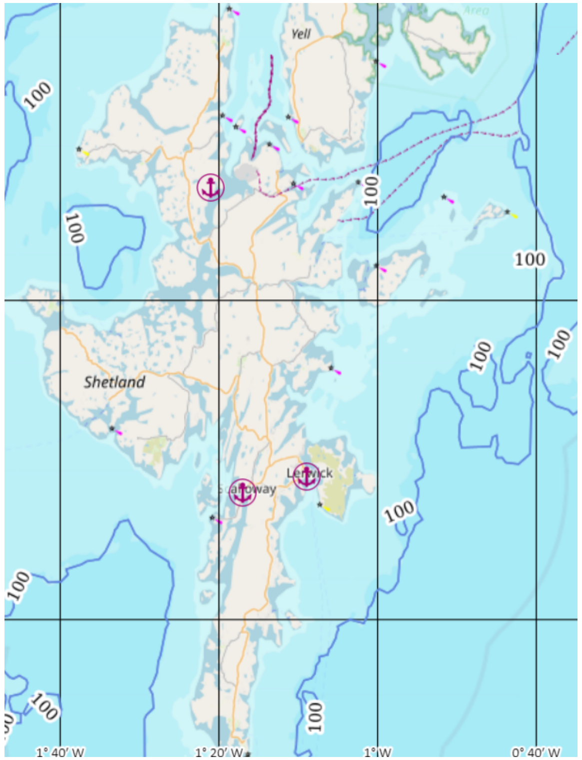


Figure 58- Shetland Harbours (Open Sea Map, 2023)

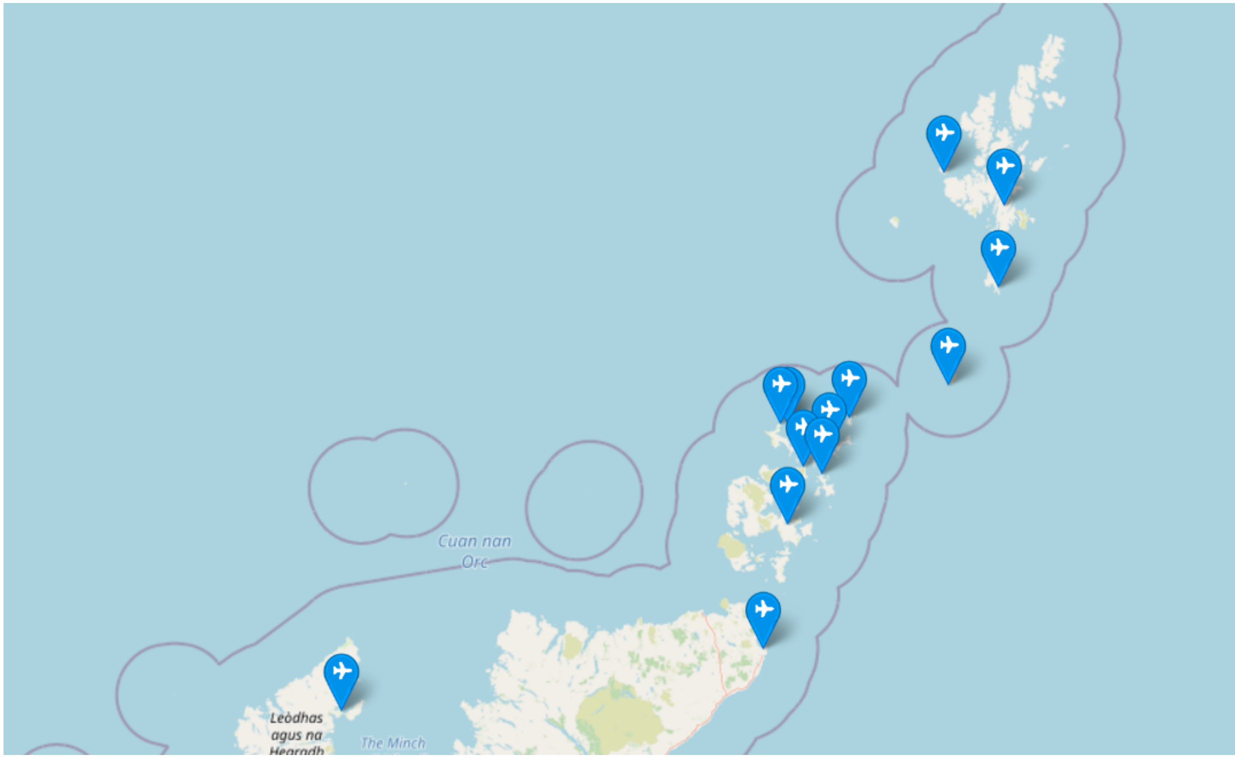


Figure 59- Shetland airports (Aiports DK, 2023)

Hydrogen

To construct the hydrogen production and storage facility on Shetland, necessary utilities should be installed such as power supply connections and salt cavern pipeline connectors (if possible) and storage tanks if the utilisation of underground salt cavern or rock cavern storage is not possible. Figure 60 shows a simplified version of an onshore hydrogen production station that utilises offshore wind energy. Similar to the offshore hydrogen platform, the Shetland energy island will include the following: PEM Electrolyser; transformer systems; heat exchanger systems; desalination system and a hydrogen compression system.

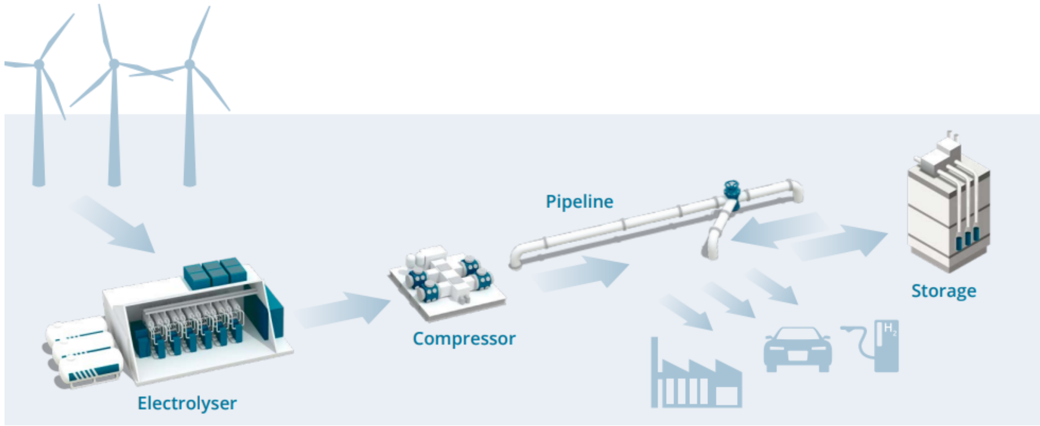


Figure 60- simplified version of an onshore hydrogen production station (Peter Adam et al., 2020)

The construction of a salt cavern storage facility on the Shetland Island will involve a variety of key stages where firstly the site must include a substantial deep salt layer that will allow cavern creation. The salt layer shouldn't have any geological faults or fractures so that the cavern integrity is upheld (Department for Energy Security and Net Zero, 2024). Mineral impurities within the cavern should be minimal to ensure that the hydrogen molecules do not react with other substances. Solution mining should then be undertaken when a well is drilled into the salt layer before injecting water. The water will dissolve the salt, create brine and then be pumped back to the surface (Department for Energy Security and Net Zero, 2024). The process is carried out until the desired size and shape is created before the brine is then treated and disposed of safely unless repurposed for use in other industrial processes. Once the cavern has been formed, infrastructure for creating, retrieving and storing the hydrogen is installed including compressors, piping and safety systems.

The cavern should then be tested to ensure its integrity, where the cavern is filled with a test gas like nitrogen and the pressure is monitored over time. if the pressure remains stable than the salt cavern should be acceptable for operation. The cavern will then be filled with a cushion gas and a working gas (hydrogen) under pressure that can be altered depending on supply and demand fluctuations (Department for Energy Security and Net Zero, 2024).

The construction of the hydrogen pipelines will require the "pigging technique" to enable the pipe wall to be inspected for any anomalies that might be present. The pipes will also be cleaned through pigging to remove any residual gas traces in the pipeline. Then, if no anomalies are found, the pipelines can be used for hydrogen. From Shetland, a minimum of 800m long additional pipeline will be welded to the existing pipeline for it to connect to the island.

Flood Defence

- **Flood Risk Assessment**
  An assessment should be carried out during the design phase to determine the risk of flooding events and its consequences throughout the design life of the energy island. Data such as flood maps, flood zones, storage area historic flood events and hydrology reports are needed to provide detailed information for the computer models. Areas with high flood risks should be avoided during the construction, and emergency preventions or defences should be prioritised on these areas in the event of a flood.

- **Stormwater Management**
  Stormwater management is to reduce excess stormwater runoff to prevent sudden runoff causing flooding and infrastructure damage. It can be done through nature with soil which can absorb and filter the stormwater, which then will be released back into the ocean. Additionally, infrastructure such as culverts, gutters, retention ponds and drainage pipes can help to channel and restore the stormwater for treatment to be further used in other aspects such as toilet flushing on energy island.

- **Pumping System**
  Flood control pumps should be installed around the energy island to drain away large volumes of water during flooding. These pumps can be activated manually or automatically during areas with severe flooding to prevent water from accumulating on the site and causing damage to the infrastructure on the island.

- **Monitoring Sensors and Early Warning System**
  Monitoring sensors are used to detect real-time data and give insight into water levels, velocity, rainfall, or weather. Analysis of this data allows early warning of flood risk allowing for immediate action in emergency response plans.

- **Sea Walls/Flood Barriers**
  Seawalls and flood barriers are flood defence which can be installed around the flood-prone areas on the energy island. They are typically made of concrete, masonry or steel and are designed to withstand the forces exerted by waves and currents to prevent high tides and storm surges reaching the infrastructure on the island (The Flood Hub, 2024).

- **Breakwaters/Groynes**
  Breakwater and groynes are both structures designed to dissipate wave energy before they reach the shore. Breakwaters are vertical walls made from rock, stone or concrete that runs parallel to the shoreline whereas groynes are low-lying structures made from wood or concrete set out into the ocean (The Flood Hub, 2024) This helps to reduce the coastal erosion and create a calmer water around the shore (The Flood Hub, 2024).

Connecting Multiple Countries

Connecting an energy island off the coast of Shetland to multiple countries would require careful planning and consideration of various factors including geographical location, construction and operation of undersea cables, connection points, seabed conditions, depth, marine life considerations, maintenance requirements, technical and economic feasibility, regulatory frameworks, and international cooperation.

One of the most common methods of connecting offshore energy infrastructure to multiple countries is through undersea cables. High-voltage direct current (HVDC) cables would be the likely choice for transmitting electricity over long distances with minimal losses. To connect the energy island to onshore grids in different countries, the most suitable routes would be chosen. It is essential that the selected routes avoid marine protected zones and any obstructions. The HVDC cables would then be laid on or under seabed with shallow gradient and soft sediment (Scottish Government, 2019b) There are currently no HVDC cables that run between different countries, however, there are plans for a 260km subsea HVDC (High Voltage Direct Current) cable between Shetland and mainland Scotland, known as the Shetland HVDC Connection (Figure 61). This cable aims to connect the renewable energy resources of the Shetland Islands, particularly wind power, to the mainland grid. This was part of broader efforts to enhance the connectivity of renewable energy sources in the UK. Once this project is complete it will allow an additional 443MW wind farm to be connected to the Great Britain grid (Scottish and Southern Electricity Networks, 2024).

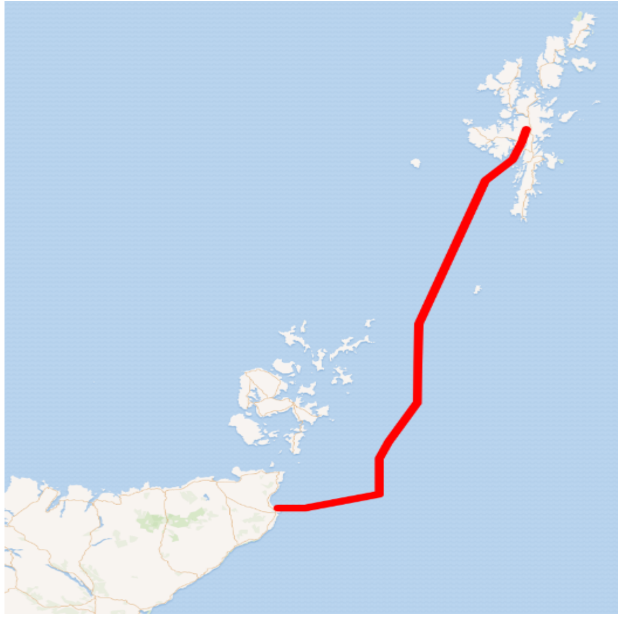


Figure 61: Shetland HVDC Connection (Wikipedia, 2024)

In Scottish waters, there are currently 88 operational cables, covering approximately 3,500km of international cables and 1,100km of inshore cables. These cables form part of an international network that passes both the North and South of Shetland, linking Europe to North America, the Faroe Islands, Iceland, and Greenland (Figure 62) (Scottish Government, 2019a). Therefore, there are also possibilities to introduce more HDVC cables between Shetland and surrounding countries in the same alignment as already existing telecom cables.

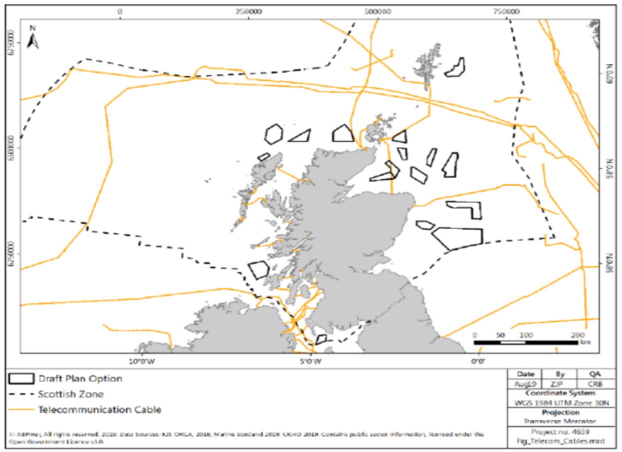


Figure 62: International telecom cable routes (Scottish Government, 2019a)

Additionally, there's a plan for the Maali power interconnector, which aims to connect Shetland with Norway. This interconnector will establish an electricity transmission link between the two countries, facilitating the exchange of power and promoting the utilisation of renewable energy. Its purpose is to enable the transfer of energy from windfarms near/on Shetland to Norway during periods of high production, and from Norway during periods of low wind (Scottish Government, 2019a).

A document from the Shetland Islands Council provides a report on the feasibility of establishing a North Atlantic Energy Network (NAEN) centred around the Shetland Islands. The report provides a comprehensive analysis of the potential for developing an energy network in the North Atlantic region with Shetland as a key hub, highlighting both opportunities and challenges associated with such a venture. The NAEN aims to harness renewable energy resources, particularly wind and marine energy, to meet local energy needs and export surplus energy to neighbouring regions (North Atlantic Energy Network, 2016). Members from relevant parties from Greenland, Iceland, Faroe Islands, Shetland, and Norway met in Copenhagen in February 2015 to discuss this idea. Each country reported on their energy production status and renewable energy potential, with thorough investigation into the technological aspects of each.

The report outlines key infrastructure requirements such as interconnection cables, renewable energy generation facilities, and energy storage solutions. The importance of collaboration between stakeholders including governments, energy companies, and local communities is also detailed, as well as potential challenges such as environmental impacts, regulatory barriers, and financing issues that need to be addressed for the successful implementation of the NAEN (North Atlantic Energy Network, 2016).

By addressing these considerations and working closely with the relevant stakeholders, it has been confirmed it would be possible to connect an energy island off the coast of Shetland to multiple countries and facilitate the transmission of renewable energy across borders. With the increasing focus on decarbonisation and the transition to renewable energy across Europe and beyond, this cross-border energy integration project is increasingly feasible and attractive. With evolving and emerging technologies, energy islands will be easily integrated into the electricity network through the expansion of projects similar to the ones detailed above and are a natural next step in connecting multiple countries to the UK utilising undersea cables.

4. Construction- Aberdeen

Overview

Converting an oil and gas platform into an energy island involves repurposing the infrastructure to transport and store renewable energy. Oil and gas platforms generally comprise of a topside which includes production equipment, accommodation, walkways, safety equipment, and additional operating equipment. Topsides are typically attached to either a steel jacket which are large lattice-like structures, or gravity base structures which are made of reinforced concrete. Both provide stability and support for the platform deck above.

The legs are the substructure of offshore platforms. These jackets are typically made of high-strength steel to withstand the forces exerted by waves, wind, and currents and are anchored into the seabed. The existing jackets, and foundations will remain in position after the removal of the deck and a new topside will be fabricated and attached (CNOOC, 2019).

The first stage in the construction process is to fully assess the existing infrastructure by doing a load assessment, including inspection for fatigue cracks, weathering, weakened members and all necessary checks to ensure the structural integrity has not been significantly reduced.

Once a full assessment has been done, the next step is to partially decommission the necessary oil and gas infrastructure. The decommissioning process is a huge part of the oil and gas industry and can be done in different ways. It begins with extensive planning to ensure an oil rig is decommissioned safely, whilst ensuring careful consideration about its impact to the environment, society, and the economy, as well as how the decommissioning will be carried out technically. Within Scotland there are several acts and legislation to be followed including The UKs Petroleum act 1998, The Energy Act 2008, SEPA regulations, and Marine (Scotland) Act 2010 along with Marine Scotland regulations. The department of energy and climate change (DECC) also outlines regulations that must be followed whilst the OSPAR ensures a project to provide detailed reasoning and justification why any parts should be left in the sea after decommissioning is complete, and detail how they will not harm the environment.

Decommissioning

The decommissioning of buzzard will be heavily based off the Brent field decommissioning process undertaken by Shell. The Brent oil field was discovered in the early 1970s and had started production by 1976, its original design was to allow a lifespan of around 25 years, but as Brent Charlie was last to stop production in 2021, its lifespan nearly doubled. Production was stopped on each platform within the Brent field at different times; Delta in 2011, Alpha and Bravo in 2014, with Charlie in 2021. All 4 platforms went up to around 300m in height from seabed to top of platforms with 3 out of 4 platforms being gravity base structures, whilst Alpha has a steel jacket support (Shell, 2024).

The method of decommissioning the brent field was to plug all wells, remove debris and completely remove the topside by cutting the concrete or steel legs and bringing in a vessel called the Pioneering Spirit, which is large enough to lift the topside, and transport it back to shore for recycling. The vessel being used is 381.5m long and positions its bows underneath at either side of the platform, once the vessel is in place it lifts the topside vertically off its already cut legs and sails it most of the way, the topside is then transferred to a smaller vessel, which works alongside the Pioneering Spirit for the remainder of the journey. After the platform is taken to shore it is then recycled as much as possible – 98% of the platform was successfully recycled from Bravo (Shell, 2024).

During the brent decommissioning process, Shell have ensured heavy stakeholder involvement and consultation, extensive planning to ensure the process is economically, socially, and environmentally friendly.

For Alpha, the process involved cutting each steel leg using personnel with rope access. Cuts were made with interlocking segments so the topside could not move horizontally – this protects it from lateral loads until the topside can be lifted. Again, the Pioneering Spirit was used to grab each leg simultaneously with horseshoe shaped clamps and lift vertically so the topside could be transported to shore for recycling. A diamond steel cutter was then used to cut the steel jacket 46m below sea level, so the top part of the steel frame could be lifted by the world's largest crane vessel. This part had to be done with careful planning, so all the non-load bearing cuts were made first, and when the final cuts were made the frame could be lifted immediately (Shell, 2021).

The decommissioning process used for the removal of Brent Alpha's topside is what would be implemented for Buzzard, each deck would be cut, lifted, and transported for recycling. Multiple stakeholders made it clear that repurposing is often too expensive and counter intuitive so it would be best to completely remove the topside and install a new one. Reinstating the topside will ensure the structural integrity is known, as well as the life and longevity of the deck.

Deck Construction

The deck of the platform is where most of the equipment and facilities will be located including substation and transformers, hydrogen infrastructure, flare boom, personnel welfare building, a harbour, and a helipad. The new deck will be constructed as four separate steel topsides which will be connected by bridges. Each topside will be prefabricated in large, specialised facilities that are equipped with the latest technology. All components will be transported to the island by specialised vessels – in reference to the Brent Field decommissioning, the Pioneering Spirit could be used. The decks will then be connected to the existing legs by the enormous cranes on the vessel and welding equipment.

The deck is designed to support heavy loads while maintaining structural integrity therefore structural, stainless steel is chosen due to its strength, durability, and resistance to corrosion in marine environments. Steel is also highly weldable, allowing for efficient fabrication and assembly of complex structures required for offshore infrastructure. Advanced engineering techniques and coatings will also be employed to enhance corrosion resistance and extend the lifespan of these structures.

The decks will be transported and installed in a 5-phase process:

- Phase 1 will include a deck to accommodate any personnel on the island for maintenance, construction, and future expansion. This will comprise of a steel truss deck with steel sheeting, with welfare facilities, a helipad, and a harbour area for boats to load/unload and fuel up.

- Phase 2 will construct a substation platform with an area of 3000m^2 and an overall mass of 15000tons, made of steel and will include AC/DC converters and voltage transformers, as well as a flare boom. These technologies are constantly advancing, currently each module could accommodate 1GW of energy from the windfarms. This means 2 of these modules would be required to be connected to the mainland cable and additional transformers would be required for hydrogen production.
- Phase 3 will include a hydrogen production plant which will be this will be made of recycled high strength steel, the construction details of this are detailed below.
- Phase 4 will include the fabrication of another, smaller steel deck with steel sheeting. Its purpose will be for future expansion, connecting to other platforms in the North Sea and energy sharing countries.
- The final phase will be the transportation and installation of each deck and connecting each deck with steel bridges.

Table 4- Platform Details

Platform Type	Area (m^2)	Overall Mass Capacity (tons)
Welfare/ship loading/helipad	2600	8000
Substation Platform	3000	15000
Hydrogen Production	3300	15750
Future Expansion	8500	11000

Transport Routes

There are existing transport links on the mainland within the Aberdeen area, including harbours and airports that link to major facilities. There is one airport, one helicopter landing facility and three major harbours/ports. All personnel will be brought in via these routes. On the island, a helipad will be required for health and safety purposes and a small dock would be essential for transporting materials and personnel for maintenance.

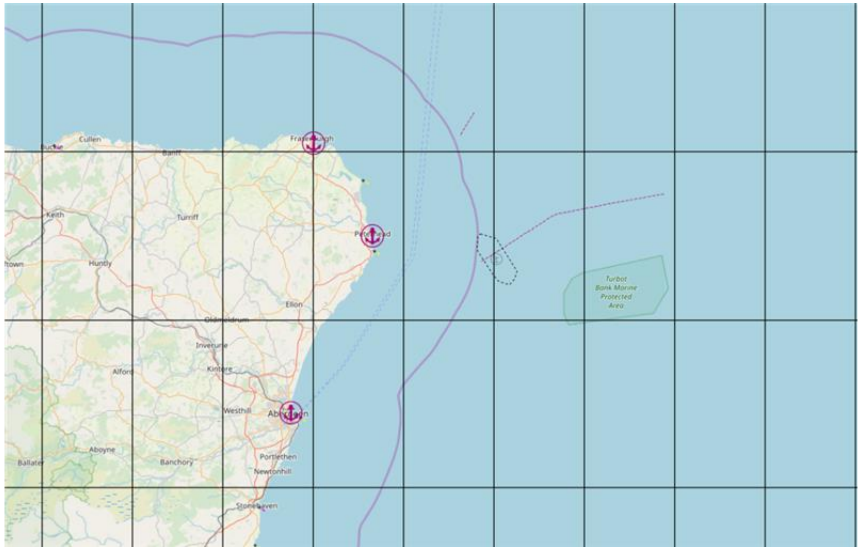


Figure 63- Aberdeen Harbours (Open Sea Map, 2023)

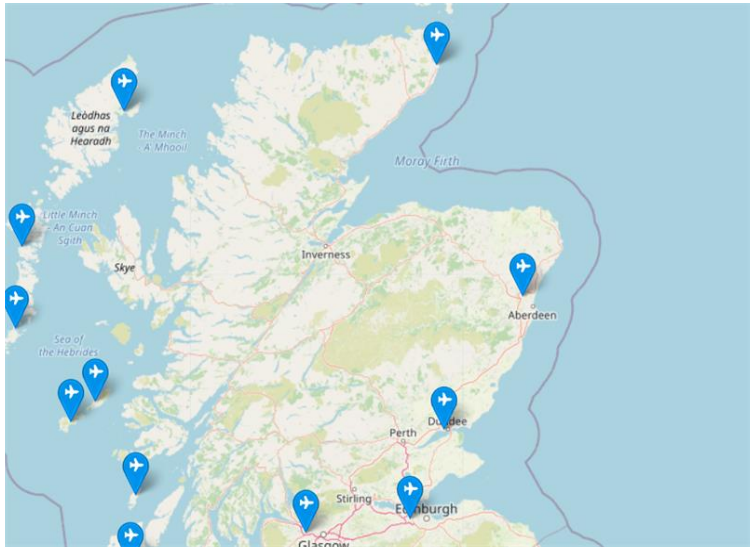


Figure 64- Aberdeen Airport (Aiports DK, 2023)

The port facilities in Scotland have the capacity to support the repurposing of existing oil and gas infrastructure including the facilities for dealing with the small pieces brought to shore, medium component parts that typically do not require heavy lifting, and large elements including full topsides or modules that require heavy lifting and specialist craneage. The facilities currently available for the servicing the oil and gas decommissioning sector will also have the capability to support the repurposing of assets in the North Sea. Most ports in Scotland have already received infrastructure removed from offshore and have processed the materials within local supply chains (Vysus Group, 2021).

Physical considerations include suitable quayside and berthing; craneage; water depth and access; laydown areas; waste management facilities; waste receiving and processing facilities; self-propelled modular transporters; drainage and containment. Aberdeen ports meet this criterion.

Offshore Wind Farm Details

300 8.5MW wind turbines are proposed to be installed on site, resulting in 2.5GW capacity in total. The turbines will exhibit similar characteristics to the wind farms already proposed at Aberdeen with a horizontal axis three-bladed design. Additionally, they will utilise a gravity-based structure along with a jacket structure supported by pin pile foundations. Inter-array cabling designed for this turbine has 34MW capacity, connecting four turbines each, which further connects to offshore substation platforms and AC to DC converter stations. A total of three offshore substations were designed for the electricity capacity of the wind farm.

Hydrogen

In order to construct an offshore hydrogen platform that is completely run by renewable energy, there needs to be a connection to the energy generated from offshore wind turbines, a transformer system to convert the AC energy generated from the wind turbines (Richardson, 2023) into HVDC for the process of green hydrogen production (Infineon, 2024) and a desalination unit is required to turn the seawater into purified water before it enters an electrolyser (Klaudia Ligęza et al., 2023). The two end products of the electrolysis are oxygen and hydrogen, the hydrogen is then compressed using a compressor before being stored subsea. After compression, the hydrogen can be transported through an export pipeline to shore whenever required, the oxygen produced can be either released into the atmosphere or it can be compressed into canisters for export and resale.

The platform used for hydrogen production will have three levels (Mainstream Renewable Power, 2024). On the first level, process functions that are required to power electrolysis are conducted, seawater is taken in where it is desalinated and the power from the wind turbines is taken onboard, distributed and interconnected. On level two, further electrolysis and cooling installations take place, as well as areas for maintenance and control. On the third floor, electrolysis takes place. During electrolysis the conditions must be cool, therefore a cooler must be present here too.

Equipment needed for hydrogen plant:

1. Desalination system
2. PEM Electrolyser
3. Transformer System
4. Heat Exchange System
5. Hydrogen Compression System

Flood Defence

- **Pumping System**
  Flood control pumps should be installed around the energy island to drain away large volumes of water during flooding. These pumps can be activated manually or automatically during areas with chronic flooding to prevent water from accumulating on the site and causing damage to the infrastructures on the island.

- **Monitoring Sensors and Early Warning System**
  Monitoring sensors are used to detect real-time data and insights of water levels, velocity, rainfall, or weather. The analysis of these data allows early warnings of flood risk for immediate actions in emergency response plans such as evacuations, shutdown procedures and contingency plans for restoring operations after the flood.

Connecting Multiple Countries

hough there are no existing power interconnectors from Aberdeen to other countries, proposals have been supported by the government to build power connections with neighbouring countries to enable the exchange of renewable energies. One of the main proposals is the NorthConnect project which connects Long Haven Bay at Peterhead across the North Sea to Simadalen at Norway (North Connect, 2024). The NorthConnect interconnector will includes HVDC subsea cables with a capacity of 1400MW and is planned to be operational by 2024 (North Connect, 2024) There are several links connecting the country such as the Western Link mentioned in the above section, and the Eastern Green Link which connects East Lothian, Scotland to Hawthorn Pit, England with a 2GW HVDC cable starting construction in 2025 (Iberdrola, 2024). The Scottish Government has also proposed an Eastern HVDC which connects the Peterhead to the north-east of England but the project is currently still developing and is proposed to be commissioning in 2028 (Scottish Government, 2019a).

Another potential connection is the existing gas pipelines on the Norwegian continental shelf. These pipelines are operated by Gassco, with a joint venture with Gassled, to initially transport natural gas from neighbouring countries to Norway and can be repurposed for the transportation of hydrogen gas (Norwegian Petroleum, 2024). As shown in Figure 65, there are four gas pipelines that originates from Peterhead, Scotland to Norway with the main one being the Vesterled pipeline which has a capacity of 1.04 million cubic meter (Norwegian Petroleum, 2024). The pipeline has been used since 1976 hence inspection is needed to assess the effectiveness and safety of the pipeline.

Figure 65- Existing gas pipeline in the Norwegian continental shelf (Norwegian Petroleum, 2024)

Maintenance Schedule

The maintenance schedule, health and safety requirements and environmental considerations will be similar for both islands, all of which are detailed below.

To ensure optimal performance and safe operation, a preventative maintenance plan is required. A preventive maintenance schedule is put in place to avoid costly downtime by implementing scheduled maintenance tasks which include regular inspection, lubrication, repair, part replacement and other necessary actions (Millwright, 2019).

Table 5- Maintenance Schedule

Task	Reason	Timescale
Inspections	To assess the condition of the island components, equipment, and systems.	Visual checks every 6 months Annual full inspections
Lubrication of components	Technicians must lubricate various components to get rid of dirt and ensure cleanliness which increases service life of equipment. (Millwright, 2019)	Every 3 months
Calibration and testing of equipment	Use predictive maintenance methodologies to detect potential issues before they lead to equipment failures.	Constantly monitored electronically
Offshore wind infrastructure	Visual inspections of interiors and exteriors to make sure everything is operational.	Minimum every 6 months
Component replacement	Replace components when a fault is detected before they lead to equipment failures.	Schedule maintenance activities accordingly.
Spare parts management	Ensure that spare parts are readily available when needed to minimise downtime and maximise the reliability of energy generation and distribution.	Minimum every 6 months
Maintenance of steel infrastructure	Corrosion protection (applying protective coatings, cathodic protection systems, and routine inspections for signs of corrosion).	Every 20 years for coating application Monthly inspections (Hurtado, 2023)
Replacement of electrolyser for hydrogen	Lifespan of electrolyser.	After 7-10 years

Health and safety

- Develop and enforce safety procedures for construction/maintenance work, including permit-to-work systems, risk assessments, method statements and confined space entry protocols specific to the energy island environment.
- Provide training opportunities for maintenance personnel to ensure they are equipped with the knowledge and expertise required to perform maintenance tasks safely and effectively.
- Monitor tides and weather to ensure all conditions are safe to carry out any travel, maintenance or construction works.
- Provide adequate training for offshore emergencies, including procedures in case of emergencies during transport to the island.
- Provide training for emergency procedures related to large scale energy infrastructure.
- Ensure all personnel are always equipped with appropriate PPE and are aware of the risks of not wearing correct PPE.

Environmental Considerations

Throughout the construction process for both islands it is essential to implement environmental monitoring programs to assess the impact of the energy island on local ecosystems and marine life. This will include mitigation measures to minimise any potential negative effects, such as artificial reefs to enhance biodiversity or underwater noise mitigation for marine mammals, also throughout construction all marine protected zones will be avoided. This will ensure compliance with environmental protections laws and regulations.

As stated by stakeholders, there is the potential for concern about the wildlife if using a remote, existing island. There is the chance that many of the remote islands in North Sea could be home to unique/rare/endangered wildlife, therefore, it has been acknowledged that the energy island proposal would have to avoid inhabited islands, marine protected areas, and islands with native species. If an existing island was to be the preferred option, more investigation into the wildlife and environment on the island would be carried out and NGOs would be consulted with. An Environmental Impact Assessment (EIA) in line with local policies and context would be developed and it would be ensured that no negative impact was inflicted on any residing wildlife on the island.

Furthermore, to promote biodiversity and wildlife/habitat protection, the energy island has the potential to incorporate measures to provide habitats for animals, increasing biodiversity net gain.

5. Timescales

The timescale from the planning to the operation of an energy island is typically 10 to 15 years. The general steps are as follow:

- Preliminary studies (1-2 years): to assess the feasibility of the energy island by analysing the site location, conducting environmental impact assessments, exploring potential renewable energy recourse, and analysing economic viability of the project.
- Planning, approval and permitting (3-4 years): to plan out the timescales and secure funding for the project and to obtain permits and approvals from relevant authorities.
- Detailed design (2 years): to develop detailed engineering designs for the energy island including its structure and infrastructure such as hydrogen storage, together with the connections within renewables, substations, national grid, and with other neighbouring countries.
- Construction (3-5 years): the construction of energy island's infrastructure which was included in the detailed design.
- Construction of offshore wind farm (5-8 years): to design and construct the offshore wind farms to be connected to the energy island (Wind Cycle Energy, 2024)
- Construction of pipelines (5 years): to design, produce and install interconnecting pipelines for power transmission (Energistyrelsen, 2022)
- Commissioning and testing (1 year): to test the power generation and transmission throughout the energy island, ensuring its effectiveness and safety performance (Energistyrelsen, 2022)
- Operational: energy islands have a typical design life of 80 years; it is proposed that a smaller amount of power will be generated in the first three years after construction with a goal to expand to 10GW (Energistyrelsen, 2022)

Shetland

The below Gantt chart shows the timescale for the energy island designed in Shetland. The design and construction of tidal turbines are also included which will take around five years in total. The preliminary studies will include surveys to assess the feasibility of salt cavern hydrogen storage options and EIA's. It is proposed that the energy island will have an approximate capacity of 3.3GW, connecting other renewables such as the proposed wind farms and developing tidal arrays, which can be expanded to reach a capacity of 10GW in 10 years of operational life.

Aberdeen

Additional time is allocated for the energy island at Golden Eagle and Buzzard platform for the decommissioning. In reference to the Brent Field decommissioning programme, the planning and process of obtaining permits for Brent took five years (NES Fircroft, 2019). The Golden Eagle or Buzzard in this case will likely take less time in the planning and permitting stages, due to less decommissioning steps to be carried out, and the difference in size between Buzzard and Brent Field. Therefore, decommissioning planning is estimated to be three to four years. The construction duration is shorter compared to Shetland as the steel decks can be constructed onshore hence it is possible for the decks to be built during the decommissioning stage and installed after. The construction phase for the energy island also includes the construction for hydrogen storage which requires reservoir and well survey to understand the feasibility of utilising depleted oil and gas wells for hydrogen storage which is around two years (Hychic, 2024). The energy island is planned to reach 7GW in the first year of operating, connecting other planned wind farms such as the MarramWind, Green Volt and Aspen Wind Farm. As it has a higher starting capacity, it is planned to reach 10GW capacity five years earlier than the Shetland Island, which is preferable for the Scotland's net zero emissions goal by 2045.

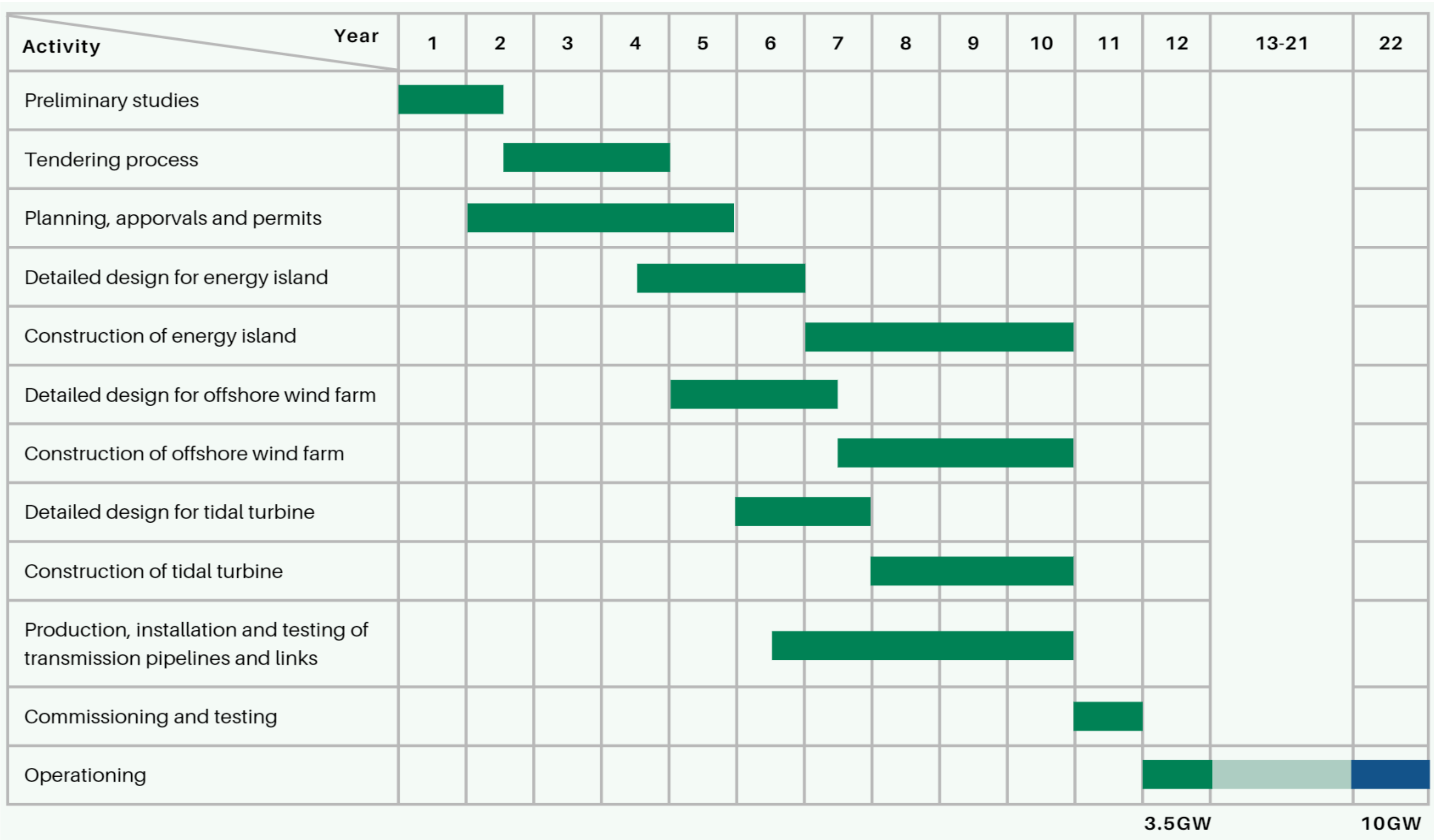


Figure 66- Timescale of Energy Island in Shetland

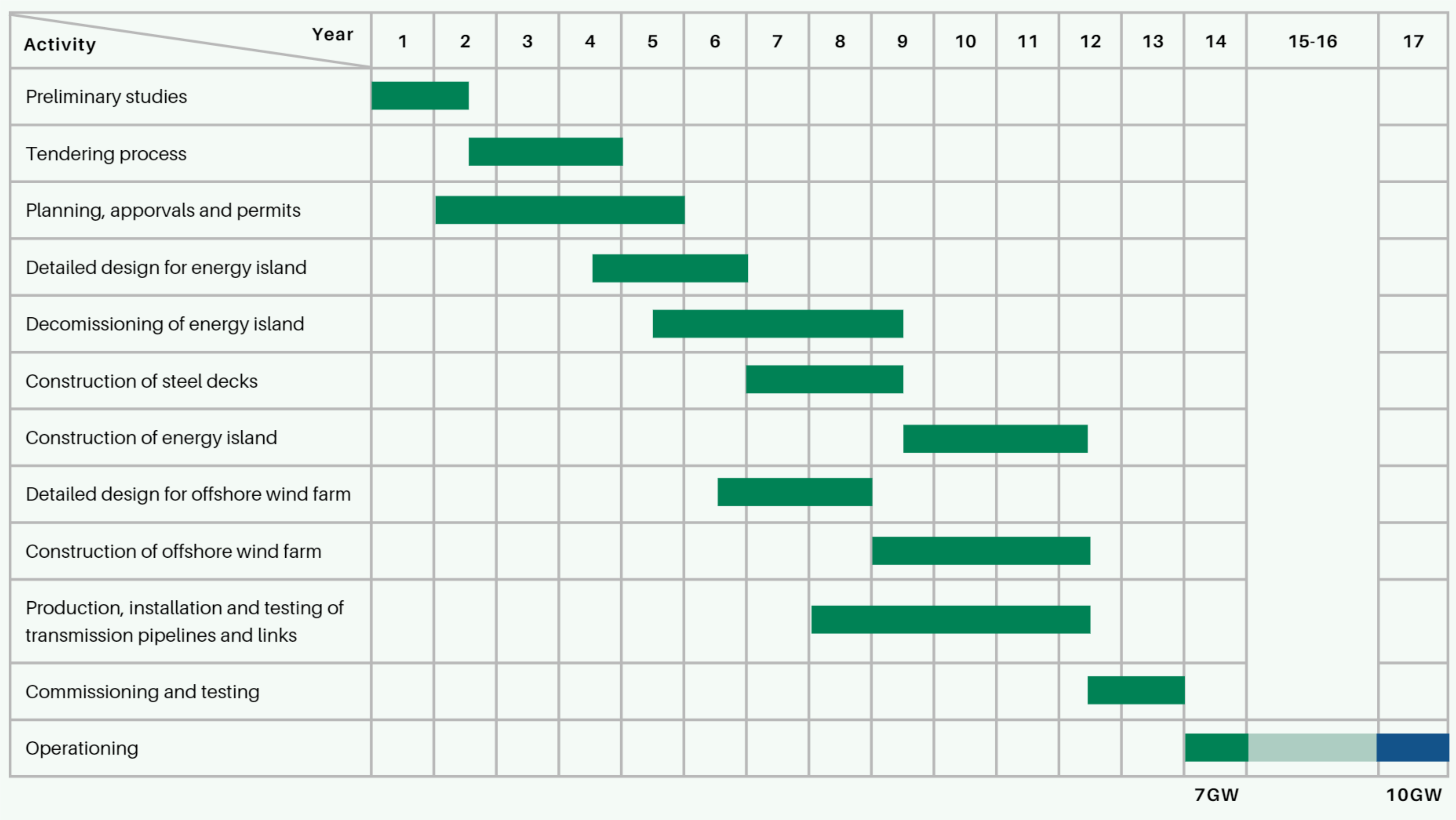


Figure 67- Timescale of Energy Island for Golden Eagle/Buzzard

6. Meeting Legislation Requirements

National Legislation and Policies

The UK set out policies responding to the climate emergency with the *Climate Change Act 2008***,** introducing legally binding 2050 targets to reduce greenhouse gas emissions by at least 80% relative to 1990 levels. In Scotland, there are objectives to meet the *Paris Agreement* by 2045. Due to these commitments, there is a need to action the energy transition more than ever and there is the vast opinion that hydrogen will play a critical role in this shift.

Key Legislation

The Oil and Gas Authority (OGA) has a role to boost the economic recovery of the UK's oil and gas resources whilst also helping the UK achieve Net Zero goals. OGA are empowered by:

- *The Petroleum Act 1998*
- *The Energy Act 2016*
- *Energy Act 2011*

In 2021, the OGA strategy was revised to place an obligation on the oil and gas industry to support the Secretary of State in meeting the target of net zero carbon by 2050. By repurposing existing rigs and pipelines to accommodate renewable energy production, the oil and gas industry can successfully undertake these commitments whilst also having a monetary incentive of producing and exporting energy.

The Offshore Safety Directive Regulator (OSDR) is the Authority responsible for overseeing industry compliance of the safety of offshore oil and gas operations in conjunction with the EU Directive. Directive 2013/30/EU ('the Directive') is implemented in the UK by various regulations including:

- *Offshore Installations (Offshore Safety Directive) Regulations 2015*

Acting in conjunction with HSE (the Health and Safety Executive), the OSDR helps to regulate any activity undertaken offshore, ensuring that appropriate measures have been taken to prevent, mitigate and control any major safety and environmental hazards that may present as well as the consequences of these hazards. OPRED and HSE are regulatory bodies that also have responsibilities to apply health and safety and environmental provisions made for the directive. These include activities that involve offshore: pipelines; decommissioning; reacting to incidents and emergencies; development of regulatory policy and technical matters; sharing regulatory information; and legal issues.

Other Regulations and Regulatory Bodies and Policies

- Marine Scotland
- Crown Estate Scotland
- Statutory Consultancies including Scottish National Heritage, Local and National Planning Authorities, Maritime and Coastguard Agency, Northern Lighthouse Board, Marine Planning Partnerships, Marine Renewables Facilitators Group and the Scottish Environment Protection Agency (SEPA)

- *Health and Safety at Work Act 1974*
- *Environmental Protection Act 1990*
- *Supply of Machinery (safety) Regulations 2008*
- *CDM 2015 Regulations*
- *MCA obligations (use of vessel for host of hydrogen generation or service provider)*
- *The Energy Act 2008*
- *The Carbon Dioxide Regulations 2010.*

It is also important to engage with local communities, governmental agencies, and stakeholders to address concerns, obtain necessary permits, and obtain support for the project before any work is undertaken.

7. Cost

The future expansion of both Shetland and Aberdeen has not been costed as this will not reflect the true economic and carbon cost of building an energy island. However, the possibility of future expansion and connection to multiple countries will be considered in the options appraisal.

As this is a feasibility study, the costings are provisional sums, which are place markers for values when details are finalised. Through benchmarking, a cost envelope was established, however, due to the projects unique scope, there is a lack of framework and examples to follow.

This cost estimate is subject to changes due to factors like, the market economy, technology advancements, inflation and relationships with other countries.

Table 6- Shetland Cost

Element	Details	Size	Total Cost	Reference
Platform				
Geotechnics (excavation, surveying, and levelling).	£4.31/m^3 (3m excavation)	190,000m^2	£2.5 million	(AECOM, 2023)
Roads	£2.13 million/km	1000m	£2.13 million	(Archer and Glaister, 2006)
Foundations	£110/m^3 concrete	15000m^3	£1.65 million	(Archer and Glaister, 2006)
Pipes	£5.62 million/km	350km	£1.97 billion	(Statista, 2021)
Cables	2.63 million/km to transfer 2GW of power	350km	£920 million	(National Grid, 2022)
Other				
ACDC Energy Converter	£217 million at each end.	X2 converters	£868 million	(National Grid, 2022)
Offshore floating windfarms	£1.3 million/MW. Proposing 100 turbines which in total will generate 0.5GW of power.	-	£650 million	(Equinor, 2023)
Welfare Building	Steel welfare unit including toilet facilities and kitchen	20ft x 8ft	£12,000	(AngloScottish, 2024)
Helicopter Pad	Standard on island helipad based on Gigha project on West Coast Scotland Island	-	£150,000	(Campbeltown Courier, 2024)
Harbour	£110 /m^3 of concrete	400m^3	£44,000	(AECOM, 2023)

Maintenance of equipment	**Subsea cable maintenance** - £134/km **Convertor station maintenance** - £1 million / convertor station / year **Turbine operations and maintenance** - £71,000 /mw/year	-		(National Grid, 2022) (Sinclair, 2024)
Shetland – Hydrogen				
Repurposing one onshore salt cavern 300,000m^3 in size	£380MM including contingency at 30%	Assuming capacity of 210,000m^3	266 million	(Vysus Group, 2021)
			TOTAL COST	£4.68 billion

Table 7- Aberdeen Cost

Element	Details	Size	Cost	Reference
	Platform			
Steel	£2.39 / Pound	6613.868lbs	£15,800	(Checkatrade, 2023b)
Pipes (replacement)	£5.62 million/km	57km	£320 million	(Statista, 2021)
Pipes (repurposing)	Included in decommissioning cost	57km	£0	-
Cables	£2.63 million/km to transfer 2GW of power	57km	£149.91 million	(National Grid, 2022)
Other				
Decommissioning of platform	Report provides an estimated cost using PEAS software which takes into account data from a range of decommissioning projects and experts to estimate a cost for the decommissioning of a 4-pile deck oil rig. The cost estimate is around £3 million, this would represent the decommissioning of one of Buzzard's 4 decks, whilst this cost would need to be multiplied by 4, it would be an overestimation as we are only removing the topside, debris and flushing the pipes and wells.	-	£10 million	(Byrd et al., 2014)
ACDC Energy Converter	£217 million at each end.	X2 converters	868 million	(National Grid, 2022)
Offshore floating windfarms	£1.3 million/MW. Proposing 300 turbines which in total will generate 2.5GW of power.	-	£3.3 billion	(Equinor, 2023)
Welfare Building	Steel welfare unit including toilet facilities and kitchen	20m x 10m	£20,000	(AngloScottish, 2024)
Helicopter Pad	Assumed the same as onshore	-	£150,000	(Checkatrade, 2023a)

Maintenance of equipment	**Subsea cable maintenance** - £134/km **Convertor station maintenance** - £1 million / convertor station / year **Platform maintenance -** £80,000/year **Turbine operations and maintenance** - £71,000 /mw/year	-		(National Grid, 2022) (Sinclair, 2024)

Repurposing Oil and Gas Infrastructure for Hydrogen Production		
	Cost	**Reference**
Utilising depleted gas field for compressed storage (2 cycles/year at 250 bar)	Approx £0.5/kg	(Department for Energy Security and Net Zero, 2024)
Capital cost of PEM Electrolyser based on Brent Delta Asset (creating 19,626 Kg H2/ Asset / day – 11 assets)	£581M	(Department for Energy Security and Net Zero, 2024)
	TOTAL COST	£5.23 billion

Table 8- Hydrogen Costs

Hydrogen Costs- Applicable to Both		
Tank/vessel for compressed H2 (120 cycles/year at 700 bar)	Approx. £2/kg	(The Oil and Gas Technology Centre, 2020)
PEM electrolyser (CAPEX (£/ MW of H2) for 893 kg/unit/day of H2 at 99.999% quality, equipment area of 61 m2/MW H2 and an efficiency of 66%	15 (£/ MW of H2)	(The Oil and Gas Technology Centre, 2020)

Converted bulk carrier? If needed	£40MM	(Vysus Group, 2021)
Total facilities CAPEX	£5MM	(Vysus Group, 2021)
CAPEX (£/kg H2)	£2.59/kg H2	(Vysus Group, 2021)
Cost Of H2 (ex. Power) (£/kg H2)	£5.30/kg H2	(Vysus Group, 2021)
Electricity (£/kg H2)	£7.2/kg H2	(Vysus Group, 2021)
Cost of H2 production (including power) (£/kg H2)	£12.25/kg H2	(Vysus Group, 2021)
Compressor	£80,000	(Vysus Group, 2021)

***hydrogen costs applicable to both proposals will not be added to the total cost as it will increase both by the same amount.

The cost to benefit analysis can be classified as Class 4. This class represents a study or feasibility at early stages which lacks detailed information on wave patterns, material amounts and carbon values. Furthermore, the price estimate is based on construction and detailed design being a preliminary assumption. Table 9 states a project of class 4 has a 1-15% level of project definition and the expected accuracy range for costing is on a lower scale of -15% to - 30% and on a higher scale of 20% to 50%. Overall, this highlights the uncertainty on the price estimate is 20-50% at this stage of the project, however, uncertainty will decrease gradually as the project is developed and becomes more well-defined (COWI, 2022).

Table 9- Estimated Cost Accuracy

	Primary Characteristic	*Secondary Characteristic*			
ESTIMATE CLASS	**LEVEL OF PROJECT DEFINITION** Expressed as % of complete definition	**END USAGE** Typical purpose of estimate	**METHODOLOGY** Typical estimating method	**EXPECTED ACCURACY RANGE** Typical variation in low and high ranges [a]	**PREPARATION EFFORT** Typical degree of effort relative to least cost index of 1 [b]
Class 5	0% to 2%	Concept Screening	Capacity Factored, Parametric Models, Judgment, or Analogy	L: -20% to -50% H: +30% to +100%	1
Class 4	1% to 15%	Study or Feasibility	Equipment Factored or Parametric Models	L: -15% to -30% H: +20% to +50%	2 to 4
Class 3	10% to 40%	Budget, Authorization, or Control	Semi-Detailed Unit Costs with Assembly Level Line Items	L: -10% to -20% H: +10% to +30%	3 to 10
Class 2	30% to 70%	Control or Bid/ Tender	Detailed Unit Cost with Forced Detailed Take-Off	L: -5% to -15% H: +5% to +20%	4 to 20
Class 1	50% to 100%	Check Estimate or Bid/Tender	Detailed Unit Cost with Detailed Take-Off	L: -3% to -10% H: +3% to +15%	5 to 100

Notes: [a] The state of process technology and availability of applicable reference cost data affect the range markedly. The +/- value represents typical percentage variation of actual costs from the cost estimate after application of contingency (typically at a 50% level of confidence) for given scope.

[b] If the range index value of “1” represents 0.005% of project costs, then an index value of 100 represents 0.5%. Estimate preparation effort is highly dependent upon the size of the project and the quality of estimating data and tools.

Revenue

The energy output of a wind farm can be calculated through the following formula:

$$Energy\ (kWh) = Capacity\ (kW) \times Capacity\ Factor \times Hours\ in\ a\ Year$$

The capacity factor is the actual energy output of the wind farm compared to its maximum potential over a given period and is estimated according to the wind conditions, turbine downtime for maintenance and other operational consideration, which is typically around 0.25 to 0.45 (Andrew, 2022). Offshore wind farms usually have a higher factor due to a higher wind speeds for better efficiency. To calculate the revenue for the energy islands, the energy output is multiplied by the average revenue of electricity in the UK for wind power which is around 8 pence per kWh (Renewables First, 2024).

Shetland

For Shetland, the initial energy capacity is proposed to be 3.5GW with an estimated capacity factor to be 0.40. After calculation, the power supply of the energy island is around 1.07 x 10^6 kWh, which leads to a revenue of 0.98 billion per year. Over the years, the revenue will increase to 2.80 billion per year when the capacity reaches its maximum at 10GW.

Golden Eagle and Buzzard

The initial energy capacity is proposed to be 7GW with an estimated capacity factor is 0.38 as the wind speeds is slightly lower. After calculation, the power supply of the energy island is around 1.07 x 10^6 kWh, which leads to a revenue of 1.86 billion per year which will then increase to 2.66 billion per year 10GW capacity.

The revenue for both sites was compared for 20 years (design life for wind turbines) from operation.

Table 10- Comparisons of revenues for Shetland and Golden Eagle/Buzzard platform

Year	Revenue for Shetland (£bil/year)	Revenue for Golden Eagle and Buzzard (£bil/year)
1 – 5	0.98	1.86
6 – 10	0.98	2.66
10 - 20	2.80	2.66
TOTAL	**37.80**	**49.20**

8. Carbon Appraisal

Table 11- Carbon Appraisal for Each Element

Element		**Shetland**	**Aberdeen**	**Greater Carbon Cost**
Decommissioning		N/A	Decommissioning of O&G rig	Aberdeen
Foundation		Concrete pad foundations	N/A (Existing)	Shetland
Roads		Subbase, base course, surface course, asphalt road layer	N/A (Existing)	Shetland
Platforms		-	4 steel platforms	Aberdeen
Transmission	Cable	350km 2GW HVDC cable from Shetland Island to Peterhead	57km 2GW HVDC cable from Buzzard to Peterhead	Shetland
Connection	Helipad	With	With	-
	Dock	$400m^2$ concrete harbour wall	Ship mooring infrastructure	Shetland
Renewable Infrastructure*	Wind turbine	100 5MW horizontal axis three bladed wind turbines	300 8.5MW horizontal axis three bladed wind turbines	Aberdeen
	Wind turbine foundation	Gravity base structure and jacket structure with pin piles	Gravity base structure and jacket structure with pin piles	-
	Inter-array cabling for wind turbine	20MW each string (connecting 4 turbines), total of 6 cables	34MW each string (connecting 4 turbines), total of 40 - 70 cables	Aberdeen
	Tidal turbine	With	Without	Shetland
	Substation	AC offshore substation platform (100m x 100m x 60m) with foundation	AC offshore substation platform (100m x 100m x 60m) with foundation	-
Energy storage		Hydrogen production plant with lesser storage	Hydrogen production plant with larger storage	Aberdeen
Infrastructure**		Prefabricated welfare building- one bathroom, staff room area, sink, office room, small medical room	Prefabricated welfare building- one bathroom, staff room area, sink, office room, small medical room	-
Flare Boom		With	With	-
Flood protection		With	With	-

*The carbon cost for the windfarms is greater for Aberdeen due to the assumed greater number of windfarms planned in this area. However, this will not be considered as a negative aspect in terms of carbon cost due to the returned benefit.

**The onshore infrastructure on mainland Scotland for connections to the National Grid and hydrogen conversion will be the same for both Aberdeen and Shetland, therefore this has been considered as a negligible factor in the carbon appraisal.

Table 12- Transportation Carbon Appraisal

Element/Materials	**Shetland**		**Aberdeen**		**Greater Carbon Cost**
	Distance		**Distance**		
	Car/Van/Lorry (km)	**Boat (km)**	**Car/Van/Lorry (km)**	**Boat (km)**	
Decommissioning	N/A	N/A	0	100km	Aberdeen
Foundations (Concrete)	42km	2.4km	N/A	N/A	Shetland
Road (Subbase, base course, surface course, asphalt road layer)	177km	230km	N/A	N/A	Shetland
Platforms	N/A	N/A	0	100km	Aberdeen
Cables	705km	230km	486km	100km	Shetland (longer cable)
Substation	0	400km	0	400km	-
Helipad Materials	177km	230km	N/A	N/A	Shetland
Dock Materials	42km	2.4km	N/A	N/A	Shetland
Wind Turbine Infrastructure	855km	230km	644km	100km	Aberdeen
Tidal Turbine Infrastructure	404km	230km	N/A	N/A	Shetland
Hydrogen Production Plant	550km	400km	550km	400km	-
Prefabricated Welfare Building	354km	230km	N/A	N/A	Shetland
Flood Protection Materials	42km	2.4km	N/A	N/A	Shetland

*Assumed 230km to and from Thurso to Shetland

**Assumed 100km to and from Aberdeen Harbour to Buzzard Platform

After speaking to industry professionals with carbon costing expertise, the chosen method to assess the carbon impact of both the Aberdeen and Shetland energy island proposal was to do a high-level overview of which would have the greater embodied carbon. The amount of components/volume of materials for each section was assessed, along with the estimated distance to transport these.

This method was advised as the aim of this project is to appraise both options, not to provide a detailed design of each. Therefore, there would be many assumptions needed to use an industry standard carbon calculating tool. This would not provide an accurate representation of the embodied carbon anticipated for each option. Additionally, the utilisation of emerging technology throughout both proposals would result in a difficulty in anticipating the resulting embodied carbon.

The distances used were collated from estimating the supply location for each component, and the closest port or harbour for the ships to leave from to transport to the island. Some components are transported from overseas or can be transported from Aberdeen/Shetland directly to the island, resulting the transport on land by lorry/car being 0km.

Based on the tables above, Aberdeen has five areas which have a higher carbon cost. Shetland also has five areas which score highest in terms of carbon cost, and Shetland will have the greater carbon cost for the transportation of materials and components. Overall, this suggests that Shetland has the greater carbon cost from the high-level appraisal carried out.

9. Funding and Ownership

The dark blue shape highlighted in Figure 68 is the area of the North Sea which is owned by Scotland. Since the energy islands are located 80 to 100km from land, all islands proposed are situated within this area and are therefore a national public land under Scotland's Crown property (House of Commons, 2014).

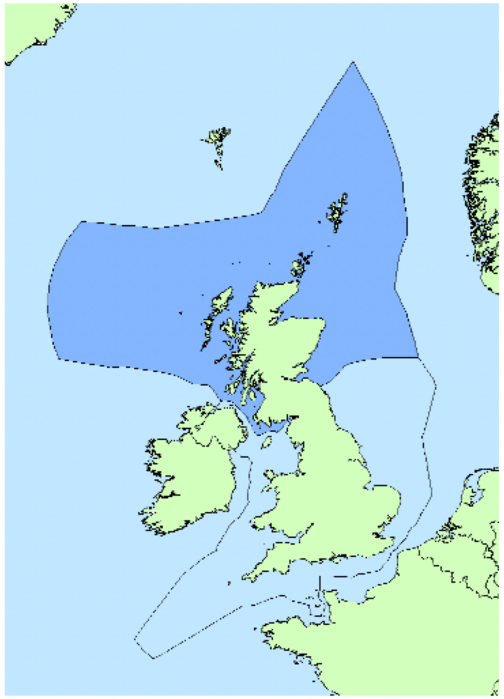


Figure 68- Scottish Owned Waters (House of Commons, 2014)

An economic analysis should be carried out to assess the project's feasibility, financial options, long-term viability, potential returns on investments for an energy island and alignment with government's policies. Potential fundings include partnerships or joint ventures and government grants in renewable energy incentives. The funding could be a joint venture between equipment owners such as oil and gas companies, and manufacturers such as suppliers for wind turbines or electrolysis equipment. This joint venture will help in securing fundings and expertise knowledge from each partner which will eventually lead to a long-term partnership between the energy companies, turbines manufacturers and other partners. Revenue generated from the sale of the electricity would then be shared between the joint venture partners according to their respective ownership stakes. The joint partnership also helps so ensure project success by the drive to succeed, reliance on one another, and risk sharing.

Additionally, fundings can also be secured through the Scottish Government's support on renewable energy initiatives, which include funding, subsidies, grants, and policy frameworks. It is advisable to engage with relevant government agencies, local authorities, industry stakeholders and other economic development agencies to help in developing a proposal which aligns with the Government's goal to further secure any support and potential grants for renewable energy projects. The proposal would also require approval from the local government, the North Sea authorities, the Scottish Environment Protection Agency (SEPA) and potentially cross-border agreements with Norway, Denmark and The Netherlands.

The funding phase takes place after this feasibility and scoping process. Potential funders could include the owners of Buzzard and Golden Eagle oil rigs, as they would be interested in making further money from their otherwise redundant platforms. Similarly, the gas pipe owners would theoretically fund the conversion of their lines to hydrogen, in order to own and make profit from the venture. Companies such as SSE and Equinor are currently leading offshore energy production for the UK and are aiming to expand their capacities massively, making them likely to be involved in an energy island project.

10. Options Appraisal

Similar to the initial SHE Engineering Summary Document, the options appraisal was carried out by scoring both the Aberdeen and Shetland proposal on 17 categories. The ranking system used is in Table 13 below. Each category has been weighted 1, 1.5 or 2 based on the expected impact each category will have on the proposal outcome. With the most important categories being weighted a 2.

Table 13- Ranking System

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

Table 14- Options Appraisal

Category	Weighting	Score		Justification
		Aberdeen	Shetland	
Location	1	5	3	• Aberdeen is more accessible. • Aberdeen is closer to more existing infrastructure. • Reduced transportation distances from Aberdeen. • Shetland will cause more harm to habitat/will have more environmental issues.
Existing pipeline utilisation	1.5	5	2	• Aberdeen has more existing pipelines. • Shorter distances to facilities from Aberdeen. • No additional connections required.
Cable length required	1	5	1	• Aberdeen requires a 57km cable and Shetland requires a 350km cable. • A longer length of new cable will lead to greater marine habitat disruption.
Proximity to existing/planned windfarms	1	5	2	• Aberdeen has 5 time more planned and current capacity for wind energy.

Tidal energy capacity	1	0	5	• Shetland has incorporated tidal energy.
Connecting to multiple countries	1.5	3	5	• Shetland have already met with multiple other countries to form a North Atlantic connection. • Further north which is closer to other countries that would like to form a connection.
Transport links	1.5	5	3	• Aberdeen has a major airport and a major harbour facility. • Aberdeen has main roads/motorways (No minor roads) to reach from other major cities. • No need to construct a road for Aberdeen.
Material Volume	1	3	4	• Aberdeen requires a lot of steel.
Material procurement	1	5	2	• Aberdeen has more opportunity to source locally.
Ease of Construction	1	2	4	• Shetland requires simpler construction and doesn't require construction in the middle of the ocean.
Energy Generation Capacity	2	5	4	• Aberdeen has greater wind energy capacity. • Shetland has tidal potential, but overall Aberdeen can generate more energy.
Storage Capacity	2	5	3	• Lack of knowledge on salt cavern availability in Shetland. • Greater potential for future expansion of storage using depleted oil and gas reservoirs.
Maintenance Required	1	2	4	• Both require similar level of maintenance, but it will be harder to carry out maintenance on oil rigs.
Stakeholder Preference	1.5	5	2	• More stakeholders voted for Aberdeen/Oil and Gas repurposing.
Economic Cost	2	2	4	• Aberdeen has the higher cost.
Carbon Cost	2	4	2	• From the high-level carbon appraisal carried out, Shetland was the option with the highest carbon cost.
Potential Revenue Within the First 20 Years	2	5	4	• Aberdeen generates more revenue over 20 years.
Total		96	69.5	

The final options appraisal, shown in Table 14, indicating that an energy island based off the coast of Aberdeen provides the most benefits due to its significantly higher score. This is primarily due to high weighting factors such as existing pipeline utilisation, available transport links, storage capacity potentials and stakeholder input. However, it is important to be aware that one of the greatest contributing factors to any major project is the overall cost, which is substantially greater for the Aberdeen based energy island.

Although this may deter key stakeholders and investors, it must be considered that regardless of the outcome for the energy island proposal, 45,000km of hydrocarbon pipelines and all 250 oil and gas platforms in the North Sea must legally be decommissioned at the end of their operational lifespan. This activity will constitute an overall cost of £56 billion to current stakeholders of North Sea assets (Scottish Government, 2024b). By repurposing existing infrastructure into value added products that previously were not accounted for, not only interests current owners of the infrastructure by providing potential future revenue, but it reduces the impact on the environment by minimising disruption caused by constructing future energy assets whilst also helping solve the challenges faced with national energy security.

Addressing Stakeholder Opinions

Comments from the stakeholders surveyed included the following. These have been taken from the responses to the questions “From our proposal, what would be your main concern?” and “What, if anything, would you change about our proposal?” The proposed remediation of these issues or section where they have addressed is also detailed below.

1. Objections from the general public and other countries. Myths and disinformation impacting the project. ***– This has been addressed by consulting with our stakeholder Fiona Milligan who has expertise in stakeholder engagement. The website is easily accessible and should therefore reduce the impact of myths and disinformation.***

2. Mention what the scale of the energy provided by this island will roughly be, would the proposed islands supply enough energy to service the entirety of Scotland? Is there potential to supply other countries such as England and Wales? ***– This has been addressed by calculating the generating capacity of the renewable energy sources. Additionally, connecting to other countries has also been discussed.***

3. The man-made island would only work in shallow water, while the offshore wind energy is now moving to deeper water. ***– This has been addressed by the decision to not include the investigation into the feasibility of a man-made island in this report.***

4. Environmental impacts / compliance, economic costs and getting the general public on board ***– Environmental impacts have been mitigated as far as possible by constructing in areas with existing infrastructure, avoiding inhabited islands, marine protected areas, and islands with native species. Economic costs have been discussed in SECTION 7. Public objection and public consultation will always be an issue, however, it is hoped that the risk of public objection will be less as there will be less parties involved when compared to onshore windfarms.***

5. Maybe include more information on benefits to the economy, climate, environment etc. ***– This has been addressed above.***

6. Converting an existing island - will this impact wildlife or the local environment? e.g. migration of birds. ***– This has been acknowledged by avoiding inhabited islands, marine protected areas, and islands with native species. However, if this was to be the preferred option, more investigation into the wildlife and environment on the island would be carried out.***

7. Talk more about the UNSDGs and how your solution can tackle specific SDGs. ***– This has been addressed in above.***

8. Grid timelines and fishermen! ***– This has been addressed by identifying that there is only a single connection to the National Grid which will reduce the risk of long waiting times and cost and that fishermen must be consulted with. However, as construction is in areas with existing infrastructure, there should be less objection from fisherman as there will be little to no disruption.***

9. Economic and Carbon cost of building an entire Island. ***– This has been addressed by the decision to not include the investigation into the feasibility of a man-made island in this report.***

10. More Clarity on carbon emissions. ***– This has been addressed in SECTION 8.***

11. Getting approval to even start concept design of this project even before prefeed, feed and detailed design. ***– This has been addressed by acknowledging the existing regulations. However, designing the approval plan and processes are not part of this scope.***

12. Rather than making an island you can use pre-existing vessels for energy and hydrogen storage. ***– This option was considered but not utilised as the aim is for as much of the infrastructure as possible is planned to be on the island.***

13. Approval would be needed from - local government, North Sea authorities, maybe SEPA, cross border agreements (Norway, Denmark and Netherlands). Do not have a proposal dependent on Government investment; seek Joint Venture Participants such as: turbine or electrolysis equipment manufacturers, other similar investors to SHE Engineering. Then plan to dilute or sell out to Pension or Infrastructure funds. ***– This is acknowledged but is not part of the scope for this project.***

14. I would not exclude the reuse of oil and gas facilities but many of them are old, and it could be expensive to repurpose them. You also get into the complex tax and legal issue of who decommissions the facilities at the end of the day and how (remember Brent spar and the huge row with Greenpeace). ***– This has been acknowledged and the decommissioning process has been investigated. However, the tax and legal issues is not part of this scope.***

15. I think that there would be a real concern about using a remote island in terms of wildlife. Probably many of the remote islands in North Sea are home to unique/rare/endangered wildlife. Worth engaging one of the NGO's. ***– This has been acknowledged by avoiding inhabited islands, marine protected***

areas, and islands with native species. However, if this was to be the preferred option, more investigation into the wildlife and environment on the island would be carried out and NGO's would be consulted with.

16. You would need to do some thorough mapping of all the issues and the impact on your project. ***– This has been addressed by acknowledging the existing issues and those mitigated by the island.***

17. It will be good to explore (if you have time) the option of floating island. Is it sensible in Scotland? ***– This is not part of the scope for this project.***

18. Cost of the Value Chain to produce Green Hydrogen vis-a-vis the price, market and hence margin for such Green Hydrogen. A high cost, technically challenging, unproven Value Chain. ***– This has been acknowledged as it is known that hydrogen production is an emerging technology. However, the development of green hydrogen production infrastructure is not part of this scope.***

19. Since you have the option to use recommissioning of the old platform. You may need to find out what existing standards or codes are available to deal with these kinds of matters. ***– This has been addressed by discussing with stakeholders in the industry on whether the platforms would be suitable for repurposing. No concerns were identified with using the case study platforms discussed in this report.***

20. If this is a completely new man-made island (excluding the repurposing O&G platform jackets), the quantity of materials, and where these will source from. ***– This has been addressed by the decision to not include the investigation into the feasibility of a man-made island in this report.***

21. Energy storage is key for our future power supplies. ***– This has been addressed above.***

11. Summary

The energy capacity estimates for both proposed options are assessed, taking into consideration the existing plans for the wind farm developments nearby the proposed energy island site. The costs of both projects have been calculated in addition to the estimated revenue – the summary is detailed below in Table 15 and 16. This study also outlines the recommended expansion for both proposals and final outcome.

Table 15- Shetland Capacity

Source		Current/Proposed Capacity	Cost	Revenue (over 20 years)
Wind	5MW horizontal axis three bladed wind turbines	2.8GW planned windfarms 0.5GW Initially Planned by SHE Engineering	£4.68 billion	£37.80 billion
Tidal	100kW tidal turbine	15.63MW planned/existing 10MW Initially planned by SHE Engineering		

Table 16- Aberdeen Capacity

Source		Current Capacity	Cost	Revenue (over 20 years)
Wind	8.5MW horizontal axis three bladed wind turbines	4.5GW planned windfarms 2.5GW Initially Planned by SHE Engineering	£5.23 billion	£49.20 billion

Note that the revenue is not a representation of net profit, and that further research must be done to detail this further, including a calculation of operational costs, maintenance and repair fees, staffing costs, and overheads.

The potential of both energy islands can be expanded further with energy storage, allowing for any excess electrical energy generated from the wind turbines to be used to generate and store green hydrogen during low demand or high levels of wind supply. Any hydrogen that has been stored can be transported through the hydrogen pipeline and used at times of high demand or low wind supply. Transporting energy through hydrogen pipelines is not only more economical than through an electrical cable, but also more efficient. The two options in this study have different potential capacities for hydrogen storage.

In Aberdeen, a large offshore hydrocarbon well asset has a typical storage capacity of 600MWh when considering its potential for hydrogen storage (Vysus Group, 2021). In the initial energy island proposal, it is suggested that 5 depleted reservoirs are utilised (taking storage capacity to approximately 3GW) with the ability to expand if necessary. GIS maps, alongside the NSTA database shows the buzzard hydrocarbon field to have 28 wells that could be investigated for the purpose of hydrogen storage on the energy island. Additionally, the UK hydrogen storage database shows that in the relative area of the Buzzard platform there is the potential to expand the storage capacity to 158,000 GWh (The University of Edinburgh, 2024).

On the Shetland Island there is no available data regarding the abundance, size and scale of underground salt caverns, therefore, the storage capacity will be based on the hydrogen production and storage facility at Teeside that utilises three 70,000 m^3 salt caverns, storing 10 GWh each (Cline, 2022). It is suggested that a similar storage capacity is exploited for the energy island in order to maximise its potential, therefore, if naturally occurring salt caverns are unavailable, there would be benefit in investigating rock cavern storage options, naturally occurring aquifers or manmade salt caverns, although these options may come at a greater cost.

In the future, more wind farms would be proposed for both islands which will require more substations, and in turn, increase the energy capacity. There is space and potential for additional substations and hydrogen storage facilities to be constructed on both islands, as well as the connection of additional windfarms. On Shetland, an assessment will be carried out to determine the number of salt caverns in the area and if there are more than anticipated on or around the island, then these can also be utilized to store hydrogen. Similarly, offshore, there are around 28 oil wells below the wellheads deck, therefore there is an opportunity to retrofit more of these wells to facilitate hydrogen storage, further boosting the islands' renewable energy infrastructure. To successfully expand the chosen energy island, it is important to keep up to date with technological advancements and industry best practices in renewable energy and offshore engineering to continually improve the projects capabilities and competitiveness.

Final Outcome:

Through extensive research and careful evaluation of both options it is suggested that the Aberdeen energy island is proposed, utilising existing offshore infrastructure such as the Buzzard platform that is legally required to be decommissioned after its operational lifespan. Although this option is significantly more challenging and expensive, with less experience of the construction process (such as repurposing oil and gas reservoirs for hydrogen storage), there are a variety of benefits that align with the interests of the Scottish Government and current investors in offshore assets.

By repurposing existing infrastructure that is planned for decommissioning, the energy island can accelerate the North Sea and Scotland’s energy transition. Repurposing assets - as opposed to removing or burying them in the ocean - provides an investment opportunity for current owners of the platforms and pipelines who’s previously may have had an uncertain future, stained with looming decommissioning costs. Additionally, leaving as much infrastructure in its current position causes the least disruption possible to marine and land environments, helping preserve ecosystems that have had to adapt to the evolving landscape of the North Sea over the last century.

Furthermore, Aberdeen is in a key location to facilitate an energy island. As one of the global energy hubs, Aberdeen has the understanding, capacity and supply chains to enable the nations shift from oil and gas and meet Scotland 2045 Net Zero targets. By utilising the city’s knowledge, help from local sustainability initiatives and position at the forefront of energy research, an energy island off the coast of Aberdeen can help make Scotland completely green.

12. Appendix I: Semester 1 Stakeholder Communication

The following slide deck was used for communications with various stakeholders in semester 1. The purpose of the slide deck was to introduce the team, describe the project and provide a structured meeting agenda to avoid going off topic or running over the meeting time.

Heriot-Watt MEng Civil Engineering Design Project

- The project credits are worth the equivalent to three courses
- Topic- Scottish Wind Energy
- First deliverable- summary report & short video, due early January
- Final deliverable- website with video, map, initial findings & summary reports, posters & model for design show in March

Aims and Objectives

The aim of this project is to challenge the sustainability of wind farms 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 on the identified problems within the wind energy industry in Scotland.
- Design a suitable solution to remediate numerous identified problems (Energy Island).
- 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).

Progress to Date

- Initial list of stakeholders created
- Multiple onshore wind farm case studies- Carrick Wind Farm, Andershaw Wind Farm & An Carr Dubh Wind Farm
- Main problems with onshore wind identified
- Summary document in progress
- Research energy island underway

Stakeholder Name	Company/Role
Dr Wolf-Gerrit Fruh	HWU- Energy Engineering Lecturer
Angus Creech	HWU- Visiting Academic
Gavin Falconer	FLS- Head of Renewables
Fiona Milligan	Boralex- Stakeholder Engagement
Daniel Clancy	GDG- Graduate Engineer
Scott Valence	Statkraft- Principal Project Manager
Kirsten Rae	Carrick Windfarm-Senior Project Manager
Ciaran Black	Statkraft- Project Manager

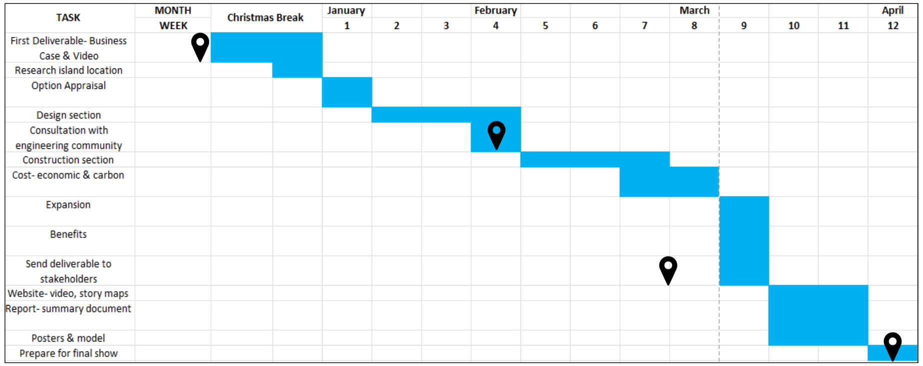
Summary Document Contents

Contents

Design Solution

- Background- Function of energy island, current Situation, Aim of an Energy Island
- Identify new stakeholders
- Research energy Island location- off the coast of Aberdeen, Edinburgh & North Scotland Islands (Orkney & Shetland)
- Options Appraisal
- Design- location, island dimensions etc, use of existing infrastructure, materials/aesthetics, connections, type of energy- wind, wave, solar, hydrogen, transport infrastructure, technology and equipment, energy capacity, energy storage, and data centre
- Construction- Time scale, processes involved, connection details under the sea and to the grid on land for both hydrogen and electricity, connections from surrounding wind turbines to islands, foundations, maintenance plan, flood/wave defence.
- Cost- economic & carbon cost
- Future Expansion
- Benefits
- Benefits to jobs availability, how energy islands impact onshore industries like ports, expected energy production, benefits to the economy, and selling energy.
- Meeting net zero goals / making offshore wind farms more sustainable

Project Timeline



By using these slides, the project team were able to provide direction to the meetings and obtain as much information and feedback from the stakeholders as possible. This helped to steer the design towards a clearer and more realistic solution.

13. Appendix II: Semester 2 Stakeholder Communication Brief

The following slide deck was used for communication with various stakeholders in semester 2, particularly with industry professionals in the oil and gas sector. The purpose of the slide deck was to introduce to team, describe the project and provide a structured meeting agenda to avoid going off topic or running over the allocated meeting time.

Who We Are?

- We are six Heriot-Watt University MEng Civil Engineering students, called 'SHE Engineering'
- We are completing our Masters Professional Design Project
- We have chosen to investigate the sustainability of windfarms in Scotland, which has led us to proposing an 'Energy Island' concept in the North Sea
- We have already contacted a range of stakeholders for the first phase of the project which involved identifying the existing issues with onshore wind

Introduction from Stakeholder

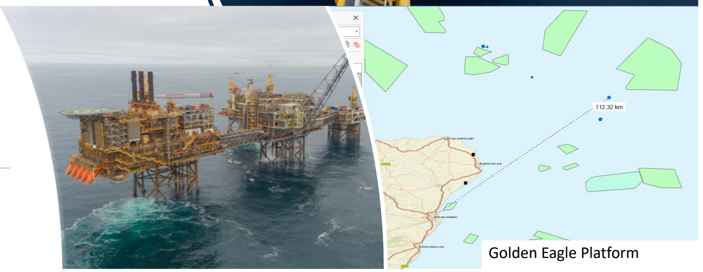
- Background
- Company/organisation you work for
- Job Role
- Experience

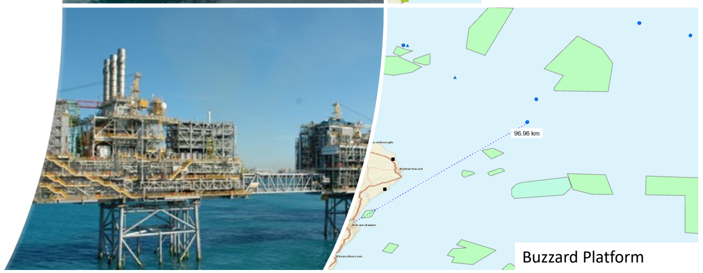
Our Project

- We propose to design an 'Energy Island' in the North Sea, either a man-made island off the coast of Aberdeen or by using a small, existing island in Shetland
- We would like to utilise existing oil and gas infrastructure which is likely to be decommissioned in the future
- Our priorities are sustainability and low carbon

Repurposing oil and gas infrastructure

- We have looked into two potential platforms which are within the right area for our project
- These are not currently planned for decommissioning, but they are closest to each other
- This would be used as a theoretical proposal

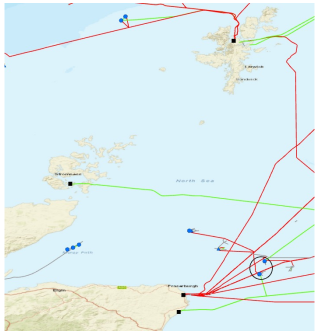




Pipelines & Cables

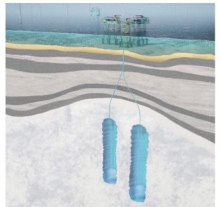
Examples of Pipelines that Could Be Used

	Pipeline Name	Nearby Platform	Length (m)	Diameter (mm)	Status	Fluid
1	4" MEG ST. FERGUS - ATLANTIC MANIFOLD	GE	77603.97	102	Abandoned	chemical
2	SAGE PIPELINE	B	323766.10	762	Active	gas
3	MILLER TO ST. FERGUS	B	239745.63	762	Not in use	gas
4	20" GAS GOLDENEYE - ST. FERGUS	B	101681.60	508	Not in use	gas
5	30 IN SIRGE GAS EXPORT	Shetland	233000.00	762	Active	gas



Energy Storage and Transport

- Flywheel Energy Storage
- Air Energy Storage — Compressed Air – CAES; Liquified Air - LAES
- Battery Storage — Lithium-Ion Battery; Vaanadium Redox Flow Battery
- H_2 Production and Storage Systems



Questions

Can you provide information on-

- load capacity, expected life span, and general design life span;
- maintenance schedules;
- dimensions of all elements including those which will be removed at decommissioning (platform etc);
- foundations in the seabed;
- decommissioning;
- advice on energy storage;
- advice on connections to land.

These slides allowed the project team to ask more specific questions to the industry professionals that would have the technical knowledge and expertise to provide guidance on the offshore energy island. The oil and gas industry was a sector that none of the project team had any preious experience in and therefore the infromation gathered from these meetings were invaluble to the project and understanding its feasibility.

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