INTEGRATING RENEWABLE ENERGY TECHNOLOGIES FOR HEAT DEMAND AND A HYDROGEN ECONOMY FOR UNST

FINAL REPORT

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Disclaimer

Although the contents were reviewed several times before being part of this report, the accuracy of the results cannot be guaranteed. The University of Flensburg as well as the authors of this document have no legal responsibility in case of any errors, omissions or misleading statements. Therefore, we recommend that expert opinion of the relevant topics should be sought before using any data presented in this report.

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Executive Summary

This is a pre-feasibility study of incorporating renewable energy to provide building heat demand and simultaneously establish production of hydrogen and its derivates, on the island of Unst, in Shetland. Renewable sources may cover energy needs and provide a substitute for oil that is imported and used for heating buildings. This, however, would leave much of the renewable energy unused.

The production of hydrogen may provide a cost-effective basis to produce Ammonia and Hydrogen Peroxide, that have a capability to supply a potential market, such as fertilizer production and fisheries. The study was implemented using a community-based approach that took into account the opinion of the community about the technologies used and their implementation through different business models. The involvement of local community was enacted through direct interaction and documentation of their concerns and perception about the project idea.

The buildings identified for heat supply consist of building stock at Saxa Vord, Balta Sound Junior High School, Nordalea Care Centre, and Unst Leisure Centre Figure 2.1.1. The heat demand for these buildings was estimated, and three scenarios were further studied, two for the occupancy variation and one for efficiency improvement.

The heat demand assessment of the identified buildings, was followed by a renewable energy resource and economic assessment of wind, solar, and geothermal sources.

Different technology assessments were carried out for hydrogen production and the subsequent derivatives; ammonia and hydrogen peroxide. The application of hydrogen as a transport fuel was also assessed.

Using a dynamic Microsoft Excel tool, a technical and financial assessment was carried out. Using diverse inputs, the tool simulates the output of the technologies involved. The tool provides essential indicators that assess the feasibility of the proposed ideas, and it allows for comparison of existing technologies and their related costs.

The tool provides a basis in formulating scenarios that indicate different conditions for the technologies to work in. These scenarios vary from a more energy efficient heat demand to a selection of hydrogen and/or derivatives production priorities. This tool also allows for the alteration of capacity of the RE technologies. In addition, the tool does an economic assessment on the scenarios to form a baseline for the feasibility of the selected option. The financial analysis and the resulting business models identify the investment opportunities along with the risks involved.

To conclude, the study provides the community and other key stakeholders such as the PURE Energy Centre, Unst Community Council, Shetland Council, and the Unst Partnership, with a decision-making tool. This tool will enable them to study appropriate project options. In the end, the renewable energy resources could potentially reduce CO_2 emissions and provide a green end-to-end supply chain of energy for heat demand and hydrogen, ammonia and hydrogen peroxide production.

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List of Acronyms

AM	Air Mass
ASHP	Air Source Heat Pump
CAPEX	Capital Expenditure
CAS	Chemical Abstracts Service
CIBSE	Chartered Institution of Building Services Engineers
CO2	Carbon dioxide
COP	Coefficient of Performance
EPC	Energy Performance Certificate
FISE	Fraunhofer Institute of Solar Energy
GBP	Great British Pound
GBP/EURO	Great Britain Pound to Euro Exchange Rate
GCRS	Geological Conservation Review Sites
GHE	Ground Heat Exchanger
GHI	Global Horizontal Irradiation
GIA	Gross Internal Area
GSHP	Ground Source Heat Pump
H2	Hydrogen
HHV	Higher heating value
HP	Heat Pump
IRENA	International Renewable Energy Agency
kg	kilogram
kJ	kilojoules
kWh	kilowatt hour

LHV	Lower heating value
m^3	cubic meter
MCS	Microgeneration Certificate Scheme
MJ	megajoules
MOD	Ministry of Defence
MSDS	Material Safety Datasheet
N_2	Nitrogen
NASA	National Aeronautics and Space Administration
NCMPA	Nature Conservation of Marine Protected Area
NH_3	Ammonia
NNR	National Nature Reserve
NTP	Normal Temperature and Pressure
O&M	Operations and Maintenance
OPEX	Operational Expenditure
PEC	Pure Energy Centre
PSA	Pressure Swing Adsorption
PV	Photovoltaics
QGIS	Quantum Geographical Information System
RE	Renewable Energy
SAC	Special Area of Conservation
SAP	Standard Assessment Procedure
SCOP	Seasonal Coefficient of Performance
SLDP	Shetland Local Development Plan
SNH	Scottish National Heritage

SPA	Special Protection Area
SSSI	Sites of Special Scientific Interest
STC	Standard Testing Conditions
STP	Standard Temperature and Pressure
UK	United Kingdom
USD	United States Dollar
WRF	Weather Research and Forecasting

Chapter 1: Introduction

The sixteen students from the University of Flensburg (Germany) studying Energy and Environmental Management and their three lecturers along with a research associate made a resident research visit on Unst island, Shetland in February to March 2019. This visit was a part of the International Class (IC) module, in which the students explore the energy related opportunities for rural communities.

The study was undertaken in accordance with the recommendations of PURE Energy Centre and Unst Partnership, who were the key partners of this case study. The students studied the previous project reports conducted by PURE Energy Centre and Unst Partnership. These reports suggested solutions for deploying RE through off grid systems using energy storage mechanisms (Estate and Islands, no date). Furthermore, the reports emphasized the role of hydrogen produced with renewable energy sources like wind turbines in a green supply chain.

The students then worked on developing the preliminary ideas presented by the PURE Energy Centre, which is discussed in this report.

Chapter 2: Methodology

2.1 Project Scope

The study aims at assessing the heat demand of the building stock at Saxa Vord, Balta Sound Junior High School, Nordalea Care Centre, and Unst Leisure Centre as shown in Figure 2.1.1

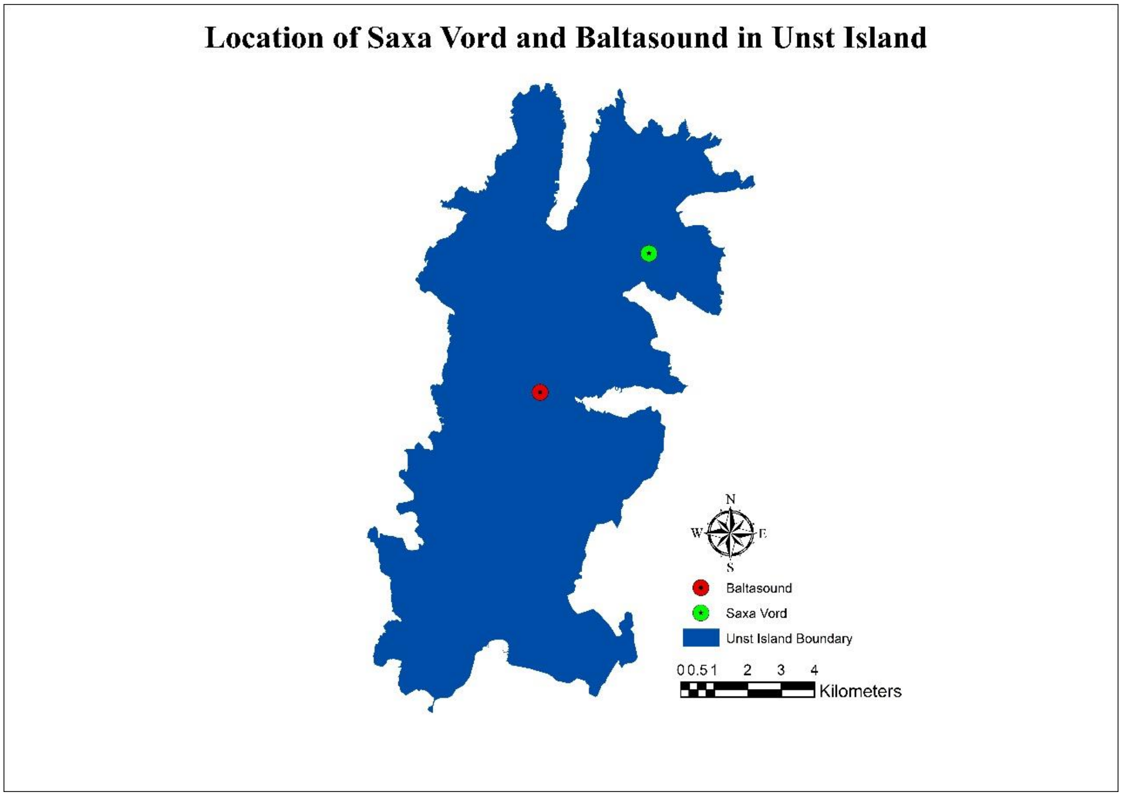

Figure 2.1.1 Location in Unst

2.2 Main Objective

The main objective of this study is to develop an integrated tool, which would make it possible to analyze the feasibility of incorporating renewable energy to provide building heat demand for the building stock at Saxa Vord, Balta Sound Junior High School, Nordalea Care Centre, and Unst

Leisure Centre and also assess the market potential of hydrogen and its derivates on the island of Unst, in Scotland.

2.3 Specific Objectives

Furthermore, the main objective was divided into following specific objectives:

- To identify stakeholders and study the perception of the community about the deployment of renewable technologies in Unst.
- To determine and analyze the current heat energy use and building efficiency of the project buildings.
- To assess the potential of the island for the production of electricity and heat from RE (wind, solar PV, solar thermal, etc.).
- To assess the potential of hydrogen production and the market for derivatives in Unst.
- To analyse and integrate the outcomes of all workgroups by designing a transparent and flexible tool.

2.4 Methodology Overview

The methodology adopted for meeting the above objectives is described briefly as under:

Three community involvement activities were planned before the students came to Unst, as their final implementation of their project. A survey questionnaire was designed and circulated using

EvaSys, a web-based software. Two workshops were conducted, one with the students of the Baltasound Junior High School and the other with the community.

The building heat demand assessment was done using historical energy consumption data from the relevant stakeholders, site visits and the use of heat intensity benchmarks. TRNSYS and NHER software were used to model the energy performance of a sample unit.

The renewable energy resource assessment was undertaken for solar thermal, solar photovoltaic, wind and geothermal heat-pumps. Software used for the assessment of solar photovoltaic and wind were PVSOL and WindPRO.

Hydrogen production, based on the available residual energy for the process, was simulated in a separate excel tool. The production of ammonia and hydrogen peroxide was also simulated in the same tool.

These inputs were then integrated in a combined excel tool.

Chapter 3: Community Activities

It can be argued that the effective implementation of renewable energy projects at the community level requires the acceptance and support of community members. Besides the technical and economic aspects, social aspects such as the existing knowledge and attitudes of the community on Renewable Energy (RE) technologies, and community involvement should be taken into consideration to enhance decision making. While several stakeholders will be involved in the future realization of RE projects, the community was identified as a very important stakeholder for the potential project in Unst. Therefore, the students from the University of Flensburg planned to interact with the community to include their ideas and opinions in the early stage of assessment and planning for a renewable project in Unst. Thus, the strategy was to use the methods listed below to collate these opinions:

1. **Survey**; to understand the community's attitudes towards renewable energy projects
2. **Seminar at Junior School**; to introduce the project idea to the future generations of Unst
3. **Community Workshop**; to interact with community members and gather their opinions and suggestions on the project idea.

The sections below summarize the outcome of these activities with the community members.

3.1 Survey

The purpose of the survey was to acquire a primary overview of opinions from the community members of Unst, to assess their acceptance, attitudes, and concerns towards the development of RE projects on the island. The survey essence derived from an article of the Climate Policy Info Hub "Social Acceptance of Renewable Energy" (Climate Policy Info Hub, 2015) focusing on five areas to discover the social aspects influencing the acceptance of renewable energy technologies mentioning:

- Awareness of climate change and knowledge of technology, which motivates the collective willingness to act and/or accept renewable energy projects.
- Fairness of decision-making process that is evidenced by open and transparent communication between the public, stakeholders, and decision makers, which allows the public to evaluate openly the projects.

- Overall evaluation and assessment of costs, risks, and benefits: - by taking into consideration all sorts of impacts as economic, environmental, and social.
- Link Local context in order to examine the community reactions and probable resistance towards projects implemented in their vicinity, and stresses on sharing benefits as a strategy to impede the probable resistance.
- Trust in decision-makers elaborating the perception of the local communities towards developers and decision makers and plays an integral role in their wholesome acceptance.

The survey design included 10 statements with a provision for only four answer categories (Agree, Strongly Agree, Disagree and Strongly Disagree) to motivate the respondents to take a position. The Survey was disseminated through an online platform and hard copies were placed in the local shops in Unst. There were 25 responses, and the main findings were:

- Respondents were aware of the climate change issue and try to behave in an environmentally friendly way on a personal level.
- Respondents had a positive attitude towards development of RE projects, although two people were not in favour of RE project development even if their concerns were addressed.
- Respondents believed that community-owned projects could bring more benefit to the community.
- Respondents had their doubts that decision makers and developers take the community interests as a priority.
- Respondents emphasized transparency and community involvement as a precondition for acceptance and support for the development projects.

25 responses out of a population about 600 people in Unst (Gall, 2017) is equivalent to only 4.1 % of the island’s community. This means by far that the sample is not representative of the

population of Unst, thus the results obtained cannot summarize the collective attitudes and opinions of the population and it requires to be conducted again.

For more information on the Survey design with statements, refer to Appendix I:

3.2 Baltasound Junior High School Seminar

The main objective of the school seminar was to introduce a simplified idea of the project to the high school students; who are the future generation of the island. In addition, it was an opportunity to know about their familiarity with renewable energy and environmental related topics like climate change. The seminar resulted in forming very good communication with the students and some of the school staff, as the Baltasound Junior High School is one of the suggested beneficiaries of the project idea. Furthermore, it was obvious that the school students had some knowledge of the benefits of renewable energies to the environment and they are aware of the importance of alleviating environmental issues such as global warming and climate change.

For more details of the seminar, refer to Appendix II: .

3.3 Community Workshop

The objectives of this workshop were:

- To provide feedback on the survey results
- To present information on the potential RE project idea for Unst by the students of University of Flensburg.
- To collect ideas and suggestions of community members on how to make RE projects acceptable through community participation and for the benefit of the community

The students from the University of Flensburg presented the survey results, the RE project idea, and then facilitated three group discussions on the: (1) foreseen concerns and potential solutions,

(2) expected benefits to the community, and (3) ways in which the community can be involved in the future project. There was a total of 10 community members in attendance for this meeting.

The opinions and suggestions generated during the community workshop will be considered and presented to the decision-makers, as a guideline of the social options for future projects. The sections below provide a summary of the discussion outcomes in the three groups:

3.3.1 Foreseen Concerns and Solutions on the Project Idea

The concerns of the participants were classified into the below listed factors:

i. Economic

- Defining the long-term benefits to the community, amidst fears of profit centric investors.
- The aesthetic impact of wind turbines on the tourism on the island, as these could reduce the number of tourists that come to the island for its scenic landscape.
- Utilization of local human skills and service during project implementation
- Existence of fuel poverty because of the need for longer heating hours, high costs of electricity charge by monopolies and transport services by ferries

Participants suggested developing a financial structure for the project to benefit community instead of individuals, financing instruments for technologies such as heat pumps, and allowing the export of electricity to the grid. Furthermore, it was proposed to explore the use of oxygen for fish hatcheries on the island as an added value of the project.

ii. Environmental:

- Avoiding installations on the island’s nature reserves and other protected areas.

iii. Social

- Emphasis that land usage benefits may not accrue to the community, but only land owners.
- The consistent development of the island’s local skills and capacity
- Efficiency measures for old buildings that ensure that their ancestral value is not destroyed.

The solutions suggested were initiating apprenticeships programs on the island to create long term job creation and sharing success stories between community members.

iv. Technical

- Providing information on the size, quantity, and site for potential wind installations
- Providing more information on the other technologies proposed for the project.
- Limitations of wind installations that may arise due to potential satellite radar site
- Elaboration of building insulation and better building heating technologies to the community members.

At the end of the discussion, participants placed higher priorities on the economic and social concerns over the technical and environmental factors. This indicates that the concept of "social sustainability" is important and the proper organization of a RE project is an enabling factor for any RE activity.

3.3.2 Expected Benefits of Potential Project to the Community

The potential benefits raised in the group discussion were based on the future deployment of RE technologies and hydrogen production on the island. The main findings are as listed below:

i. Expected economic benefits;

  - The main benefits discussed were job creation and stimulation of the local economy, in which local industries such as fish farms would benefit from locally produced hydrogen peroxide, which could be provided at lower cost.
  - The possibility of producing fertilizer to meet internal demands and then considering exporting any excess was also a benefit which the participants suggested.
  - The participants also expressed the idea of creating a Community Benefit Fund, which would channel the revenue from the new installations to community benefits. The main point was that the money would be circulated within the island's economy.

ii. Expected social and socio-economic benefits:

  - Some of the major social benefits highlighted by the participants were stimulating population growth, mitigating energy poverty and clean energy, and safeguarding the services.
  - They also suggested that developing RE projects could serve as a knowledge-hub in Unst, which could serve as examples to other islands as well as inspire the future generation.
  - The idea of improving the fabric of buildings was raised, as the present condition of the building materials is degrading owing to the discontinuous supply of expensive available energy for heating.

iii. The environmental benefits pointed towards decreasing the environmental impact in the form of CO_2 emissions.

The participants prioritized the economic and social benefits, followed by the socio-economic benefits, while the environmental benefits were considered as a by-product of the economic benefits.

3.3.3 Community Involvement on the Potential Project

The main findings from this discussion with the community members were:

The emphasis by participants on ensuring that the local community should have a role in the process of decision making of renewable energy projects, also suggesting the formation of decision-making sub – committees.

i. The participants also claimed that they are interested on a personal level to participate in the planning and implementation process for renewable energy projects.
ii. The participants also highlighted the importance of introducing renewable energies, along with raising awareness about the specific benefits of RE projects to the community level, through meetings and awareness sessions, case studies of conducted projects in other communities, and facilitating visits to RE projects sites.
iii. The participants also expressed the possibility of providing project equity and the ability of some community members to contribute financially in implementing RE projects.

However, they insisted on the importance of raising awareness and addressing the concerns of the community before investing in these projects.

iv. Another point was the involvement of the community through apprenticeships and employment, with the possibility of job creation after implementing RE projects. The participants have also pointed to the benefit of using local skills and expertise within the community and involving them through participating in online publicity of RE projects.

v. The participants expressed their personal willingness to contribute to RE projects, based on their interests and abilities, through attending workshops and awareness meetings, spreading this knowledge and encouraging others to attend or even by facilitating such meetings. They also showed interest in giving publicity through media channels like the local newspaper and radio stations.

For more details on the activities of the Community Workshop, refer to Appendix III:

3.3.4 Recommendations

There were only 10 community members in attendance for the workshop, which does not seem representative of the views of all the adult population residing in the community.

However, our recommendations are that the above points raised during the activities are vital and should be highly considered before project implementation phase by addressing the key areas on:

- Creating awareness to the community by providing more consistent information on the proposed RE technologies and any other auxiliary productions (such as hydrogen production) through workshops, newspaper articles or the media.
- Job creation by utilizing local skills / expertise, initiating apprenticeship programs, and highlighting any other value addition to the community as a result of the RE project.
- The formation of a community sub-committee for inclusion in planning and decision making, and a Community Benefit Fund to manage funds accrued from any RE project to develop Unst.
- Providing solutions for the high heating requirement in buildings on the island and advising on improvements that can be applied to materials in old buildings.
- Minimizing the capacity and quantity of wind turbine installations, while taking care to avoid installation on protected areas and not affecting the aesthetic landscape view

- Clarity on the financing of the RE project and providing for the incorporation of co-ownership by the community, in order to ensure that community benefits is a priority.

Chapter 4: System Architecture

4.1 Introduction

The system is divided in two main branches. The first branch integrates different technologies for heating the buildings and supply the heat demand while the second branch utilizes the energy for producing hydrogen, oxygen, ammonia and hydrogen peroxide in the priority that the user defines. This framework is translated to two tools, in Microsoft Excel, separately for two locations: ‘Baltasound’ and ‘Saxa Vord’. This section details the relationship between the system components in this framework, and after that briefly introduces the two excel tools.

The broad architecture of the entire system is demonstrated in Figure 4.1.1

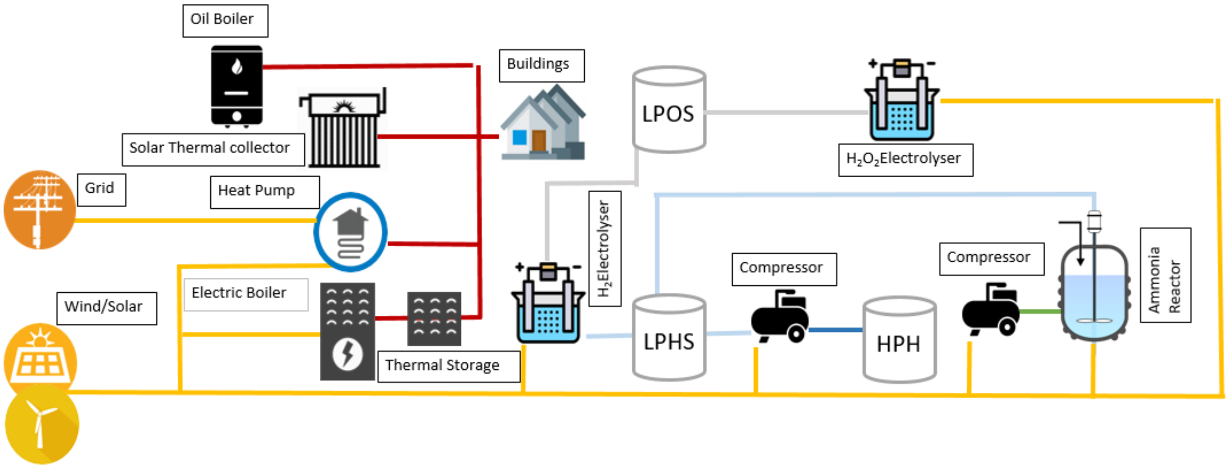

Figure 4.1.1 Overall System Architecture

Source: Author

4.2 Heating System Layout

Within the scope of our design, the energy supplied from RE technologies is utilized to meet the heat demand. The heating system integrates different components aiming to deliver hot water for space heating and for domestic use at a temperature of 70 ° C. The heat pump, electric boiler, thermal storage and the backup oil boiler enable the system to achieve a reliable heat supply.

Further, into the operation, the system divides into two blocks; electricity and heat. Figure 4.2.1 summarizes the basic heating system architecture:

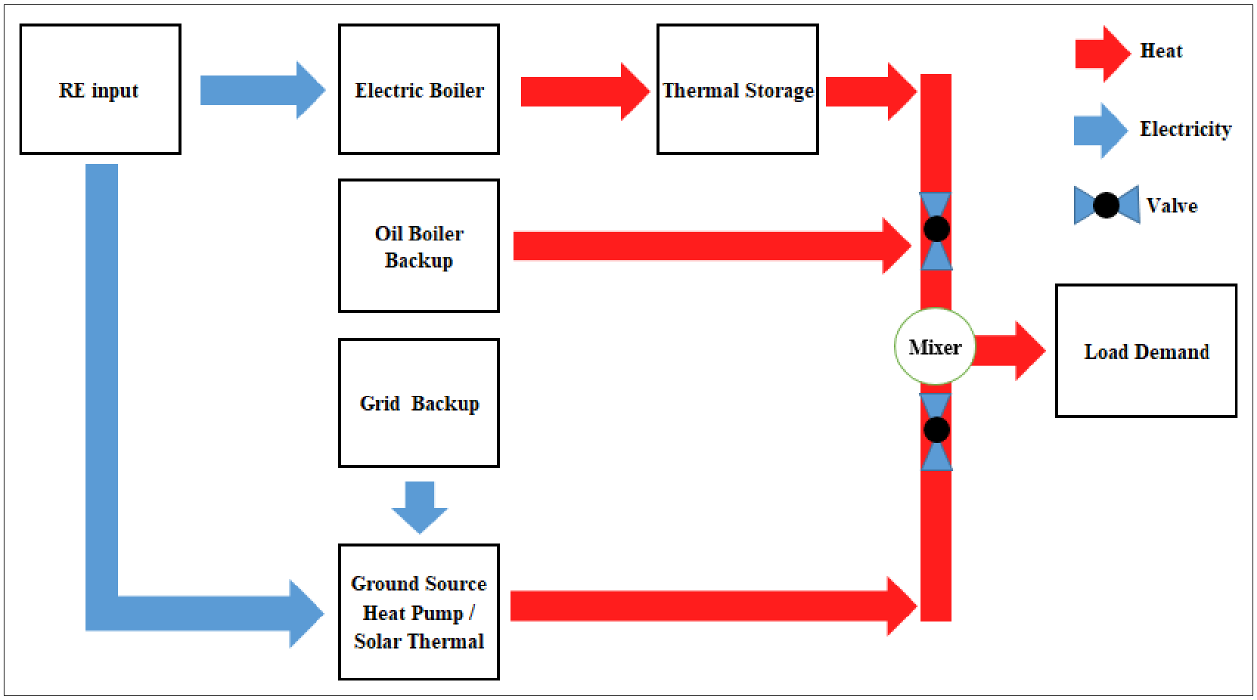

Figure 4.2.1 General Architecture of Heating System of Buildings

Source: Authors

The electric block comprises of two components ground source heat pump and electric boiler, both utilizing electricity acquired from RE. The system also includes a provision of electricity supply from grid only to the heat pump allowing it to serve as a backup in case of shortage of supply due to the fluctuation and intermittency of RE.

As per the heat block, the (heat pump/solar thermal) acts as a base load supplying hot water at a temperature of 45 ° C. The electric boiler works in parallel supplying hot water to the thermal storage at a temperature 90 ° C. In addition, an oil boiler is available also as a backup in case of shortages replacing the supply from hot water storage. The modelling assumption is that the water temperature coming from thermal storage is adjusted by changing the water flow rate in order to attain the desired temperature for the wet heating system.

The heating system layout adopts to the various loads, considering their geographical locations, area of the property, and the aggregated demand. Considering loads, for Saxa Vord Resort the demand accounted as a bulk delivering it via a mini district-heating scheme, assuming that all electrical heaters will be replaced by a wet heating system. This is required by the system since existing electrical storage heaters do not provide enough storage capacity to balance the intermittent supply of the wind resource. In Baltasound, each building has its own central heating system and electricity from the wind turbine is distributed to the properties.

4.3 Hydrogen and Derivatives System Layout

As can be seen in the diagram, the process is divided in four main blocks: hydrogen and oxygen production, hydrogen peroxide production, hydrogen for transportation and ammonia production. Figure 4.3.1 shows the flow of the products, from an initial state of water, until the final states. Refer to Chapter 8:for a detailed explanation of the process.

The system compares the energy input and the energy required for the process with first priority, if the process cannot be completed because there is not enough energy or additional inputs are not available, the energy goes to the process with second priority. If the first process is executed the remaining energy goes for the process with second priority. This logic will be repeated between the second and third process.

Ammonia and hydrogen peroxide production require the confirmation of two inputs. In the case of ammonia, it requires energy and hydrogen while in the case of hydrogen peroxide it requires energy and oxygen.

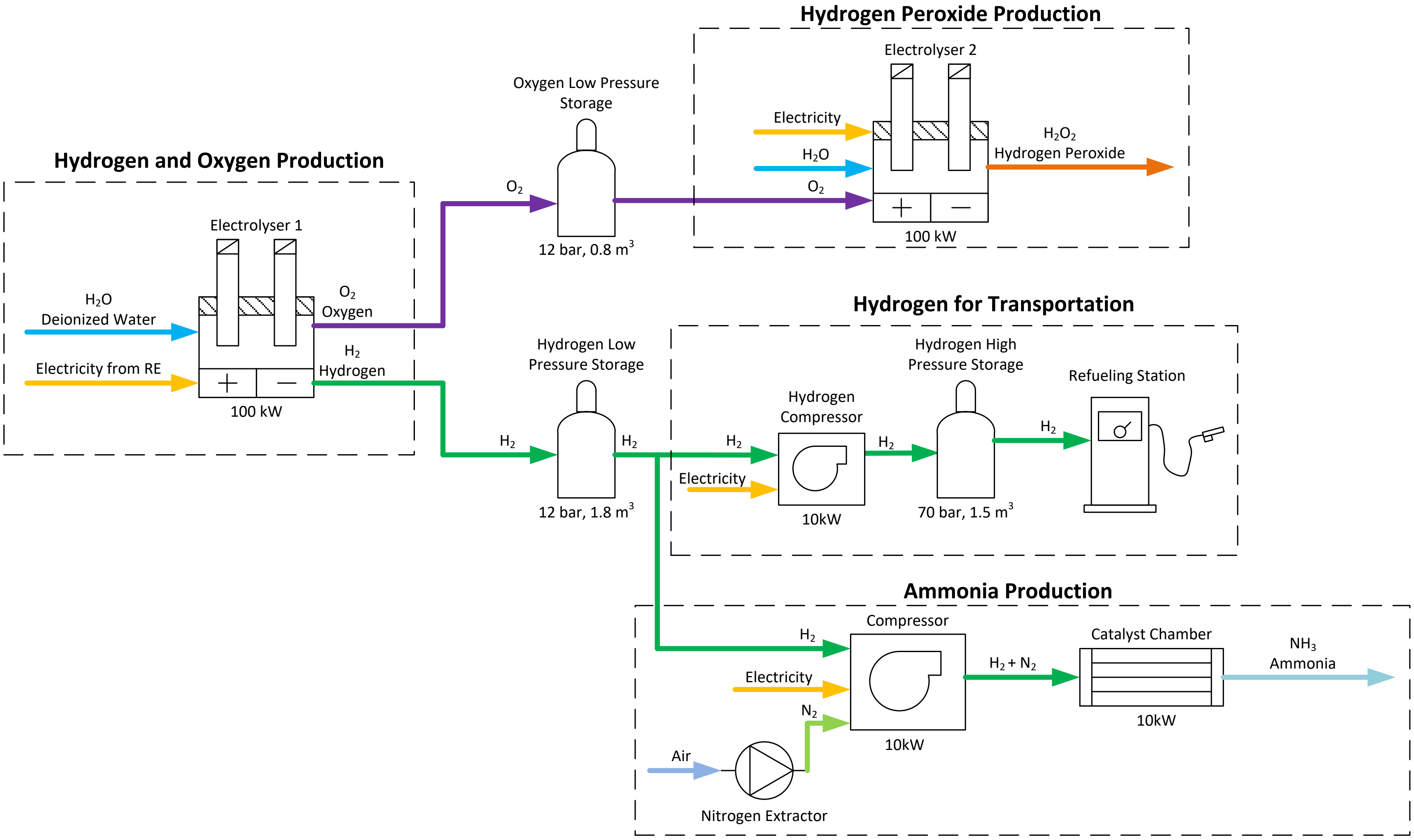

Figure 4.3.1: Architecture of Production System for Hydrogen, Ammonia and Hydrogen Peroxide

Source: Authors

4.4 Baltasound

The three demand centres in Baltasound are the Unst Leisure Centre, Nordalea Care Centre and Baltasound Junior High School. The current situation is that each building has its own heating system which uses Oil boilers as the heating source. An hourly heating demand assessment of each of these buildings was conducted and this is explained in Chapter 6.

Considering that current consumption is from oil, the study explores alternate cleaner heating systems for meeting this demand. This could technically include heat pumps from geothermal energy (ground source) and/or air sourced technology, to be electrically powered by a renewable energy system. Solar thermal collectors were also considered as an option as alternative to heat pumps.

The renewable energy system consisting of wind turbine(s) and / or solar PV system provides intermittent energy, which doesn't always coincide with demand. Therefore, it was prudent to explore using a thermal storage for the buildings which recharges from an electric boiler when there is excess energy produced by the RE system.

This interaction within the components of each of the three buildings' heating system is modelled into Ms. Excel by adding parameters derived from the technical assessment. This is detailed in Chapter 7:for renewables and in Chapter 6 for thermal storage.

To arrive at a cost of heating due to new investments in the buildings' heating system and RE system, costs for investment in capital, operations and fuel expenditure were conducted along with technical assessment. These financial parameters are used in the tool to estimate cost of heating from the combined system (per building) and compare with current or future expected expenditure by the leisure centre, school and care centre on heating.

4.5 Saxa Vord

The Saxa Vord buildings are considerably far from Baltasound, which required the modelling of a separate RE system, and thus a separate excel tool. The heat demand assessment along with the possibility of different occupancy patterns, seasonal variation, increased building efficiency was conducted (refer to Chapter 6) and this is modelled into the tool for Saxa Vord.

The Saxa Vord resort has both wet heating systems as well as dry heating systems, which source the heat from either the oil boiler or grid electricity. Similar to Baltasound, the Saxa Vord buildings' heating system is also assessed for improvement by introducing heat pumps (or solar thermal collectors), thermal storage (supplied by electric boiler). This would be supplied by a renewable energy system with wind turbines and/or solar PV to supply the heating system's electric demand.

The collective ownership of the buildings by Saxa Vord provides the opportunity for a combined district heating system. Thus, thermal storage and pipeline layout feasibility assessment was conducted for Saxa Vord. Finally, the payback assessment of investing in the new heating system is an output for the building owners in the model.

It was agreed that an important component of the whole feasibility study is production of Hydrogen, Ammonia and Hydrogen Peroxide (Hydrogen and its derivatives). Saxa Vord was chosen for simulating the production of these derivatives because of the high possibility of a larger project that could come up in its vicinity. This is because viability of the relatively new market expected for the chemical production project is still volatile. Therefore, it should be possible to simulate scenarios assuming that it can be subsumed within a larger company (if so decided by the community), diversifying the portfolio and thus diluting risk. The presence of a school and more residential complexes in Baltasound than Saxa Vord was also a factor that contributed to this selection.

Unlike the institutional buildings selected for the study in Baltasound, the hourly heat demand of any given year from Saxa Vord is more susceptible to variation in the future. But within a given year, the load is fixed and cannot be varied. On the other hand, electricity demand for the Chemical Production Project is more flexible. It can be run on residual load from the Renewable Energy system after meeting heating demand of Saxa Vord buildings. This is link between two projects.

The model treats production of the chemical derivatives as a separately owned project. However, it may be noted that for aforementioned feasibility reasons, it is possible to simulate co-ownership with the ESCO handing renewable energy production (combined financial indicators).

The ownership possibilities are left flexible in the model and this is further clarified in the description of the excel model in the Chapter 5:.

Chapter 5: Introduction to the Modelling Tool and Simulation of Scenarios

5.1 Introduction to the Modelling Tool

The system architecture described in the previous section was translated to MS Excel tools for Baltasound and Saxa Vord, which are flexible and at the same time transparent for the user. The tool is developed in order to check the feasibility of the renewable energy production and hydrogen and hydrogen derivatives production in Unst. Hence, it simulates the operation of the energy production and demand centres on an 8760 h time series.

The model also allows to modify various parameters in order to arrive at different user-defined scenarios. It must be considered that exact real-world situations cannot be simulated in the model and this should be considered while interpreting results. In order to make the modelling simpler, a number of assumptions were made.

5.1.1 Assumptions of the Model

- The return temperature of the wet heating systems is assumed to be 40 ° C. Therefore, the inlet water temperature to heat pumps and thermal storage is at this temperature.
- The temperature of water stored in the thermal storage is assumed to be 90 °C.
- The outlet water from the thermal storage and heat pump is assumed to be mixed in order to attain the required inlet temperature for the wet water heating system.
- The demand for space heating and domestic water heating is treated together in the model in energy terms. However, in real case the temperature requirement varies. It is assumed that water to domestic water heating gets separated and gets heated further according to the required temperature.
- The outlet temperature of the heat pumps is 45 ° C.
- The heat pumps are modelled in such a way that they adjust their output according to the demand capped by their capacity.
- A 60-kW ground source heat pump and an 8-kW air source heat pump are included in the model. The ground source heat pump may be scaled from 40 kW to 80 kW while it is assumed to have the characteristics of a 60-kW heat pump. Similarly, air source heat pumps from 5 to 15 kW are assumed to have the same characteristics of the 8-kW air source heat pump.

5.2 Simulation of Scenarios

Nothing in this world is constant. Everything is subject to change and has their own sensitivities. Considering this, various demand scenarios for buildings Chapter 6 and different priorities to hydrogen derivatives were considered while performing the simulation. Results of following scenarios have been described in this report:

- Scenario 1: Heat Demand only scenario/Saxa Vord Resort
- Scenario 2: 900 kW wind, heat priority and hydrogen production scenario/Saxa Vord Resort
- Scenario 3: Shifting heating and electrolyser priorities and Hydrogen Storage /Saxa Vord Resort

Some of the scenarios have sub scenarios as base case[1] demand scenario, full occupancy [2]demand scenario and 25 % efficiency on full occupancy demand scenario. The technical outcomes along with financial indicators are mentioned in the results of each scenario. Before going to the results of each scenario, a brief introduction to the financial analysis has been presented in the following section.

5.3 Financial Analysis

5.3.1 Methodology

In order to estimate economic impact, the approach adopted was to evaluate from the ownership perspective. Types of owners:

- Building owner: This refers to owners of buildings of Saxa Vord and Baltasound. Each set of buildings has its own inputs and outputs and they are separately visible in Baltasound. However, this is combined under one building ownership in Saxa Vord.
- Energy Service Company (ESCO): The ESCO is an incorporated as a society, company or cooperative which may be owned privately, publicly, in joint ownership as public-private ownership or collective by the community as a cooperative or trust.
- Entity producing Hydrogen, Ammonia and Hydrogen Peroxide: The chemicals' production is treated separately in the model. However, the financials are represented with separate ownership as well as ownership by the ESCO itself.

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[1] "Base Case" refers to a use of the buildings entirely for tourism

[2] "full occupancy" refers to a use of the buildings as residences and for tourism

Keeping the above ownerships in mind, the model structure produces results for following projects:

a) **Baltasound**:

Table 5.3.1 The details of financial modelling at Baltasound

Component / Project	Owner	Consumer	Parameters Fin. Analysis	Link to other components/projects
Heating System Leisure Centre	Unst Leisure Centre	Self-Consumption	Payback Period, Cash Flow (NPV)	Tariff paid to ESCO
Heating System School	Baltasound Junior High School	Self-Consumption	Payback Period, Cash Flow (NPV)	Tariff paid to ESCO
Heating System Care Centre	Nordalea Care Centre	Self-Consumption	Payback Period, Cash Flow (NPV)	Tariff paid to ESCO
Renewable Energy (RE) System	ESCO	Buildings (Leisure Centre, School and Care Centre)	NPV, IRR, Debt Service Coverage Ratio (DSCR	Income from Buildings (Leisure Centre, School and Care Centre)

Source: Authors

b) Saxa Vord

Table 5.3.2 The details of financial modelling at Saxa Vord

Component / Project	Owner	Consumer	Parameters Fin. Analysis	Link to other components/projects
Project 1: **Heating System Saxa Vord owned by ESCO**	ESCO	Saxa Vord Buildings (through Heating system management company) Saxa Vord owners Directly	NPV, IRR, Debt Service Coverage Ratio (DSCR)	Income from Saxa Vord Buildings (directly or through heating system management company)
Project 2: **Chemicals Production System (H_2, NH_3 and H_2O_2)**	ESCO; or Other company	Businesses in Unst that may have a demand for H_2, NH_3 and H_2O_2)	NPV, IRR, Debt Service Coverage Ratio (DSCR)	Cost visible to ESCO; or Tariff paid to ESCO
Combined: (Combined of projects 1 and 2) **Renewable Energy (RE) System**	ESCO	Saxa Vord Buildings Chemicals Production System	NPV, IRR, Debt Service Coverage Ratio (DSCR)	Income from Saxa Vord Buildings; And/or Income from Chemical Productions System
Project 3: **Heating System Saxa Vord**	Saxa Vord Owners; Heating System Management Company	Self Consumption; Saxa Vord Buildings	Payback Period, Cash Flow (NPV)	Cost of heating visible to Heating System Management Company; or Tariff paid to ESCO

Source: Author

It is considered that the building owners in Saxa Vord and Baltasound would invest in their own heating system or through another energy management company. This investment constitutes the heat pumps or solar thermal collectors, thermal storage, electric boiler, heat distribution system and backup from oil boilers.

5.3.2 Inputs and Assumptions

The projects feasibility for different scenarios was studied by generating the cashflow statement of Projects 1 and 2, as well as for the installation of RE sourced heating system by buildings. Costs and revenue were adjusted to an inflation rate of 1.4% estimated from historical figures (TradingEconomics, 2019).

To better reflect future cashflow, discount rate was set to Weighted Average Cost of Capital (WACC) calculated at 3.72% for Project 1 and 3.77% for Project 2 in the United Kingdom (WACC Expert, 2019), reflecting marginally higher risk for the derivatives project[3].

The input for investment costs, operational expenses and fuel rates were calculated individually for all components of the project as mentioned in Chapter 8:. Currency conversion selected for all values is that One GBP equals EUR 1.15 or USD 1.32 as of 25th February 2019 (XECorp., 2019).

5.3.3 Project Financing

Parameters for financing chosen to simulate scenarios included constant repayment structure over a maturity period of 15 years and interest rate of 3.75 %. The interest rate assumed was significantly lower than business loan figures by commercial banks. However it is marked up higher than rates offered for SMEs by cooperative / regional banks (Barclays, 2019; MoneyFacts, 2019). Assets have been capitalized over lifetime of assessment by straight line depreciation of assets for 10 years. It must be noted that losses were carried forward to defer tax liability, subject to regulatory restrictions (GOV.UK, 2018).

5.3.4 Indicators

One of the important indicators of output costs was the levelized cost of electricity, heat and derivatives which was calculated to estimate pricing of the products in the market. The method to calculate LCOE was referred to from the Simple Levelized Cost of Energy (LCOE) Calculator by National Renewable Energy Laboratory (NREL, 2010). The tool includes the

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[3] WACCs of 3.72% and 3.77% were calculated using WACC Expert for United Kingdom, drawing an analogy between Project 1 with Utilities Sector and Project 2 with the Chemicals sector. Corporate tax of 19% for UK (GOV.UK, 2019) was incorporated as a detailed assumption while calculating weighted cost of debt in the calculation.

option to mark up this value and establish a profit-based tariff flexible to subsidy or price premiums.

The bankability of Projects 1 and 2 for the ESCO was measured in terms of Debt Service Coverage Ratio (DSCR), which is required to above market benchmarks for financing. Since these projects are technically high risk due to uncertain demand, especially the derivatives, the financing institution would require values as high as 1.4, but this can be reduced to lower ranges like 1.1-1.2 if there is assured government support to meet some costs as operational premiums or capital subsidy (Barclays, 2019).

The value for investors and shareholders is visible in terms of the Net Present Value (NPV) that represents discounted cashflow over the 25-year period chosen for lifetime analysis. For the ESCO, combined value of NPV is a significant indicator of overall viability, where the high risk of one project can be offset by the other, as is demonstrated in the tool. This can be achieved by methods like cross-subsidizing between the projects, proportionate to value for the buildings or derivatives and the consistency of demand.

In case of a positive NPV, the Internal Rate of Return (IRR) of the project is an indicator of good investment, when exceeding the WACC of company. For the assessment of the investors, the IRR Shareholders indicator presents the estimated return on their holding in the enterprise which could be the ESCO or the Energy management company for the Buildings. It is here that opportunity for local investors exist to collaboratively generate a sustainable and clean energy driven economy.

In order to evaluate the return on investment of the buildings, their payback period is calculated vis a vis existing scenario, which accounts for a cashflow from savings on oil consumption or electric consumption from existing grid. This indicator is critical in perceiving the choice for the building owner between existing dependence (cost of heating) on the current heating system or a purely RE driven system with heating system design improvement.

5.3.5 Uncertainties in Financial Parameters

The flexibility in the model is important considering the high variability in inputs which are possible. Considering this, there are some factors to consider while interpreting results from the scenarios simulated in following sections:

- Demand Assessment approximation is affected by the sporadic occupancy pattern in case of Saxa Vord, unbalanced between seasons and future plans, thus affecting agreement on tariff and therefore revenue.
- Variability of wind energy is also subject to volatility due evident by studied wind patterns, and this directly affects revenue stream.
- The price of oil is a constant assuming value available from 2018, but it is an extremely volatile component of the system given its high dependence on global markets, especially over long period of time.

5.4 Introduction to simulation

The model was simulated for the two project locations: Saxa Vord and Baltasound (Leisure Centre, School, Nordalea Care Centre). The energy production for Baltasound was simulated initially considering the low demand of this location. The hydrogen production centre was not simulated for this location, considering the lower wind speeds at this location and the proximity of the school. Following sections describe the simulation results for both the locations.

5.5 Simulation results for Baltasound location

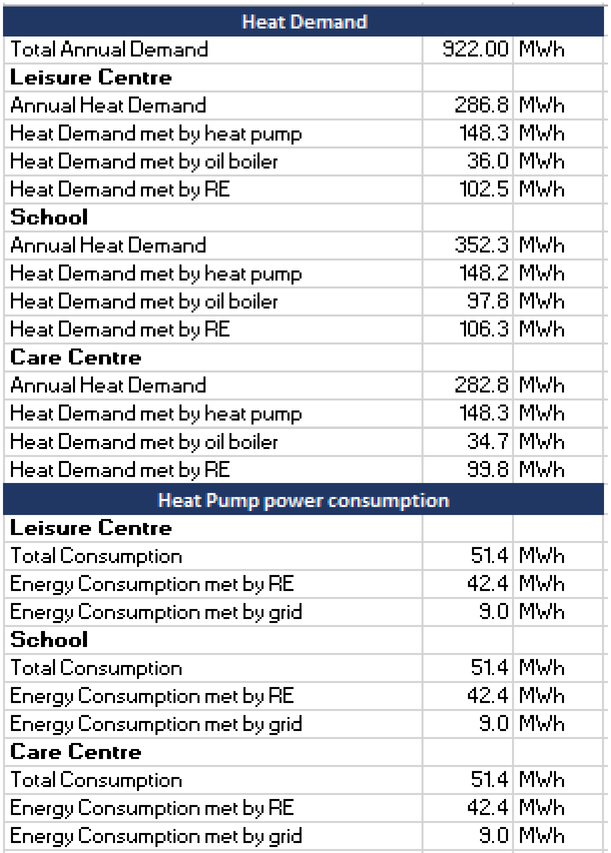
The target of the simulation was to obtain an optimum mix of the renewable energy technologies to meet the heat demand and minimize the oil consumption for all the three locations in Baltasound. Considering the annual demand of 922 MWh for the location, one 100 kW turbine along with other technologies were simulated.

Table 5.5.1 Details of the simulated energy mix

Energy Technology	Capacity simulated
Wind	100 kW
Heat Pump	2x10 kW for three locations
Thermal Storage	1000 kWh (17 m^3) for 3 locations
Electric Boiler	100 kW for 3 locations

Source: Authors

The oil consumption percentage came out to be 18 % of the total demand and 17.5 % of the heat pump consumption was supplied from the grid Table 5.5.1. The Levelized cost of heating obtained was 0.10 to 0.12 GBP/kWh for the three locations and the levelized cost of renewable energy was 0.068 GBP/kWh. The buildings receive no payback during the 25 years life time with this configuration. Reducing the number of heat pumps increases the oil consumption. However, the buildings still receive no payback due to the high initial investment cost of the turbine and the low demand of the location. The RE heat supplying project to the buildings also ends up with negative NPV due to a low demand of the location. Using a cheaper wind turbine will make the project feasible. Also, this situation should be regarded as a potential for integrating the buildings demand with the green hydrogen production by using a larger capacity wind turbine. A similar opportunity exists for the Saxa Vord Resort project location and this will be simulated for the Saxa Vord Resort location.



Heat Demand		
Total Annual Demand	922.00	MWh
Leisure Centre		
Annual Heat Demand	286.8	MWh
Heat Demand met by heat pump	148.3	MWh
Heat Demand met by oil boiler	36.0	MWh
Heat Demand met by RE	102.5	MWh
School		
Annual Heat Demand	352.3	MWh
Heat Demand met by heat pump	148.2	MWh
Heat Demand met by oil boiler	97.8	MWh
Heat Demand met by RE	106.3	MWh
Care Centre		
Annual Heat Demand	282.8	MWh
Heat Demand met by heat pump	148.3	MWh
Heat Demand met by oil boiler	34.7	MWh
Heat Demand met by RE	99.8	MWh
Heat Pump power consumption		
Leisure Centre		
Total Consumption	51.4	MWh
Energy Consumption met by RE	42.4	MWh
Energy Consumption met by grid	9.0	MWh
School		
Total Consumption	51.4	MWh
Energy Consumption met by RE	42.4	MWh
Energy Consumption met by grid	9.0	MWh
Care Centre		
Total Consumption	51.4	MWh
Energy Consumption met by RE	42.4	MWh
Energy Consumption met by grid	9.0	MWh

Figure 5.5.1 The output of the simulation showing contribution of different sources to meet the heat demand

Source: Authors

5.6 Simulation results for Saxa Vord Resort Location

The Saxa Vord resort has a higher demand than the buildings considered in Baltasound location. In the base case demand scenario section 6.4 , the annual demand is 1527 MWh which is 1.65 times the annual demand of Baltasound location. Hence, the scenario without hydrogen production (Heat Demand only scenario) just to meet the heat demand of the location was simulated.

5.7 Scenario 1: Heat Demand Only Scenario Saxa Vord Resort

The simulation was performed to meet the heat demand with renewables with minimum oil consumption. In the simulation tool, the electrolyser capacity was set to zero.

Table 5.7.1 Details of the simulated energy mix for the Heat Demand Only Scenario

Energy Technology	Capacity simulated
Wind	100 kW
Heat Pump	2x40 kW
Thermal Storage	1000 kWh (17 m^3)
Electric Boiler	100 kW

Source: Authors

The thermal storage size was chosen by observing the levelized cost of heat and the oil consumption percentage of the buildings. The storage size was chosen as 17 m^3 based on Figure 5.5.1. After 17 m^3, the decrease in LCOH was considerably low. For selecting the storage size, the same approach has been used in the simulation of all scenarios.

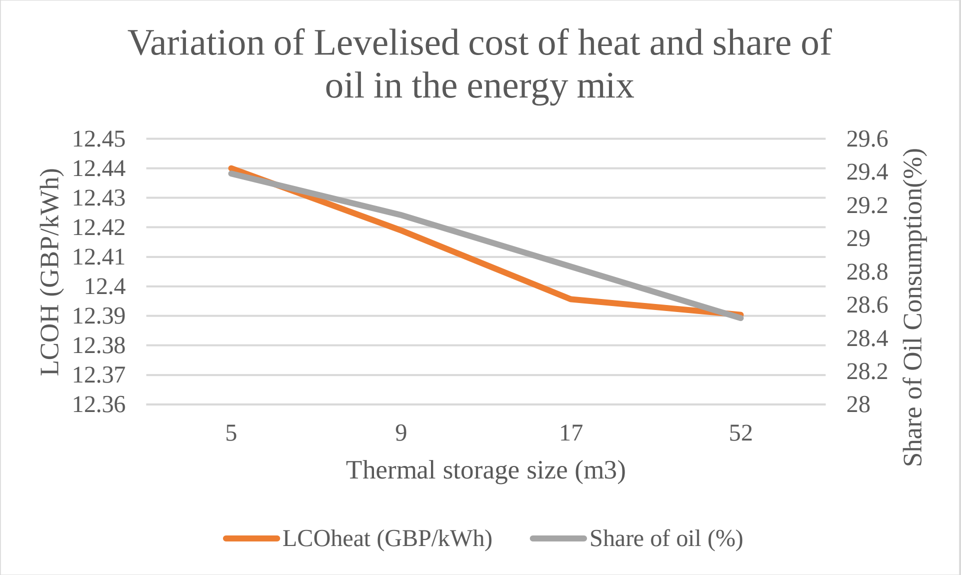


Figure 5.7.1 Variation of LCOH and share of oil consumption with change in storage size

Source: Authors

The monthly distribution of energy mix and the RE and grid contribution to heat pump power requirement obtained are shown in Figure 5.7.2 and Figure 5.7.3.

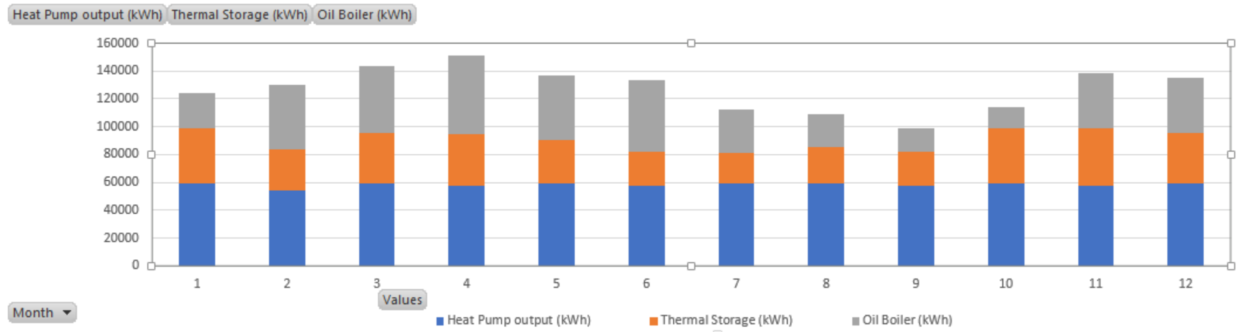


Figure 5.7.2 Monthly distribution of the energy mix in meeting the heat demand

Source: Authors

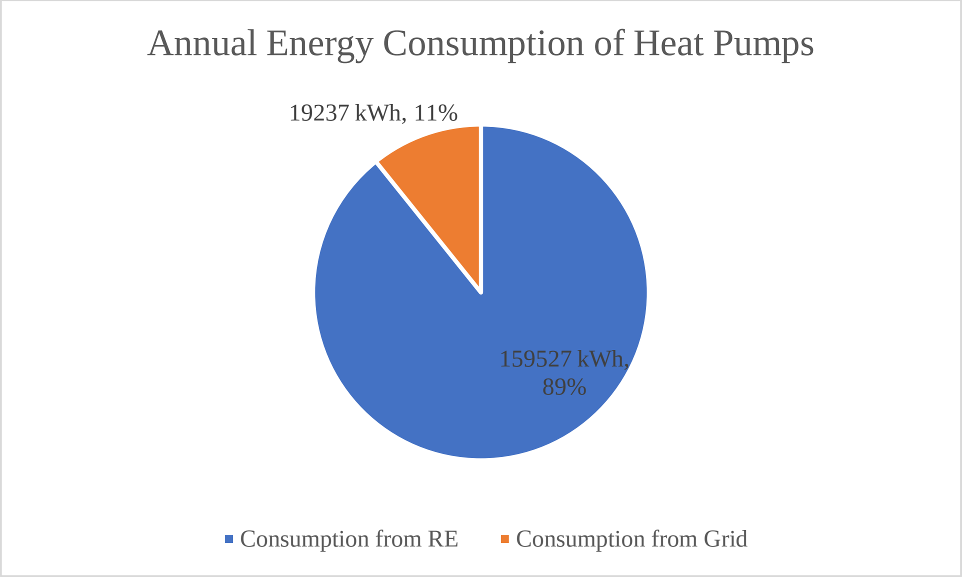


Figure 5.7.3 Annual energy consumption of heat pumps

Source: Authors

The Levelized cost of heat for this scenario was 0.12 GBP/kWh and the levelized cost of RE electricity was 0.15 GBP/kWh which is relatively higher cost. A payback calculation of investing in building heating system gives a payback in 10 years. However, due to the lower demand of buildings the IRR of the RE heat supplying project was found to be 1 %. This again highlights the opportunity to integrate a hydrogen production centre with a large capacity wind turbine. This scenario was simulated, and results are presented in the coming sections.

5.8 Scenario 2: 900 kW Wind turbine and hydrogen production with heat as priority.

In this scenario are going to be evaluated the impacts in the energy mix and heating technologies required to reach the heat demand as a priority and to produce hydrogen with the remaining energy in Saxa Vord, considering a variation in the demand according to a:

- Base case demand in section 6.4
- Full Occupancy demand in section 6.4
- 25% Efficiency on full occupancy demand in section 6.5.2.1

The production of ammonia and hydrogen peroxide is not simulated in this scenario. The control philosophy is defined as “Heat priority” and the indicators that are going to be compared are the IRR, IRR Stakeholders, NPV, DSCR and the Levelized Cost of Electricity, levelized cost of heat, levelized cost of hydrogen and the adequate technology configuration for the heating system Saxa Vord project, chemical production system project and ESCO project.

5.8.1 Base case demand

Inputs

In order to fulfill the heat demand of the base case, several simulations were performed in order to understand the behavior of the parameters and their impacts in the outputs. As a result, it was found the best configuration in order to cover the demand and production of hydrogen. The energy mix and heating technologies were selected according to the Table 5.8.1 below.

Table 5.8.1 Input parameters base case scenario 900 kW

Technology	Installed Capacity	Units
Wind capacity	900	kW
Heat pumps	100	kW
Thermal storage	1000	kWh
Hydrogen electrolyser	800	kW

Source: Authors

As described in the previous section, there is no possibility of producing hydrogen with a 100 kW turbine, increasing the number of turbines increases also the costs and is not recommended. According to this a 900 kW turbine is selected due to its advantage in cost and energy production.

In order to define the configuration, the impacts of the heat pump were evaluated as can be seen in the Table 5.8.2 below. According to this is was found that using 2 heat pumps of 50 kW obtains adequate and positive output parameters.

Table 5.8.2 Heat pump capacity analysis for 900 kW turbine – Base case demand

Heat pump Capacity kW	Payback Years for heating system Saxa Vord	IRR for ESCO project	LCOE GBP/kW	LCOH GBP/kW	% of oil used	% of Share of heating from thermal storage
40	3	10	0.045	0.088	27.52	49.55
60	3	10	0.045	0.087	18.24	47.36
80	2	10	0.045	0.085	11.05	43.08
90	2	10	0.045	0.085	8.157	40.25
100	**2**	**10**	**0.045**	**0.085**	**5.864**	**36.87**
120	3	10	0.045	0.085	2.671	28.93

Source: Authors

Same procedure was developed to define the optimize the thermal storage size, as a result a 1000 kW was selected as the best option.

Table 5.8.3 Thermal storage analysis for 900 kW turbine- Base case demand

Thermal storage kW	Payback Years for heating system Saxa Vord	IRR for ESCO project	LCOE GBP/kW	% of oil used	% of Share of heating from thermal storage
500	3	10	0.045	6.681	36.03
1000	**2**	**10**	**0.045**	**5.864**	**36.87**
1500	3	10	0.045	5.312	37.40

Source: Authors

The residual Load after covering the heating demand is used for the Hydrogen production in order to take advantage of the excess energy in the system. To obtain the best configuration, it was analyzed the production of hydrogen to obtain positive indicators. Nevertheless, more variations in the control philosophy and priorities were analyzed and are explained in the later sections.

This analysis considers heat has priority over the use of high-pressure storage of hydrogen. According to this configuration different sizes of electrolyser were analyzed as shown in the Table 5.8.4 below, the size selected is 800 kW were the LCOE and cost of hydrogen obtain good results.

Table 5.8.4 Hydrogen electrolyser capacity analysis for 900 kW turbine- Base case demand

Hydrogen electrolyser kW	Payback Years for heating system Saxa Vord	IRR for ESCO project (%)	LCOE GBP/Kw	Cost hydrogen GBP/ kg
650	3	10	0.048	2.25
700	3	10	0.046	2.33
750	3	10	0.045	2.43
800	3	10	0.045	2.55
850	3	10	0.045	2.69

Source: Authors

Outputs

The energy demand is covered with a total wind generation of 4101 MWh with a capacity factor of 52.02% and a total excess energy of 274.1 MWh.

The Ground Source Heat Pump contributed 875.2 MWh to a total demand of 1527.76 MWh with an annual unmet demand of 81.15 MWh that is being covered with the oil boiler. The electricity consumed by the electric boiler is 618 MWh which is powered by wind energy.

The hydrogen production outputs can be seen in the Table 5.8.5 below.

Table 5.8.5 Hydrogen production with 900 kW turbine- basic demand scenario

Hydrogen Production				
Produced Hydrogen:	51948.4	Kg	51.95	Tonnes
Produced Oxygen:	205736.4	Kg	205.7	Tonnes
Utilized Energy:	2861.0	MWh		
Capacity Factor:	46.57%			
LPS Hydrogen	108.50	Kg		
Pressurized Hydrogen	5183993	Kg	51.84	Tonnes
Excess Oxygen	20573638	Kg	205.7	Tonnes

Source: Excel tool

Financial Indicators

The LCOE obtained is 0.045 GBP/kWh.

The LCOH obtained is 0.085 GBP/kWh.

The cost of hydrogen obtained is 2.55 GBP/kg.

As can be seen in the Table 5.8.6 below the indicator involved with hydrogen production, Hydrogen Production project and ESCO project are positive.

Table 5.8.6 Financial indicators for 900 kW turbine – Basic case demand

Outputs		
Indicator	**ESCO Project**	units
IRR	10%	%
IRR Shareholders	17%	%
NPV	3,653.296.12	£
DSCR (min)	1.367256831	-
ADSCR	1.755640863	-

Source: Excel tool

The Saxa Vord heating system project has a payback period of 2 years in the heating system investments.

5.8.2 Full Occupancy demand

Now a sub scenario when the residential buildings are permanently occupied was simulated in order to identify the sensitivity of the project towards the demand.

Inputs

The configuration simulated can be seen in Table 5.8.7 below.

Table 5.8.7 Input parameter 900 kW -Full occupancy demand

Technology	Installed Capacity	Units
Wind capacity	900	kW
Heat pumps	100	kW
Thermal storage	1000	kWh
Hydrogen electrolyser	800	kW

Source: Authors

The same methodology was utilized to define the heat pump capacity as can be seen in Table 5.8.8 below

Table 5.8.8 Heat pump capacity analysis for 900 kW turbine – Full occupancy demand

Heat pump Capacity kW	Payback Years for Saxa Vord heating system project	IRR for ESCO project	LCOE GBP/Kw	% of oil used	% Share of heating from thermal storage
40	3	10	0.044	48.12	35.59
80	3	10	0.044	33.61	33.81
100	3	10	0.044	27.11	32.18
120	3	10	0.044	21.32	29.92

Source: Authors

Even though increasing the heat pump capacity decreases the oil consumption, in reality in order to keep the heat pump efficient it is run at a lower output (45 ^{o}C in the modelling assumption) and inlet temperature. Therefore, the heat pump should not be allowed to cover the entire heat demand throughout the year. Especially in winter, when the inlet temperature to wet heating system is required to be around 60 ^{o}C. Therefore, energy from heat pump has to be complemented with the energy from thermal storage to achieve higher temperature. In this case, we do not increase the heat pump capacity beyond 100 kW.

Same procedure was developed to define the adequate thermal storage size, In the table below it can be seen that there is no considerable change in the % of oil used and the % Share of heating from thermal storage. As a result, it was decided to keep 1000 kW as was selected in the basic demand scenario.

Table 5.8.9 Thermal storage analysis for 900 kW turbine- Full occupancy demand scenario

Thermal storage kW	Payback Years	IRR	LCOE GBP/Kw	% of oil used	% Share of heating from thermal storage
500	3	10	0.044	27.38	31.92
1000	**2**	**10**	**0.044**	**27.11**	**32.18**
1500	3	10	0.044	26.94	32.38

Source: Authors

Outputs

The energy demand is covered with a total wind generation of 4101 MWh with a capacity factor of 52,02% and a total excess energy of 274.1 MWh as in the basic demand scenario.

The Ground Source Heat Pump 875.5 MWh from a total demand of 2151 MWh with an annual unmet demand of 589.0 MWh that is being covered with the oil boiler. The electricity consumed by the electric boiler is a total of 695.8 MWh which is powered by wind.

The hydrogen production outputs can be seen in Table 5.8.10 below.

Table 5.8.10 Hydrogen production with 900 kW turbine- Full occupancy demand scenario

Hydrogen Production				
Produced Hydrogen:	53435.8	Kg	53.44	Tones
Produced Oxygen:	21162.8	Kg	211.6	Tones
Utilized Energy:	2936.8	MWh		
Capacity Factor:	41.91%			
LPS Hydrogen	108.17	Kg		
Pressurized Hydrogen	53327.59	Kg	53.33	Tones
Excess Oxygen	211626.80	Kg	211.6	Tones

Source: Excel tool

Financial Indicators

The LCOE obtained is 0.044 GBP/kWh.

The LCOH obtained is 0.085 GBP/kWh.

The cost of hydrogen obtained is 2.59 GBP/kg.

As can be seen in Table 5.8.11 below the indicator involved with hydrogen production, Hydrogen Production project and ESCO project are positive.

Table 5.8.11 Financial indicators for 900 kW turbine – Full occupancy demand

Outputs		
Indicator	**ESCO project**	Units
IRR	10%	%
IRR Shareholders	17%	%
NPV	3,596.362.58	£
DSCR (min)	1.358206064	-
ADSCR	1.743334864	-

Source: Excel tool

It could be seen that in the case of full occupancy demand the payback period of building heating system investment has increased to 3 years. Therefore, a scenario with better efficiency of the buildings was further simulated to see the effect in financial parameters.

5.8.3 25 % efficiency on the full occupancy demand

The inputs remain the same as in the full occupancy scenario in order to see the effect of increasing the efficiency in the buildings.

Outputs

Total excess energy of 118.2 MWh as in the basic demand scenario.

The Ground Source Heat Pump 871.2 MWh from a total demand of **1613 MWh** with an annual unmet demand of 188.38 MWh that is being covered with the oil boiler. The electricity consumed by the electric boiler is a total of 568.9 MWh.

It can be seen an increase on the hydrogen production from 53.44 to 55.13 tons implementation of the efficiency in comparison with the full occupancy demand and around 4 tons from the basic case demand from 51.95 to 55.13 tons of hydrogen production.

Financial Indicators

The LCOE obtained is 0.045 GBP/kWh.

The LCOH obtained is 0.085 GBP/kWh.

The cost of hydrogen obtained is 2.51 GBP/kg.

When implementing 25 % efficiency in the buildings, the financial indicator IRR for the ESCO project does not change but it could be seen that the payback period of heating systems Saxa Vord project improved to 2 years.

5.8.4 Conclusions for this scenario

- The LCOE, LCOH and cost of hydrogen remain similar with the variation on the demand.
- The oil consumption helps to maintain the levelized cost prices almost constant, nevertheless, is possible to observe a considerable increase of share considerable from base case scenario to full occupancy scenario.
- The production of hydrogen varies in around 2 to 4 tons with the variation of the demand.
- Payback period for Saxa Vord heating systems project increases with increase in heat demand.

5.9 Scenario 3: Shifting Heating and Electrolyser Priorities and Ammonia Production.

As per the previous section, the best performance of the project was reached when only hydrogen is produced as the result for the price of ammonia and hydrogen peroxide was above the market price. In this section, it will be analysed the effect of shifting the control priority from heat demand to hydrogen and the profitability of the project with an increased high-pressure hydrogen storage. With the shift of priority, an increase in the capacity factor of the hydrogen electrolyser is expected and a decrease on the cost of production. Nonetheless, an increased cost for heating the buildings is also expected. Both conditions will influence the overall performance of the projects which will be evaluated.

In order to evaluate such scenarios; hydrogen peroxide production and Electric Batteries were disabled for all the simulations and the rest of the parameters were fixed as shown in the Table 5.9.1.

Table 5.9.1 Fixed Inputs for Priority Shifting Scenarios

Scenario	Base Scenario		Full Occupancy	
Wind Turbine	Enercon (900 kW)	1	Enercon (900 kW)	1
Heat Pumps	50 kW	2	50 kW	2
Electric Boiler	100 kW	1	100 kW	1
Heat Storage	1000 kWh	1	1000 kWh	1
Electrolyser	750 kW	1	750 kW	1
LPHS capacity	150 kg	1	150 kg	1

Source: Authors

5.9.1 Heating Supply

The heating supply has the advantage of having a back-up system for supplying the demand. This flexibility can be used for taking advantage of the peaks of wind production while providing uninterrupted heat supply for the systems. However, an increase in the oil consumption may negatively affect the Levelized Cost of Heating the buildings. As it was expected, the change in control philosophies generated a different share of energy in the buildings. The different shares are shown in the Table 5.9.2.

Table 5.9.2 Thermal Energy Balance for Saxa Vord Heat Demand

Fuel	Base Case		Full Occupancy	
	Heat Priority	H_2 Priority	Heat Priority	H_2 Priority
Heat Pump (MWh)	875	875	876	876
Electric Boiler from RE (MWh)	563	264	692	283
Oil Boiler (MWh)	89	388	583	992
Total (MWh)	**1527**	**1527**	**2151**	**2151**

Source: Authors

In the base case scenario, it is important to emphasize that when heat is priority 94 % of the energy utilized by the heat pump was coming from the wind turbine, if the priority is shifted to hydrogen, only 42 % of the energy input for the heat pump comes from the wind turbine and the remaining 68 % is coming from the grid.

The different shares of energy affect the cost of heating the buildings and the LCOE, this will be shown in the next sections.

5.9.2 Hydrogen Production

The shift of the priority to hydrogen and derivatives will have a positive effect in the capacity factor and production. This is shown in the Table 5.9.3.

Table 5.9.3 Hydrogen and Derivatives Production Performance

	Base Case		Full Occupancy	
	Heat Priority	H_2 Priority	Heat Priority	H_2 Priority
H_2 CF (%)	45%	52%	44	52%
Pressurize Hydrogen (Ton)	53.6	61.8	53.2	61.7
H_2 Utilized Energy (MWh)	2956	3407	2896	3407
H_2 Compressor Energy (MWh)	614	707	602	707

Source: Authors

As expected, the capacity factor increased a 7 % while the hydrogen production and the utilized energy increased a 15 % compared with the heat priority scenario.

5.9.3 Production Costs and Heating Costs

The differences in capacity factors, energy sources, production rates and stored fuels and the total utilized energy of the scenarios should not affect the LCOE because the same amount of total energy is being utilized. However, the cost of heating buildings and cost of hydrogen and its derivatives will be affected. The results of the simulation are detailed in Table 5.9.4

Table 5.9.4 Cost for Different Scenarios

Cost	**Base Case**		**Full Occupancy**	
	Heat Priority	H_2 Priority	Heat Priority	H_2 Priority
LCOE (GBP/kWh)	0.04	0.04	0.04	0.039
Cost of Heat (GBP/kWh)	0.072	0.092	0.076	0.093
Cost of H_2 (GBP/kg)	4.94	4.53	4.94	4.52

Source: Authors

As it was expected, with the base case demand the priority is a determinant factor for achieving lower costs. When hydrogen was set as a priority High Pressure Hydrogen decreases its production cost by 8 % due to the increase of the capacity factor while the cost of heat the buildings increased an 27 % due to the use of oil and grid electricity in the heat pump. In the same way in the full occupancy scenario the cost of heating buildings increased by a 22 % and the cost of producing hydrogen decreased by 8.5 %.

5.9.4 Monthly Production

The integration of non-dispatchable power plants with more than one energy demands, as is heat for buildings and electricity for electrolysers, allows the system to install extra energy capacity in case this can be used by the demand with less priority. The winner of this integration is the participant with first priority because the extra capacity installed will allow the system to supply more reliable energy at a relatively lower price.

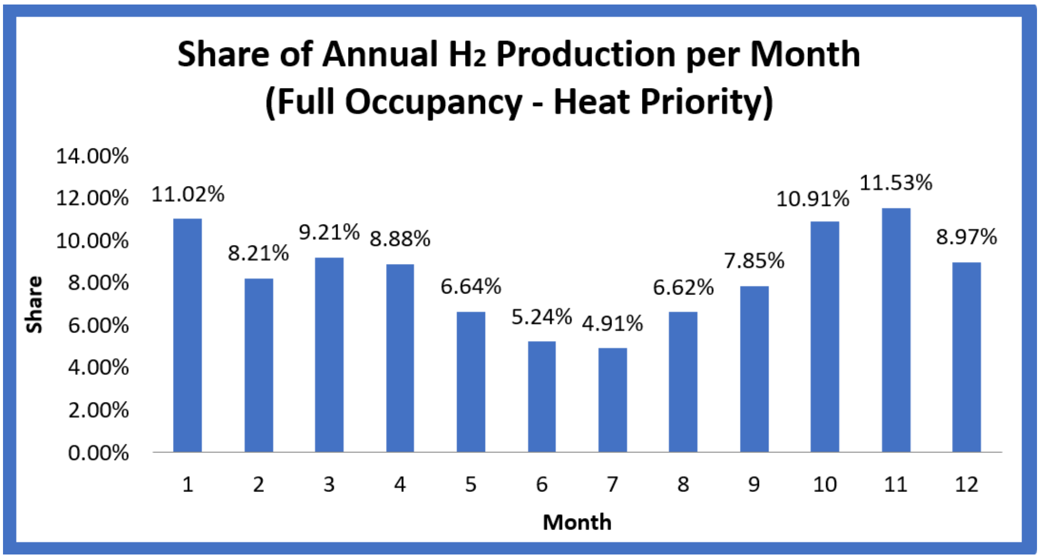


Figure 5.9.1 Monthly Share of Annual Production of Hydrogen (Heat Priority)

Source: Authors

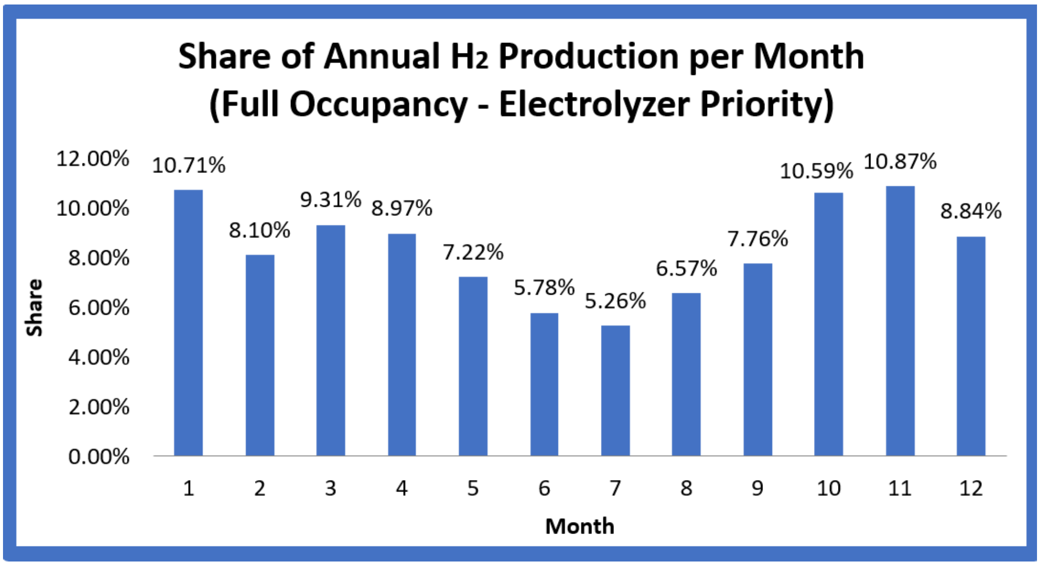


Figure.5.9.2 Monthly Share of Annual Production of hydrogen (Hydrogen Priority)

Source: Authors

As shown in Figure 5.9.1 and Figure.5.9.2, when hydrogen is a priority the production is less dependent of the peak months (October, to January) as they have decreased their share of the total production. Spring and Summer months have increased their share when hydrogen is first priority. Due to the overall increase of production, August and September have a lower share of the annual production.

The same pattern can be observed in the following figures. In Figure 5.9.3 the heat supply is regularly working with the heat pump and electric boiler. The share of the oil boiler is very less in all the months. On the other hand, in Figure 5.9.4 can be seen that the share of energy from renewables to the heat supply, depends on the peak of production that are available in the winter months. It can also be seen that the heat pump is utilizing with a higher input of the grid.

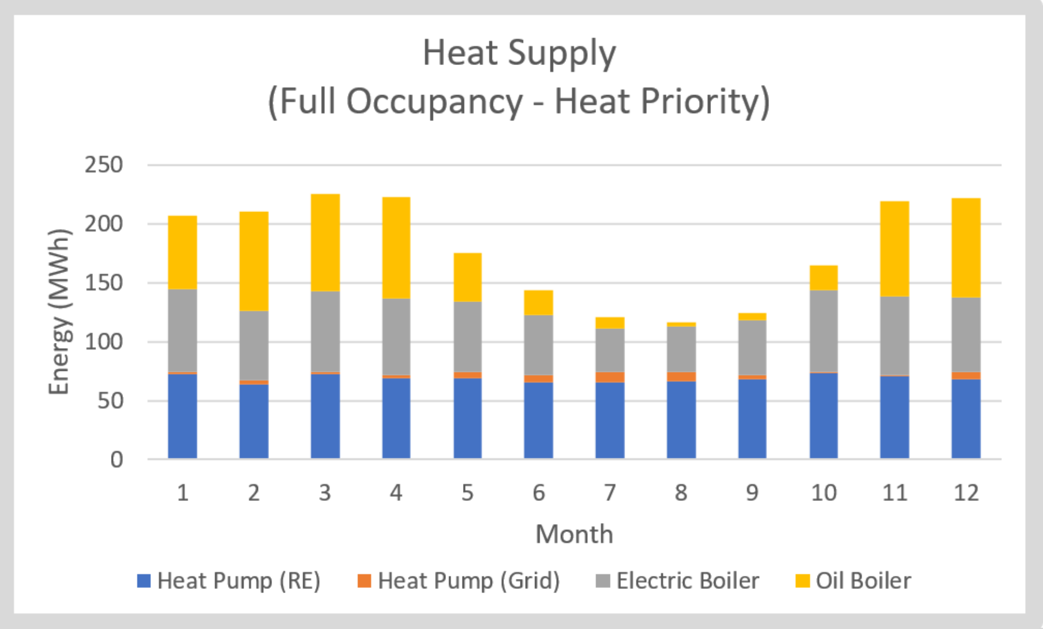


Figure 5.9.3 Heat Supply by Technology (Heat Priority)

Source: Authors

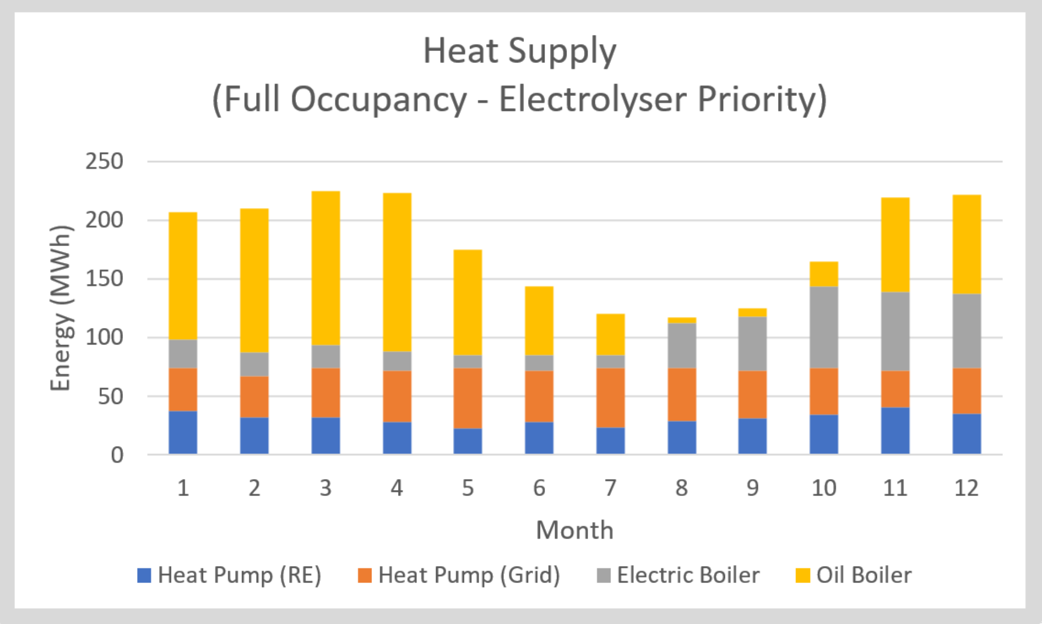


Figure 5.9.4 Heat Supply by Technology (Hydrogen Priority)

Source: Authors

For the scenarios with Base Case demand, the IRR improved from 6 % to 7 % when the priority was shifted from Heat Demand to Hydrogen Priority. In the same way, the NPV increased by 674,000 GBP going from 1.256 million GBP to 1.93 million GBP. In the same way, there was an improvement for the Full Occupancy scenarios when priority was shifted from heat demand to hydrogen production, the IRR improved from 6 % to 7 % while the NPV changed from 1.22 million GBP to 1.95 million GBP.

5.9.5 Including Ammonia Production along with the hydrogen

Under this sub-scenario, the effect of including the ammonia production is analyzed. The produced ammonia in the model has a higher cost than the price found in the market. However, the ability to produce ammonia represents an advantage to the island because there are more applications for the products. In order to evaluate up to what point ammonia can be produced and the whole project would be profitable, the ammonia production will be included and increased from 27 annual tons up to 105 tons. Therefore, in the heat priority scenario, ammonia is prioritized over hydrogen production.

Table 5.9.5 Effect of Ammonia Production and Financial Results

NH3 Produced (Tons)	27	54	80	105
IRR	5%	4%	3%	2%
IRR Shareholders	7%	5%	3%	1%
NPV (GBP)	779 600	312 350	(153 500)	(615 500)
Cost of NH3 (GBP/kg)	3.95	2.47	1.97	1.72
CF	82%	82%	81%	80%

Source: Author

As shown in the Table 5.9.5, the result is that the profit earned by the produced pressurized hydrogen compensates for the gap of ammonia price and makes the whole project sustainable.

5.10 Summary

The simulation of the Baltasound location shows that there is no payback for investing in building heating systems and not attractive for the renewable energy production entity also. However, this is an opportunity for a higher demand center like renewable hydrogen production center to be integrated with a large capacity wind turbine. The outcomes on financial indicators of the Saxa Vord heating system project (project 3) and the ESCO project (project 1 and project 2 combined) are summarized in Table 5.10.1, Table 5.10.2 and Table 5.10.3

Table 5.10.1 Summary of financial indicator of the Saxa Vord scenario 1

<table>
<tr><th>Scenarios vs Impacts</th><th>Building Heat Demand (Project 3)</th><th>ESCO (Project 1 and Project 2 combined)</th></tr>
<tr><td rowspan="2">Scenario 1</td><td>The cost of wind electricity production is higher. However, the buildings have a payback period of 10 years.</td><td>The lower demand of buildings makes the project less attractive for RE-Buildings</td></tr>
<tr><td colspan="2">The lower demand for buildings could be regarded as an opportunity to integrate renewable hydrogen production centre with a larger wind turbine.</td></tr>
</table>

Source: Author

Table 5.10.2 Summary of financial indicators of Saxa Vord Scenario 2

<table>
<tr><th>Scenarios vs Impacts</th><th>Building Heat Demand (Project 3)</th><th>ESCO (project 1 and project 2 combined)</th></tr>
<tr><td rowspan="2">Scenario 2 (900 kW turbine with heat demand priority and hydrogen production)</td><td>The payback period for the building heating system investment increases with increase in demand</td><td>The ESCO project returns positive IRR of around 10 % for all the demand scenarios</td></tr>
<tr><td>For the heating system, the payback period is 2 years for base case demand and 3 years for the full occupancy scenario. Investing in efficiency improves the payback period</td><td>-</td></tr>
</table>

Source: Author

Table 5.10.3 Summary of financial indicator of Saxa Vord Scenario 3

<table>
<tr><th>Scenarios vs Impacts</th><th>Building Heat Demand (Project 3)</th><th colspan="2">ESCO (Project 1 and Project 2)</th></tr>
<tr><td rowspan="2">Scenario 3</td><td>When Derivatives are priority, less energy for heating is available, so share of grid electricity increases. This increases heating cost for the building</td><td colspan="2">If derivatives are priority, the electricity available to buildings is unreliable, which increases gap between LCOE of RE and acceptable tariff agreement with building
.
When there is a heat priority, production of hydrogen is lower. This leads to higher cost of production. The financial indicators were not affected when the heat and electrolyser priority was modified.</td></tr>
<tr><td colspan="2">Derivatives priority creates an expectation gap between cost of producing RE based electricity and expected building tariff. The ESCO’s interest would seem to conflict with the energy management company of the building heating system.</td><td>The production cost of both the derivatives were higher than the market price. However, small shares of ammonia (54 tonnes) can be produced and the project is still profitable due to the profit margin from hydrogen production.</td></tr>
</table>

Source: Author

Chapter 6: Heat demand assessment

6.1 Introduction

This chapter covers not only the methodology used to determine and analyse the current heat energy use and efficiency of the project buildings, but also the results of these assessments. It also highlights the state of the current building stock and the emissions that could be avoided if renewable heating is implemented at 100 % or a techno-economically feasible level. It also includes a valuation for the implementation of a mini district wet heating system and hot water storage tank at Saxa Vord resort.

6.2 Building Stock information

Geographically the buildings are located on Unst island, Shetland, Scotland, United Kingdom. The project buildings are the Nordalea Care Centre, Unst Leisure Centre, Baltasound Junior High School and buildings at Saxa Vord.

Table 6.2.1 and Table 6.2.2 represent the project building stock with their gross internal area, methodology used, and building base load for Baltasound and Saxa Vord respectively. The corresponding building ID and building location can be paired using the maps in Figure 6.2.1 and Figure 6.2.2. UK energy benchmarks are only computed with gross internal area (Communities and Local Goverment, 2008, p. 28) . The BBRI (2005, p. 16) defines the gross internal floor area as the:

> ‘area of a building measured to the internal face of the perimeter wall at floor level. It includes areas occupied by internal walls and partitions, columns, piers and other internal projections, internal balconies, stairwells, toilets, life lobbies, fire corridors, atria, measured at base level only, and covered plant rooms. It excludes the perimeter wall thickness and external projections, external balconies and external fire escapes.’

The gross internal area was therefore estimated from building plans provided by the different stakeholders.

6.2.1 Unst Leisure Centre

Managed by the Shetland Recreational Trust, Unst Leisure Centre is open for all people of all ages and abilities. The centre has a 12.5 m x 5 m pool with a lagoon, games hall, squash court, gym, community room, viewing balcony with two pool tables, football table and several vending facilities (Shetland Recreational Trust, no date).

According to a site visit in February 2019, the leisure centre is currently oil heated by two Clyde Combustion 505-9 boilers each 305 kW 6 bars 90^{o}C boilers and domestic hot water supplied a Hoval CT 180 calorifier. An air handling unit running through a heat exchanger from the boiler ensures the air temperature and humidity in all parts of the buildings is comfortable. The pool water is kept at 28 ^{o}C all year round. An Energy Performance Certificate done by Green Tourism indicated the area of the building is 1370.6 m^2 and the energy intensity is 256.86 kWh/ m^2.

The heating oil used, kerosene 28 second or burning oil, has a net calorific value of 43.69 ± 0.51 MJ/kg and an emission factor of 72 ± 1.8 t CO_2/ TJ (Staffell, 2011, p. 2).

6.2.2 Nordalea Care Centre

According to the Community Care Services of the Shetland Islands Council (2013a), the care centre is a resource centre for adults built to accommodate up to 7 residents. There are 6 single rooms and one double room. Each of the rooms has an en suite toilet and shower. There is a lounge in the residential area of the building and large lounge, dining room and conservatory (Community Care Services Shetland Islands Council, 2013b).

The Energy Performance Certificate in the building issued in 2009 indicated that the building was constructed in 2002, has a gross internal area of 1082.9 m^2 and energy intensity of 231 kWh/m^2. Further analysis of the oil consumption data provided by the Shetland Island Council indicated that the heat energy intensity in 2011-12, 2012-2013, 2013-14 and 2014-15 as 316.34 kWh/m^2, 315.02 kWh/m^2, 274.83 kWh/m^2 and 290.29 kWh/m^2 respectively with the years starting from April to March. The building is primarily floor heated and kept at around 20 ^{o}C by two Falcon GTE 7 oil boilers each rated 92 kW 4 bars 110 ^{o}C and domestic hot water supplied using a 44.8 kW calorifier. A Perkins P100 kerosene 28 fuelled 100 kVA three phase generator is also used for backup during period of power blackout and runs from the same kerosene storage as the boilers.

6.2.3 Baltasound Junior High School

Baltasound Junior high school is UK’s most northern education institution. The school currently provides nursery, primary and secondary education for the whole island of Unst. Some of the buildings are reported to have been built as late as 1879 (Baltasound Junior High

School, no date). By building ID, 8 is currently not used and left in a dilapidated stated. The school is open from 8:55 to 15:40 Monday to Thursday and only 8:55 to 14:00 on Friday. The school library is open Monday to Thursday 9:30 to 15:00 (BaltaSound Junior High School, no date). The school is currently all air heated using two Clyde Combustion 351-8 boilers each 261.872 kW 60 psi 100^{o}C boilers and domestic hot water is supplied by a Hoval CT 180 calorifier. The hot water from the boiler is fed into a central air heating system that circulates hot air to the whole building simultaneously.

Table 6.2.1 Building Stock Summary at Baltasound.

Building ID	Methodology	Building by use	GIA[4]/m^2	Heat Intensity kWh/m^2/year
1	I	Nordalea Care Centre	1082.9[5]	290.29[6]
2	I	Unst Leisure Centre	1370[7]	256.86[8]
3	I	Old School Building	131	Not required
4	I	Main School Building	4291	
5	I	School Oil Store	57	
6	I	School Building-Part of music room	40	
7	I	School Building - Music Room	312	
17	I	School Old Building	1216	

Data Sources: Authors' analysis in QGIS of (OpenStreetMap Contributors, 2018) and Oil consumption data from Shetland Island Council or Shetland Recreational Trust

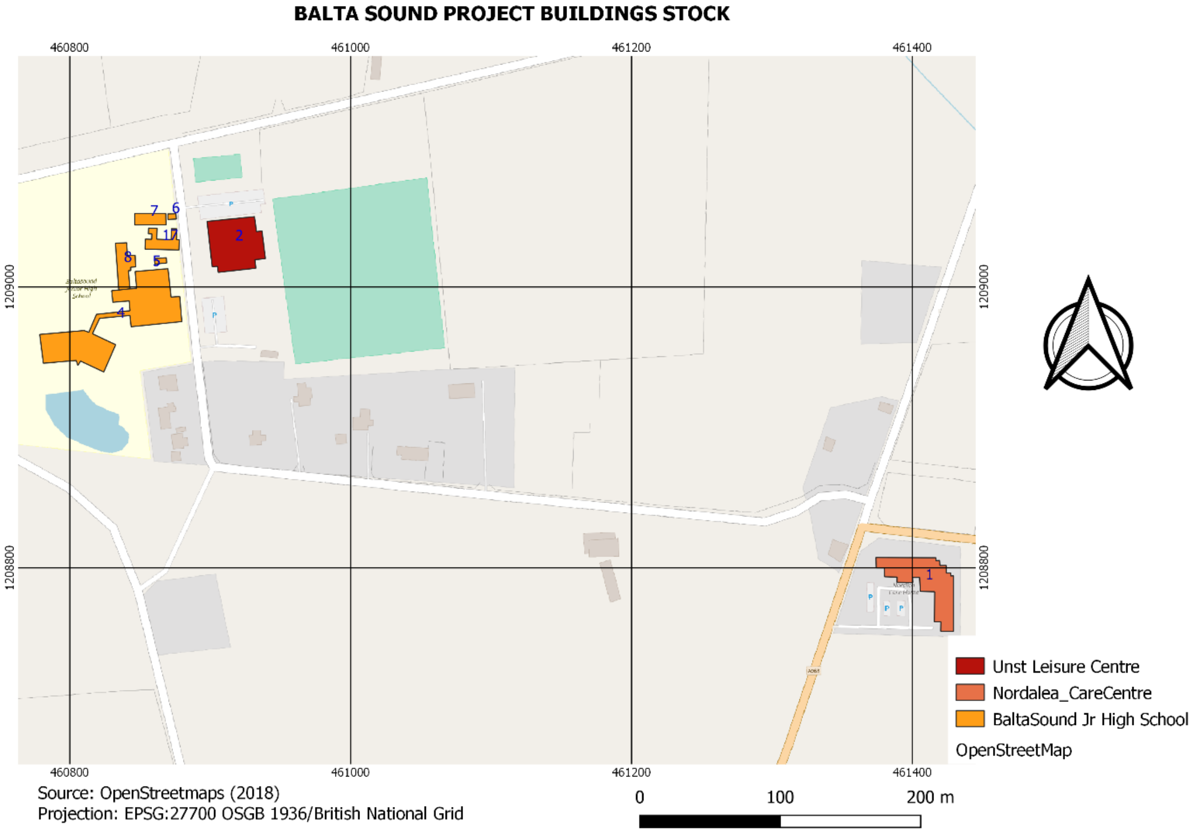


Figure 6.2.1 Baltasound Building Stock.

Source: Authors' analysis in QGIS of (OpenStreetMap Contributors, 2018)

6.2.4 Saxa Vord

Saxa Vord project building stock was constructed between 1989 and 1992. It has a mixed building usage and also different ownerships.

Table 6.2.2 and Figure 6.2.2 show the related building usage and location. An information meeting with site care taker indicated that the buildings were built under the Ministry of Defence specifications.

From a site visit in February 2019, by building ID, buildings 29 to 34 are linked with a wet heating system using a 450 kW Ideal Viceroy GT400 oil boiler. The boiler supplies both domestic hot water and space heating. Buildings 26 to 28 are going to be demolished and therefore are not included in the analysis, however the model allows for their incorporation in case they are simply renovated. Buildings 11,14-16 and 18-23 use electricity for both space heating and domestic hot water. The Nordabrake houses, building IDs 21 and 22, are both fitted with 4 kW insulated domestic hot water heaters as well as electric panel heaters and electric storage heaters. The mini-district heating system is old and requires reinvestment to improve its efficiency. There is evidence of degraded insulation and poorly insulated joints and flanges.

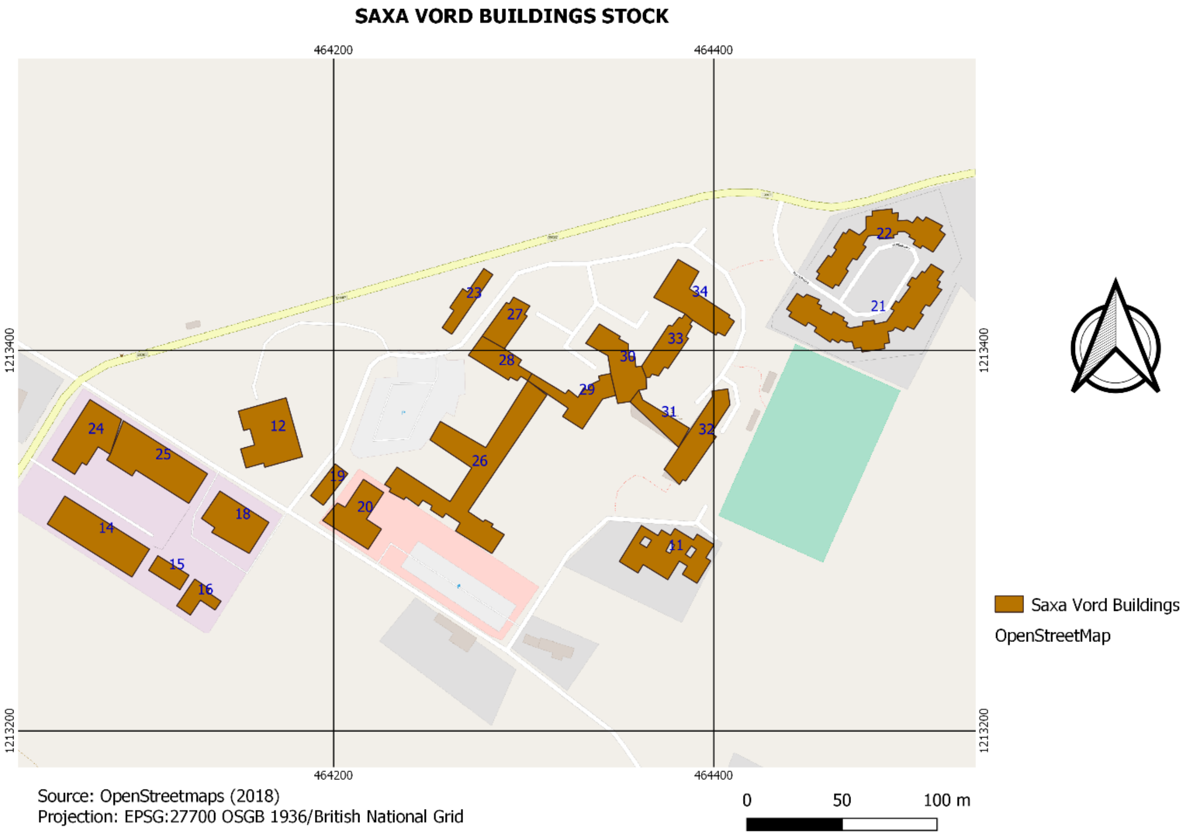


Figure 6.2.2 Building Stock at Saxa Vord.

Source: Author based on analysis in QGIS of (OpenStreetMap Contributors, 2018)

Table 6.2.2 Building Stock Summary

Building ID[9]	Methodology[10]	Building by use	GIA[11]/ m^2	Heat Intensity kWh[12]/m^2/year	Baseload [13]/ % of yearly demand
11	II	taftens Housings	1190	181	14.9%
12	II	Old Power house to be demolished	969	Not required	
14	II	Brewery	680	180	
15	II	Demolished	122	Not required	
16	II	Demolished	99	Not required	
18	II	Machinery Store (not heated)	816	Not required	
19	II	Guard room	114	181	14.9%
20	II	Medical Centre	673	200	16.7%
21	II	Nordabrake Housing 1	1200	181	14.9%
22	II	Nordabrake Housing 2	960	181	14.9%
23	II	Sheckleton Block	383	181	14.9%
24	II	Unst Distillery ltd	34	180	16.7%
25	II	Store	34	120	55.0%
26	II	Accommodation Blocks 12a	2652	181	16.7%
27	II	NAAFI Shop & Thrift shop (Retail plus office &Stores)	425	170	55.0%
28	II	Station HQ (Offices & Stores)	408	120	55.0%
29	II	Gymnasium (Indoor Recreation facilities)	332	440	55.0%
30	II	Kitchen area (Kitchen, offices &Stores)	859	370	55.0%
31	II	Amenity Centre (Lounge, coffee shop)	583	350	55.0%
32	II	Accommodation Blocks 12b	734	181	16.7%
33	II	Combined mess (Dining, bar & lounge areas)	503	350	16.7%
34	II	Accommodation Blocks 12c	808	181	16.7%

Data Sources: Authors' analysis in QGIS of (OpenStreetMap Contributors, 2018) and (Department of Energy& Climate Change UK, 2014, pp. 5–9)

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[9] Linked to Figure 6.2.2

[10] Method II is explained in Section 6.3

[11] Gross internal area obtained by adjusting gross external area obtained by analysing (OpenStreetMap Contributors, 2018) with QGIS by 85 % (space management group, 2006) or obtained from documentation provided by Saxa Vord management.

6.3 Methodology for hourly heat demand projection

Two main methodologies, Method I and Method II, as indicated in Table 6.2.1 and Table 6.2.2 were used to develop the distribution of heat demand with hours for the project buildings. At the core of these is the concept of heat degree days or hours.

According to Tony (2006, p. 1) ,

> ‘Degree-days are essentially the summation of temperature differences over time, and hence they capture both extremity and duration of outdoor temperatures. The temperature difference is between a reference temperature and the outdoor air temperature. The reference temperature is known as the base temperature which, for buildings, is a balance point temperature, i.e. the outdoor temperature at which the heating (or cooling) systems do not need to run in order to maintain comfort conditions.’

Primarily a reference temperature of 15.5°C (Field, 2008a, p. 12) was used. difference between the reference temperature and average temperature of the day as long as its positive.

The prediction of building heat demand is based on the notion that heat loss from a building is directly proportional to the difference between the indoor and outdoor temperatures (Tony, 2006, p. 6), with time the energy becomes an equivalent of power, since power is a product of energy and time, such that the equation in Equation 6.3.1 becomes valid. The constant of proportionality reflects the resistance to heat flow or the cumulative U values of the materials between the building indoor and outdoor. It’s called the overall heat loss coefficient

$$\begin{aligned}\text{Heating energy demand (kW}\cdot\text{h)} &= \text{overall heat loss coefficient (kW}\cdot\text{K}^{-1}\text{)} \\ &\quad \times \text{degree-days (K}\cdot\text{day)} \times 24\ \text{(h}\cdot\text{day}^{-1}\text{)}\end{aligned}$$

Equation 6.3.1 Heat energy flow out of a building and indoor and outdoor temperature relationship:

Source: (Tony, 2006)

There is a limit to the proportionality of outdoor temperature to the building heat use as expressed in Figure 6.3.1 and when monthly building heat demand and monthly heat degree

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[12] Heat intensities obtained from (The Scottish Government, 2013, p. 36; Department of Energy& Climate Change UK, 2014, pp. 5–9; Ramboll Energy and The Carbon Trust, 2014)

[13] Base load share of heat demand computed from share of domestic hot water demand as illustrated in Section 4.3.2

days is plotted, a region where linearity is lost is observed. The plot is called the performance line of a building.

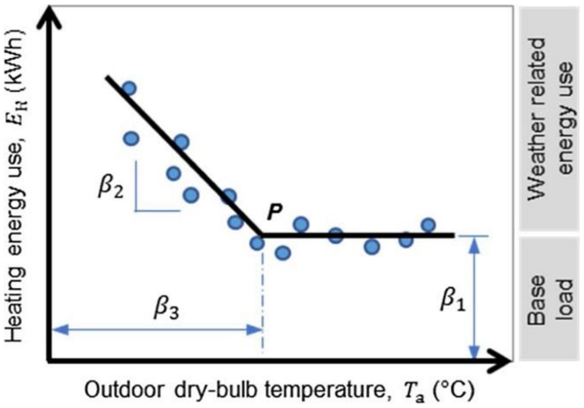

Figure 6.3.1 Relationship of outdoor temperature to heat demand in a building:

Source: (Meng and Mourshed, 2017, p. 261)

The non-weather-related heating of the building which is termed as the based load is not proportional to the heat degree day and had to be first deducted from the monthly heat demand of each building type before projections were made for temperature correlated demand.

Generating heat degree hours from the actual hourly temperature distribution, would show large variation in heat demand from hour to hour, which would be un-realistic because of building thermal storage and the user profiles of the buildings. Therefore, the daily average heat degree day was assumed to be overall heat degree day across the 24 hours that day. Figure 6.3.2 shows the generated heat degree hours for the projection location.

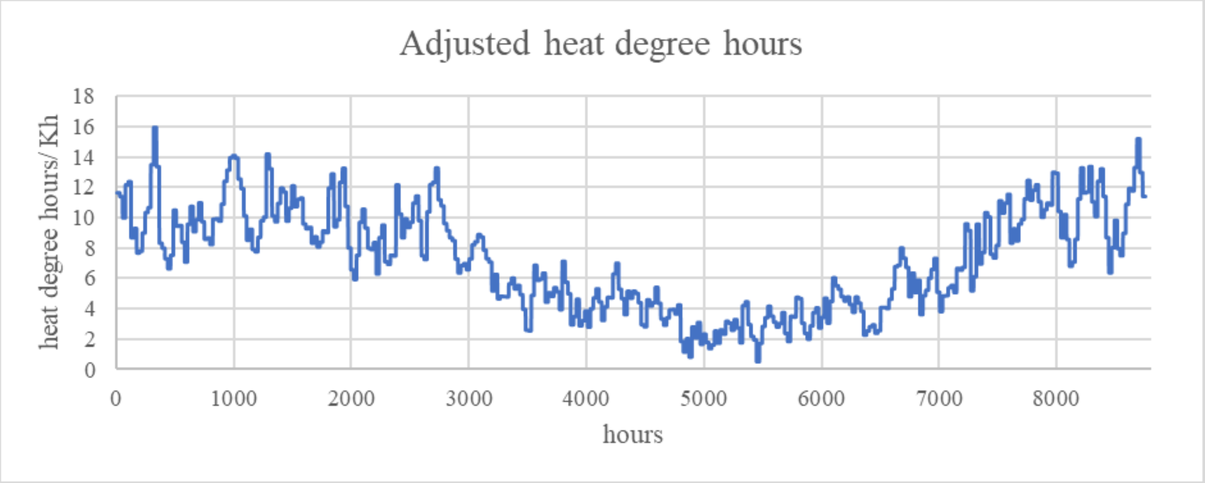

Figure 6.3.2 Project adjusted heat degree hours.

Source: (Meteoblue, 2019a)

The distribution shows that mid-year in the summer a few days were warm enough to have the heating systems off or supplying domestic hot water demand in since values close to zero are observed.

Below are the methods discussed in detail;

a) Method I based on historical oil and or electricity consumption for project buildings
b) Method II based on heat intensity benchmarks with adjustments using occupancy factors, wind factor and Energy Performance Certificate found in project buildings.

The limitations of the methodology used to determine the building heat demand by degrees days are the human factor like flipping the thermostat off on cold days, it ignores variation in occupancy and activity over the weekend and public holidays, and accuracy is affected by energy efficiency improvements.

6.3.1 Building heat demand assessment: Method I

For Baltasound Junior High School and Nordalea Care Centre (NCC) historical data of oil and electricity consumption from April 2014 to May 2015 was availed by Shetland Island Council. Basing on interviews and site visits at the respective premises in February 2019, it was devised that oil is the primary fuel used for heating. An overall boiler operational efficiency of 80 % was assumed and the heat demand obtained by applying this efficiency to the oil consumption data. Monthly Modern-Era Retrospective analysis for Research and Applications (MERRA) temperature data from April 2014 to May 2015 was downloaded from a NASA website[14] and heat degree day month generated to ensure approximate coincidence with the oil consumption data (Paul W. Stackhouse *et al.*, no date).

The generated heat degree days at a base temperature of 15.5 °C for the Baltasound Junior High School (Field, 2008a, p. 12) and at 20 °C for Nordalea Care Centre were plotted against the adjusted oil consumption. The resulting plots called the building performance lines, as shown in Figure 6.3.3, were used to establish the buildings base temperature and temperature correlated heat demand (Rodrigues *et al.*, 2002, p. 8). Figure 6.3.3 shows that the monthly base load of the care centre is 19,996 kWh while that of the school is less at 9,070 kWh. The temperature correlated demands are 3.8368 kWh/°C day and 0.6762 kWh/°C day for the school and care centre respectively. The regression correlation coefficient of the care centre at 0.1796 indicates there is less correlation with the outdoor temperature to the building internal temperature since its heated to a high temperature year-round.

Furthermore, using a similar approach for the Unst leisure centre, the energy demand was established from the Energy Performance Certificate. The share of heating oil was established by relating the total CO_2 emissions to the respective CO_2 emission factor and hence the respective energy required to deliver the emissions. This was done because it was hard to deduce the monthly oil consumption from the data provided by the stake holder. Heat degree hours were computed and realised from 2017 temperature data for a base temperature of 28 °C and 15.5 °C (Field, 2008b). The share of energy from the swimming pool whose room

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[14] https://power.larc.nasa.gov/data-access-viewer/

temperature is maintained at 28 °C was computed basing on the share of the total building area by the swimming pool and weighted heat degree days from both parts of the building.

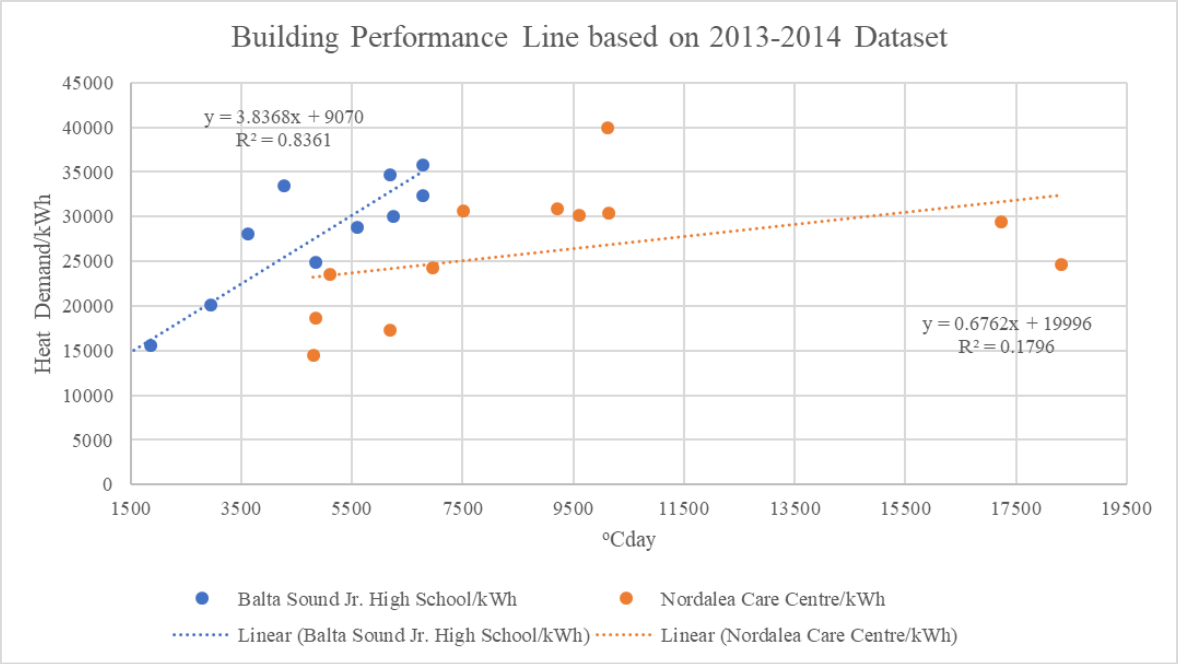

Figure 6.3.3 1Building performance line for Baltasound Junior High School and Nordalea Care Centre.

Source: Author based on analysis of Oil consumption data from Shetland Island Council and MERRA temperature data.

This was based on the fact that an interview with the Leisure Centre manager justified these operational characteristics of the building and that heating oil is the main fuel used for heating the building. The corresponding heat demand by the different parts of the building were then divided by their corresponding heat degree hours. The result, a constant for each building zone, was used with heat degree day distribution to realise the effect hourly heat demand as illustrated in Equation 6.3.2 to Equation 6.3.7.

$$Area\ indexed\ degree\ days = \frac{(total\ building\ area - area\ of\ swimming\ pool)\ degree\ days\ at\ 15.5^0}{total\ building\ area} + \frac{area\ of\ swimming\ pool\ \times\ Degree\ days\ at\ 28^o}{total\ building\ area}$$

Equation 6.3.2 Area indexed degree days

$$Swimming\ pool\ heat\ demand = \frac{heat\ degree\ days\ at\ 28^0}{Area\ indexed\ degree\ days} * total\ building\ heat\ demand$$

Equation 6.3.3 Swimming pool heating demand

$$Rest\ of\ the\ building\ heat\ demand = \frac{heat\ degree\ days\ at\ 15.5^0}{Area\ indexed\ degree\ days} * total\ building\ heat\ demand$$

Equation 6.3.4 heating demand for the rest of the building

$$kWh/\ heat\ degree\ hour = \frac{Heat\ demand\ for\ building\ section}{Degree\ hours\ \ for\ building\ section}$$

Equation 6.3.5 kWh per degree hour constant

$$Building\ section\ heat\ demand = (kWh/heat\ degree\ hour) * observed\ heat\ degree\ hour$$

Equation 6.3.6 Building section heat demand

$$Total\ hourly\ heat\ demand = hourly\ heat\ demand\ from\ swimming\ pool + hourly\ heat\ demand\ from\ the\ rest\ of\ the\ building$$

Equation 6.3.7 total hourly heat demand

Figure 6.3.4 then shows the resulting heat demand projections by buildings. It shows that the demand of the care centre is pretty much constant throughout the year with a minimal impact of the variation in temperature. This is anticipated since the building is kept at higher constant temperature, while for the leisure centre and school the demand varies by season due to adjustment of the indoor temperature in the building with changes in the outdoor temperature.

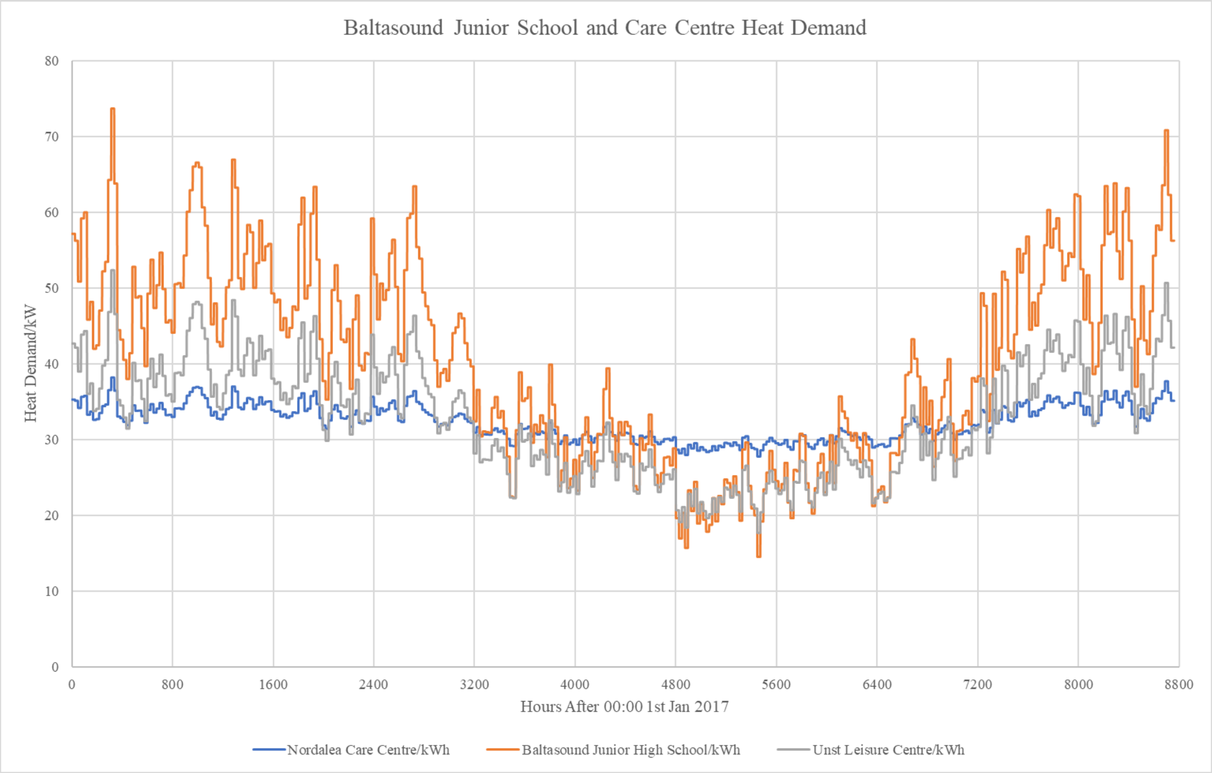

Figure 6.3.4Baltasound Buildings heat demand

Source: Author based on analysis in Ms. Excel

6.3.2 Building heating assessment: Method II

For method II, heat intensity benchmarks from a publication by the Department of Energy & Climate Change and the Scottish Heat map were used to determine the yearly heat energy use of the buildings with an adjustment of 12 % due to the wind factor and (The Scottish Government, 2013, p. 36; Department of Energy & Climate Change, 2014, pp. 5–9; Ramboll Energy and The Carbon Trust, 2014). Furthermore, an occupancy factor was applied to the demand after distributing by the hour. This methodology was primarily applied in Saxa Vord due to the fact the that consumption data provided by the Saxa Vord management didn't have an occupancy pattern availed as well for the different buildings.

$$Heat\ intensity\ benchmark\ (kWh/m2/year)\ = \frac{Building\ annual\ heat\ demand}{Building\ Gross\ internal\ Area}$$

Equation 6.3.8 heat intensity benchmark relationship to gross internal area and building heat demand

The building heat demand includes both domestic hot water demand and space heating.

Since most residential buildings in Saxa Vord were constructed between after 1983, an energy intensity of 181 kWh/m^2/year (The Scottish Government, 2013, p. 36) was considered for the buildings classified as dwellings as shown in Table 6.2.2. The building's base load heat demand was assumed to be equal to the share of domestic hot water demand from the total heat demand. The share of space heating and domestic hot water by building type were assumed from literature as discussed below.

Scottish dwellings consume 74 % and 13 % of their energy for space heating and water heating respectively (Clarkson, Palombi and Lloyd, 2017, p. 62). In the UK services sector 9 % of the energy supplied is used for water heating and 45 % for space heating (The Open University, 2018, pp. 8–9). For Leisure Centres, the Chartered Institution of Building Services Engineers (no date, p. 4) estimates the heating energy demand to be 74 % (56.5 % space heating and 17.5 % hot water) of the total building energy use. Furthermore the Carbon Trust (Carbon Trust, no date) estimates that schools consume a total of 60 % of their total energy in space heating (2 % of this from electricity and 58 % from fossil fuel) and 16 % for hot water demand (1 % of this being electric and 15 % being from fossil fuels). The computed proportions of the base load computed using Equation 6.3.9 are illustrated

$$\%\ share\ of\ base\ heat\ load = \frac{share\ of\ domestic\ hot\ water\ demand}{sum\ of\ share\ of\ space\ heating\ and\ domestic\ hot\ water}$$

Equation 6.3.9 Percentage share of base heat load in total demand

$$Building\ heat\ demand = base\ load\ +\ temperature\ correlated\ demand$$

Equation 6.3.10Equation used to predict the building heat demand

The hourly temperature-correlated part of the demand coefficient was determined by dividing the difference between the projected building heat demand and the base load with the total number of degree hours as shown in Equation 6.3.12. The hourly base load was determined by dividing the yearly base load, which was computed from the share of base load for projected demand, with the total number of hours in a year 8760 as shown in Equation 6.3.10. The hourly temperature correlated part of the demand obtained by multiplying the hourly observed heat degree hour with the proportionality constant was established as discussed from Equation 6.3.12. Equation 6.3.13 illustrates how the hourly heat demand was estimated from the sum of the hourly base load and hourly temperature correlated demand.

$$hourly\ base\ load\ = \frac{Projected\ demand\ x\ share\ of\ base\ load\ for\ projected\ demand}{8760}$$

Equation 6.3.11 Hourly base load computation for method II

$$\begin{aligned} & hourly\ temperature\ correlated\ demand\ coefficient \\ & = \frac{(Projected\ demand - Projected\ demand\ x\ share\ of\ base\ load\ in\ total\ demand}{Total\ heat\ degree\ hours} \end{aligned}$$

Equation 6.3.12 hourly temperature correlated demand computation for method II

$$\begin{aligned} & hourly\ heat\ demand \\ & \quad = \ hourly\ base\ load + \ degree\ hour \\ & \quad * hourly\ temperature\ correlated\ demand\ coefficient \end{aligned}$$

Equation 6.3.13 Method II hourly heat demand formula

Figure 6.3.5 shows the projected total building heat demand at Saxa Vord at 100 % occupancy implying that all buildings are occupied throughout the year.

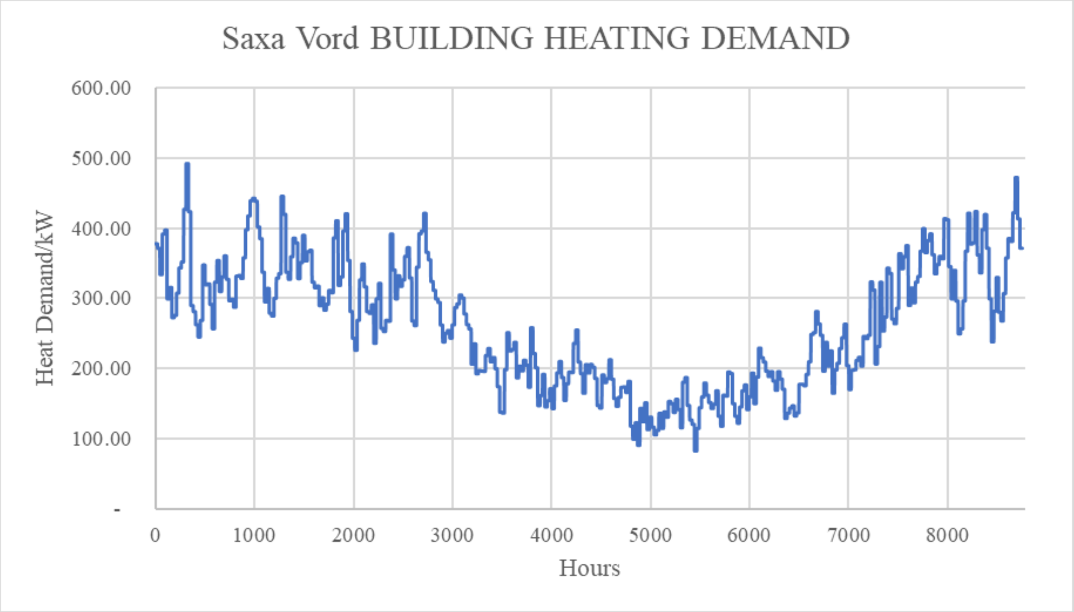

Figure 6.3.5 Projected building demand at 100 % Occupancy at Saxa Vord

6.4 Building Occupancy Scenarios

To model for the impact of tourism on room occupancy, the Saxa Vord main buildings blocks were assumed to have an occupancy similar to that of Scottish accommodation buildings as estimated by J. John *et al.* (2017, p. 11 Table 3) in the tourism scenario. On the other hand, the occupancy of the residential blocks was assumed to peak in summer and reduce in winter to 15 %, primarily to heat the rooms to ensure the buildings retain their quality as shown in Figure 6.4.1. Figure 6.4.2 shows the tourism plus residential occupancy scenario in which the residential blocks are assumed to be fully occupied year-round due to the anticipated development of a space centre in Saxa Vord.

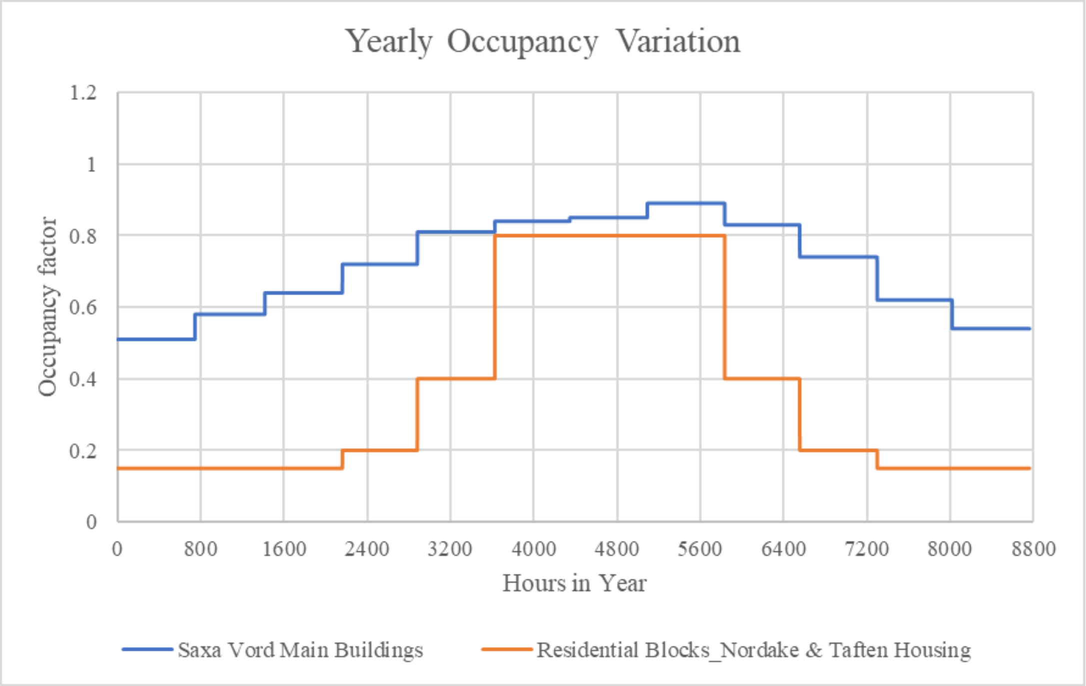

Figure 6.4.1 Yearly occupancy variation in tourism scenario for Saxa Vord main Buildings block and the residential blocks.

Source: Authors' analysis

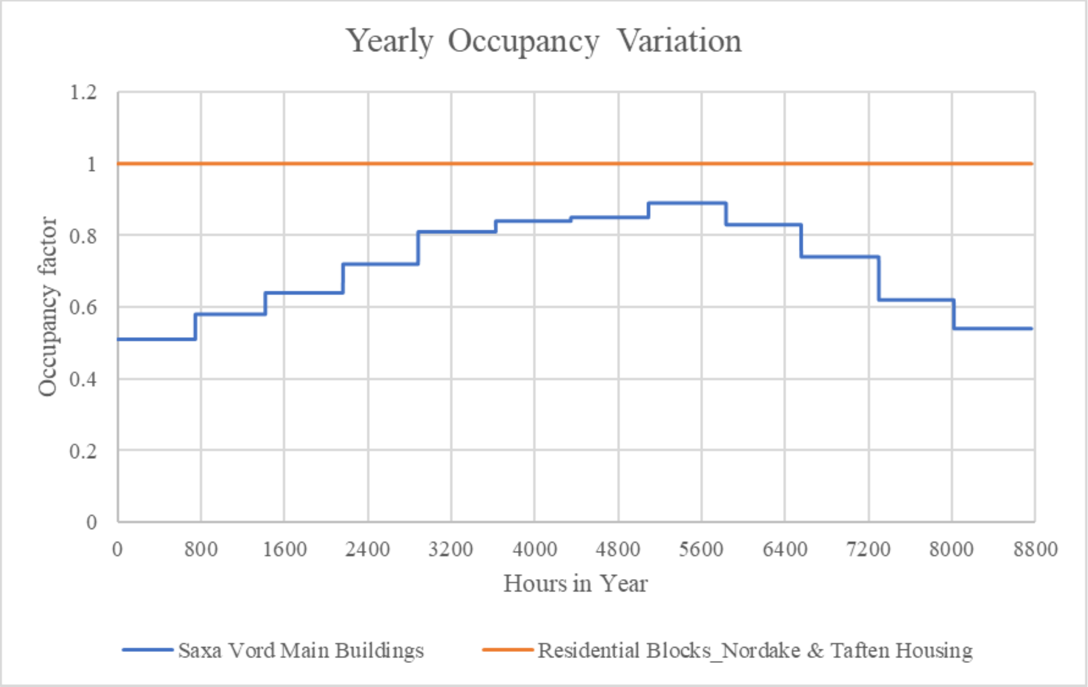

Figure 6.4.2 Tourism and residential scenario.

Source: Authors' Analysis

6.5 Energy Efficiency Methodology

Energy efficiency assessment of a building's thermal system can be conducted with observations of the three elements below:

i. Existing building envelope.
ii. Existing heat distribution system, e.g. pipes for wet heating system.
iii. Existing heat generation technologies, i.e. boiler.

One residential unit from Nordabrake building in Saxa Vord was selected for assessment. The reason for selecting Nordabrake is because a residential example allows to utilise the UK Standard Assessment Procedure (SAP), and NHER Software (National Home Energy Rating)[15] for energy efficiency assessment, which are both specified for dwellings. . It is assumed that the results can be transferred to all the buildings considered in the project because they are approximately built at the same location and the same time and have the same construction.

Space heating demand was the major focus for energy efficiency assessment and energy demand. Space heating was observed to take up most of the building energy and more energy savings potential could therefore be realised in this area.

For assessing the existing building and its components, a unit from Nordabrake was selected, and TRNSYS[16] software and NHER software were both used to determine the energy performance and SAP rating for the respective unit. Using these, two different software for building energy consumption assessment was important because of their methodology of energy simulations and output reports. The NHER provides SAP rating and CO_2 emissions based on the age of the building and its location, with less detailed input data. The TRNSYS software requires more detailed input and allows one to perform energy efficiency improvements to assess the energy savings potential and helps in establishing different scenarios for assessment. During the calculation process constructional data was not available due to many limitations so in that case assumptions were made to move forward. The results of the software used were assessed to understand the energy efficiency potential of the model unit and the rest of the Nordabrake housing. The unit building was measured and modelled

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[15] An energy efficiency assessing software for new build house designed by UK government- authorities(National Energy Services, 2010)

[16] Transient System simulation software (Caram, Ph and Labaki, 1997)

using AutoCAD and SketchUp. The actual orientation of the building considered for simulation was 313°.

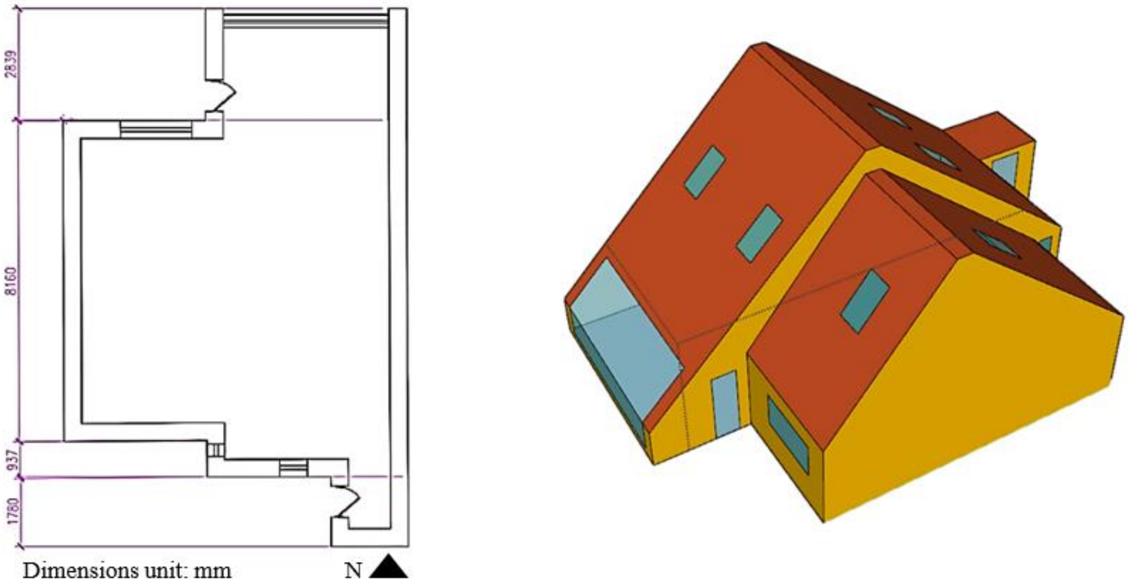

Figure 6.5.1 schematic developed SketchUp model and plan

Source: Author using Sketch UP and AutoCAD

The results of the software used were assessed to understand the energy efficiency potential of the model unit and the rest of the Nordabrake housing.

6.5.1 Energy Simulation Results for Current Scenario

The simulation results, from NHER software, for one unit of Nordabrake resort for space heating total to 25,318 kWh/year and total CO_2 emission of 14,816 kg/year from an emission factor of 0.519 kg CO_2/kWh. The SAP rating for the unit is 1 and the SAP band is G. This implies the building has a poor energy performance. The SAP report from the simulation is attached in Appendix VIII: In comparison, the excel model generates an estimated annual heat demand of 20,691.4 kWh/ year with an intensity of 172.48 kWh/m^2.

The summary of the results is shown in Table 6.5.1 below. The table also shows the intensity of energy consumption and CO_2 emission per unit area.

Table 6.5.1 Energy simulation results from NHER software for sample building unit.

Parameter	Energy Consumption (kWh/year)	CO_2 emissions (kg/year)	Energy Rate (kWh/m^2/year)	CO2 emissions (kg/m^2/year)
Space Heating	25,318	13,140	184.80	95.91
Water Heating	2,175	1,129	15.88	8.24
Total	28,547	14,816	208.37	108.15

Source: NHER output

As a comparison, the TRNSYS energy simulation results show that the space heating for the building consumes 21,428 kWh/year. The energy intensity for space heating for the model building is 158.73 kWh/m^2/year. The values are approximately equal to the building space heating excel model. However, it should be mentioned that the area input for TRNSYS includes garage area of 15 m^2 which is not included in excel model. The assumptions made during the TRNSYS software energy simulation include that the building is occupied by 2.5 people and the heating system runs continuously throughout the year. These inputs are not required by the NHER software. Air change of infiltration and ventilation has been assumed as 0.27 1/h and 0.6 1/h respectively.

Some assumption other of current scenario with significant impact on energy consumption of building is shown in Table 6.5.2 below. Some of the material selection, such as mineral wool, polystyrene for walls and floors and types of windows, has been made based on assumptions while the thermal properties' values have been taken from TRNSYS library. A site visit to the Medical Centre in Saxa Vord, Building ID 20, from Figure 6.2.2 in February 2019 indicated the loft was insulated using mineral wool therefore it was assumed that the same insulation was applied to the Nordabrake house that was modelled.. However, because the mineral wool was not in good condition, a mineral wool with high conductivity value of 0.54 kJ/hm K from the TRNSYS library was selected.

The difference in the space heating energy results of NHER with two other results can be due to the reasons that the NHER takes the sample unit as an aged building as per its construction date and does not allow changes while TRNSYS software required the entry of the current building state manually basing on the observation of the different materials used.

The simulation results for the current scenario provide basis for calculating energy efficiency potentials for the unit building. The TRNSYS software allows inputs for energy efficiency improvements such as manipulating building component layers, constructional and insulation materials. That’s why the results of TRNSYS simulation have been used to compare the energy efficiency scenarios with the current scenario results

Table 6.5.2 TRNSYS Inputs for Current Scenario energy simulation

Current Scenario					
	Material			**Place of Use**	**Used Area (m^2)**
1	Double-Glazed Windows			All windows	6.9
	U-Vlaue	2.82	W/m^2K		
	G-Vlaue	0.64	100%		
	Single Glazed Windows				12.69
	U-Vlaue	5.69	W/m^2K		
	G-Vlaue	0.89	100%		
2	Mineral wool			Roof	123.58
	Conductivity	0.54	kJ/hmK		
	Capacity	0.015	kJ/kgK		
	Density	570	kg/m^3		
	Thickness	100	mm		
3	Polystyrene'			Ext-Walls	92
	Conductivity	0.14	kJ/hmK		
	Capacity	1.25	kJ/kgK		
	Density	30	kg/m^3		
	Thickness	100	mm		
3	Polystyrene			Floor	92
	Conductivity	0.14	kJ/hmK		
	Capacity	1.25	kJ/kgK		
	Density	30	kg/m^3		
	Thickness	3	mm		
4	Cork			Floor	92
	Conductivity	0.16	kJ/hmK		
	Capacity	0.18	kJ/kgK		
	Density	100	kg/m^3		
	Thickness	4	mm		

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6.5.2 Building Energy Efficiency Study Scenarios

6.5.2.1 Energy Efficiency Scenarios Definition

After assessment of the results of the current scenario, three energy efficiency scenarios were created each targeting an effective building component for efficiency improvement, to estimate the energy savings potential of each individual component for the unit building. Table 6.5.3 to Table 6.5.5 below shows the three scenarios.

Table 6.5.3 All window improvement scenario.

all windows Improvement									
material			**place of use**	**used area (m^2)**	**average window size**	**Material + labour**	**cost per window (£)**	**life time (year)**	**Total price/£**
window double glazed			all windows	19.59	0.9	21766.67	1000	25	21766.67
u value	1.07	w/m^2K							
g value	0.62	100%			-	-	-	-	
Total									**21766.67**

Source of costs *(Palmer, Livingstone and Angela, 2017)*

Table 6.5.4 External Wall improvement TRNSYS simulation cost.

Ext Wall Improvement Scenario							
material			**place of use**	**used area (m^2)**	**Material + labour (£/m2)**	**life time (year)**	**Total price/£**
Mineral wool	100	mm	Ext-Walls	52.51	180	25	9451.80
conductivity	0.13	kJ/hmK					
capacity	0.9	kJ/kgK					
density	80	kg/m^3					
Total							**9451.80**

Source of costs *(Palmer, Livingstone and Angela, 2017)*

Table 6.5.5 TRNSYS Roof improvement scenario.

Roof Improvement Scenario							
Material			**place of use**	**used area (m^2)**	**Material + labour (£/m2)**	**life time (year)**	**Total price/£**
Mineral wool	100	mm	Roof	123.58	40	25	4943.20
conductivity	0.13	kJ/hmK					
capacity	0.9	kJ/kgK			-		
density	80	kg/m^3			-		
Total							**4943.20**

Source of costs *(Palmer, Livingstone and Angela, 2017)*

In addition, another scenario which is a mixture of the other scenarios, except window scenario where only greenhouse window has been taken for improvement.

Table 6.5.6 TRNSYS 30% energy efficiency scenario.

Energy Efficiency Scenario _30%									
material			**place of use**	**used area (m^2)**	**average window size**	**material +labour**	**cost per window / £**	**life time (year)**	**Total price /£**
1.window double glazed									
			greenhouse	12.69	0.9	14100.00	1000	25	14100.00
u value	1.07	w/m^2 K							
g value	0.62	100%			-	-	-	-	
2. Mineral wool									
Thickness	100	mm	Ext-Walls	52.51		180	£/m2	25	9451.80
conductivity	0.13	kJ/hmK							
capacity	0.9	kJ/kgK			-	-	-	-	
density	80	kg/m^3			-	-	-	-	
Thickness	100	mm	Roof	123.58		40	£/m2		4943.2
Total									28495

Source of cost data *(Palmer, Livingstone and Angela, 2017)*

The idea to develop different scenarios was to get the most cost-effective and energy saving improvement to the building unit.

6.5.3 Energy Efficiency Cost Scenarios

For each energy efficiency scenario and its measures, annual costs were calculated to assess the investment against the annual energy savings potential. This is important to analyse so that an informed decision can be made about which measure could provide with the most benefit.

Table 6.5.7 below shows the energy efficiency improvements and the related costs to the measures, for different scenarios.

Table 6.5.7 Costs of different energy improvement measures in relation to energy savings

	Scenarios	Capex /£	Energy Demand/kWh	Energy Reduction percentage per £	Annualised CAPEX[17]/£	Cost of measure £/kWh
0	current	0	21433.83	0.00%	0.00	0.0000
1	Roof Improvement	4943.2	19841.38	7.43%	307.13	0.1929
2	All Windows Improvement	21767	16036.11	25.18%	1352.40	0.2505
3	Ext-Wall Improvement	9451.8	21071.36	1.69%	587.26	1.62
4	scenario 30%	28495	14981.20	30.10%	1770.44	0.2744

The cost of measure/£ indicates the investment per each kWh of energy saved for each scenario. This indicator helps to identify the most suitable scenarios taking into count the energy efficiency and financials. Based on the indicator, the scenario Roof Improvement and scenario All Windows Improvement prove to be the most feasible among the four scenarios created. Therefore, the respected scenarios have been selected as project energy efficiency scenarios. Their energy demand reductions are lying above 7% and 25%.

The External Wall Improvement scenario shows the highest cost of measure/£ which is 1.62 £/kWh. This is because the external walls of the buildings have a good insulation in their existing condition. So, the additional energy efficiency measures do not improve the energy efficiency with a greater difference as compared to the other scenarios, and the investment cost does not return a lot of value.

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[17] Annualised for 25 years

6.5.4 Wet heating System

Furthermore, to determine if there are higher carbon emission avoidance benefits and economic benefits from the conversion of the existing system to a wet heating system, a cost benefit analysis was added to the overall project study. The proposed system layouts are discussed within this section.

To estimate the costs of installing a wet heating system, the buildings were linked with hot water distribution pipes in QGIS as shown in Figure 6.5.2 below, and the location of the hot water tank was estimated as well by ensuring that the tank is closest to the building with the highest heat demand. The costs for installing radiators and plumbing within the buildings are however excluded in the analysis.

6.5.4.1 Wet Heating System Pipework

The main methodology used was to size the maximum demand of the buildings on a design day when the temperature is -5 ^{o}C. The corresponding adjustments using the building base load and the temperature correlated component of the head demand would yield the maximum building heat demand at this temperature using heat degree day at -5 ^{o}C. This demand was then adjusted for an assumed loss at a rate of 5 %, considering the transmission distances are small, to yield a peak heat demand.

i. Saxa Vord

To size the pipes at Saxa Vord a proposed route was drawn in QGIS as shown in Figure 6.5.2.

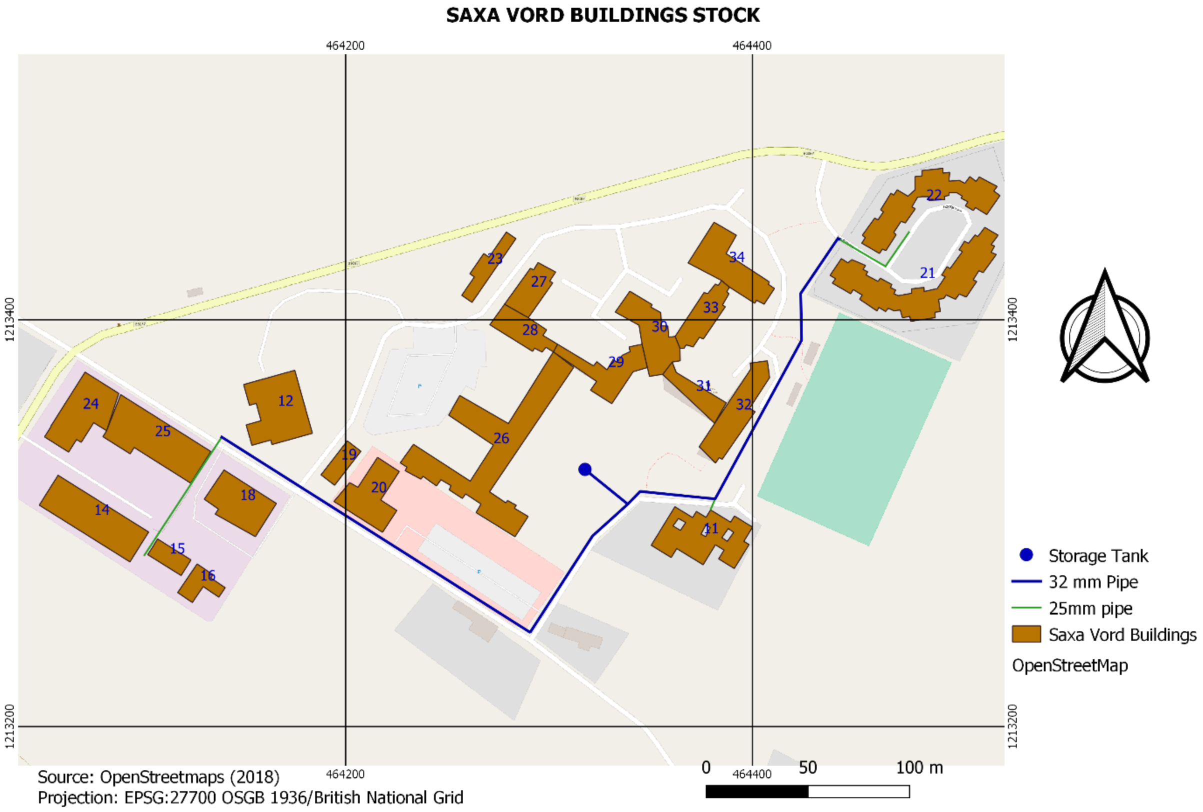


Figure 6.5.2 Proposed system route at Saxa Vord for a wet heating System.

Source: Author based on Analysis in QGIS of (OpenStreetMap Contributors, 2018)

Based on the peak heat demand of each building and the temperature difference between supply and return water of 35 ^{o}C, the mass flow rate was calculated to choose the convenient pipe diameter for each section of the pipe line.

A steel twin pipe system is suggested, which has a polyurethane foam insulation and aluminium foil as a diffusion barrier. Such a flexible pipe system has approximately 30 years of continuous operating life and at 140^{o}C is rated for 25 bars of maximum pressure. Some other parameters and assumptions taken into consideration are a 10 % heat loss through the pipes, a water velocity less than 3 m/s (Jones *et al.*, no date, p. 36) and fittings resistance of 33 %. Furthermore, the pressure loss per meter of pipe was based on D'Arcy-Weisbach Equation friction loss chart (Steel and Friction, no date).

The proposed pipe sizes of pipes vary between 32 mm for the main pipe and 20-25 mm for the branches connecting the Boiler house, brewery, distillery and Saxa Vord self-catering resort buildings. According to a publication by the IEA ETSAP (2013, p. 5 Table 4), the total piping costs could vary from 300 to 350 €/m which is equivalent to 260-303.45 £/m at an exchange rate of 0.86 €/£. The total pipe length from Table 1.7 is 565 m, therefore the investment cost is £ 171,195.0.

It is also important to consider a water pump to pump the water through the most resisting circuit (index circuit) with a pipe loss of 22.7 m head, delivering a flow rate of 1.706 l/s, considering 2 % pump energy. This pump is estimated with 45.08 m of water Column which is equivalent to 4.508 bar.

The sizing and calculations of the estimated pipes can be found in Appendix VII: in the appendix.

$$Equivalent\ annual\ cost\ of\ capital = \frac{Asset\ Price\ x\ Discount\ Rate}{1 - (1 + Discount\ Rate)^{-number\ of\ periods}}$$

Equation 6.5.1 Equivalent annual cost of an asset

Assuming annual service and maintenance cost of 1 % of CAPEX (IEA ETSAP, 2013, p. 5), a 20-year period and a discount rate of 3.72 % the annualised capital cost computed based on Equation 6.5.1 for the project locations is as shown below in Table 6.5.8.

Table 6.5.8 Annualised capital cost for 20 years for Saxa Vord piping works for mini district heating system.

Indicator	Saxa Vord	Units
Pipe runs	565	m
Capital Cost	171,195.0	£
Annual OPEX	1711.95	£
Annualised CAPEX	3300	£
Total annual cost	5011.95	£ per annum

Source: Author (s)

6.5.4.2 Thermal Storage

Thermal storage came into picture as an important strategy to balance the system, using insulated thermal storage tank allows storing the surplus of electricity as heat and delivering it back to the system whenever there is a shortage of supply. The recommended thermal storage technology is a welded steel hot water tank. This allows using the high specific heat content per volume of water (Danish Energy Agency, 2018b).

Considering the heat capacity of water as 1.16 kWh/m^{3}K (AEE – Institute for Sustainable Technologies, 2010) and a temperature difference between inlet and outlet as 45 ˚C, the basic requirement to store 1 kWh of energy is approximately 19 litres.

Calculations conducted using the following formula:

$$\boldsymbol{Qs = (m\,Cp)\Delta T}$$

Equation 6.5.2 Sizing of Thermal Storage

Source: (AEE – Institute for Sustainable Technologies, 2010, p. 3)

Having

Qs	Total heat capacity of the storage tank	[kWh]
m	Volume of storage tank	[m^3]
Cp	Heat Capacity of Water	[1.16 kWh/m^{3}K]
ΔT	Temperature difference	[K]

The (Danish Energy Agency, 2018b, sec. 54) recommends these guidelines for commissioning the hot water tank ;

1. Steel structure with concrete base allowing more flexibility and lower CAPEX cost,
2. In order to impede corrosion, keep water at pH 9.8, or use additional heat exchanger and pasteurize the tank,
3. Use 300 mm insulation mineral wool and increase to 450 mm for long-term storage.
4. The height/diameter factor influences heat losses, achieving a 1.8 ratio limits the heat losses to a maximum of 2.1 % per week at 90 ˚C.

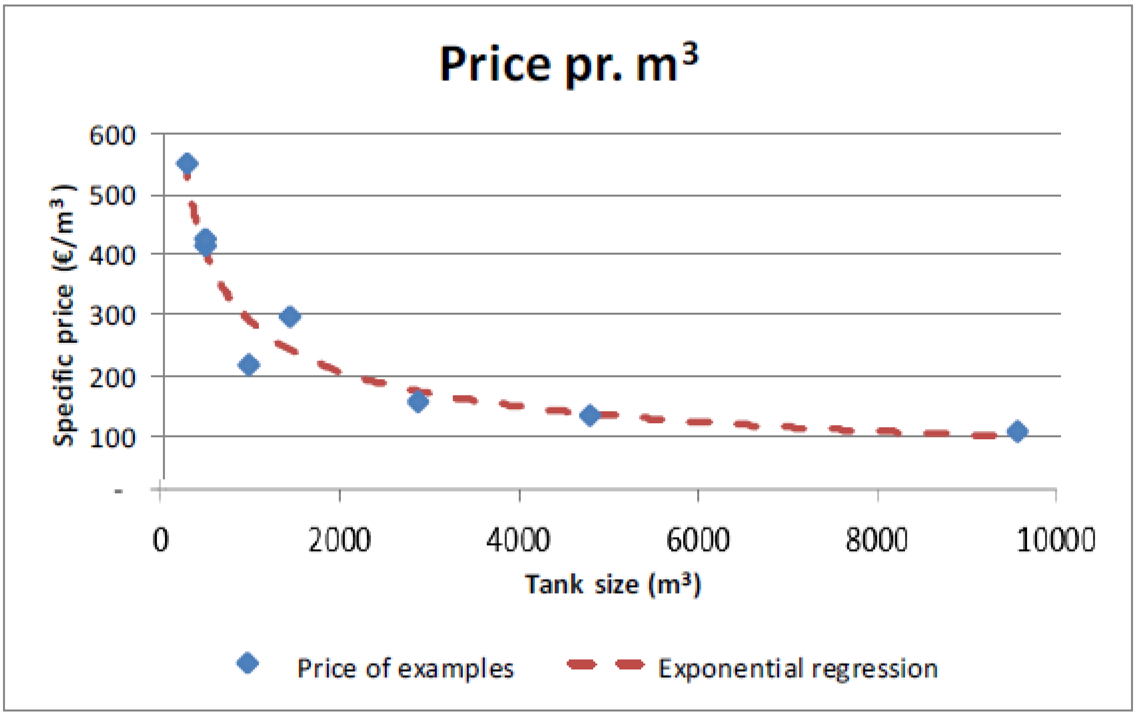


Figure 6.5.3 Specific price of hot water storage tank as function of volume.

Source: (Sørensen *et al.*, 2013)

A report published by the Department for Business Energy & Industrial Strategy states that within the UK market 11 million tanks for thermal energy storage are implemented on domestic scale for intra-day applications (BEIS, 2016, p. 33). The economics of scale plays an integral role when implementing a thermal storage system as the CAPEX shows a significant drop when increasing the plant size, offering a valuable indicator for developers when planning the layout of the heating systems. The figure above provides a reference for the variation of CAPEX as a function of plant size.

For the UK market, the same relation presented in the figure above is developed. As per small scale integrated hot water and space heating tanks up to size 1.5 m^3 the average prices is 3,950 £/m^3, while for large scale tanks until a size of 300 m^3 it costs 360 £/m^3, the costs drop significantly to 131 and 105 £/m^3 for 4,300 m^3 and 12,000 m^3 respectively (BEIS, 2016, pp. 38–39).

Furthermore, into economics the table below summarizes the economic indicators related to hot water steel storage tanks.

Table 6.5.9 Economic Indicators for thermal storage

Indicator	Value	Source
Capex (£ / kWh)	3	(Danish Energy Agency, 2018b, p. 59, Technology Data for Energy Storage)
Fixed O&M (£ / kWh / a)	1	
Round Trip Efficiency (%)	98	
Technical Life time (years)	40	
Economic Life time (years)	20	(IEA-ETSAP and International Renewable Energy Agency (IRENA), 2013, ETSAP - Thermal Energy Storage)

6.5.4.3 Electric and Oil Boiler

As a supplementary to the heat pump, the energy supplied from RE is utilized to heat the water using also an electric boiler in order to reach the desired temperature of 90˚C, in addition the system includes a supplementary oil boiler for backup. As per technology specifications, Table below summarizes the data related to both boilers:

Table 6.5.10 Economic & Technical Indicators for Electric & Oil Boilers

Indicator	Value		References
Electric Boiler			
Capex Capacity 1-5 MW (£ / kW)	130.5		(Danish Energy Agency, 2018a, p. 227, Technology Data for Energy Plants for Electricity and District Heating Generation.)
Fixed O&M (£ / kW / a)	930.9		
Variable O&M (£ / kWh $_{\text{output}}$)	0.000783		
Efficiency (%)	98		
Technical Life Time (years)	20		
Minimum Load (% of full load)	5		
Oil Boiler			
Rating (kW)	100	1000	(Ernst & Young, 2007, sec. Appendix D p.47, Renewable Heat Initial Business Case)
Capex (£/kW)	50		
Opex (£/a)	330	3,400	
Life time (years)	20		
Efficiency (%)	85		
Average price of heating oil (£/l) – Base Case	0.7388		Saxa Vord Bills

Chapter 7: Renewable Energy Analysis

7.1 Wind

7.1.1 Methodology

This study was conducted to assess the wind potential of proposed sites by using the ArcGIS$^{®}$10.4.1 (Esri, 2019) software for site assessment and WindPRO$^{®}$3.2 software (EMD International, 2019) for wind project.

In the initial phase, the site assessment was conducted based on the Shetland local development plan (The Highland Council, 2016). Protected areas in the vicinity of the proposed sites, which are sensitive to a wind turbine, were defined and then excluded.

Safety measure of road and separation distance from residential areas were also studied and region within those areas were excluded. WindPRO$^{®}$3.2 software was used to generate the wind resource map of Unst Island. The remaining areas which are located close to proposed sites and have high wind speed, were selected for this study.

Finally, for one site near Saxa Vord Resort and another near Baltasound the wind potential of several potential wind turbines was assessed.

7.1.2 Wind Turbine Selection

The Scottish wind turbine market was studied in terms of size, availability and services provided by manufacturers. It was found that seven wind turbine suppliers, supply wind turbines in all areas of UK (The Renewable Energy Centre, 2019). Due to the weather condition in Unst, wind class 1 turbines, which operate and withstand extreme weather conditions were selected for this study (Renewable First, 2015).Wind class 1 turbines are specially design for tough operating conditions and they are equipped with smaller rotors and hub heights (Renewable First, 2015). Two wind turbines class1 were selected for this study (100 kW and

900 kW), because of the load and system scenario variation. The specification for the same is shown in Table 7.1.1.

Table 7.1.1 Wind Turbine Specification

No	Brand/Name	Rated Power/kW	Rotor diameter /m	Default Hub-Height/m	Survival Wind Speed/ m/s	Country of Origin
1	Xant M-21	100	21	38	70	Belgium
2	Enercon E-44	900	44	45	59.9	Germany

Source: Author based (Bauer & Matysik, 2019 & WindPro, 2019)

Enercon E-44 wind turbine is also used in Garth wind farm in Yell (EMN Plant Ltd., 2019), which is the closest wind farm to Unst Island.

7.1.3 Site Selection

To identify the suitable sites for an onshore wind project in the vicinity of the proposed load centres, the entire island was assessed to consider all important planning issues. The supplementary guidance for onshore wind by Shetland Island Council, provides spatial planning policies for onshore wind energy. This guideline classifies the regions of Shetland in three different categories (The Highland Council, 2016, p. 8).

1. Spatial Planning Policy One: This planning policy states that a wind turbine is not acceptable within these areas, which contain the national parks and areas with national importance called National Nature Reserve (NNR) (The Highland Council, 2016, p. 8). Hermaness NNR is within this category and is located on northern west of island. It is excluded for this study.

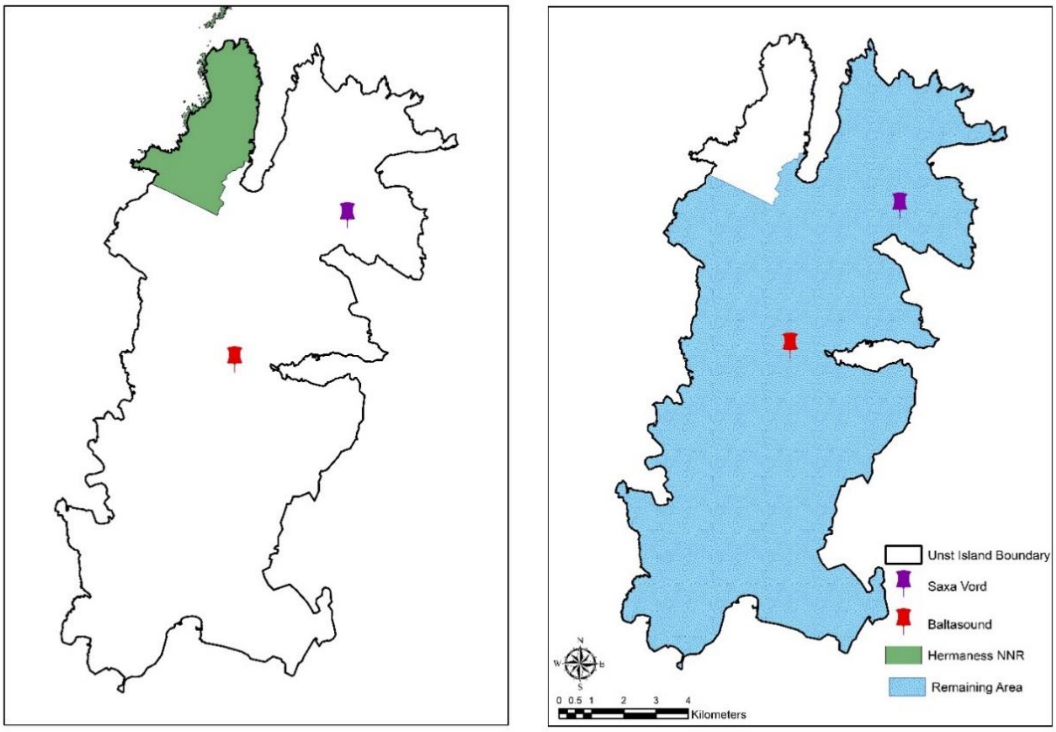


Figure 7.1.1 Hermaness NNR Site

Source: Author based (Scottish Natural Heritage, 2016; McGarva, 2017)

2. Spatial Planning Policy Two: The areas included in this category, are recognized to be sensitive to large scale wind energy because of their national and international natural heritage value. Areas defined in this category include wild land, Scottish Natural heritage Natural Reserve (SNH NR), gardens & designed landscapes, RAMSAR or wetland protected areas, Sites of Special Scientific Interest (SSSI), Special Protection Areas (SPA) and Special Areas of Conservation (SAC) (The Highland Council, 2016, p. 8). Due to national and international value of marine and geological protection area, this study includes the Nature Conservation of Marine Protected Areas (NCMPA) and Geological Conservation Review Sites (GCRS). Development of large scale wind farm is permitted in this area, but on a condition that all the environmental considerations must be carefully considered during the planning, site selection and design phase of the wind projects (The Highland Council, 2016, p. 8). These regions represent some of the valuable natural heritage of Unst such as flora, fauna, geology and geomorphology. These areas were excluded for this study because of time constraints and unavailability of the exact data to study and survey the impact of wind turbine (Scottish Natural Heritage, 2017).

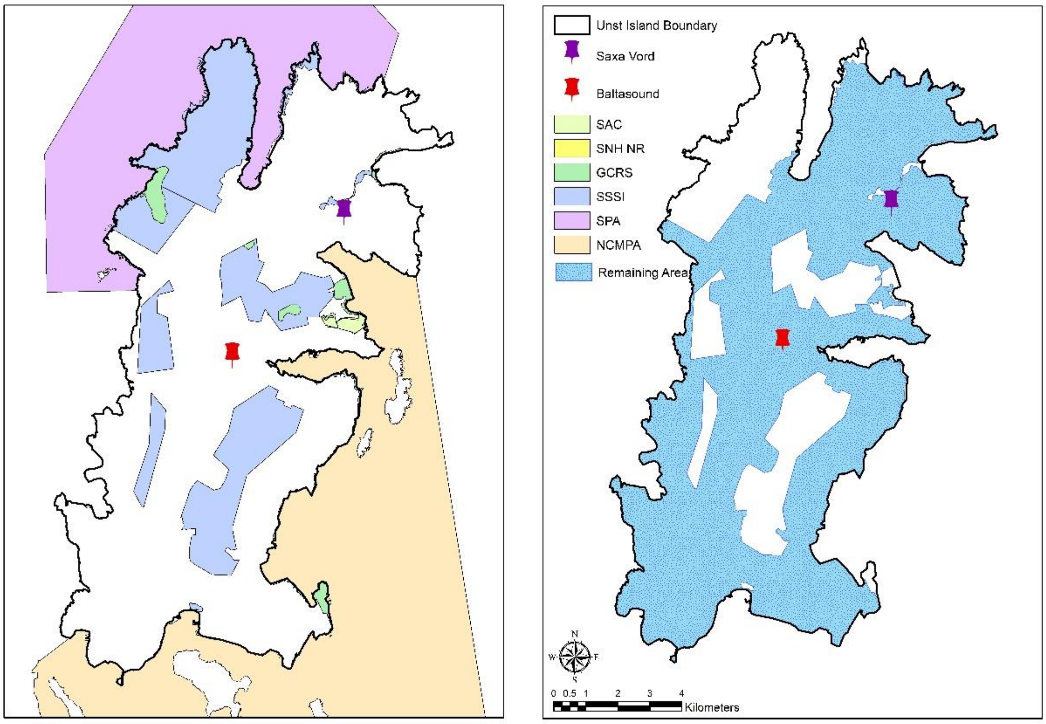


Figure 7.1.2 Areas of Significant Protection

Source: Author based (Scottish Natural Heritage, 2016; McGarva, 2017)

3. Spatial Planning Policy Three: The remaining areas contain the regions where installation of large scale wind energy (20MW to 50MW) is allowed, but potential development must satisfy the development criteria according to the Shetland Local Development Plan (SLDP) (The Highland Council, 2016, p. 8). The regions with potential development of large-scale wind energy is shown in Figure 7.1.3. Areas around the proposed load centres also come under Ministry of Defence (MOD) areas, which mostly cover all of the Saxa Vord Resort and Baltasound (The Highland Council, 2016, p. 11). During the initial planning phase of specific sites, this issue should be shared with MOD.

Other environmental impacts of wind turbines are related to aquatic environment. Development of wind turbines can exert a potential threat to groundwater flow regime and quality (Northern

Ireland Environmental Agency, 2015, p. 4). Therefore, a buffer of 50 meters was created around all regions, which contain water in the island, and it was excluded.

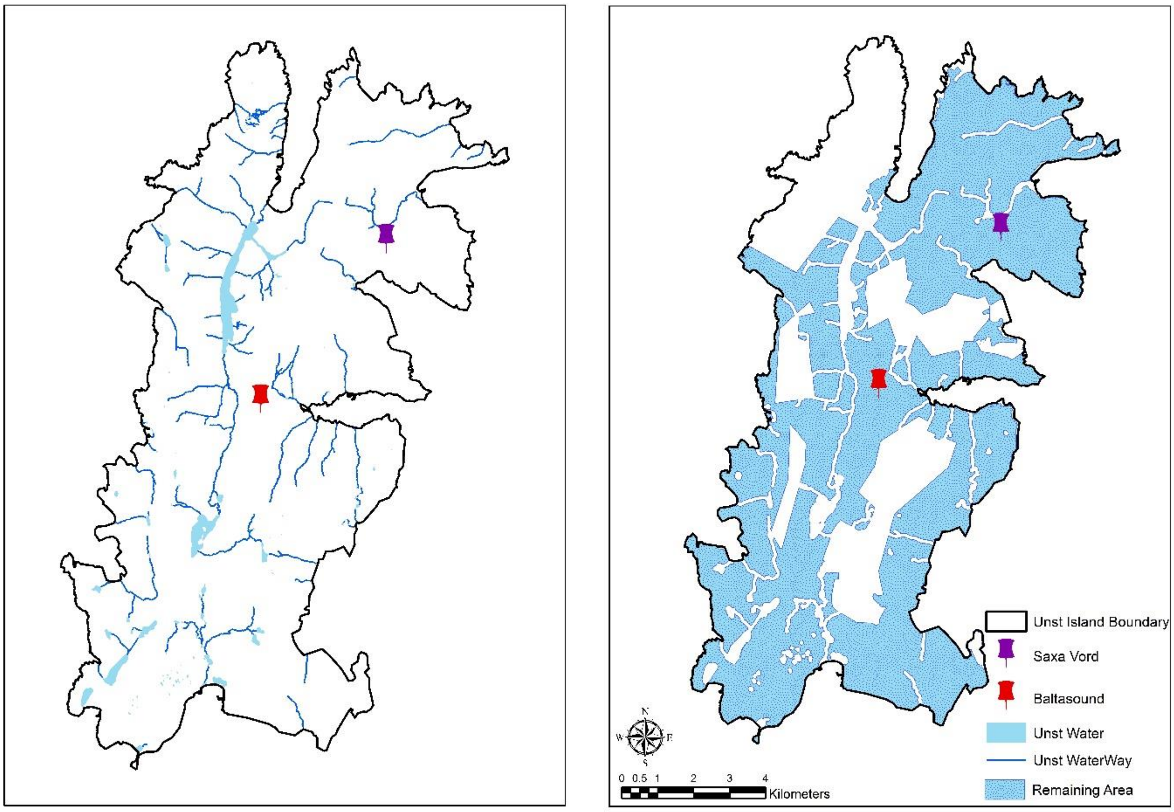


Figure 7.1.3 Unst Inland Water

Source: Author based (McGarva, 2017)

The safety clearance with respect to roads is also considered for this study. A buffer of 50 meters (10% of hub height plus the hub height of wind turbine) was created around the roads and the area within the buffered regions was excluded which is shown in Figure 7.1.3. Since the hub height of both wind turbines do not have too much differences in length, only the safety clearance for Enercon E-44 wind turbine was considered.

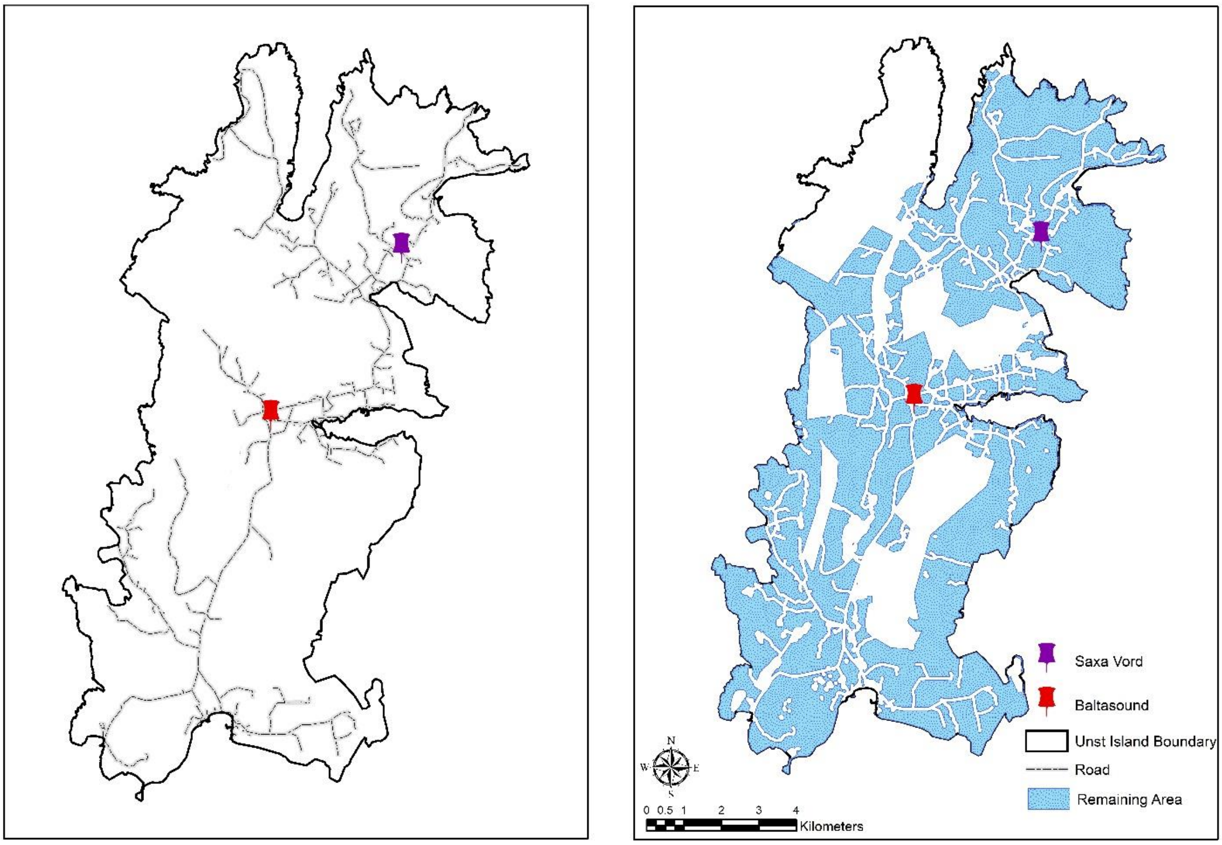


Figure 7.1.4 Unst Road

Source: Author based (McGarva, 2017)

The separation distance of wind turbine from residential areas (most of buildings are residential area) in Shetland island, is based on noise limitation of wind turbine. According to local development plan (The Highland Council, 2016, p. 23) for onshore wind energy in Shetland island, the noise limitation of wind turbine ranges between 38.6dB(A) during the day to 34.6dB(A) during the night. By increasing the distance from wind turbine the noise level will decline and with to some extend it follows the rule of inverse square law (Salt and Hullar, 2010). The remaining area from Figure 7.1.4 was considered to find the areas where the noise is limited by a value of 35dB (A).

7.1.4 Wind Resource Map

A wind resource map was generated by WindPRO®3.2 software based on mesoscale data purchased from EMD with the hub height of 50m, the location is shown in Figure 7.1.5. The closest areas to proposed load centres with high wind potential was studied to generate the noise map by spotting both wind turbines. The closest area by considering all onshore wind turbine-planning issues near Saxa Vord Resort has a distance of almost 1.5 km from the proposed load centre. Other closest area for Baltasound is located almost 1km away from the proposed load center. These two areas were selected for this study.

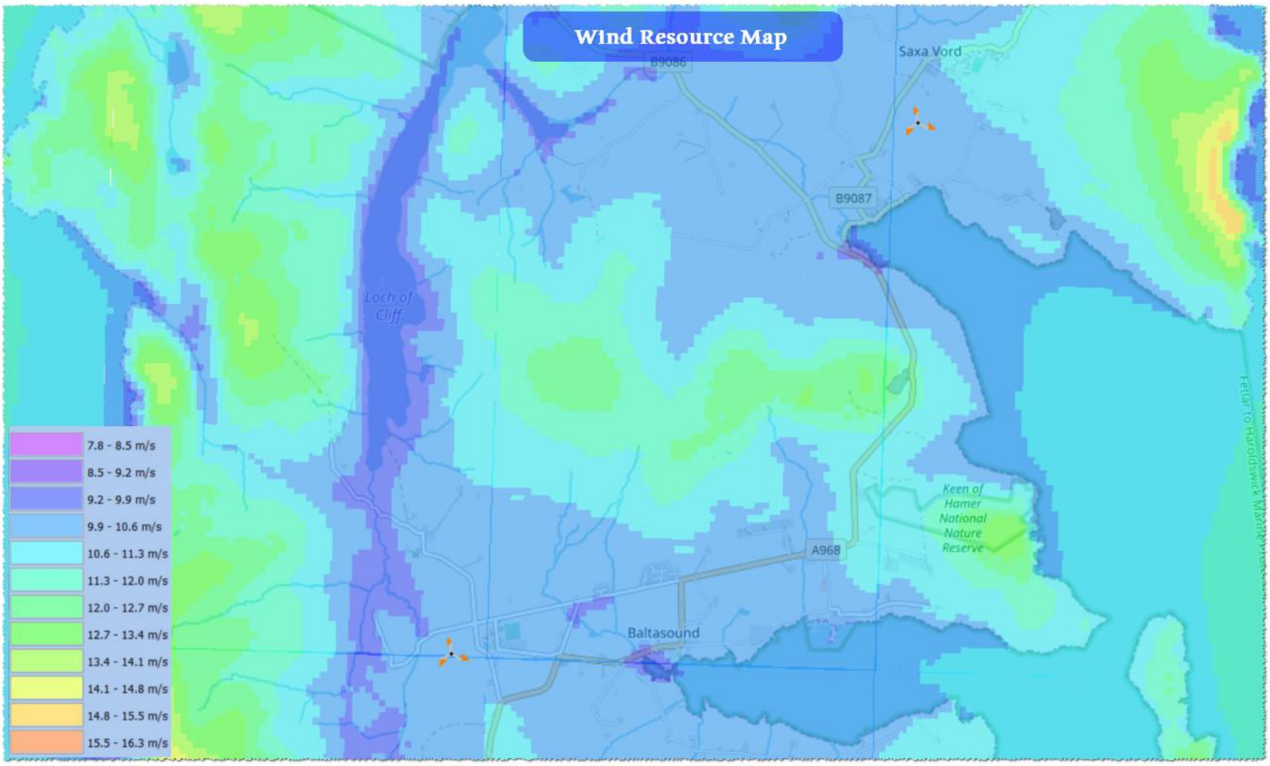


Figure 7.1.5Wind Resource Map

Source: WindPro

7.1.5 Wind Energy Project Design

WindPRO®3.2 software was used to design the wind project and all layers such as land’s roughness area, roughness line, elevation data grid and elevation contour lines were downloaded online by WindPRO®3.2 software (EMD International, 2019). Buildings in the vicinity of wind turbine act like obstacles and affect the wind speed and directions. Therefore, they are taken into consideration for the simulation.

7.1.5.1 Wind Data

Mesoscale wind data was purchased from EMD (EMD International, 2019) and was used to design the wind project in both locations. The mesoscale wind data is based on Weather Research and Forecasting (WRF) on hourly bases with small spatial resolution and is provided for three years starting from October 2015 to October 2018 (*EMD International*, 2019). The location of the generated metronomic station is shown in Figure 7.1.5. Wind Resource Map and also the generated Saxa Vord meteo-station data was used to generate the wind resource map.

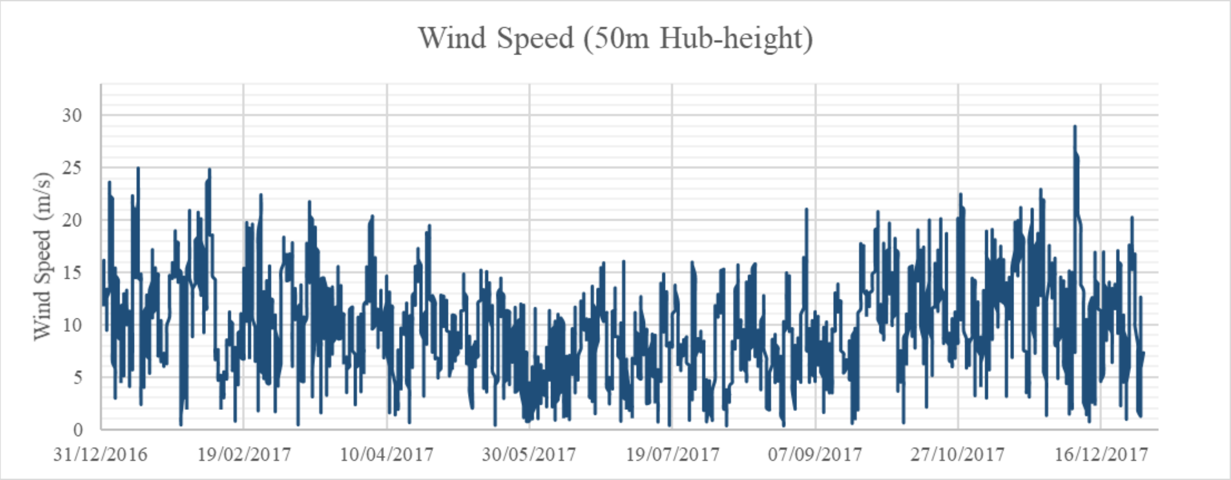


Figure 7.1.6 Hourly Wind Speed of Generated Saxa Vord Resort Meteo-Station

Source: WindPRO

Figure 7.1.6 shows the hourly wind speed variation for 2017, the reference year (*EMD International*, 2019).

7.1.5.2 Saxa Vord Proposed Wind Project

For the Saxa Vord wind project both Enercon and Xant wind turbine were studied. Since the wind direction is quite scattered throughout the months, a 5 times rotor diameter separation distance for both wind turbines were assigned during the simulation. The location of wind turbines in proposed project site were optimized and wind turbines were spotted where the wake effect was minimised by WindPRO®3.2 software. The mesoscale data generated in the vicinity of Saxa Vord Resort was used to generate the annual energy profile of wind turbines which is shown in table below.

Table 7.1.2 Saxa Proposed Vord Wind Energyy Project

No	Wind Turbine / Rating	QTY	Annual Energy (MWh/y)	Capacity Factor (%)
1	Xant (100kW)	1	562.7	57.8
2	Enercon (900kW)	1	4560.2	52

Source: Author based on WindPro

7.1.5.3 Baltasound Proposed Wind Energy Project

The separation distance between wind turbines is five times the rotor diameter. The generated Baltasound meteo-station wind data was used to generate the annual energy profile of wind turbines in this location.

Table 7.1.3 Baltasound Proposed Wind Energy Project

No	Wind Turbine / Rating	QTY	Annual Energy (MWh/y)	Capacity Factor (%)
1	Xant (100kW)	1	453	46.5
2	Enercon (900kW)	1	3225.7	36.8

Source: WindPro

7.1.6 Cost

Table 7.1.4 shows the cost breakdown of both types of wind turbines based on study by University of Flensburg students in Durness (Adensanya *et al.*, 2017). The connection cost of wind turbine from the proposed wind project site to the load centre is estimated based on Scottish Hydro Electric Power Distribution plc (Scottish and Southern Energy Power Distribution, 2014). The capital, operational and maintenance cost of grid connection is added to the total project's cost. The capital, operational and maintenance cost are all adjusted to current prices (International Renewable Energy Agency (IRENA), 2018; The Statistics Portal, 2019).

Table 7.1.4 CAPEX and OPEX of Wind Turbines

Saxa Vord			
Description	**900 kW Enercon**	**100 kW Xant**	**Unit**
Total Capex	2,097,780	614,986	GBP
O&M	47,561	11,256	GBP/year
Baltasound			
Description	**900 kW Enercon**	**100 kW Xant**	**Unit**
Total Capex	2,015,307	475,090	GBP
O&M	46,731	9,848	GBP/year

Source: Author based (Adensanya *et al.*, 2017; Cirincione, Wolfsthal and Rajkumar, 2018; The Statistics Portal, 2019; WindPro, 2019)

Some uncertainties due to remoteness of Unst Island will affect the cost of the proposed project such as the transportation cost of wind turbine to the site and service cost for operation and maintenance of wind turbine would be higher.

7.2 Heat Pumps

Heat Pumps (HP) are a sort of renewable energy technologies which extract heat from the air (Air Source HP) or from ground (Ground Source HP) in order to supply buildings' heating demand. The main advantage of implementing this technology is its reduced electricity consumption inasmuch as its design efficiency rounds the 400% (Mitsubishi Electric, 2014b, p. 13) ; it means that for producing four units of heat power, a HP will only need one unit of electricity power . Modern oil-fired boilers and electric radiators have an annual average efficiency of 92 % and 100 % respectively (Danish Energy Agency, 2018, p. 30&142).

7.2.1 Ground Source Heat Pump (GSHP) Capacity Estimation

The capacity of the GSHPs to be installed is limited by the area available for the installation of the horizontal ground heat exchanger. The method presented in (Department of Energy and Climate Change (DECC), 2013) were used to estimate the maximum size of the heat pump for the different locations.

The first step is to calculate the length of the heat exchanger according to the area available, and the recommended separation between trenches, as follows.

(L_b) - Length of the Ground Heat Exchange (GHE)	(m)	
(A) - GHE area	(m^2)	$L_b = A/d$
(d) - Minimum centre-to-centre spacing of the slinky GHE	(m)	

Once the length of the GHE is obtained, the maximum power that can be extracted from the ground (i.e. the heat pump evaporator capacity) can be obtained by using the following calculation.

(G)- Maximum power extracted from the ground	(W)	$G = g * L_b$
(g)- Specific heat power extraction from the ground	(W/m)	

Finally, the HP capacity can be estimated as shown next.

(SCOP)- Seasonal Coefficient of Performance of the HP		$H = G/(1 - \frac{1}{SCOP})$
(H)- HP heating capacity at 0°C ground return temperature and design emitter temperature.	(W)	

The *specific heat power extraction from the ground (g)* will depend on the thermal conductivity, the mean ground temperature, and the HP's full load equivalent run hours per year, among other variables. The value of (g) for different locations across the UK, as well as the recommended separation between trenches, can be taken from (Department of Energy and Climate Change (DECC), 2008). In case the specific data for the locations is not available, the thermal conductivity in Unst can be assumed to be similar to the one in the Fair Isle, 1.42 (W/m/K) (Busby, 2016, Table 2); while the mean ground temperature in Unst is equal to 8.6 °C as can be evidenced in (Busby, 2015).

7.2.2 Ground Temperature Modelling

The performance of a GSHP depend intrinsically on the ground temperature at the depth at which the loops are placed; typically, 2 m below the earth surface. The equation given by Kasuda and Achenbach in 1965 for the calculation of the seasonal variation of the shallow ground temperature was used in our approach (Chiasson, 2017, p. 224).

$$\mathrm{T(d,t) = T_M - A_s.e}^{\left[-\mathrm{d}\left(\frac{\pi}{365\alpha}\right)^{1/2}\right]}\mathrm{.\cos}\left[\frac{2\pi}{365}\left(\mathrm{t - t_0} - \frac{\mathrm{d}}{2}\left(\frac{365}{\pi\alpha}\right)^{1/2}\right)\right]$$

Equation 7.2.1 Shallow Earth temperature as a function of depth and day of the year

Source: Kasuda & Achenbach, 1965

Where,

$T(d,t)$ −is the ground temperature at a depth (d), and after (t) days after the 1st of January.	(°F)
T_M − is the mean (average) surface temperature of the ground during the year; typically, the average annual air temperature for the given location	(°F)
A_s − is the amplitude of the surface temperature function throughout the year	(°F)
d − is the depth at which we want to know its temperature	(ft)
α − is the soil thermal diffusivity	(ft^2/day)
t_0 − is the time difference (in days) between the beginning of the calendar year and the occurrence of the minimum surface temperature	days

As reported in (Busby, 2015), the weather station Baltasound N°2, located in Unst, registered between 2002 and 2009 a mean ground temperature of 8.6°C at a depth of 0.3 m, with an amplitude of 16.2°C. The coldest day in the period from 1980 to 2016 was February 17th according to the analysis conducted by (Weather Spark, 2019). Similarly, in (Busby, 2016) the thermal diffusivity across the UK have been measured through weather stations; the thermal diffusivity in Unst was assumed the same as in the Fair Isle, 0.9003x10-^{6} m2/s (0,8372 ft^2/day). By using the previous values, the computation of the yearly ground temperature at a depth of 2 m resulted in the following outcome.

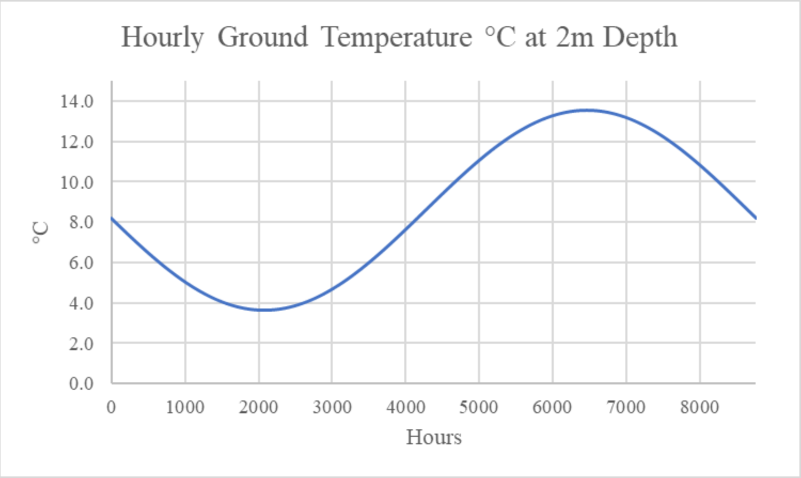


Figure 7.2.1Unst Ground Temperature at 2m Below the Earth Surface

Source: Author

7.2.3 GSHP Performance Modelling

Two GSHPs were included in the tool; from the manufacturer MITSUBISHI the model CRHV-P600YA-HPB with a capacity of 60 kW (certified for the Microgeneration Certificate Scheme-MCS from UK the Government according to (Mitsubishi Electric, 2016, p. 3)); and from the manufacturer VIESMANN the model Vitocal 300-G-Type129 with a capacity of 28.8 kW.

In order to model their performance, the data books from the manufacturers were used (for more details see (Mitsubishi Electric, 2014b, p. 13) and (VIESSMANN, 2010, p. 9)). The relationships among the brine temperature (brine temperature was assumed as 95% of the ground temperature), the outlet water temperature, the heat production and the coefficient of performance (COP), which are provided by the manufactures' data book, were used to estimate the maximum heating output across the year and the SCOP.

The results for the Mitsubishi CRHV-P600YA-HPB at different capacities and outlet water temperatures are summarized in Table 7.2.1.

Table 7.2.1 GSHP Performance at Different Water Outlet Temperature and Output Heating Power

Mitsubishi CRHV-P600YA-HPB						
Outlet Water Temperature °C (Spread 5°C)	30	35	40	45	50	55
Yearly Heat Production (kWh) –at 100% of its capacity	525,600					
SCOP–at 100% of its capacity	5.27	4.73	4.30	3.85	3.43	3.23
Yearly Heat Production (kWh) –at 75% of its capacity	394,200					
SCOP–at 75% of its	5.32	4.74	4.29	3.84	3.42	3.04
Yearly Heat Production (kWh) – at 50% of its capacity	262,800					
SCOP- at 50% of its	5.07	4.53	4.14	3.73	3.33	2.98

Source: Author based on (Mitsubishi Electric, 2014b, p. 13)

Figure 7.2.2 illustrates a one-year performance for the Mitsubishi CRHV-P600YA-HPB when running at 100 % of its capacity and with an outlet water temperature of 45 °C.

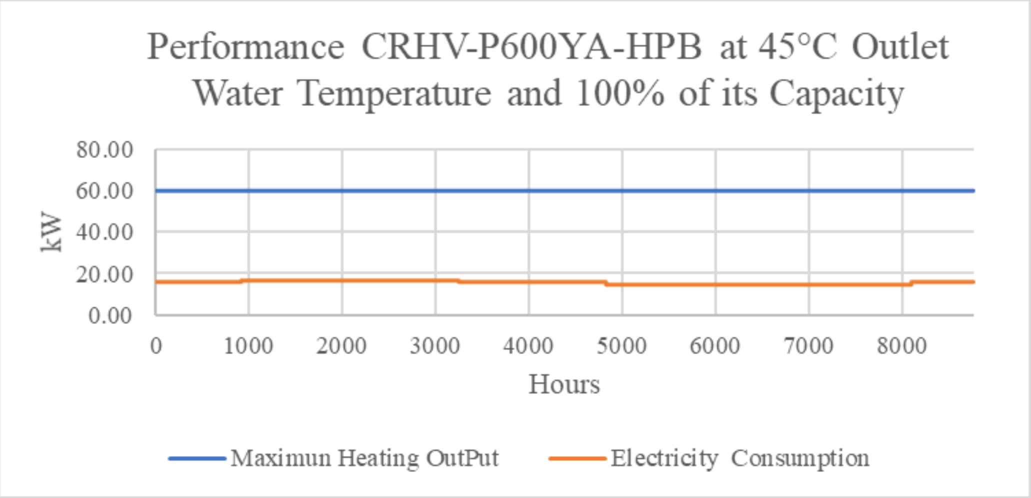


Figure 7.2.2 CRHV-P600YA-HPB GSHP Performance Modelling

Source: Author based on (Mitsubishi Electric, 2014b, p. 13)

7.2.4 Air Source Heat Pump (ASHP) Performance Modelling

Similarly, two ASHPs from the manufactures MITSUBISHI were added to the tool; models CAHV-P500YA with a capacity of 45 kW and PUHZ-W85VHA2-(BS) with a capacity of 8.5 kW were selected. Both are certified for the Microgeneration Certificate Scheme (MCS) from the UK Government.

For the performance modelling of CAHV-P500YA, its efficiency priority mode was included in the tool (for more details see (Mitsubishi Electric, no date, p. 10)), while for the PUHZ-W85VHA2-(BS) its nominal performance was selected (for more details see (Mitsubishi Electric, 2015, p. A63)). The hourly air temperature in Unst in 2017 was obtained from (Meteoblue, 2019c); by using this time series in combination with the datasheets from the manufactures, which relate the intake air temperature of the HP with its outlet water temperature, the heating output and the electricity consumption, it was possible to estimate the hourly maximum heat production across the year. The results at different outlet water temperatures are condensed in Table 7.2.2.

Table 7.2.2 ASHPs Performance at Different Water Outlet Temperature

Mitsubishi CAHV-P500YA		
Outlet Water Temperature °C (Spread 5°C)	**Yearly Heat Production (kWh)**	**SCOP**
35	387,778	3.97
45	388,140	3.33
55	388,661	2.66
60	389,001	2.44
65	389,182	2.09
70	389,363	1.76
Mitsubishi PUHZ-W85VHA2-(BS)		
Outlet Water Temperature °C (Spread 5°C)	**Yearly Heat Production (kWh)**	**SCOP**
35	77,092	3.87
40	77,321	3.46
45	77,548	3.04
50	77,279	2.71
55	77,024	2.37

Figure 7.2.3 illustrates the hourly performance of PUHZ-W85VHA2-(BS) at an outlet water temperature of 45°C.

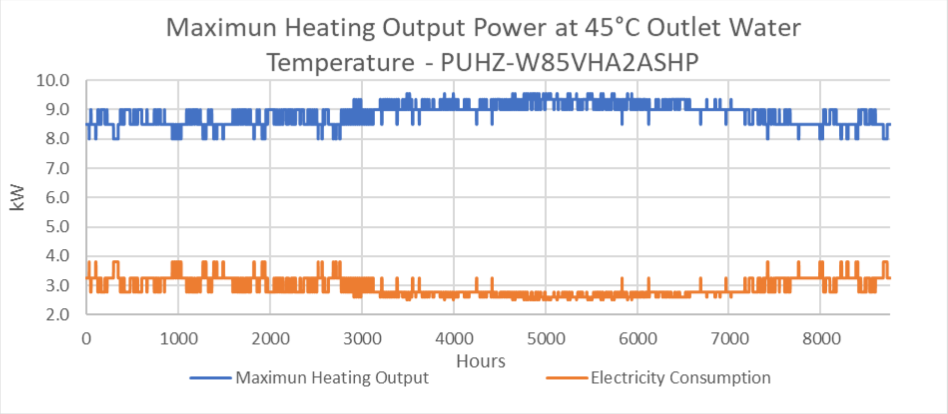


Figure 7.2.3 PUHZ-W85VHA2ASHP Performance Modelling

Source: Author based on (Mitsubishi Electric, 2015, A63; Meteoblue, 2019a)

7.2.5 COSTS

The investment and maintenance of a heat pump heating system, either ground or air source, vary depending of its size and location. According to (Generating Renewable Energy Business

Enterprise (GREBE), 2017), the investment cost (including the HP and installation, horizontal groundwork , machinery, equipment, design, engineering and civil works) for a 55 kW horizontal GSHP in Scotland ranges between £900-£1,050/kW, whereas a 6-11kW GSHP varies from £940-£1,830/kW. Similarly, an ASHP requires an investment of £800-£1,200/kW.

These costs do not include the cost of the heat distribution system, gets lower as the capacity increase, and are aligned with the costs presented in (Danish Energy Agency, 2018, p. 91) .

It is important to point out that the information presented by (Generating Renewable Energy Business Enterprise (GREBE), 2017, p. 11) shows that vertical heat exchangers costs around three times more compared to a horizontal heat exchanger; this difference gets higher as the rated power is the system increases. This report also evidences that in the case of horizontal GSHP, the ground loops account for approximately 19 % of the investment and increase along with the capacity of the system.

Regarding the operational costs, the values for ASHPs and GSHPs of different capacities in the UK are summarized in (Sweett Group, 2013, p. 16, 25). In order to estimate the costs for the year 2017, these numbers were affected by the inflation in the UK as found in (The Statistics Portal, 2019).

The average value of the costs discussed above are show in Table 7.2.3.

Table 7.2.3 CAPEX and OPEX for GSHP and ASHP in the UK

<table>
<tr><th colspan="6">Ground Source Heat Pump (GSHP)</th></tr>
<tr><td>Capacity</td><td>(kW)</td><td colspan="2">6 - 11</td><td>55</td><td>Source</td></tr>
<tr><td>Capex (2017)</td><td>(£/kW)</td><td colspan="2">1,385</td><td>975</td><td>(Generating Renewable Energy Business Enterprise (GREBE), 2017, p. 11)</td></tr>
<tr><td>Average Opex (£/kWh) including electricity costs @ 2017</td><td>(£/kWh)</td><td colspan="3">0.0538810</td><td>(Sweett Group, 2013, p. 25)</td></tr>
<tr><td>Lifespan GSHP</td><td>(years)</td><td colspan="3">25</td><td rowspan="2">(Generating Renewable Energy Business Enterprise (GREBE), 2017, p. 8)</td></tr>
<tr><td>Lifespan Ground loops</td><td>(years)</td><td colspan="3">50</td></tr>
<tr><td colspan="6">Air Source Heat Pump (ASHP)</td></tr>
<tr><td>Capacity</td><td>(kW)</td><td>5</td><td>10</td><td>15</td><td>Source</td></tr>
<tr><td>Capex (2017)</td><td>(£/kW)</td><td>8,620</td><td>11,494</td><td>13,793</td><td>(Danish Energy Agency, 2018, p. 91)</td></tr>
<tr><td>Average Opex (£/kWh) including electricity costs @ 2017</td><td>(£/kWh)</td><td colspan="3">0.0754334</td><td>(Sweett Group, 2013, p. 15)</td></tr>
<tr><td>Lifespan ASHP</td><td>(years)</td><td colspan="3">20</td><td>(Mitsubishi Electric, 2016, p. 13)</td></tr>
</table>

Source: Author(s)

7.3 Solar PV and Solar Thermal

7.3.1 Solar Resource

7.3.1.1 Solar Irradiation

The solar resource in Unst is very low in comparison to most places in the world. The average annual Global Horizontal Irradiation for reference year 2017 is 742 kWh/m^2 (Meteoblue, 2019) as presented in Figure 7.3.1. The intra-annual variation is significant with winter months receiving minimum irradiation. About 282 kWh/m^2 is received as direct irradiation while 460 kWh/m^2 insolates as diffused irradiation (PVSOL)

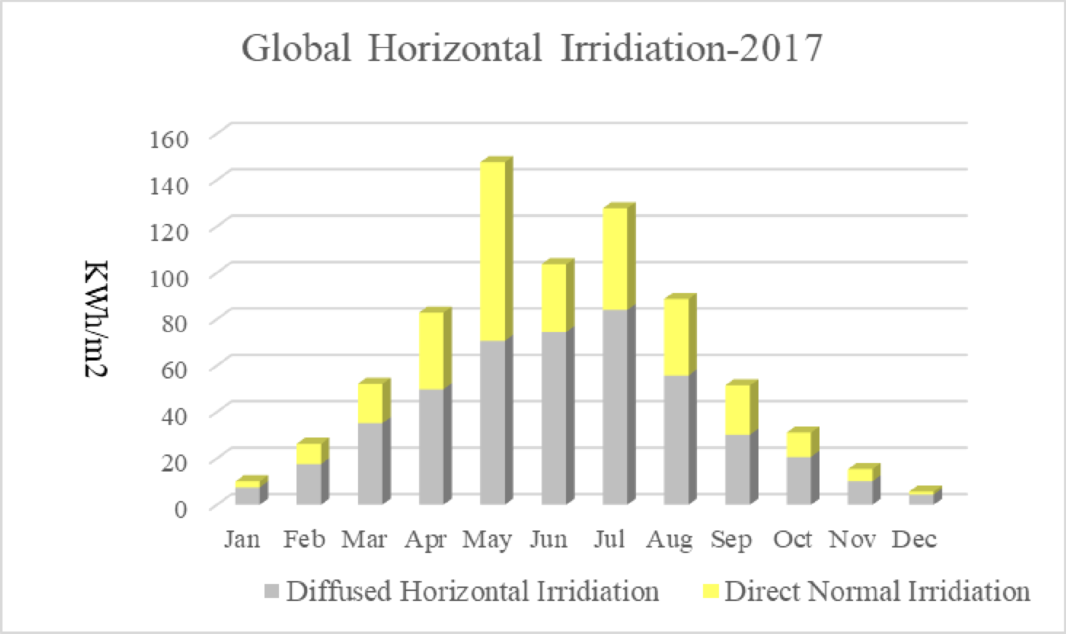


Figure 7.3.1 Global Horizontal Irradiation

Source: Illustration by author based on (Meteoblue, 2019c)

7.3.1.2 Ambient Temperature

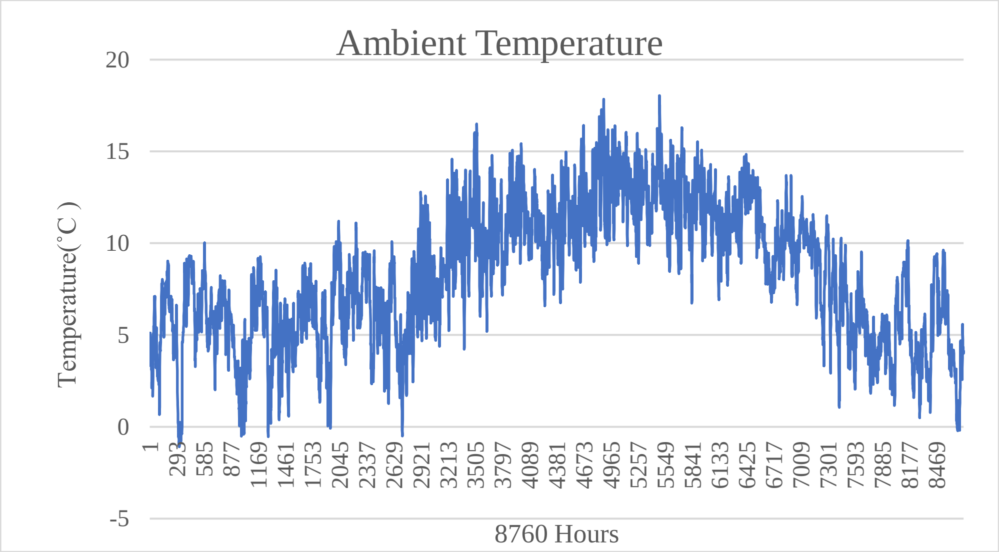


Figure 7.3.2 Ambient Temperature for 2017

Source: (Meteoblue, 2019)

The temperature data was obtained from Meteoblue (2019) for 2 m above the ground for the base year 2017. Figure 7.3.2 above shows that the temperature is highest from April to September. The maximum temperature did not exceed 18 ˚C whereas the minimum was -1.08 ˚C.

7.3.2 Site Selection

The roof PV and solar thermal installation is constrained with respect to aspect and tilt angle considerations, and to optimize the generation, ground mount installation is preferred. Land in Unst is mostly flat with gentle slopes and in the flat areas; the effect of aspect is minimal if any. Generally, south-facing aspects of land area is considered while selecting a site for the PV and solar thermal. In Baltasound and Saxa Vord there are plenty of suitable land areas for PV and solar thermal installations.

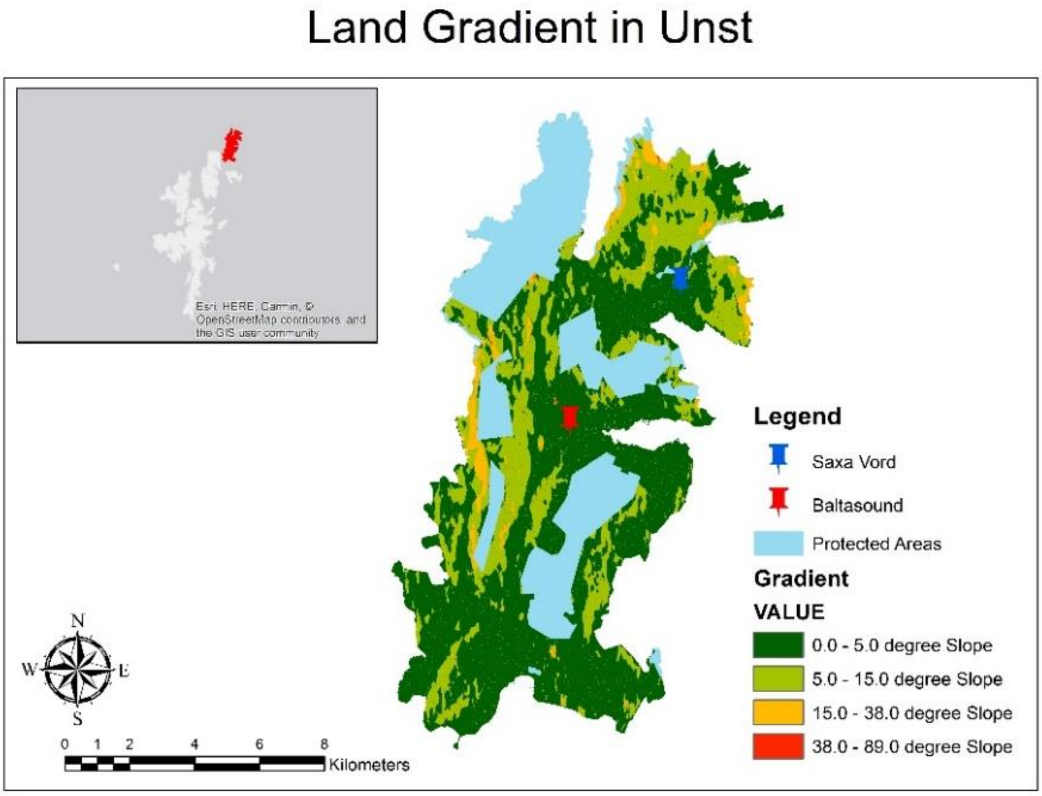


Figure 7.3.3 Land Gradient in Unst

Source: Illustration by Author based on (Scottish Natural Heritage, 2016)

7.3.3 Solar PV

7.3.3.1 Panel Selection

Photovoltaic panels of three manufacturers namely Jinko Solar, Trina Solar and Sun Power are proposed for Unst as per the discussion held with Pure Energy Centre. The selection of panel is based on the results from PVSOL considering specific yield and thermal gain/loss.

7.3.3.2 Thermal Gain/Loss

Panels are tested at a Standard Testing Condition (STC) temperature of 25 °C, irradiance of 1000 W/m^2 and at AM 1.5 (Fraunhofer ISE, n.d). A higher ambient temperature reduces the voltage with a minimal increase in current, hence reducing the overall output. In opposite, lower temperature positively increases the voltage with a minimal decrease in current, thereby resulting in a gain in output as shown in Figure 7.3.4.

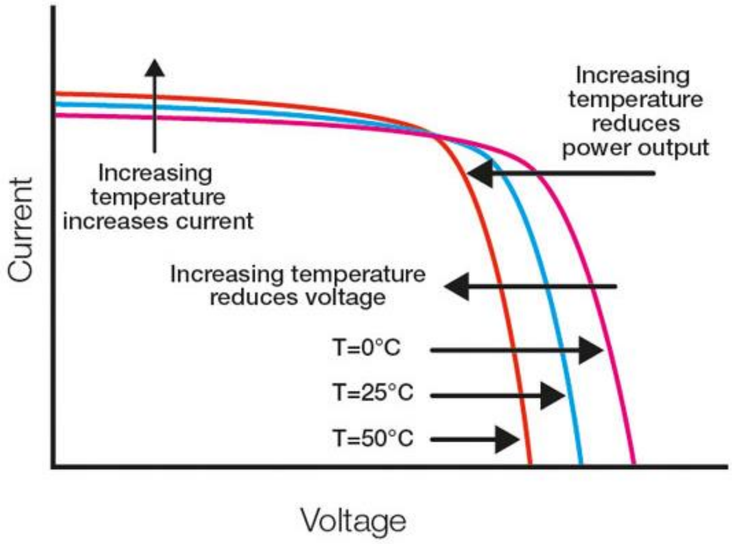


Figure 7.3.4 Effect of Temperature

Source: (Seaward Group USA, 2018)

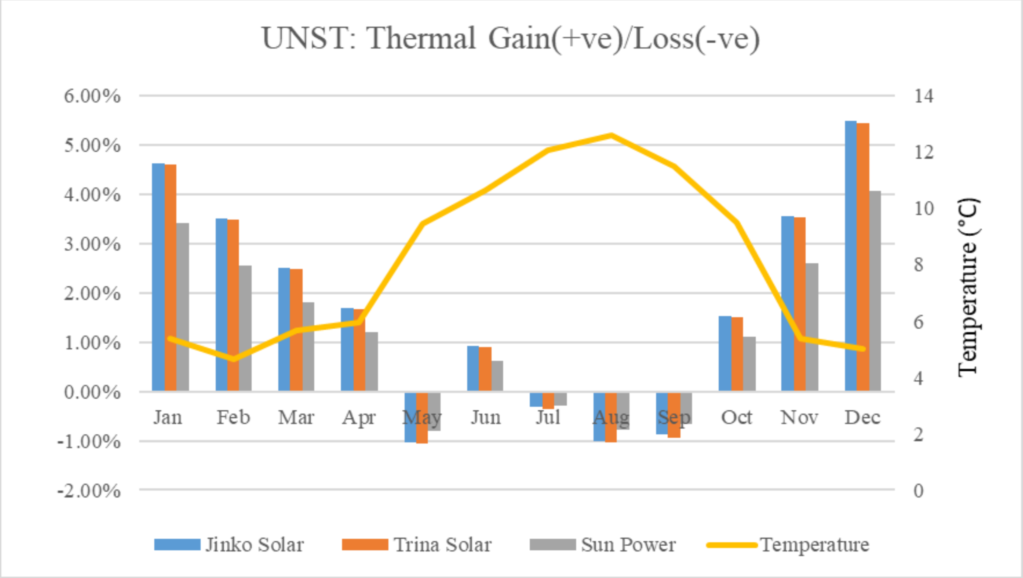


Figure 7.3.5 Thermal Gain and Loss

Source: Illustration by Author based on results from PVSOL

Most poly-crystalline panels tend to have a higher thermal coefficient as compared to the mono-crystalline panels whereas mono-crystalline are more efficient than poly-crystalline.

Higher thermal coefficient results in higher thermal gain in colder regions as depicted by Figure 7.3.5

7.3.3.3 Specific Yield

Specific yield can be defined as energy produced by a unit capacity of a system. In solar PV it is usually expressed in kWh/kWp. The higher the specific yield better the performance and vice-versa. The specific yield may depend on multifarious factors such as design, location, irradiation, panel efficiency, thermal coefficient, losses etc. In essence, higher thermal coefficient and higher efficiencies are more appropriate for places like Unst. The Sun-Power monocrystalline panel (SPR-X21-327-BLK) performs slightly better than other two panels.

Table 7.3.1 Panel Comparison for Specific Yield in Unst

Manufacturer	Panel Type	Model	Thermal Coefficient (%/°C)	Efficiency (%)	Specific Yield (kWh/kWp)
Jinko Solar	Poly-Crystalline	JKM330P-72	-0.41	17.10	793.14
Trina Solar	Poly-Crystalline	Trina TSM-280-PD05	-0.41	17.10	781.67
Sun Power	Mono-Crystalline	SPR-X21-327-BLK	-0.30	23.30	797.11

Source: Illustration by Author based on results from PVSOL

7.3.3.4 Mechanical Design

7.3.3.4.1 Optimized Tilt Angle

The tilt angle was optimized using PVSOL software by comparing specific yield (kWh/kWp) for different possible tilt angle. The tilt angle with the highest specific yield is the optimized tilt angle for the module array. In summer when the sun elevation angle is higher, the tilt angle should be lower to optimize the production and on the other hand, tilt angle should be higher when the sun elevation angle is lower during winter days. However, in a fixed rack system, sunrays are not perpendicular throughout the year. The optimized tilt angle from PVSOL is found to be 43° in Unst.

7.3.3.4.2 Inter-Row Distance

Considering the Sun Power panel (SPR-X21-327-BLK) as discussed in the earlier section, the designed inter-row distance between the panels is 2.50 meters. The sun elevation considered for the inter-row spacing is 9 am and 3 pm of 20th March and 20th October, wherein the sun angle is at 20°. This particular date and time are considered as the worst-case sun angle for a shadow free inter row distance.

7.3.3.5 Prospective Performance

For 4.91 kWp installation, the prospective yield is 3,909.80 kWh and the corresponding capacity factor is 8.93 after accounting for all the losses (viz. inverter loss, mismatch loss, cable loss etc.) as shown in Table 7.3.2. The energy yield is highest for the month of May and lowest in December in line with the irradiation as illustrated by the figure below. Due to the weak solar resource, the capacity factor is substantially less than the world average of 17.1 percent for the year 2017 (IRENA, 2018,p.66). The inference that can be drawn from the lower capacity factor is that any endeavour inclining towards the deployment of solar PV will come at a higher cost.

For the excel model 4.91 kWp of a system is simulated in PVSOL for a more comprehensive and credible results. This particular capacity is the reference capacity and for capacity larger than 4.91 kWp a multiplicative factor is applied.

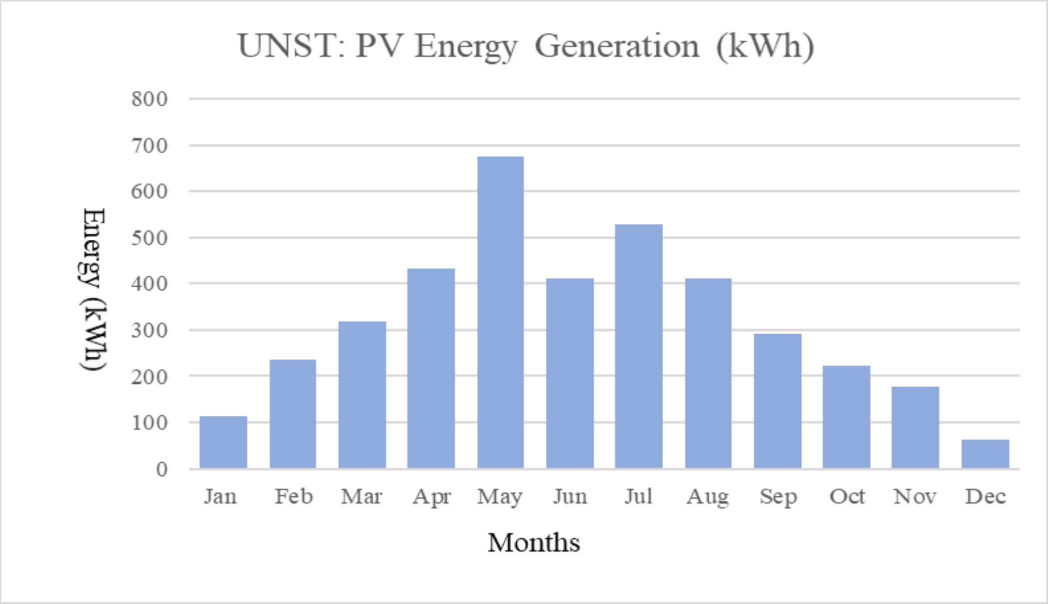
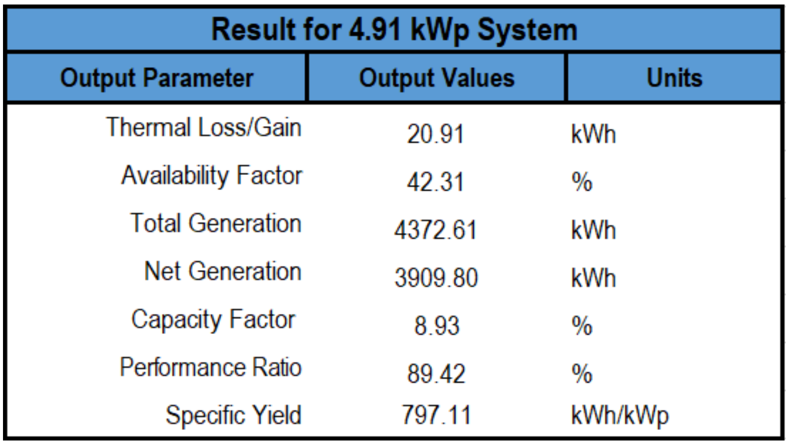


Figure 7.3.6 Monthly Energy Yield

Source: PVSOL

Table 7.3.2 Results



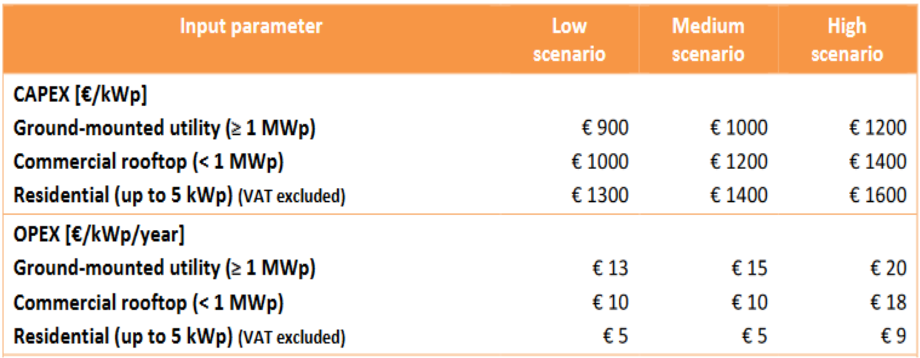
Result for 4.91 kWp System		
Output Parameter	**Output Values**	**Units**
Thermal Loss/Gain	20.91	kWh
Availability Factor	42.31	%
Total Generation	4372.61	kWh
Net Generation	3909.80	kWh
Capacity Factor	8.93	%
Performance Ratio	89.42	%
Specific Yield	797.11	kWh/kWp

Source: PVSOL

7.3.3.6 Cost

A paper by Tjengdrawira et al., (2016, Table 2) categorizes the cost of PV under three category namely, low scenario, medium scenario and high scenario, with low scenario based on places with high solar resource and high scenario based on places with low solar resource. The low scenario applies to country like Italy and high scenarios applies to country like Netherland and the UK. As per Tjengdrawira et al., CAPEX and OPEX information is collected from multiple sources like "project partner, project advisory board as well as recent publications on PV system pricing" (2016, p.18).

Table 7.3.3 CAPEX and OPEX



Input parameter	Low scenario	Medium scenario	High scenario
CAPEX [€/kWp]			
Ground-mounted utility (≥ 1 MWp)	€ 900	€ 1000	€ 1200
Commercial rooftop (< 1 MWp)	€ 1000	€ 1200	€ 1400
Residential (up to 5 kWp) (VAT excluded)	€ 1300	€ 1400	€ 1600
OPEX [€/kWp/year]			
Ground-mounted utility (≥ 1 MWp)	€ 13	€ 15	€ 20
Commercial rooftop (< 1 MWp)	€ 10	€ 10	€ 18
Residential (up to 5 kWp) (VAT excluded)	€ 5	€ 5	€ 9

Source: (Tjengdrawira, Richter and Theologitis, 2016,Table 2)

A CAPEX of 1,218 £/kWp (1400€/kWp from the table above) and correspondingly OPEX of 16 £/kWp (18€/kWp from Table 7.3.3) is considered for further calculations.

7.3.4 Solar Thermal

Non-concentrating collectors (flat plate and evacuated tube solar collectors) were considered for the project because of the low solar irradiance in Unst. Some important aspects of non-concentrating collectors are listed below:

i. Evacuated Tube Collectors

- The sunrays are always perpendicular to the circular surface of the evacuated tube collector (like Thermomax DF400 model).
- The investment cost of the evacuated tube collector is about 20-40 % higher than flat plate collectors (Solar Panel Plus, 2014, p. 1).

ii. Flat plate Collectors

- Flat plate collectors are easy to install and widely proven.
- They are cheap than the evacuated tube collector as illustrated in Table 7.3.5.

7.3.4.1 Efficiency Calculation of the collector

The following equation was used to determine the overall efficiency of the collector.

$$\eta = \eta_o - \frac{a_1(t_m - t_a)}{I} - \frac{a_2(t_m - t_a)2}{I}$$

Equation 7.3.1 Overall efficiency calculation

Source: (ESTIF, 2007, p. 1)

η=overall collector efficiency

η_o= zero loss efficiency=optical efficiency

a_1=First order heat loss coefficient ($W/m^2.K$)

a_2=Second order heat Loss Coefficient ($W/m^2.K$)

I=Global Radiance on the Collector (W/m^2)

t_m =Collector Mean Temperature (˚C)

t_a=Ambient Temperature (˚C)

The values of ηo ,a_1 and a_2 were obtained from the Kingspan Company collector catalogue. The collector mean temperature was calculated as the mean temperature of both the incoming and outflowing fluid temperature. Global Radiance on the collector was calculated with the optimum tilt angle for the optimum energy production throughout the year. The ambient temperature was obtained from Meteoblue (Meteoblue, 2019c).

The 8760-hour efficiencies were calculated to find the hourly energy output from the collector.

7.3.4.2 Indirect Water Heating System

In this system, non-toxic and non-freezing heat transfer fluid is used. The heat transfer fluid has higher boiling point and lower freezing point when compared to water. It circulates in a closed loop. The fluid transfers the heat from solar collector to the water in the storage tank. Ethylene glycol and Propylene glycol solutions are commonly used heat transfer fluids (Lanru Jing, 2007). Kingspan uses propylene glycol solution for Thermomax DF400 and FPW flat plate collectors and is considered for further analysis (Kingspan, 2019, p. 1)

Volker Quaschning (2004, p. 1) discusses the operation of the solar collector system, stating that temperature sensors are used to monitor the temperature of water in the storage tank and fluid temperature in the solar collector. When the temperature of the collector is higher than the tank temperature, the controller starts the pump and pushes the heat transfer fluid through the collector. The heated fluid flows down the heat exchanger and transfers the heat to the water in the storage tank. If the temperature is lower in the collector, the controller switches off the pump. The process continues, transferring heat to the water in the storage tank.

7.3.4.3 Annual yield of collector

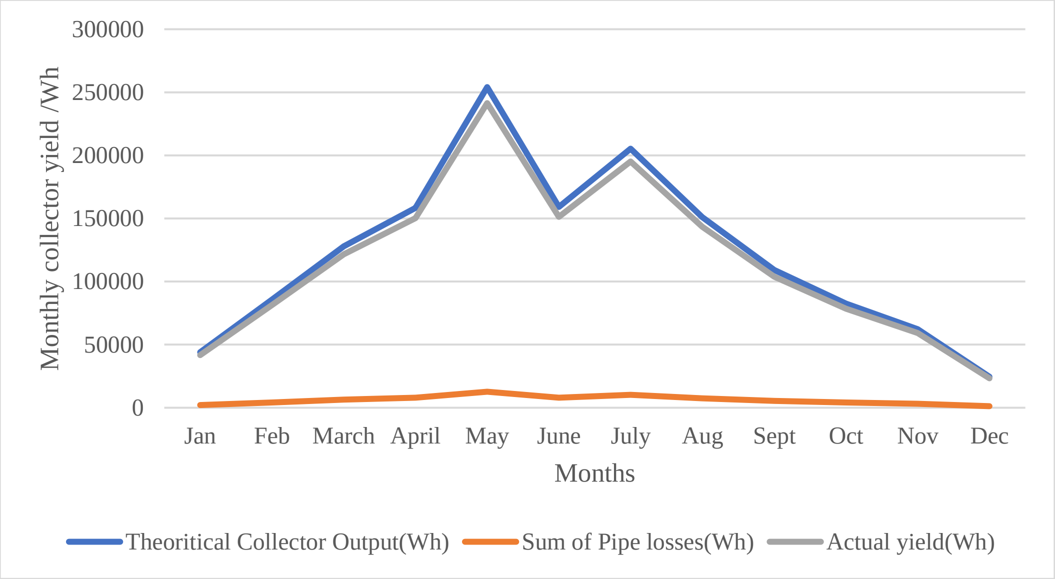


Figure 7.3.7 Actual Collector yield Calculation

Source: Author based (ESTIF, 2007; Meteoblue, 2019a)

Figure 7.3.7 above shows the actual yield from the collector. The actual yield of the collector is calculated by deducting the pipe losses. The heat gained on the collector by the solar radiation needs to be transferred to the storage with the minimum heat losses. In order to prevent substantial losses, pipe insulation plays a vital role. The insulation reduces the heat loss by convection and radiation. Pipe loss of 5 % has been considered for the project basing on ESTIF (2007, p. 4) .

7.3.4.4 Mechanical Design

7.3.4.4.1 Optimum Tilt Angle

The optimum tilt angle of 43° was calculated using PVSOL to produce the maximum energy output from the system.

7.3.4.4.2 Inter Row Distance

The system was designed to supplement the heat supply when the wind speed is low i.e. April to September. The sun angle of 30°was considered for the month between April 20 to September (9 am to 3 pm). The inter row distance for selected collectors viz. Thermomax DF400 Collector and FPW Flat Plate (Kingspan) was calculated as 3.74 m and 2.34 m respectively. The different size of the collector resulted in different row distance(Kingspan, 2019, p. 1)

7.3.4.5 Cost

The following formula was used to calculate the unit area cost of flat solar collector.

$$Price[\frac{€}{m2\ gross}] = 1000\ A_c^{-0.16}$$

Equation 7.3.2 Cost calculation of flat solar thermal

Source: (Trier, 2018, p. 3)

A_c=Gross collector area

Basing on Trier (2018,p.3), the price of the system is given by the Equation 7.3.2 above and it includes the following parameters :

- Cost for the collector panels
- Cost of piping, mounting and the installation work of the collector
- Cost of heat exchanger, pumps, control and regulatory system for the system
- Cost of heat transfer fluid
- Heat exchanger substation.

The calculated cost is validated with the capital cost from Finland as shown in Table 7.3.4.

Table 7.3.4 CAPEX and OPEX of flat plate collector

Reference for cost of collector (Flat Plate)			
Collector area (m^2)	**CAPEX** $(€/m^2)$	**OPEX** $(€/m^2)$	**OPEX (in %)**
4-20	500-1,000	50-100	10%
20-100	500-750	40-60	8%
100-1,000	450-500	20-25	5%
15,000	280-340	20	

Source: (Entreprises, n.d, p. 16)

For solar thermal system installed with flat plate collectors, the latter accounts for 45 % of the total capital system cost, 20 % is for storage, 25 % is for installation and commissioning, and the remaining 10% is small system component costs (Entreprises, n.d., p. 6). Normally, the investment cost of evacuated tube collectors are 20 to 40 % more expensive than flat plate collectors (Solar Panel Plus, 2014, p. 1). However, 20% was assumed keeping in mind the economies of scale for large heating systems. The rest factors affecting the capital cost discussed earlier are considered to remain constant. The cost of evacuated tube system increased by the factor of 1.09 as per the assumption mentioned earlier. The operational cost is considered as percentage of the capital cost as detailed in Table 7.3.4 (Entreprises, n.d., p. 16).

Based on the product datasheet of the Thermomax DF400 and FPW, a life of span of 25 years was considered (Kingspan, 2019, p. 1).

7.3.4.6 Cost Comparison for Evacuated and Flat Plate Collector

Table 7.3.5. Cost comparison for evacuated and flat plat collector

Type of collector	Number of Collector (m^2)	Area of collector (m^2)	land required (m^2)	Annual yield (MWh/yr)	Cost/m 2 (£/m2)	Total Cost (£)	Specific cost (£/MW h/yr)	Investment Cost Difference /£
Evacuated Tube	203	609	1,774	374	340	207,026	553	-18,929
Flat Plate	270	602	1,039	376	312	188,096	501	

Source: Author based on (Kingspan, 2019; Meteoblue, 2019; Trier, 2018)

Table 7.3.5 shows the cost comparison between the Thermomax DF400 and FPW flat plate collector. The calculation was done with the assumption that all thermal energy was used and with constant fluid inflow and outflow temperatures of 40^o and 50^o respectively. The cost comparison in Table 7.3.5 was done exclusively considering the investment cost of collectors.

The above calculation in Table 7.3.5 shows that Flat Plate (FPW) collectors are more affordable than the evacuated tube (Thermomax DF400) collector.

7.4 Chapter Summary

Wind, solar PV, solar thermal and heat pump renewable energy technologies have been assessed in the context of Unst. The results indicate a high potential for electricity generation from wind turbines near the Saxa Vord Resort and Baltasound. Similarly, both ground and air source heat pumps, have shown a promising potential if used for supplying heat to the buildings within the scope of the present study.

Due to the low solar irradiation throughout the year, the implementation of solar PV and solar thermal technologies in Unst, although feasible, require a high investment which seem to be less attractive when compared to the yearly energy yield.

Chapter 8: Hydrogen and its derivatives

8.1 Hydrogen Production

8.1.1 Introduction

Hydrogen as a green fuel is a possibility because of its high energy content (1 kg of Hydrogen has three times the energy of 1 kg of gasoline (Koponen, 2016)), its capacity to be stored for long periods without degradation (Gazey, 2014, p. 21), existing technology for hydrogen based vehicles and the technology to produce it without the use of fossil fuel: Water Electrolysis. However, improvements still have to be achieved in hydrogen storage with high volumetric density that is required in transport applications. Currently, technologies depend on high compression rates that consume a considerable portion of the energy content in the gas (Gazey, 2014, p. 23).

Electrolysis is frequently used to produce green hydrogen in situations where electricity is produced using VRE, such as Wind and Solar. The dependency of VREs on climate conditions results in certain moments where this energy is unused. This unused energy can be diverted to produce hydrogen by water electrolysis.

Although Hydrogen by its self is a valuable gas, many other valuable chemicals can be produced by using Hydrogen as a prime resource. These chemicals are called hydrogen derivatives, and the two analyzed during this chapter because of their applications are: Ammonia and Hydrogen Peroxide. A major application of hydrogen is its use in the transport sector, to power a wide arrange of vehicles: from small cars, to large ferries.

8.1.2 Technology Comparison for Electrolysis

Two electrolyser technologies were considered and compared to propose the most suitable for the present system. These technologies were selected because of their commercial availability and operating conditions. Each one has certain advantages and disadvantages when compared to the other, as seen in Table 8.1.1 below.

Table 8.1.1 Comparison of Electrolyser Technologies

Description	Alkaline	PEM	Sources
Purity level of hydrogen produced	99.5-99.9998%	99.9-99.9999%	(Koponen, 2016)
Investment	1,250 €/kW	1,800 €/kW	(Pure Energy Centre, 2019b)
Partial load operation limits	20-100% of full capacity	5-100% of full capacity	(Koponen, 2016)
Ramp up speed	0.13%-10% full load/s	10%-100% full load/s	(Koponen, 2016)
Lifetime of stack	60,000-90,000 h	20,000-90,000 h	(Koponen, 2016)

PEM allows for a high level of purity of hydrogen and a faster response to an intermittent energy supply, which would allow it to adapt to the variations that occur when supplying energy with wind or solar technologies. For the production of derivatives, a high-level purity of hydrogen and oxygen is not required, relative to fuel cell applications. Alkaline is a more mature technology, which allows it to have a lower cost and a higher degree of confidence in the reported lifetimes from manufacturers (Pure Energy Centre, 2019b).

Of the two technologies only alkaline was modelled and considered in the tool because of the data and methodology available and the local existence of a supplier with the know-how to maintain the equipment (Pure Energy Centre).

8.1.3 Alkaline Electrolyser Modelling

To model the Alkaline Electrolyser, three major and unique divisions are considered to structure the model. The model is based on the PhD dissertation by Ross Gazey (Gazey, 2014). The first division is the Polarization curve (I-V curve) that represents the required cell voltage for the desired current density for the electrolyser cell. This, in turn, depicts the losses such as: activation potential losses, ohmic losses, and concentration overpotential losses, which need to be overcome for the electrolyser to function in the real world. The second division is the Faraday efficiency that compares the theoretical production of the Hydrogen gas to the actual production, in essence taking into account the parasitic current losses for the electrolyser. The parasitic currents refer to the electrons that do not contribute to Hydrogen gas formation from the H^+ ions on that cathode. The third division is the thermal model that takes into account the heat generated by the electrolyser due to a higher cell voltage required that is needed to overcome the aforementioned losses. The thermal model from (Gazey, 2014) takes into count the thermal transients that have an effect on the production of hydrogen when there is an intermittent power input to the electrolyser such as from Wind and/or Solar PV. The electrolyser needs to reach an optimum temperature to function at high efficiencies. Due to the intermittent power input, the electrolyser has a susceptibility of operating as a partial-load and may be switched on and off several times, depending on the input. This hinders the electrolyser to reach its optimum temperature of operation. Hence, there is a loss in efficiency of hydrogen production and compared to the ideal (full-load) operation of the electrolyser, the hydrogen production becomes expensive owing to lower capacity factor. The effect of thermal transients is more prominent in large-scale electrolysers; scaling in MW ranges. The effect of thermal transients, between 20°C to 60°C, has an efficiency increase of around 3% - 4% on a 100% load operation of the electrolyser (Gazey, 2014, p. 72).

The size range of the electrolyser required for hydrogen production for this project and the small efficiency change over a range of temperatures, the operation of the electrolyser has been considered at a constant temperature; 60 °C. This consideration is, further made, on basis of literature; (Sanath, Silva and Middleton, 2017), (Spyros Voutetakis, Fotis Stergiopoulos, Panos Seferlis, 2010), and (Salami *et al.*, 2014). Another rationale for choosing the operation of the electrolyser at a constant temperature of 60°C is the possibility of installing the electrolyser right next to the thermal storage tank where the exchange of the heat from the electrolyser operation and the thermal storage can make the electrolyser work at a rather constant and higher temperature. This also adds the possibility of using lesser electrical energy in total, as the heat energy

A simplified approach was taken into account where the hydrogen production efficiency curve from (Gazey, 2014), at 60 °C, was re-modelled in excel and a 5th degree polynomial was developed to model the operation of the electrolyser as a function of the power input. The re-modelled curve is shown in Figure 8.1.1. Hydrogen Production efficiency as a function of power input as percentage of rated electrolyser power rating.

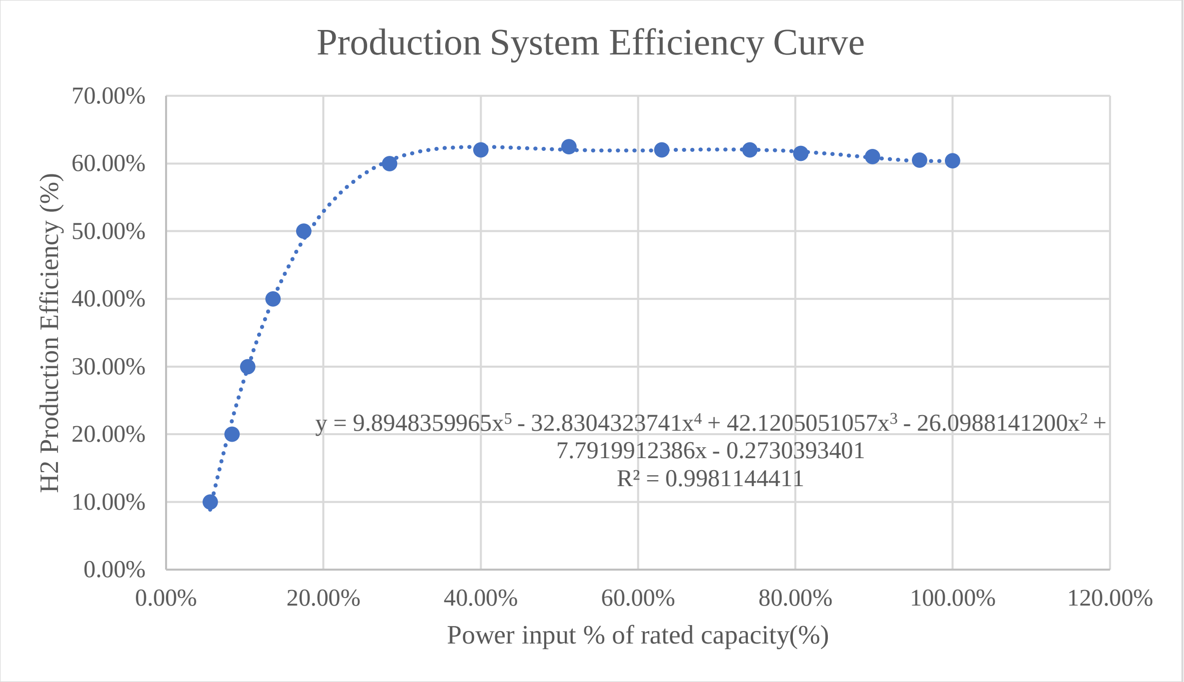


Figure 8.1.1 Hydrogen Production efficiency as a function of power input as percentage of rated electrolyser power rating

Source: Author based on *(Gazey, 2014, p. 72)*

The polynomial gives the H_2 production as efficiency percentage of the input energy the electrolyser. The input to the polynomial is the power input as percentage of the electrolyser maximum power rating. The H_2 production efficiency is then translated to the energy content of the H_2 quantity in kWh, and then converted to mol/hour values using the lower heating value of the hydrogen gas. The oxygen mol/hour values are calculated using simple stoichiometric equation of breaking the water molecule into H_2 and O_2. The values of H_2 and O_2 production in mol/hour are then converted to kg/hour using molar masses.

The electrolyser model then returns annualized output indicators such as electrical energy required to produce 1 kg of H_2 (kWh/kg), the total H_2 gas produced in kg, and the residual energy left after the electrolyser operation; both with and without battery operation.

8.1.4 Hydrogen and Oxygen Storage

In order to supply the necessary hydrogen and oxygen for the production of derivatives and for a refuelling station for a hydrogen-based transportation system, storage vessels at different pressures are required. The use of storage allows for a production of derivatives that is independent of the operation and current production rate of hydrogen.

In the proposed tool both hydrogen and oxygen are stored at the output pressure of the (12 bars) (Pure Energy Centre, 2019a) before being utilized for production of derivatives. In the case of hydrogen for use in transportation a higher pressure (700 bar) is required to allow for a higher volumetric energy density (Pure Energy Centre, 2019b).

In order to model the storage of hydrogen and oxygen, the use of a compressibility factor was required. This factor allows describing the behaviour of non-ideal gases at high pressure in an accurate way. The Z factor is used to adjust the ideal gas equation in order to accommodate the additional compression energy, as can be seen in Equation 8.1.1 below (Gazey, 2014, p. 134).

$$P = Z\rho RT$$

Equation 8.1.1 Adjusted ideal gas equation

Source: (Gazey, 2014, p. 134)

Where:

P: Absolute Pressure (Pascal)

Z: Compressibility factor

ρ: Molar density (mol/m^3)

T: Absolute Temperature (Kelvin)

R: Universal gas constant 8.31434 (Nm/mol K)

Z values for hydrogen were calculated using a method developed by (Lemmon, Huber and Leachman, 2008) which uses an equation based on absolute pressure and temperature.

Z values for oxygen were calculated utilizing a table with reported values for given temperatures and pressures and using linear interpolation to obtain the approximate value (Perry and Green, 2008).

To account for the electricity demand of compression of hydrogen a curve was used that plots the energy requirement against the final pressure of the gas (Makridis, 2016). For an initial pressure of 12 bars and a final pressure of 700 bar the compression energy was calculated as

11.454 kWh/kg-H_2, which is one third of the energy content of hydrogen when utilizing the LHV.

8.1.5 Costs associated with the electrolyser operation

The cost of the Electrolyser is broken down into capital cost, operational cost and cost of auxiliary equipment. The costs are presented in Table 8.1.2:

Table 8.1.2 Cost of Electrolyser System.

Description	Value used in tool	Reference information	Source
Capital cost for Alkaline Electrolyser	1,087.5 £/kW	1 MW Alkaline Electrolyser, 1.250 million €	(Pure Energy Centre, 2019b)
Operational cost for Alkaline Electrolyser	3 % of Capital Cost per year	3 % of Capital Cost per year	(Pure Energy Centre, 2019b)
Hydrogen Low Pressure Storage	24,650 £/m^3	A 600 litre vessel , 17,000 €	(Pure Energy Centre, 2019b)
Hydrogen High Pressure Storage	243,600 £/m^3	50 litre cylinder, 14,000 €	(Pure Energy Centre, 2019b)
Water Purification System:	71 £/kW of Capacity	Mechanical vapor compression system with a max flow rate of 200 kg of H_2O/h, £47,000.	(Pure Energy Centre, 2019b)
Hydrogen Compressor	263 £/kW of Capacity	Compressor of a capacity of 350 Nm^3/h from 30 to 200 bars, €250,000. Compressor of a capacity of 350 Nm^3/h from 200 to 700 bars, €350,000.	(Pure Energy Centre, 2019b)
Lithium-Ion Batteries	457.80 £/kWh	600 US$/kWh	(IRENA, 2017)

The life time of the electrolyser, compressor and water purification system was considered to be 20 years (Pure Energy Centre, 2019b). The stack of the electrolyser is to be replaced every seven years with a cost of 41% of the Capital Cost of the Alkaline Electrolyser. All other components are considered to have a lifetime of 25 years (Pure Energy Centre, 2019b).

8.1.6 Electric Storage Modelling for H_2 Production

The Electric Storage, for Hydrogen production specifically, has been considered to increase the capacity factor of operation of the alkaline electrolyzer when it is susceptible to an intermittent power input. The battery acts as a buffer in between the Wind turbine/Solar PV plant output and the electrolyzer input and stabilizes the operation of the electrolyzer for Hydrogen Production.

A battery model has been incorporated to the system model which is based on energy flows, in kWh, in and out of the battery for simplicity purposes. The battery is modelled to take in industry standard inputs from the user such as the Battery/Cell rating in Ah, the battery system voltage, the minimum Depth of Discharge, and the maximum discharge current. The charging and discharging efficiencies are also to be provided by the user and are easily available from the data sheets of the different type of battery manufacturers. The model also allows the user to change the charging and discharging currents in and out of the battery respectively as a percentage of the maximum charging and discharging currents. The rating of the battery bank is then translated to energy values in kWh to perform energy calculations. These inputs provide flexibility to the user to model different chemistries of batteries and analyze which chemistry is suitable for the operation and the specific application that the electrolyzer is intended to be used.

The operation of the battery takes into account a simple charging and discharging strategy. The discharge operation performs checks whether a discharge is required or not to maximize the power input to the electrolyzer and whether the battery has enough energy left to discharge with the intended discharge rate. The discharge of the battery bears the discharge efficiency. The charging regime, similarly, performs checks such as the battery State of Charge in the previous hour; whether there is room to charge the battery or not to prevent overcharging, and the excess energy available after the electrolyzer operation; to identify if there is energy available for charging. Another check of battery discharging is required for the charging operation for the current specific hour. If the battery is discharging in that hour, the charging operation cannot occur. The charging of the battery also bears the charging efficiency. To calculate the state of the charge of the battery for the current hour, the previous hour is looked upon for the battery operation of either charging or discharging.

8.1.7 Design Possibilities

For the hydrogen production system, several design arrangements are possible depending on the user preferences and the economics involved in the project. The selection of the electrolyser technology and the associated costs play a major role in the technical robustness of the system as well as in producing low-cost hydrogen and oxygen. The Polymer Electrolyte Membrane (PEM) electrolyser, as discussed before, is more receptive to the intermittent power inputs and has a better switch on and switch off operation capability. This results in a more robust partial load operation as it takes less effect on the electrolyser stack life. In comparison, the alkaline electrolyser partial load operation has a minimum limit between 15-20 %, as discussed in 8 .1.2. This in turn decreases the capacity factor of operation even more when compared to the PEM electrolyser stack.

To enhance the stack life and for a smoother operation of the electrolyser stacks, either PEM or Alkaline, a battery buffer smoothens the variable input power to a great extent. This smoother operation not only adds value to the life of the electrolyser stacks but also causes an increase in the capacity factor of operation of the electrolyser. This translates to more kg of H_2 produced from the same amount of energy input. The battery absorbs the excess the excess energy when available from the intermittent renewable sources and then discharges energy when required. This means a cheaper production of H_2 from the given production centres.

Figure 8.1.2 and Figure 8.1.3 display the power input to the electrolyzer and the subsequent H_2 production without the battery operation and with the battery operation, respectively.

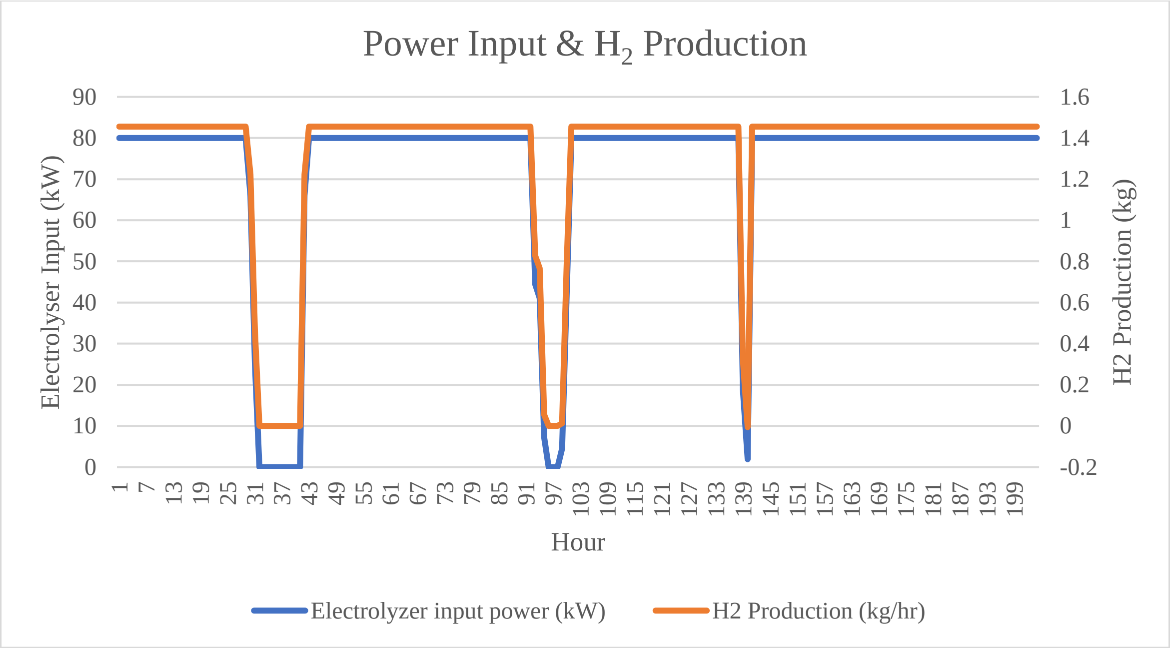


Figure 8.1.2 Power input and H_2 production without battery operation.

Source: Author

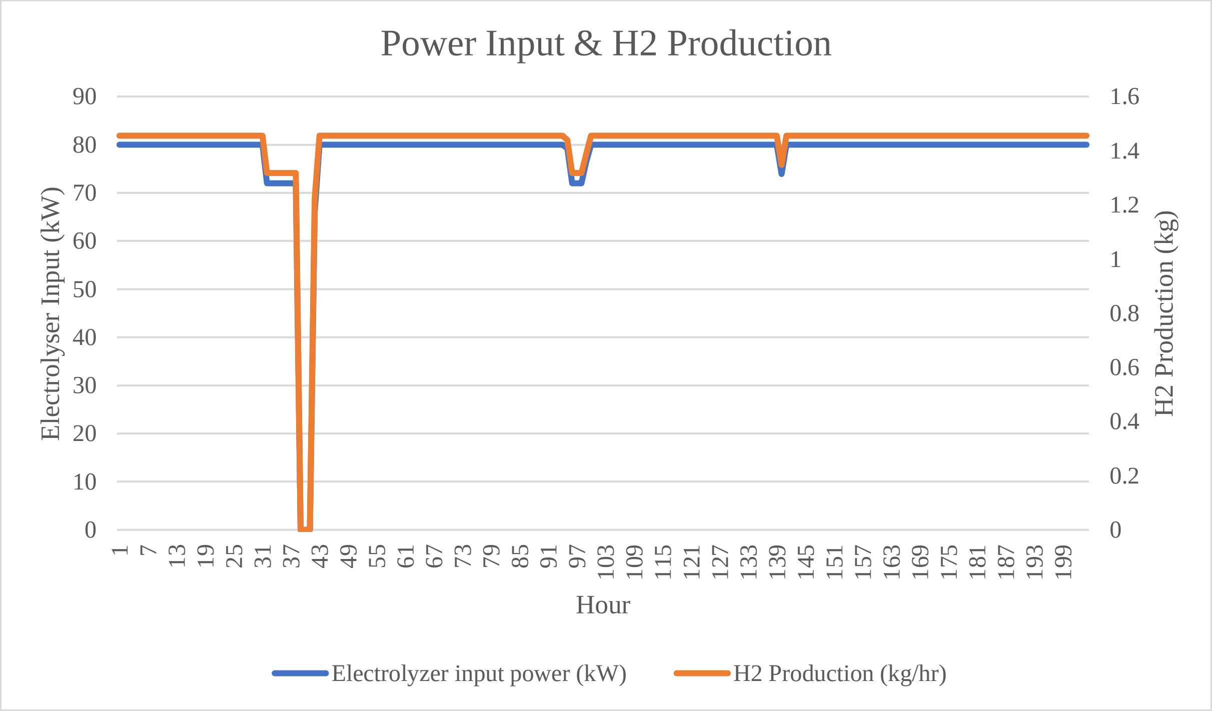


Figure 8.1.3 Power input and H_2 production with battery operation.

Source: Author

The area under the curve of Electrolyser input, in both Figure 8.1.2 and Figure 8.1.3 depict the electrical energy used in that time frame to produce H_2 gas. Figure 8.1.3 shows electrolyser operation with battery operation, displays more electrical energy used, interpreting from the area under the graph and hence more H_2 produced. The curves, when Figure 8.1.2 and Figure 8.1.3 are compared, also show more smoothness of power input and H_2 production that indicates and optimized operation from the durability of the electrolyser stack perspective.

The battery operation in conjunction with the electrolyser is shown in the schematic shown in Figure 8.1.4 (Adapted from Spyros Voutetakis, Fotis Stergiopoulos, Panos Seferlis, 2010), depicting the battery placement.

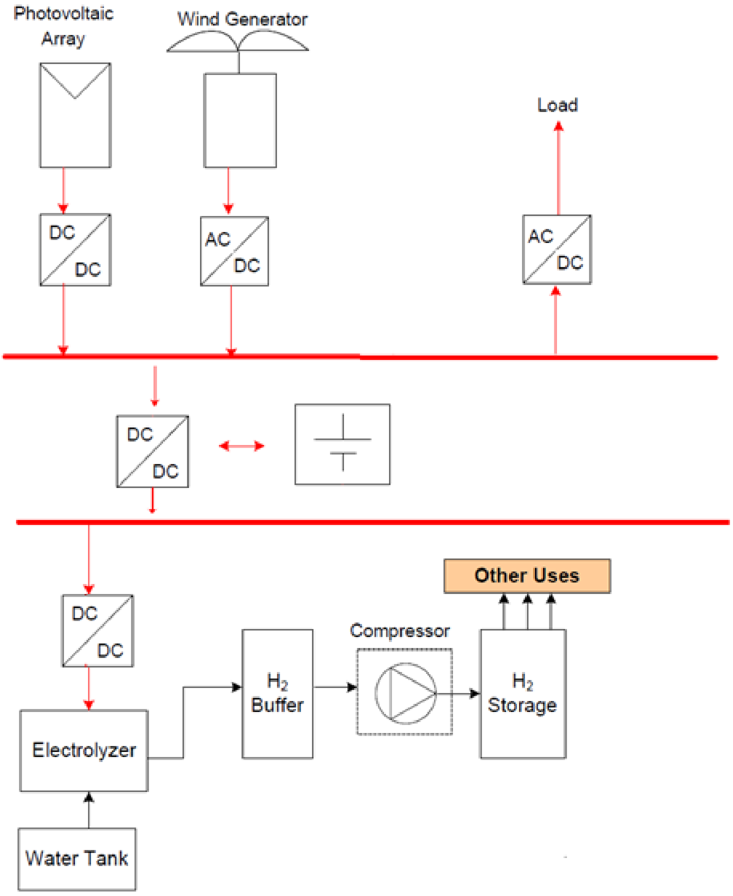


Figure 8.1.4 Schematic for Battery incorporation with Electrolyser operation.

Source: *(Spyros Voutetakis, Fotis Stergiopoulos, Panos Seferlis, 2010)*

The suitable battery chemistry for this operation is the lithium-ion technology. Due to its high specific power capacity, high discharge rate, and lower depth of discharge, the technology is well suited for the operation required with electrolyser (Www.batteryuniversity.com, no date). Integrated with a good battery management system, the lifetime of the battery can be prolonged and worked more efficiently. Due to these reasons, the model provides the financial evaluation of the lithium-ion technology only, as technically and commercially it is the optimal solution for the operation.

In a scenario where the electrolyser operation is the priority over the building heat demand, of taking electrical power from the 900 kW Wind turbine, the battery is operated to analyse the effect on the operation of the electrolyser and the hydrogen production. The capacity factor of the electrolyser is observed to increase when it has a low-scale rating in kW. For example, a 100 kW rated electrolyser operates at a capacity factor of 82.38 % and with 1 MWh/120kW battery storage, the capacity factor increases to 90.93 %. The hydrogen production varies from 13.15 tonnes to 14.5 tonnes. For 650 kW electrolyser, which is a realisable size for the project, the capacity factor is 47.61 % and with 1 MWh/700 kW the capacity factor increases to 48.28%. The hydrogen production, in this case, varies from 49.6 tonnes to 50.26 tonnes. So, for the same energy storage capacity, at different discharge rates, given the size ranges of the electrolyser the battery does not provide a significant increase in production and does not make a financially viable investment as well, for a minimal gain, at high cost of 600 USD/kWh of storage, totalling up to 720,000 USD, as mentioned in Table 8.1.2.

8.1.8 Transportation

With a price of 133 pence per liter (Rogers, 2018), Unst is in the 7th place for most expensive place to purchase diesel in the UK. This high cost and the prospect of producing Hydrogen through Renewable Energies creates the window of opportunity for a demand substitution. Low cost solutions presently exist in the UK that allow users to partially convert their vehicles to hydrogen, reducing fuel consumption in up to 50% (Autogaspol, 2014).The diesel demand of ferries, public buses and vehicles for community service is estimated in order to compare to the Hydrogen production and determine what percentage of the demand can be covered in a given scenario.

8.1.9 Ferries

Currently two ferries, Bigga and Geira, are in operation, connecting the isles of Unst, Fetlar & Yell. The hydrogen demand considering they were completely converted to hydrogen was reported as 165,543 kg of hydrogen per year (Unst Partnership Ltd, 2016).

8.1.10 Bin Lorry for Garbage

A bin lorry for garbage operating in Unst reportedly covers a weekly distance of 80 miles. Considering a fuel economy of 4.4 miles per gallon of diesel (Sandhu *et al.*, 2015) this would be equivalent to 20.65 kg of hydrogen per week or 1,073.68 kg per year.

8.1.11 Care Center Van

The vehicle owned by Nordalea Care Center in Unst is reported to travel 12 days per month (Pure Energy Centre, 2019b). Considering an average distance of travel of 12 miles (round trip between Baltasound and Uyeasound) and a fuel economy of 54 miles per gallon of diesel (Parkers, 2018) this would be equivalent to 3.03 kg of Hydrogen per month or 36.34 kg per year.

8.1.12 Public buses connecting Unst and Lerwick

According to Zettrans (2019), one bus travels between Unst and Lerwick (round trip) every day between Monday and Saturday. Considering a distance of 65 miles between the two locations and an efficiency of a hydrogen bus of 6.25 miles/kg of Hydrogen (Unst Partnership Ltd, 2016) the total demand of hydrogen would be of 124.8 kg Hydrogen per week or 6,489.6 kg per year.

8.1.13 Public buses inside Unst

According to Zettrans (2019), buses travel between Haroldswick and Belmont (round trip) seven times a day between Monday and Saturday. Considering a distance of 15 miles between the two locations and an efficiency of a hydrogen bus of 6.25 miles/kg of Hydrogen (Unst Partnership Ltd, 2016) the total demand of hydrogen would be of 201.6 kg Hydrogen per week or 10,483.2 kg per year.

8.2 Ammonia Production

The main objective of this section is to assess the viability of using renewable technologies for a small-scale production (less than 1,000 tonnes per annum) of ammonia on Unst:

- to meet the local demand or a portion of the demand for ammonia by the community.
- to study other uses of ammonia which could be of added value (revenue) to the community

8.2.1 Brief introduction to the process

The synthesis to produce ammonia is through the Haber-Bosch process (Ababio, 1980, p. 409). This process involves the combination of nitrogen and hydrogen gases in a proportion of 1:3 respectively, under pressure conditions of 200 atmospheres, and temperature ranging between 400 °C – 500 °C in the presence of a catalyst (Chemistry Libre Texts, 2017) as shown in Figure 8.2.1. This is an exothermic reaction that yields ammonia (NH_3), and heat as a by-product as indicated in Equation 8.2.1 below.

$$N_2\ (g) + 3\ H_2\ (g) \rightleftharpoons 2\ NH_3\ (g) + \text{heat}\ \Delta H = -\ 92.4\ \text{kJ}\ (46.2\ \text{kJ per mole}\ NH_3\ \text{produced})$$

Equation 8.2.1 The Haber-Bosch Equation

Source: (Chemistry Libre Texts, 2017)

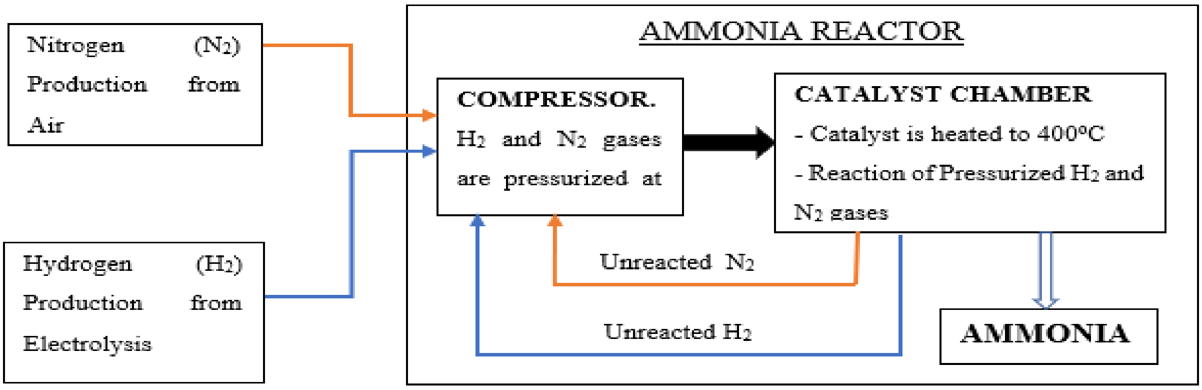


Figure 8.2.1 The Haber-Bosch Process

Source: Author based on (BBC Bitesize GCSE Chemistry, no date).

The expected yield of ammonia is about 15 % after each pass of the gases through the catalyst chamber (Ababio, 1980, p. 278). However, the further recycling of the unreacted gases produces achieves an overall conversion of about 98 % (Chemistry Libre Texts, 2017).

Furthermore, studies by Brightling (2018) indicate that;

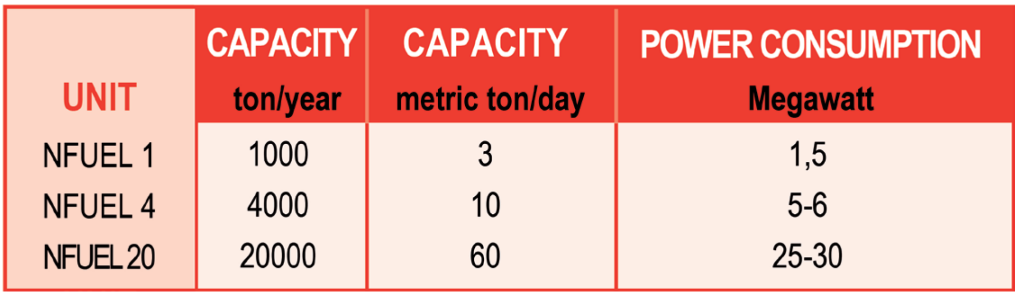
> ‘In reality, ammonia synthesis is coupled with hydrogen production to improve efficiency. Hence, the energy consumed, and costs of ammonia production depends greatly on the selection of feedstock used to produce hydrogen. This also plays a role in the amount of carbon dioxide (CO_2) emitted, which ranges from about 1.6 ton per ton NH_3 produced to 3.8 ton per ton NH_3 produced when hydrogen is produced from fossil fuels such as natural gas and coal respectively.’

In the case of Unst, hydrogen production through water electrolysis and powered by renewable energy is being proposed. Thus, eliminating the release of CO_2 to the environment for ammonia produced, while catering for the variability and intermittency of the renewable source.

Also, the catalyst studied for this case is a fused iron oxide (Fe_3O_4), some offering advantages of low cost and reduced susceptive nature to H_2 poisoning over Ruthenium and Cobalt catalyst, even though its efficiency for the reaction is as low as 70 % (Bañares-Alcántara *et al.*, 2014, p. 48).

8.2.2 Example of a Small-Scale Technology: Proton Venture

The main challenge in this study was to consider a small-scale ammonia production plant for which Proton Ventures was found to be a suitable choice. It is based in Netherlands and is a pioneer in manufacturing small scale ammonia plants with the lowest being 1000 tonnes annually and 3 tonnes per day as shown in Figure 8.2.2 (Proton Ventures, no date). The company was contacted with a request for important information, however no related information could be received from them. However, after doing literature review, important information regarding the energy requirement and cost was obtained, which helped to estimate the important parameters of the ammonia plant for the study.



UNIT	CAPACITY ton/year	CAPACITY metric ton/day	POWER CONSUMPTION Megawatt
NFUEL 1	1000	3	1,5
NFUEL 4	4000	10	5-6
NFUEL 20	20000	60	25-30

Figure 8.2.2 Proton Ventures: Small scale ammonia production units

Source: (Proton Ventures, no date)

8.2.3 Chemical Properties of Ammonia

According to the Pub Chem Open Chemistry Database (no date) and (Ababio, 1980, pp. 409 - 410), ammonia also known as “Azane” or CAS number “7664-41-7” has some of the properties listed below in Table 8.2.1:

Table 8.2.1 Selected Properties of Ammonia

PROPERTY	VALUE
Appearance	At room temperature, it is a colourless gas
Odour	It has a characteristic pungent or choking smell
Type of compound	It is an alkaline gas
Molecular weight	17.031 grams per mole
Boiling point	- 33.3 ^{o}C
Melting point	- 77.7 ^{o}C
Energy Content	18.6 kJ g^{-1} (LHV), 22.5 kJ g^{-1} (HHV)
Density	0.763 grams per litre at STP (0^{o}C and 1 bar)
Thermal Decomposition	It can be decomposed at temperatures above 500^{o}C

Source: (Pub Chem Open Chemistry Database, no date; Ababio, 1980)

In addition, the National Fire Protection Association provides a guide on ammonia’s hazard ratings with respect to flammability, health, and stability as shown in Figure 8.2.3.

Figure 8.2.3 Impact ratings of Ammonia

Source: (My Safety Signs, no date)

Table 8.2.1 only indicates some selected properties of ammonia, while a material safety datasheet (MSDS) provides detailed information on its properties, impacts on health and environment, and conditions for handling ammonia. A sample of a MSDS by BOC (a provider for industrial gases in UK and Ireland) can be assessed at https://www.boconline.co.uk/en/images/sg-002-ammonia-v1.44_tcm410-39616.pdf.

8.2.4 Inputs to the System Tool

In order to provide the input to the Excel Tool, three main calculations were conducted, namely: mass balance, energy balance and financial parameters, which are explained as under.

8.2.4.1 Mass Balance

To estimate the amount of ammonia produced based on the hydrogen production, the mass balance calculation was conducted for Equation 8.2.1 as under.

$$N_2\ (g) + 3H_2\ (g) \rightleftharpoons 2NH_3\ (g)$$

Atomic weight of N_2 is 14.007 g and H_2 is 1.008 g. Thus,

$$(2 \text{ x } 14.007) + (3 \text{ x } 1.008) \rightleftharpoons (2 \text{ x } 14.007 + 3 \text{ x } 1.008)$$
$$28.014 + 3.024 \rightleftharpoons 31.038$$

Thus, to produce 31.038 g of ammonia, 28.014 g of nitrogen and 3.024 g of hydrogen is required. Therefore, it was found after calculation that for 1 kg of hydrogen produced 5.62655 kg of ammonia, which in turn required 4.63194 kg of nitrogen. These values were used for adding a logic in the System Tool, for calculating the ammonia produced with respect to the available hydrogen and required nitrogen. Also, there is a provision in the tool to input share of the hydrogen available for the ammonia production.

The unreacted hydrogen and nitrogen are continuously circulated in the ammonia reactor, until about 98 % of these gases are utilized (Chemistry Libre Texts, 2017). This was taken into consideration in the calculations.

8.2.4.2 Energy Balance

The energy requirements for ammonia production in literature considers the coupled unit of the electrolyser, the nitrogen generator unit, and the ammonia reactor. From the report by (McNaught *et al.*, 2014, p. 19), the estimated energy required for ammonia production by Proton Ventures is 13 kWh per kg ammonia produced. This includes energy utilized for both hydrogen production and the nitrogen generator unit.

In addition, from Wiessner (1988), a Pressure Swing Adsorption nitrogen generator unit requires an average of 0.29 kWh/kg N_2 produced, and offers an advantage of a compact solution, requires little maintenance, and short start up times with less risk of apparatus clogging when compared to the cryogenic or fractional distillation method.

As per Brown (2018), considering that about 83 to 92 % of the energy is used for hydrogen production from electrolysis. Hence, considering 83 % for hydrogen production and the energy required for nitrogen production, it was calculated that the Haber-Bosch synthesis will require about 1.92 kWh/kg NH_3 produced.

The energy required for the heating the catalyst, magnetite (Fe_3O_4) to about 400°C for the first hour was estimated as 0.47 kWh (refer to Appendix IX: for calculation details). Equation 8.2.1 indicates that ammonia synthesis releases 92.4 kJ for the 2 moles of NH_3 produced, and the heat of reaction generated by the production of ammonia is sufficient to maintain the temperature level in the catalyst chamber.

8.2.4.3 Cost

Owing to the commercial unavailability of a smaller scale ammonia production plant than 1000 tonnes in market, the cost calculation was done with the help of literature review.

According to a study done by McNaught *et al.* (2014, p. 27), the capital cost for a 50 tonne ammonia plant was stated to be in the range of 1.2 to 2 million £. Thus, for the present study, an average of 1.6 million £ was considered for a 50-tonne plant. And for a 100 tonne per annum plant, the capital cost was said to be 2.25 million £. Thus, with these two values, a linear forecast Figure 8.2.4 was obtained to determine the CAPEX of the plant. It is important to mention here that the size of the ammonia plant was estimated based on the actual ammonia which can be produced annually when it is working at 100 % for 340 days for the selected configuration in the excel tool. The CAPEX was then calculated with the help of this estimated size with the help of the linear forecast shown in Figure 8.2.4.

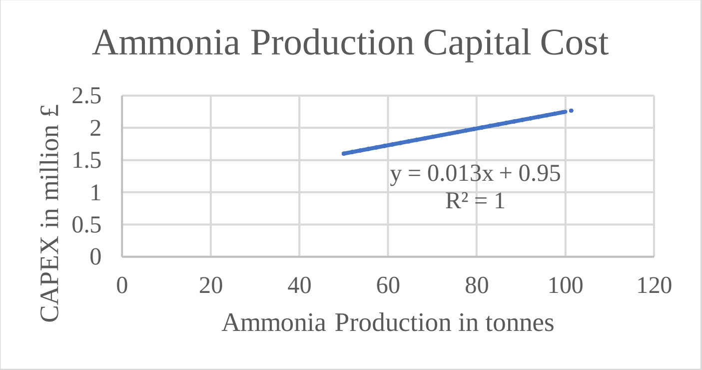


Figure 8.2.4 Linear Extrapolation for Capital Cost of Ammonia Production

Source: Author based on (McNaught *et al.*, 2014, p. 27)

As reported by Vrijenhof (2010), about 2 % of the CAPEX is taken as OPEX for the ammonia plant.

As per (Bartels, 2008, p. 52; Patil, Laumans and Vrijenhoef, 2014, p. 325), the life time of the ammonia production unit is 30 years and it is comprised of compressors and the ammonia reactor. The nitrogen production unit has a life time of 20 years (Patil, Laumans and Vrijenhoef, 2014, p. 325). (Patil, Laumans and Vrijenhoef, 2014, p. 326) state that the catalyst unit has a guaranteed operation of 15 years.

Since the lifetime of nitrogen production unit and catalyst is shorter than that of the ammonia plant, the initial investment cost for these components was computed as a percentage of total CAPEX. This value was used as the re-investment cost for the components whose lifetime ends before 30 years. Some information received from Pure Energy Centre regarding the cost of the nitrogen units during one of the sessions was used for the cost estimation. With the help of this data and calculating the corresponding size of the plant required for a 1,000 tonne plant, it was estimated that 2.16 % of the CAPEX of the ammonia plant is the nitrogen production unit cost.

The cost of the catalyst was estimated as 0.037 % of total CAPEX, using the cost data from (Alibaba.com, no date) for 1,000 tonnes of ammonia plant.

8.2.5 Potential Market for Ammonia in Unst Shetland.

In this section the potential market for ammonia in Shetland would be described.

8.2.5.1 Fertilizer

About 80 % of the ammonia produced globally is used for fertilizer production (Bañares-Alcántara *et al.*, 2014). As per the description of the Shetland economy on their website (Shetland.org, no date), the main agricultural activity is sheep raring (hence grazing), but they also have herds of cattle for dairy and beef. Even though most of the fruits and vegetables in Shetland are imported, there is also some local produce.

A preliminary demand calculation was done, because the actual demand for fertilizer was unavailable. As per Department of Environment & Rural Affairs (2018), in the year 2017 the annual overall application of Nitrogen to tillage crops and grassland together was 91 kg N/ ha (0.091 t / ha). The Shetland Island Council (2018) estimates that the area of land with crops excluding fallow land was 211 hectares as of 2017. Thus, after calculating the total nitrogen fertilizer demand in Shetland in the year 2017 was **19.20 tonnes**.

This is the approximate demand that was calculated. Considering a possibility that the project produces more ammonia in one of the scenarios, which leads to increase in fertilizer production, the excess could be suggested to be exported to the other neighbouring island of Orkney. This in turn would yield extra revenue.

8.2.5.2 Transportation

Although use of ammonia for transportation is quite old, the new technology to adapt to the ammonia as a fuel is still under development.

For Unst, use of ammonia as a fuel was studied for bin lorry used to collect garbage. Starkman, James and Newhall (1967) state that modifications are required to be done in the existing diesel engines to be able to use ammonia as a fuel. Also, the possibility of operating on dual-fuel (95 % ammonia and 5 % diesel) could also be considered.

Bin lorry for garbage

Coren (2016) stated that garbage trucks are amongst the most inefficient vehicles on the road, working on diesel with an average of 4.4 miles per US gallons of diesel (Sandhu *et al.*, 2015). As per the available information, the bin lorry covers a distance of 80 miles per week; thus, using about 18.18 US gallons (68.82 litres) of diesel per week.

(NH3 Fuel Association, 2018) states that for a 300 miles range, the tank size for a diesel fuel is 8.8 US gallons (33.31 litres), whereas for ammonia fuel is 27.4 US gallons (103.72 litres). This means that the fuel requirement for ammonia is 3.11 times that of diesel.

Thus, to cover a distance of 80 miles per week 56.54 US gallons (214.03 litres) of ammonia will be required. Translating to weight (Greenwood and Earnshaw, 1997), it’s 146.09 kg or **0.146 tonnes** per week **(7.59 tonnes annually)**.

8.2.5.3 Storage

The use of ammonia as a hydrogen carrier or “storage” arises from the low volumetric density and high-pressure storage requirements for hydrogen at 200 bar and 350 bars, which in turn leads to a higher cost for storage. Ammonia (NH_3) has advantages of a higher volumetric density at storage pressure of 10 bar, no carbon footprint, and an established infrastructure and knowledge for its handling, storage and distribution over the years (Bartels and Pate, 2008, p. 2).

From Equation 8.2.1 it can be deduced that 1 mole of NH_3 contains 1.5 moles of H_2, which is about 17.8 % of its atomic mass. Table 8.2.2 outlines the volumetric densities of hydrogen and ammonia, considering their boiling points and pressure requirements.

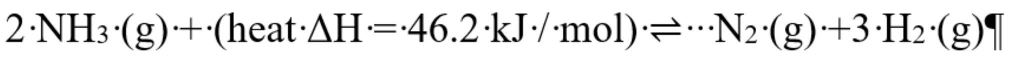
Table 8.2.2 Properties of ammonia and hydrogen densities for storage

Parameters	Value	H_2 content
Liquid ammonia at -33 ºC and 1 bar (kg/m3)	682.6	121.5
Liquid ammonia at 25 ºC and 10 bar (kg/m3)	610.3	108.6
Liquid hydrogen at – 252.9 ºC and 1 bar (kg/m3)	70.8	70.8
Liquid hydrogen at 25 ºC and 150/200 bar -LP (kg/m3)	10.9	10.9
Liquid hydrogen at 25 ºC and 350 bar -HP (kg/m3)	23	23

Source: (Aqua-Calc, no date; Bruce *et al.*, 2018)

From Table 8.2.2, at 25ºC and 10 bar, ammonia stores considerably more hydrogen content than hydrogen stored at 200 bar (low pressure) or 350 bar (high pressure) where the boiling point for ammonia and hydrogen is – 33 º C and – 253 º C at 1 bar respectively as was also deduced from (Bañares-alcántara and Nayak-Luke, 2017). The cost for storage of ammonia was estimated at a factor 10 of the cost of hydrogen storage at 2,645£ /m3 (Pure Energy Centre, 2019b).

Hydrogen is derived from the reversible ammonia synthesis as in Equation 8.2.1. This decomposition of ammonia also yields nitrogen and is free of greenhouse gas emissions.



$$2\,NH_3\,(g) + (heat\ \Delta H = 46.2\ kJ / mol) \rightleftharpoons N_2\,(g) + 3\,H_2\,(g)$$

Equation 8.2.2 Decomposition of Ammonia

Source: (Hacker and Kordesch, 2003, p. 122)

However, the efficiency and energy consumption of hydrogen extracted from ammonia needs to be considered as this will also contribute to part of the cost.

8.2.6 Ammonia Market Price

The market price for ammonia is closely dependent on the price for the feedstock commonly used for hydrogen production such as natural gas or coal, hence there are large uncertainties and variations in market price structure, even geographically. Hence, a market value of £650/tonne of NH_3 quoted by McNaught *et al* (2014, p. 9). was considered as this is a similar study focused on using wind energy for ammonia production in rural Scotland.

8.2.7 Results and Recommendations

As seen in the above sub-chapters, the small-scale ammonia production is costlier as compared to the large scale. Although there could be potential application for ammonia in Unst, the exact amount of production is dependent on the size of the electrolyser plant, which in turn depends on the scenario.

8.3 Hydrogen Peroxide

8.3.1 What is Hydrogen Peroxide?

Hydrogen peroxide is a chemical compound from two atoms of hydrogen and two atoms of oxygen. It has strong oxidizing properties. Therefore, it is utilized as a bleaching (whitening) agent in different industries. In this study case, hydrogen peroxide is particularly important, because it is utilized as antibiotic for fish farms and hatcheries (Pert *et al.*, 2015).

Under ambient conditions, hydrogen peroxide has the following characteristics:

Table 8.3.1 Characteristics of Hydrogen Peroxide at Ambient Temperature

State	**Liquid**
Colour	Transparent, sometimes a pale blue may be noted
Smell	Odourless
pH	3.7
Freezing point	-33 °C
Boiling Point	108 °C
Density	1.13 g/cm^3

Source: (George and Vns, 2015)

According to George and Vns (2015), hydrogen peroxide is considered a hazardous chemical because of its toxicity in case of oral ingestion or inhalation of vapours. In case of contact, it may provoke skin corrosion/irritation and serious eye damage/irritation.

8.3.2 Production of Hydrogen Peroxide

Worldwide, 99% of hydrogen peroxide is produced through an anthraquinone process (Intratec, 2016). However, this process requires annual productions of at least 3,000 tons due to its high investment cost. For that reason, we will consider an electrochemical method which can be scaled down and its economic viability depends on the price of electricity (Gonzales, 2012).

The redox reaction of hydrogen and oxygen is the basic process to generate hydrogen peroxide applying electrolysis. This process requires energy that may be provided by an external DC supply or using hydrogen and the electrolyser as a fuel cell. For this study, the first option has been considered as the production of hydrogen peroxide will work as a flexible load for a better integration of non-dispatchable energy technologies.

This process takes place in the cathode as it is shown in Figure 8.3.1. It can also be noted that the anode requires H_2O from which the hydrogen ions will be obtained. These hydrogen ions will react with the oxygen in the cathode in order to form hydrogen peroxide. As it is shown in Figure 8.3.1 the pathway of two electrons is required for the reaction (Li, 2017).

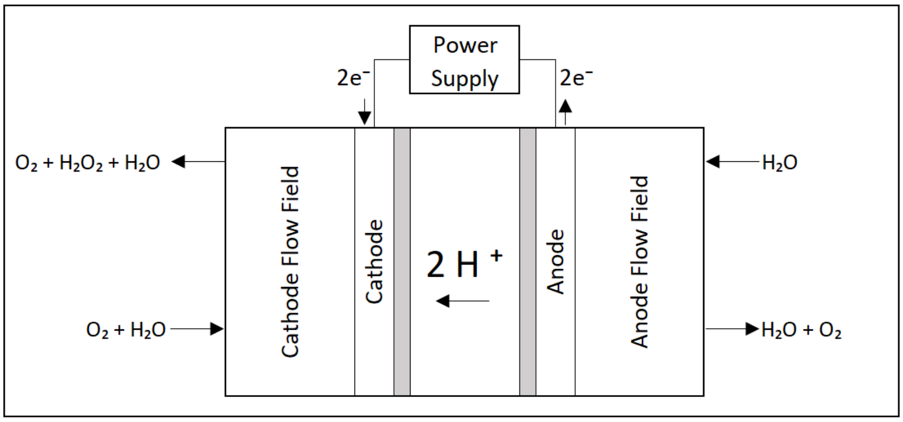


Figure 8.3.1 Electrolysis Mode Operation

Image source: (Li, 2017).

According to Figure 8.3.1, the reaction that takes place in the anode is:

$$2\,H_2O \;\leftrightarrow O_2 + 4H^+ + 4e^-$$

Equation 8.3.1 Anode Reaction for Hydrogen Peroxide Production.

Source: (Li, 2017)

While in the cathode, where the formation of hydrogen peroxide takes place, we have the following chemical reaction.

$$O_2 + 2H^+ + 2e^- \leftrightarrow H_2O_2$$

Equation 8.3.2 Cathode Reaction for Hydrogen Peroxide Production.

Source: (Li, 2017)

8.3.3 Mass and Energy Balance

In order to evaluate how much hydrogen peroxide could be obtained from the oxygen provided by the first electrolyser, the mass and energy balance of the reaction in the cathode was calculated from the Equation 8.3.2 and the following results were obtained.

$$O_2 + 2H^+ + 2e^- \leftrightarrow H_2O_2$$

$$O_{2\,MOL} + 2H^+{}_{MOL} + 2e^- \leftrightarrow H_2O_{2\,MOL}$$

$$Atomic\ Weight\ of\ Oxygen{:}\ 15.999\ u\ and\ Atomic\ Weight\ of\ Hydrogen{:}\ 1.008\ u$$

$$2\ \times 15.999\ _{O_2}kg\ + 2\ \times 1.008\ _{H_2}kg\ + 2e^- \leftrightarrow (2\ \times 15.999 +\ 2\ \times 1.008)\ _{H_2O_2}kg$$

$$31.998\ _{O_2}kg\ + 2.016\ _{H_2}kg\ + 2e^- \leftrightarrow 34.014\ _{H_2O_2}kg$$

$$\frac{34.014\ _{H_2O_2}kg}{31.998\ _{O_2}kg} = 1.06$$

$For\ each\ kilogram\ of\ Oxygen, 1.06\ kilograms\ of\ Hydrogen\ Peroxide\ will\ be\ produced.$

As can be seen in Equation 8.3.1, per each mol of oxygen, two mols of hydrogen are produced. In order to maintain a balance in the cathode's reaction, is required to inject the extra oxygen that comes from the hydrogen electrolyser.

8.3.4 Logic for hydrogen peroxide production simulation in excel

Inputs required for the production of hydrogen peroxide via electrolysis are water, energy and oxygen. The oxygen is injected in the cathode to obtain hydrogen peroxide instead of hydrogen as in a regular electrolysis process, allowing the production of hydrogen peroxide.

According to Li (2017)**,** the production rate of the hydrogen peroxide is proportional to the current intensity when there is no limitation of the oxygen supply as it is shown in Figure 8.3.2 below.

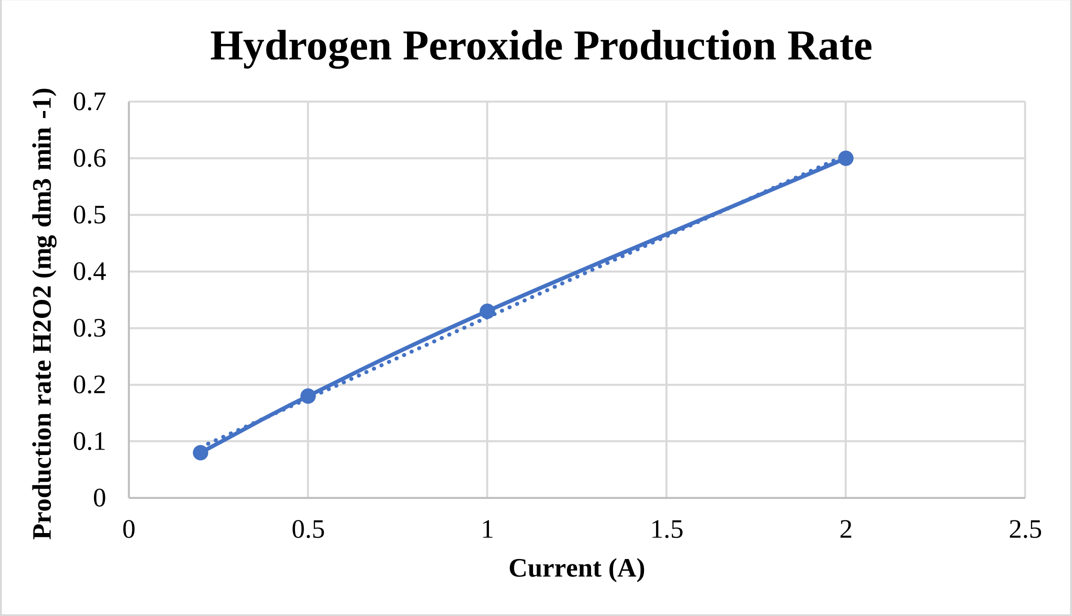


Figure 8.3.2 Hydrogen Peroxide Production rate against intensity.

Source: Author based on (Li, 2017)

In order to simulate this behaviour, according to the data of Figure 8.3.2 below the linear regression equation was obtained Equation 8.3.3 where “**y**” is the quantity of Hydrogen produced and “x” the current.

$$\mathbf{y = 0.2866x + 0.0324}$$

Equation 8.3.3 Linear regression Hydrogen Peroxide production rate.

Source: Author

Therefore, the current to be used in the Equation 6.3.3 is calculated according the electrolyser capacity and available energy for the production, for this is also considered that the electrolyser can work in a minimum partial load of 20 % and that the efficiency of the reaction is already been considered in the production rate. The electrolyser voltage is 400 V (Pure Energy Centre, 2019b).

Finally, to fulfil the specific supplies for the production of hydrogen peroxide, it was important to ensure the requirement of oxygen in the simulation. Therefore, according to the mass balance calculations discussed above, it was observed that for each kg of H_2O_2 0.94 kg of oxygen is required. As a result, the simulation of hydrogen peroxide production has a dual dependency on the energy available for the electrolyser and the available oxygen in the low-pressure storage of oxygen.

The outputs obtained are the hydrogen peroxide produced in kg, oxygen utilized in kg and the energy utilized in kW in an hourly and annually basis.

According to Drogui *et .al* (2001, p. 876) the concentration obtained after electrolysis generation of Hydrogen peroxide according to this production rate is 15 mg/l, what represents 1% w/w. This is a really low concentration in comparison with the concentration that can be founded in the market but is the necessary concentration for the application in fisheries as is going to be explained below.

8.3.5 Applications

Hydrogen peroxide is utilized in aquaculture for veterinarian purposes, in the case of the United States the FDA (Food and Drugs Administration) approves a concentration of 35 % w/w (Yanong, 2018) while in the UK, concentrations of 35 % w/w and 50 % w/w are allowed. These concentrations must be diluted for getting concentrations of 1500 ppm (2.1 mg/l) in the fish environment according to the recommendation of the manufacturers in Scotland (Pert *et al.*, 2015). Hydrogen peroxide works as an antibiotic for certain infections. It has been found that it has secondary effects in the fish and it may endanger the health of fish for up to two weeks, this is due to the fact that it has damaging effects for the mucous[18] of the gill (OneKind, 2018).

According to a publication by the Scottish Government (2018), Shetland's fisheries have increased the demand of hydrogen peroxide in the last few years and by 2017 the demand of hydrogen peroxide in Shetland was 625,000 of litres of hydrogen peroxide with a concentration of at least 35 %w/w, as can be seen in the Figure 8.3.3.

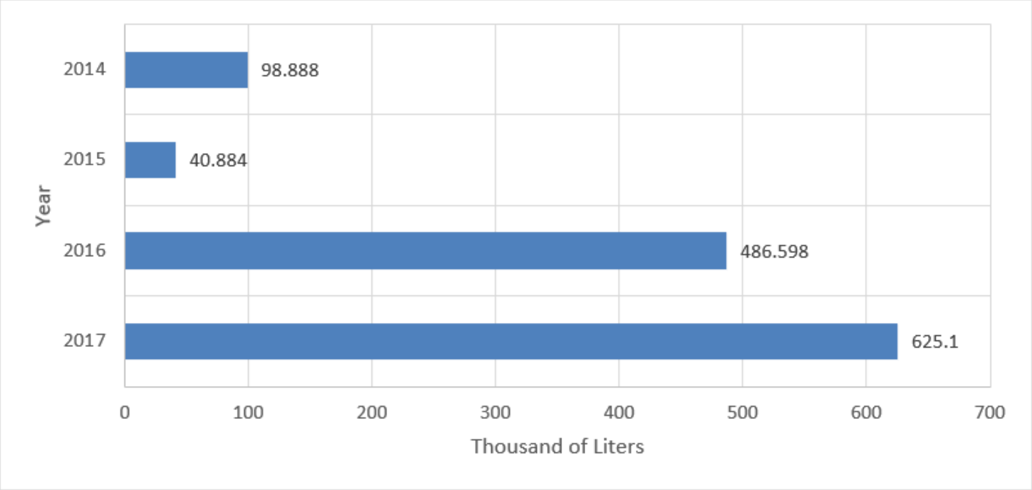


Figure 8.3.3 Consumption of Hydrogen Peroxide in Shetland's Fisheries

Source: (Scottish Government, 2018)

8.3.6 Economics Parameters of Hydrogen Peroxide

The economic parameters Capital cost and Operational cost were calculated for the Hydrogen Peroxide production.

The CAPEX takes into account the alkaline electrolyser Cost (1,087.5 GBP/kW) and the water purification system cost (71 GBP/KW), same prices as presented before in the hydrogen

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[18] The mucous of the gill protects fish against infections and hydrogen peroxide has a temporary negative effect over the mucous.

production sector, considering also the reinvestment of the replacement of its components of the electrolyser.

The OPEX considers 3% of CAPEX for the electrolyser as mentioned before and cost of electricity utilized for the production, which changes according to the configuration of the renewable energies in the simulation in the excel tool.

Generally, the production of H_2O_2 by electrochemical process is considered expensive due to the high consumption of energy and the cost that it incurs, as was mentioned before in the section 8.3.2 . Therefore, the economic viability of the hydrogen peroxide in the present study highly depends in the low costs of energy that are expected from the renewable sources.

Due to the low concentration that can be obtained in the production of hydrogen peroxide, the price that is going to be calculated in the system is considerable high compare with the market price (2.52 GBP/l at 35% w/w (ReAgent, no date)). Nevertheless, it will be a clean hydrogen peroxide with a low ecological footprint and will create income flows that remain in the island.

8.4 Final Remarks

Hydrogen, ammonia and hydrogen peroxide allow the proposed energy system to go beyond supplying heat, as they produce an economic impact in other sectors of society. Transportation, fisheries and agriculture could all benefit from locally produced resources that increase their competitiveness and sustainability.

Chapter 9: Conclusion and Recommendations

The completion of the case study is marked by the formation of the excel tool and the case study report that would be submitted to the key partners.

The demand assessment of buildings in the project locations: Saxa Vord Resort and Baltasound were performed in order to assess the feasibility of the renewable energy production and hydrogen production centre near the project locations. The renewable energy production simulation in the Baltasound location shows that the demand of the location is low for the renewable energy project to be attractive. However, this should be seen as an opportunity to integrate a renewable hydrogen and derivatives production centre in the location. At the Saxa Vord Resort location, the renewable energy production along with the hydrogen production were simulated. In order to assess the feasibility, various scenarios were simulated in the modelling tool considering various project structures with ESCO (Energy service company) ownership. The financial calculations were performed treating the ownership of heating systems and hydrogen production centre as different entities. The results show that integrating the buildings heat demand with the hydrogen production centre is a promising project.

According to the simulations, hydrogen was the only product that was possible to produce at a lower price than the market cost. Nonetheless, it is possible to include small share of ammonia production and the overall project is still profitable. This opportunity increases the utility of the hydrogen produced in the island as ammonia may be used as fuel, for producing fertilizers or as a hydrogen storage. Therefore, there is the possibility to have a diverse portfolio and participate in different markets.

In terms of renewable technologies, wind turbines, air and ground source heat pump, solar photovoltaic and solar thermal technologies have been assessed. The results of the simulations showed that wind and heat pump technologies are suitable for the supply of heat for the building within the scope of the project, both from a technical and economical point of view. Solar PV and solar thermal technologies seem to be less promising for the island.

Overall, the study shows that the renewable energy potential of the island is underutilised and there are ample opportunities for the island to harness its rich renewable energy potential, especially with wind. The community can benefit from the project in many ways. A hydrogen and derivatives production centre for supplying the local demand will help the money flow to stay within the community. The interaction with the stakeholders, although a sample size, reveals that the community has expectations and concerns about the project. A project with proper involvement of the community could is hence recommended. However, a suitable business model has to be implemented.

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Appendix I: Survey Design and Sample

The survey was created using EvaSys software.

Appendix Figure I-1 EvaSys Software Logo

Source: (Evasys, no date)

EvaSys is a web-based software that allows users to design paper based, web-based, or hybrid surveys. Accordingly, it collects and clusters the data acquired from respondents, and finally delivers to the developers an evaluation of results obtained by quantifying statistical indicators (Mean, Median, Mode, and Standard Deviation) and by plotting trends and presenting it in an interactive display.

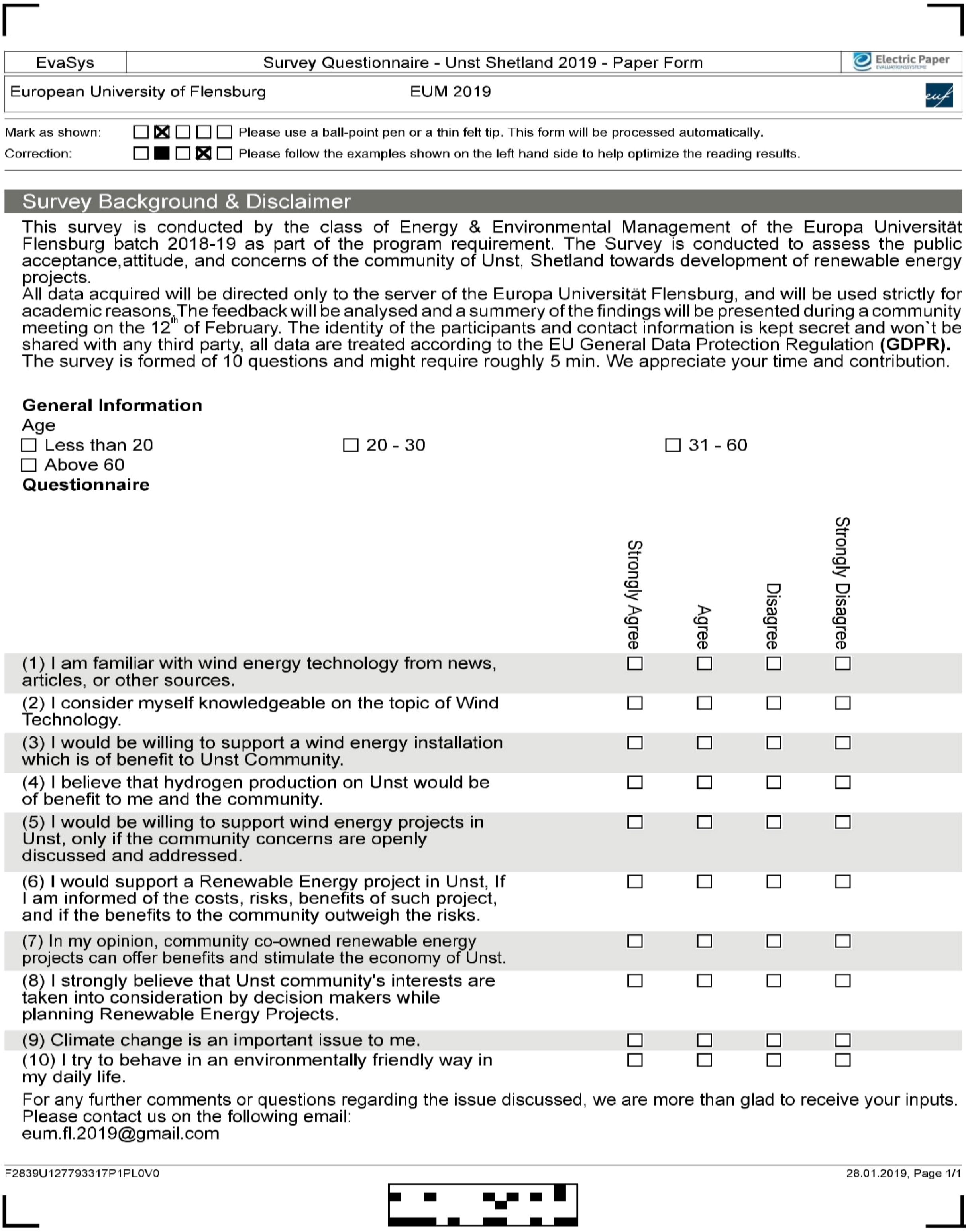
The EvaSys Team of the University of Flensburg offered an instructor account, which allows designing a personalized questionnaire, and later publishing a survey having the University logo within the heading for validation. The survey questionnaire was prepared as part of the activities of the stakeholders' group for the international class of the M.Eng. Energy and Environmental Management in Developing Countries 2019.

All data acquired was directed only to the server of the University of Flensburg. The identity of participants and contact information treated according to the EU General Data Protection Regulation (GDPR), was kept secret and not shared with any third party.

The survey named Unst Shetland 2019 was distributed in two forms: one as web-based open link (https://evasys.uni-flensburg.de/evasys/online/) with one password (unst2019), and the other as a paper-based version distributed by Mrs. Elizabeth Johnson from Pure Energy Centre, which was later collected by the program directors upon arrival to Unst.

In addition, an email eum.fl.2019@gmail.com was created to receive further comments and feedback from respondents since there was no provision for further comments on the survey sheet or the web-based interface.

A sample of the survey is attached below in Appendix Figure I-2:



EvaSys	Survey Questionnaire - Unst Shetland 2019 - Paper Form	Electric Paper
European University of Flensburg	EUM 2019	

Mark as shown: ☐ ☒ ☐ ☐ ☐ Please use a ball-point pen or a thin felt tip. This form will be processed automatically.

Correction: ☐ ■ ☐ ☒ ☐ Please follow the examples shown on the left hand side to help optimize the reading results.

Survey Background & Disclaimer

This survey is conducted by the class of Energy & Environmental Management of the Europa Universität Flensburg batch 2018-19 as part of the program requirement. The Survey is conducted to assess the public acceptance,attitude, and concerns of the community of Unst, Shetland towards development of renewable energy projects.

All data acquired will be directed only to the server of the Europa Universität Flensburg, and will be used strictly for academic reasons,The feedback will be analysed and a summery of the findings will be presented during a community meeting on the 12th of February. The identity of the participants and contact information is kept secret and won`t be shared with any third party, all data are treated according to the EU General Data Protection Regulation **(GDPR).**

The survey is formed of 10 questions and might require roughly 5 min. We appreciate your time and contribution.

General Information

Age

☐ Less than 20 ☐ 20 - 30 ☐ 31 - 60

☐ Above 60

Questionnaire

	Strongly Agree	Agree	Disagree	Strongly Disagree
(1) I am familiar with wind energy technology from news, articles, or other sources.	☐	☐	☐	☐
(2) I consider myself knowledgeable on the topic of Wind Technology.	☐	☐	☐	☐
(3) I would be willing to support a wind energy installation which is of benefit to Unst Community.	☐	☐	☐	☐
(4) I believe that hydrogen production on Unst would be of benefit to me and the community.	☐	☐	☐	☐
(5) I would be willing to support wind energy projects in Unst, only if the community concerns are openly discussed and addressed.	☐	☐	☐	☐
(6) I would support a Renewable Energy project in Unst, If I am informed of the costs, risks, benefits of such project, and if the benefits to the community outweigh the risks.	☐	☐	☐	☐
(7) In my opinion, community co-owned renewable energy projects can offer benefits and stimulate the economy of Unst.	☐	☐	☐	☐
(8) I strongly believe that Unst community's interests are taken into consideration by decision makers while planning Renewable Energy Projects.	☐	☐	☐	☐
(9) Climate change is an important issue to me.	☐	☐	☐	☐
(10) I try to behave in an environmentally friendly way in my daily life.	☐	☐	☐	☐

For any further comments or questions regarding the issue discussed, we are more than glad to receive your inputs. Please contact us on the following email:
eum.fl.2019@gmail.com

F2839U127793317P1PL0V0 28.01.2019, Page 1/1

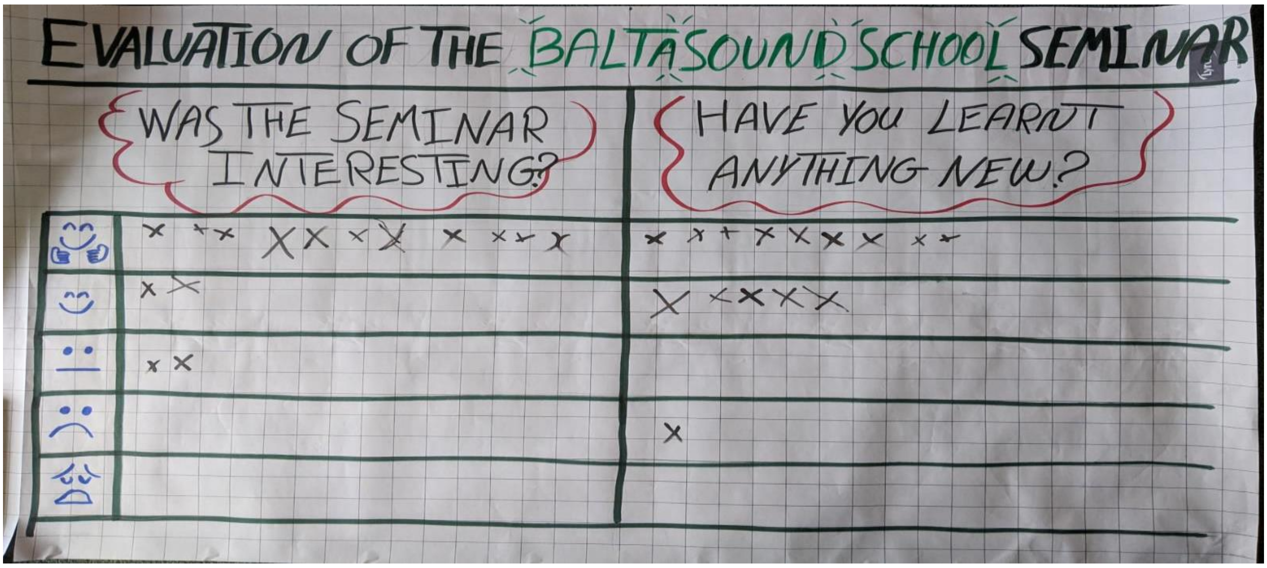
Appendix Figure I-2 Survey Questionnaire

Appendix II: Baltasound Junior High School Seminar

The seminar was held on 12th February at Baltasound Junior High School from 9:15 to 10:35 in the morning. 15 pupils, the head teacher of the school (Mr. Paul Thomson) and two of the teachers were in attendance.

The seminar started with an introduction of the pupils. The students from University of Flensburg were introduced through a game in which the pupils had to guess the country of origin of the students. A simplified project idea was presented, within which the familiarity of RE, the importance of using RE technologies and some environmental related topics were discussed.

As part of the seminar's agenda, the pupils presented varied topics about Unst. The presentations gave information about the location of Unst, services in the island, events and festivals, and lifestyle in Unst. The seminar ended with a brief evaluation conducted by University of Flensburg students.



Appendix Figure II-1Evaluation Results of Baltasound School Seminar

Appendix III: Community Workshop

The community workshop was held on the 12th of February 2019 at Balta Light Function Room, Hagdale in Unst, Shetland from 18.30 – 20.00. The focus of the community workshop was to present the survey results, introduce the project idea and to hold group discussions with the community members on their opinions to enhance the project idea. The group discussion was divided into three sub-groups namely:

1. **Concerns and Solutions Group**: to discuss any foreseen concerns about the project idea
2. **Benefits Group**: to collect ideas on the benefits which the community would expect from such type of project.
3. **Community Involvement Group:** to hold discussions about the ways that the community thinks that they can be involved in RE projects for their community 's benefits

There was a total of 10 attendees and each of them was given the option to choose one out of the three sub-groups to participate in, according to personal interest. The activity in the three sub-groups took place simultaneously.

A. Group Discussion on Foreseen Concerns and Solutions

This group's discussion was centred around the community members' foreseen concerns on the presented RE project idea by the University of Flensburg students, and was also intended to collect their opinion on ways to address all concerns mentioned. There were five community members present for this.

Activity 1

The Participants were asked to discuss the question: "**What are the Community's concerns about the project idea?**", with a supplementary request to also determine if the concerns raised should be classified under the economic, technical, social and environmental aspects. All their responses were noted down on a flip chart. This was followed by the next activity.

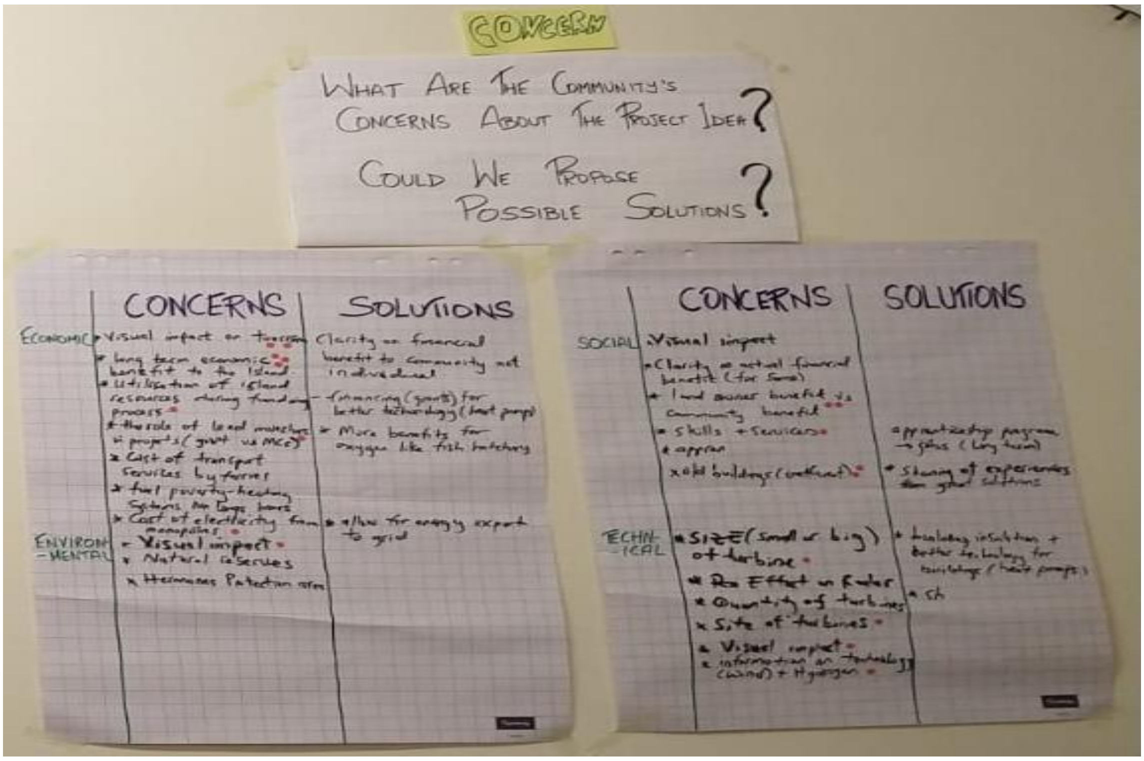
Activity 2

After stating the concerns, the participants were asked to propose suggestions to any of the raised concerns which could be addressed or solved. This was done by asking the next question: "**Are there any solutions to these challenges?**". Their responses were further noted on the flip charts beside the earlier mentioned concerns in Activity 1.

Activity 3

Then participants were then asked to prioritize the classified concerns (such as economic, social, environmental or technical), for which each participant was given three sticky dots.

Each participant was given the choice to place all their dots on one aspect, or distribute it between three aspects, or otherwise reflecting his or her order of priority.



Appendix Figure III-1Results of concern group discussion

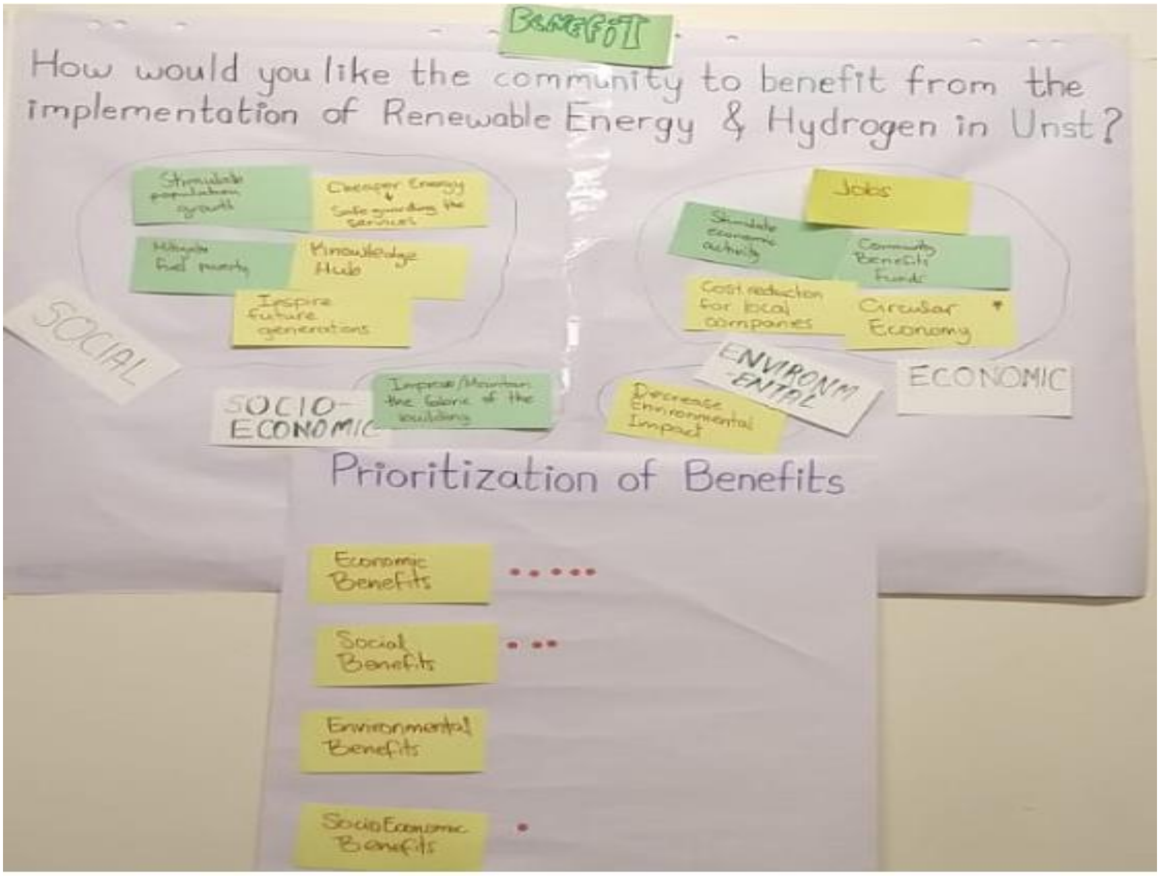
B. Group Discussion on Benefits

The first activity involved gathering answers and the participants' view to the question: "**How would you like the community to benefit from the implementation of RE and hydrogen project in Unst**?" Their answers were written on cards and arranged in the four clusters: economic benefits, social benefits, socio-economic benefits and environmental benefits.

Activity 2

So, the four clusters were arranged on another flipchart and the participants were given three votes and asked to vote the clusters of their choice. So out of the total of nine votes, five votes were obtained by the economic cluster, three were obtained by the social cluster and one was obtained by socio-economic cluster. The environmental cluster received no votes, because it was considered as a by-product of the economic benefit.

The main conclusion was that everything is linked with the economics. Once economic benefits for the community is higher, it'll lead to the social, and environmental benefit.



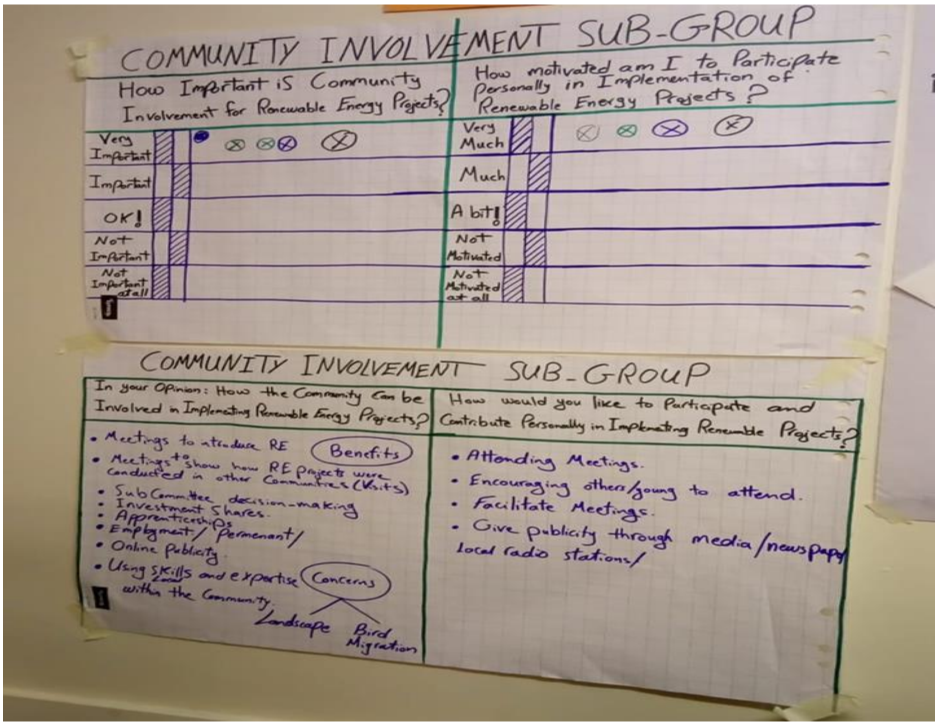
Appendix Figure III-2 Benefits Group discussions results

C. Group Discussion on Community Involvement

Two participants with two children chose the community involvement group to discuss the potentials of engaging the local community in planning and implementing RE projects.

The activity contained two exercises and lasted for 30 minutes. The first exercise had a table of two questions to measure the importance and motivation of community involvement in planning and implementing RE projects. The second exercise was an open discussion about "**How the community can be involved in planning and implementing RE projects?**" and "

How would you like to participate and contribute personally in implementing RE projects?"



COMMUNITY INVOLVEMENT SUB-GROUP

How Important is Community Involvement for Renewable Energy Projects?	How motivated am I to Participate Personally in Implementation of Renewable Energy Projects?
Very Important	Very Much
Important	Much
OK!	A bit!
Not Important	Not Motivated
Not Important at all	Not Motivated at all

COMMUNITY INVOLVEMENT SUB-GROUP

In your Opinion: How the Community Can be Involved in Implementing Renewable Energy Projects?	How would you like to Participate and Contribute Personally in Implementing Renewable Projects?
• Meetings to introduce RE • Meetings to show how RE Projects were conducted in other Communities (Visits) • SubCommittee decision-making • Investment Shares. • Apprenticeships • Employment/ Permenant/ • Online Publicity. • Using Local Skills and expertise within the Community. Benefits Concerns Landscape Bird Migration	• Attending Meetings. • Encouraging others/young to attend. • Facilitate Meetings. • Give publicity through media/newspap local radio stations/

Appendix Figure III-3 Community Involvement Group Results

Appendix IV: Potential Stakeholders and beneficiaries of the project

Appendix Table IV-1Potential stakeholders of the project

Potential Stakeholders	Field of work
Pure Energy Centre	The main technical partner working in the fields of renewable energies, hydrogen, compact natural gas, oxygen, nitrogen and Fuel Cell technologies
Unst Partnership Limited	A local development organization located in the island of Unst, engaging in all community development projects and activities on the island.
Shetland Islands Council	The local authority and owner of some of the governmental buildings such as Baltasound Junior High School, and Nordalea Care Centre.
The Highlands and Islands Enterprise	The Scottish government development agency.

Potential beneficiaries of the project:

- Saxa Vord Resort
- Baltasound Junior High School
- Unst Leisure Centre
- Nordalea Care Centre

Appendix V: Companies Contacted during the Project

Appendix Table V-1 Companies contacted during project assessment

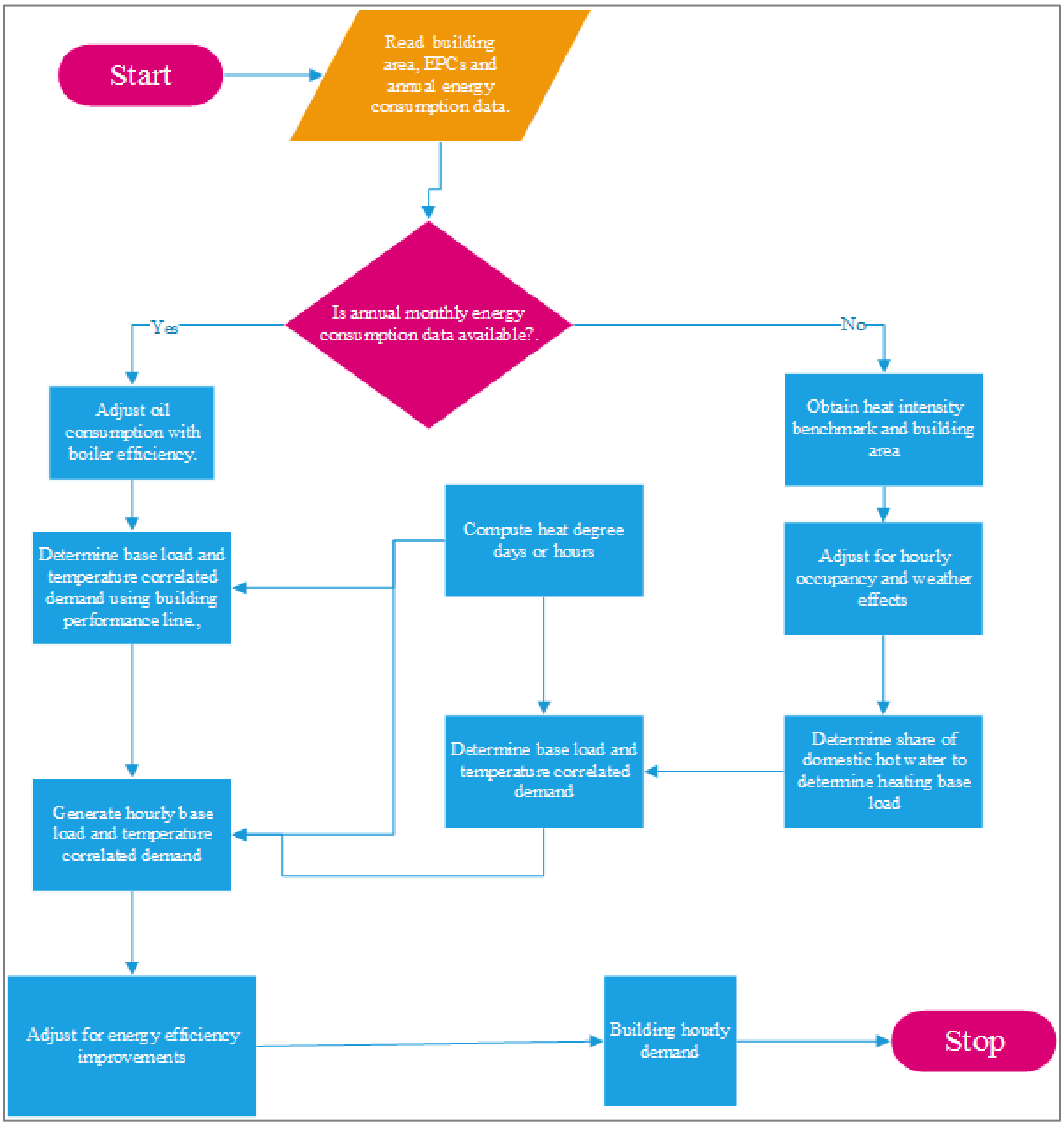
Company	Country	Reason for Communication	Website
Xant	Belgium	Wind Turbines Datasheet	http://xant.com/
Enercon	Germany	Wind Turbines Datasheet	https://www.enercon.de/en/home/
Jinko Solar	China	Solar PV Datasheet	https://www.jinkosolar.com/
Trina Solar LTD	China	Solar PV Datasheet	https://www.trinasolar.com/en-uk
Sunpower Corporation	USA	Solar PV Datasheet	https://us.sunpower.com/
E&H Building Contractors	UK	Referred to Kingspan	https://www.ehbuildingcontractors.com/
Kingspan	UK	Solar Collectors Datasheet	https://www.kingspan.com/group/
Mitsubishi	Japan	Heat Pumps Datasheet	https://les.mitsubishielectric.co.uk
Viessmann Group	Germany	Vitocal Heat Pumps Datasheet	https://www.viessmann.co.uk
Northman Group	UK	Japsi Electric Boilers	http://www.northmangroup.co.uk/
Precolor	UK	Hot Water Storage Tank	https://www.precolortankdivision.co.uk/
Tanks Direct	UK	Hot Water Storage Tank	https://www.tanks-direct.co.uk/
Pure Energy Centre	UK	Hydrogen Electrolyser	https://pureenergycentre.com/
Proton ventures	Netherlands	Ammonia Electrolyser	https://www.protonventures.com/

Appendix VI: Building heat demand assessment model description

As illustrated in Appendix Figure VI-1, the building heat demand projection model requires data on building area, heat intensity benchmarks and historical oil consumption. If there is historical oil consumption, method I is used else method II is used. In method I, historical oil consumption data is adjusted with a boiler conversion efficiency and this when plotted by the generated heat degree days or hours enables one to realise a building performance line. From the performance line the base load is the intercept and the gradient the correlation between heat demand and heat degree days. These are then adjusted to develop hourly figures and used to project the building heat demand with the observed heat degree hours. For method II, the model reads heat intensity benchmark and multiplies it with the building area to determine the total annual heat demand. This is further adjusted with weather and occupancy factors. From historical statistics by type of building or use, a base load is assumed to be the share of domestic hot water since its pretty much constant year-round. The temperature correlated part of the demand is then the remaining share. This is divided by the cumulative degree days to determine the constant of proportionality. The hourly base load and constant of proportionality are then applied to the heat degree hours to determine the hourly head demand. Further adjustment like improvements in efficiency can be made to the total to determine the final heat energy demand of the building.

The Heat_Demand_Assessment_Model Ms. Excel model is made up of 22 sheets. First is a sheet which gives the usage insights on the role of each of the sheets. The input sheet enables one to select a simulation scenario either the base case scenario or energy efficiency scenarios, view the carbon emissions from the simulated scenario,

The base year used in the model is 2017 and 2017 weather statistics were used to realise the hourly head demand. The SV_Heat_Demand_15.5HDH_2017 sheet relates the changes in energy efficiency, building occupancy and the building heat demand at Saxa Vord. The BS_JS_NCC_ULC_2017 sheet generates the heat demand for the building stock at Baltasound. The ULC_Demand_2017 sheet generates the Unst Leisure Centre heat demand since for it a unique 28^{o}C heating day is required for the swimming pool heating. BS_JS_NCC_Demand_2014_2015 generates the heat demand for Baltasound Junior high school and Nordalea Care centre from the historical 2014-15 oil consumption statistic. The Occupancy_Scenario sheet is a display of the simulated occupancy scenario.



Appendix Figure VI-1 Building hourly heat demand projection methodology.

Source: Illustration by Author

The Financial Analysis sheet is an analysis primarily of energy efficiency measures and the investment in wet heating system. The radiator_sizing sheet provides benchmarks for the capacity of the existing or required radiator capacitors for the wet heating system at either building location. The BS_JS&NCC _Building_P_Lines1314 sheet generates a building performance line to realise the base load and temperature correlated coefficients for Baltasound Junior high school and Nordalea Care Centre using the 2014-15 historical data and heat degree days. April_2014_May_2015_MERRA generates heat degree days from MERRA data.

Method_II_Benchmark&Area is a summary of the benchmarks and the corresponding building area and also generates base load and temperature correlated figures using the share of domestic hot water by building usage. Energy_Efficiency Matrix enables the application of the assumed energy efficiency to each type of building in the model. Existing_Energy_Use_Data is the historical oil and electricity usage data from the relevant stake holder. 2017_15.5HDH_NEMS12 is the 15.5 heat degree day generating sheet from the raw 2017_NEMS12_DataSet sheet. 2017_28HDH_NEMS12 generates heat degree days at 28 degrees. HDD_042014-052015 generates heat degree days for April 2014 to May 2015. 8760_HDH_Datasets is a summary of all the 8760 heat degree days in the model. Energy_Scenario _Simulations is a display of the simulation results from TRNSYS and TRNSYS_Simulation_Scenario is an analysis of the capital cost for energy efficiency improvement by scenario.

Appendix VII: Pipe Sizing

Appendix Table VII-1Pipe sizing and costing at Saxa Vord

Pipe Name	Peak Demand /kW	Main Loss 10 %	Flow Rate/ gpm	Velocity (m/s)	Pipe size (mm)	Friction Loss per 100ft (psi)	Pressure Loss per meter of pipe (pas/m)	Actual Pipe Length (m)	Fittings Resistance 33%	Effective Pipe Length/ m	Branch Head Loss (Meters Head)
Main Saxa Vord Pipe from Storage to compound	114.00	1.10	11.25	0.91	32.00	2.71	613.47	200.00	1.33	266.00	16.64
Saxa Vord Self Catering Compound 1	51.00	1.10	5.03	0.81	25.00	3.07	695.13	29.00	1.33	38.57	2.73
Saxa Vord Self Catering Compound 2	63.00	1.10	6.22	0.95	25.00	4.08	922.47	27.10	1.33	36.04	3.39
Taftens Houses	63.00	1.10	6.22	0.95	25.00	4.08	922.47	13.20	1.33	17.56	1.65
Main Distillery and Brewery Pipe	88.00	1.10	8.69	0.84	32.00	2.31	522.31	237.00	1.33	315.21	16.79
Distillery	52.00	1.10	5.13	0.81	25.00	3.07	695.13	37.00	1.33	49.21	3.49
Brewery	36.00	1.10	3.55	0.90	20.00	5.01	1132.39	21.70	1.33	28.86	3.33

Source: Author

SAP Worksheet

Design - Draft

This design submission has been carried out using Approved SAP software. It has been prepared from plans and specifications and may not reflect the property as constructed.

Assessor name	building-IC-2019	Assessor number	1
Client	shetland stokholders	Last modified	01/03/2019
Address	18 Nordabrake 18 Haroldswick, Saxa Vord, Unst, Schotland, ZE2 9TP		

10a. Fuel costs - individual heating systems including micro-CHP

	Fuel **kWh/year**		**Fuel price**		**Fuel cost** **£/year**	
Space heating - main system 1						
high-rate cost	25318.82	x	15.29	x 0.01 =	3871.25	(240)
low-rate cost	0.00	x	5.50	x 0.01 =	0.00	(240)
Water heating						
high-rate fraction			0.31			(243)
low-rate fraction			0.69			(244)
high-rate cost	678.24	x	15.29	x 0.01 =	103.70	(245)
low-rate cost	1496.34	x	5.50	x 0.01 =	82.30	(246)
Electricity for lighting						
high-rate cost	948.39	x	15.29	x 0.01 =	145.01	(250)
low-rate cost	105.38	x	5.50	x 0.01 =	5.80	(250)
Additional standing charges					24.00	(251)
Total energy cost			(240)...(242) + (245)...(254) =		4232.05	(255)

11a. SAP rating - individual heating systems including micro-CHP

Energy cost deflator (Table 12)	0.42	(256)
Energy cost factor (ECF)	9.77	(257)
SAP value	-2.76	
SAP rating (section 13)	1	(258)
SAP band	G	

	Energy kWh/year		Emission factor kg CO_2/kWh		Emissions kg CO_2/year	
Space heating - main system 1	25318.82	x	0.519	=	13140.47	(261)
Water heating	2174.59	x	0.519	=	1128.61	(264)
Space and water heating			(261) + (262) +	(263) + (264) =	14269.08	(265)
Electricity for lighting	1053.77	x	0.519	=	546.91	(268)
Total CO_2, kg/year				(265)...(271) =	14815.98	(272)
Dwelling CO_2 emission rate				(272) ÷ (4) =	108.15	(273)
EI value					18.49	

EI rating (section 14)					18
EI band					G

	Energy kWh/year		Primary factor		Primary Energy kWh/year
Space heating - main system 1	2	x	3.07	=	77728.78
Water heating	74.59	x	3.07	=	6675.98
Space and water heating			(261) + (262) + (263) + (264) =		84404.76
Electricity for lighting	10	x	3.07	=	3235.06
Primary energy kWh/year					87639.83
Dwelling primary energy rate kWh/m2/year					639.71

Appendix IX: CATALYST CALCULATIONS

The catalyst being considered is Magnetite Fe_3O_4. From , the mass of Iron catalysts used should comprise pelleted iron oxide with density of at least 2.6 g cm-3 (i.e. 2600 kg m-3) (Jennings, 1985). As per a case study report by (Cheema and Krewer, 2018) for ammonia production of 3 tons per day (i.e. 3000 kg per day), the total volume of catalyst bed required was 0.076 m3.

Volume of catalyst required

In this case, a production capacity of 4.5 kg NH_3 per hour (i.e. 108 kg per day) is considered.

If, 3000 kg requires a total catalyst volume of 0.076 m^3

Then, 108 kg requires a total catalyst volume of **x** m3

$$\text{Hence, volume of catalyst required} = \frac{108*0.076}{3000} = 0.00274\ m^3$$

Mass of catalyst required

mass = volume * density

Hence, mass of catalyst required = 0.00274 * 2600 = 7.124 kg

Heat energy required to heat catalyst to 400^oC

$$Q\ (\text{heat energy}) = m * cp * \Delta T$$

Where m = mass of catalyst

Cp = specific heat capacity of catalyst at 25 ^oC

ΔT = change in temperature (difference between temperature at start of reaction and desired end temperature i.e. 400^oC).

To estimate number of moles that contain 7.1 kg; 1 mole of Fe_3O_4 contains 231.55 g, or 0.232 kg.

Hence, 30 moles of Fe_3O_4 contains 7.124 kg.

The specific heat capacity (c_p) of Fe_3O_4 at 25^oC = 143.5 J/mol ^oC (Chemistry Libre Texts, 2016)

ΔT = 400^oC – ambient temperature in Unst (7^oC) = 393 ^oC

Therefore Q (heat energy required) = 30 moles * 143.5 J / mol ^oC * 393^oC

= 1,691,865J

= 1691.87 kJ

= 0.47 kWh