Department of Mechanical and Aerospace Engineering

An Investigation into the Adoption of a Hydrogen Economy in the Falkland Islands through the use of a Hydrogen Fuel Cell Combined Heat and Power System, and Integration with Renewable Energy Systems.

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Signed: Findlay Fisher Date: 23/08/19

Abstract

The need to develop and adopt clean and sustainable sources of energy has reached its peak, and the longevity of the planet hangs in the balance and we rapidly approach the point of no return if global temperatures climb much higher. The search for such energy sources has drawn the attention to hydrogen as a diverse energy carrier, offering benefits such as energy storage and transportation with minimal losses, a near limitless supply of energy, and at the cost of minimal emissions if integrated with renewable energy systems. This thesis models both the cogeneration potential of hydrogen and the capacity for producing a sustainable and clean supply of energy to a isolated community in the Falkland Islands. The proposed hydrogen fuel cell combined heat and power system is compared to that of the existing fossil-fuel based power generation system to investigate the performance of each system and evaluate the benefits afforded by a hydrogen economy. The results obtained through the simulation of a number of system configurations were promising for the immediate future; a hydrogen fuel cell in combination with the installed renewable energy systems can meet the electrical demand of the main Island town. However, the system envisioned for the future would require upgrades to the existing systems as both the energy demands and generation technologies continue to grow.

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1. Introduction

Fossil fuels have been the primary source of energy for hundreds of years due to their large energy density and ease of storage and transportation; using oil, coal and natural gas for power generation, kerosene for heating, and petrol and diesel in our cars. However, rising concerns on the effects of harmful emissions from burning fossil fuels have climaxed in recent years, following a report issued by the Intergovernmental Panel on Climate Change (IPCC) warning of the irreversible repercussions of global temperatures rising more than 2°C above preindustrial levels. (IPCC, 2018)

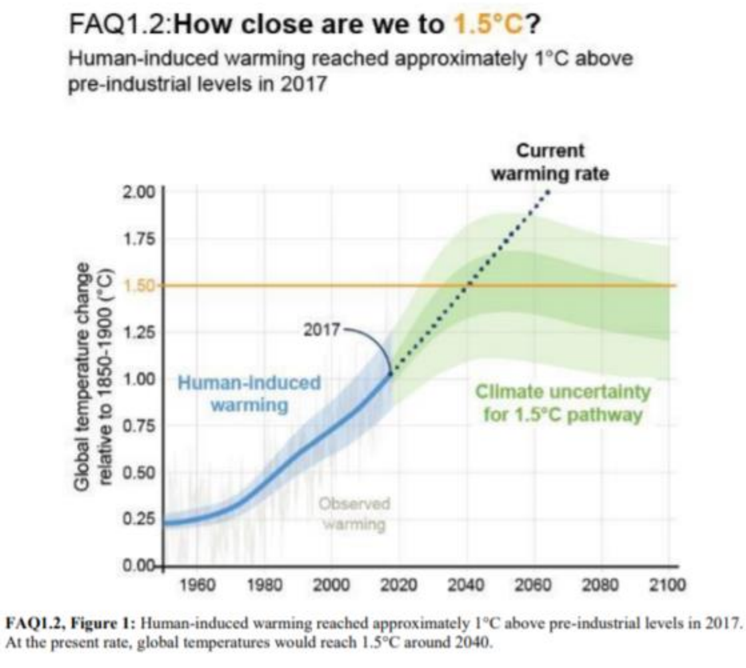

Figure 1 Global Temperature Trends (IPCC, 2018)

The response to combatting climate change has been mixed around the world, but in countries such as Scotland, renewable energy systems have matured to the stage where enough electricity has been generated to fulfil the national power demand nearly twice over from wind energy captured in only 6 months. (Weatherenergy.co.uk, 2019)

Research into clean and sustainable sources of energy prompted the development of hydrogen fuel cell technologies, which had been conceived as early as the mid 1800's. Hydrogen, the most abundant element in the universe, is an extremely flexible energy carrier. It can be produced from a near limitless supply in the form of water, with very low emissions if generated through the use of renewable energy systems. It is diverse in its applications as a fuel source through the use of hydrogen fuel cells for both small and large scale electricity and heat generation and transportation, and it provides a means of long term energy storage or long distance transportation of energy with minimal transmission losses compared to its purely-electric counterparts. Its viability at present is limited by the cost of both the fuel cell technologies and hydrogen fuel supply. The adoption of a hydrogen economy may provide a long-term solution to a low-carbon future, and in certain applications offers greater advantages than competing clean energy solutions.

OCTA, the Association of the Overseas Countries and Territories of the European Union recognises the energy supply challenges faced by small islands economies because of their isolation and often remote location from the nearest mainland, namely grid access and import/ export of fossil fuel based energy. With a dependable and cost effective energy supply, business investment and employment follow and lead to economic growth and stability for the islands' communities. Accordingly EU Research is being commissioned into renewable energies that work in synergy with the OCTs natural resources be that wind, wave, hydro or solar energy capture and effective storage to achieve a self-sustaining power supply. Indeed, OCTA have stated that ' an island environment is an ideal living lab for piloting smart grid applications’ such as extension of wind farm performance, electric transport and evidencing the energy saving impact for homes and businesses, REF.

This EU initiative lends support and justification for the chosen field of this research investigation into the Falkland island energy systems and gives a global context to direct their long term strategic planning towards a fully self- sustainable integrated hydrogen fuel based economy in the future.

The Falkland Islands is a British Overseas Territory off the South East coast of the South American coast, with a history of surpassing British and global goals for sustainable energy integration through renewable energy systems adoption. The Falklands is an island community with no connection to the mainland of Argentina and with a weak and outdated grid infrastructure that only covers the larger settlements and not the scattering of farms around the rest of the island. They continue to rely heavily on imports of diesel and kerosene to bear the brunt of the power and heating load in the larger towns and have been unable to make the most of their expensive windfarm due to the added expense of battery storage. Their situation is further compounded with inadequate infrastructure that cannot handle the increased load. (Worlddata.info, 2019) Being a fuel-based economy, it was theorised that the conversion to a hydrogen economy would not only provide obvious reductions in carbon emissions but would also offer a particularly suitable path to a more sustainable and secure energy future.

This thesis shall investigate the current heating and electricity generation systems in the Falklands in order to develop a sustainable and clean power source and explore the next steps in minimising the island’s dependency on fossil fuels for the future.

1.1. Aim

This thesis aims to provide analysis on the potential performance, emissions and cost of adopting a Hydrogen economy in the Falkland Islands, by modelling a hydrogen fuel cell CHP system with links to other renewable energy systems and Hydrogen storage capabilities. The hydrogen fuel cell CHP system will be modelled alongside current and competitive technologies considering fuel pricing and energy tariffs and compared to the existing fossil-fuel based power system currently in use in the Falklands.

1.2. Scope

The current state of Hydrogen fuel cell technologies and Hydrogen fuel prices limits itself as a competitive alternative in comparison to fossil fuels and their energy generation technologies. This thesis will model the Hydrogen fuel cell technologies and fuel source at a competitive price to that of the fossil fuel systems, and their related costs, that are currently active on the Falkland Islands. It is expected that the relative cost of Hydrogen fuel cell technologies will decrease over time as more research and development is carried out in the field, which will have a incremental effect on the supply price of Hydrogen.

For the purposes of this thesis, it is assumed that the supply of Hydrogen will be provided to the Falkland Islands by the current provider of fossil fuels to the Islands, Stanley Services ltd (Stanley-services.co.fk, 2019)

The Hydrogen fuel cell system will be compared to a model of the currently active fossil-fuel system supplemented by renewable energy generation in the form of a wind farm. This model was developed using electricity generation data obtained directly from the Stanley Power Station and Sand Bay windfarm.

Heating and electrical demand was kept constant across all system configurations.

All analysis was conducted for the period 6th July 2018 to 5th July 2019. This period was selected as it provided the most current data at the time of writing.

1.3. Method

This section will detail the modelling scenarios and data analysis method used through the course of this research investigation to evaluate the various energy systems that could be employed in the Falkland Island, either individually or in combination, to sustain or eventually replace their fossil-fuel based energy requirements. An initial research and review of appropriate literature was carried out to identify a location that currently presented many challenges for conventional energy supply, had natural renewable resources and offered maximum potential benefit in a drive to achieve 100% self-sustaining CHP systems and removed reliance on and decrease use of fossil fuels. Due to its remoteness from nearest mainland, its maritime climate & prevailing weather conditions (America et al, 2019) challenging the logistics of its supply chain, the Falkland Islands presented an ideal candidate for this research investigation. From this point the detailed project scope and aims were defined. A decision was made on the most appropriate available software to analyse combined heat and power systems with inbuilt databases on climate (EnergyPRO) and electrical & heating demand profile estimator (HOMERpro). Following this, trials were conducted with the software to determine its capabilities and the input data required.

Climate data spanning a full year to account for seasonal variations in weather was obtained at hourly intervals, a frequency that would then afford sufficiently detailed appreciation of daily variations in weather conditions.

A number of system configurations were created to allow for the comparison between the existing and proposed power supply systems and the evaluation of the performance of each.

1.3.1 System Configuration 1 – Current Diesel & Wind CHP System

This configuration represents the currently active CHP system employed in Stanley. This system features a primary power generation source provided by 8 diesel generators at the Stanley Power Station, supplemented by power generated by the 6 330kW wind turbines at the Sand Bay wind farm. (Thewindpower.net, 2019) This configuration was constructed using the power generation data provided by Stanley Power Station for both diesel and wind power. This configuration will provide the baseline to which the proposed Hydrogen-based configurations will be compared.

1.3.2 System Configuration 2 – Hydrogen Fuel Cell CHP System w/ RES Integration

This configuration represents the simplified Hydrogen CHP system proposed, which will take the place of the diesel generators in System Config. 1, and will be supplemented by the electrical generation of the Sand Bay wind farm. The fuel cell will be sized according to the average and peak electricity demand of the city. This CHP system aims to provide 100% of the electrical demand of Stanley. The heating potential of this system will then be assessed to identify the contribution that can be made towards the heating demand of Stanley.

1.3.3 System Configuration 3 – Hydrogen Fuel Cell CHP System w/ RES Integration for Hydrogen Production

This configuration represents the envisioned fully sustainable Hydrogen CHP system for the Falklands. This is an iteration of System Configuration 2 with the integration of renewable energy systems, specifically the wind power generation capabilities of Sand Bay wind farm, being utilised in this configuration to create the required supply of Hydrogen through electrolysis. Assessment of this configuration will require the evaluation of the maximum achievable generation potential of the Sand Bay wind farm to evaluate if it is capable of producing a sufficient supply of Hydrogen to maintain the energy demand on the CHP system. Following this, an assessment shall be made to see if the hydrogen CHP system sized for System Configuration 2 is able to meet the increased electrical demand once the direct contribution from the wind farm was removed. However, EnergyPRO does not feature a means of modelling hydrogen production with an electrolyser. In order to evaluate the annual hydrogen production, the total annual electrical supply from the wind farm was used as the input to a generic industrial-scale PEM electrolyser.

2. Literature Review

2.1. A Brief Summary of the Falkland Islands

2.1.1. Overview

The Falkland Islands is an archipelago consisting of the two main islands, East Falkland and West Falkland, and 776 smaller islands, situated around 300 miles east of the Southern Patagonia coast. The islands cover an area of 4,700 square miles with a population of 3,400, around 2,500 of which live in the capital; Port Stanley. The remainder of the population are dispersed between the many farms that provided the primary source of the Islands' income through the production of wool and other agricultural products. According to the Census of the Falkland Islands, conducted in 2016, Stanley consists of 900 houses and 73 flats. The initial discovery and ownership of the islands is a contentious issue as the British, French, Spanish and Argentines have all held settlements on the island. This conflict was reignited with the invasion of Argentine forces in 1982. However, most islanders claim British descent, and the islands are known as a self-governing British Overseas Territory, relying on the UK for their defence and foreign affairs policies. (Globalislands.net, 2019)

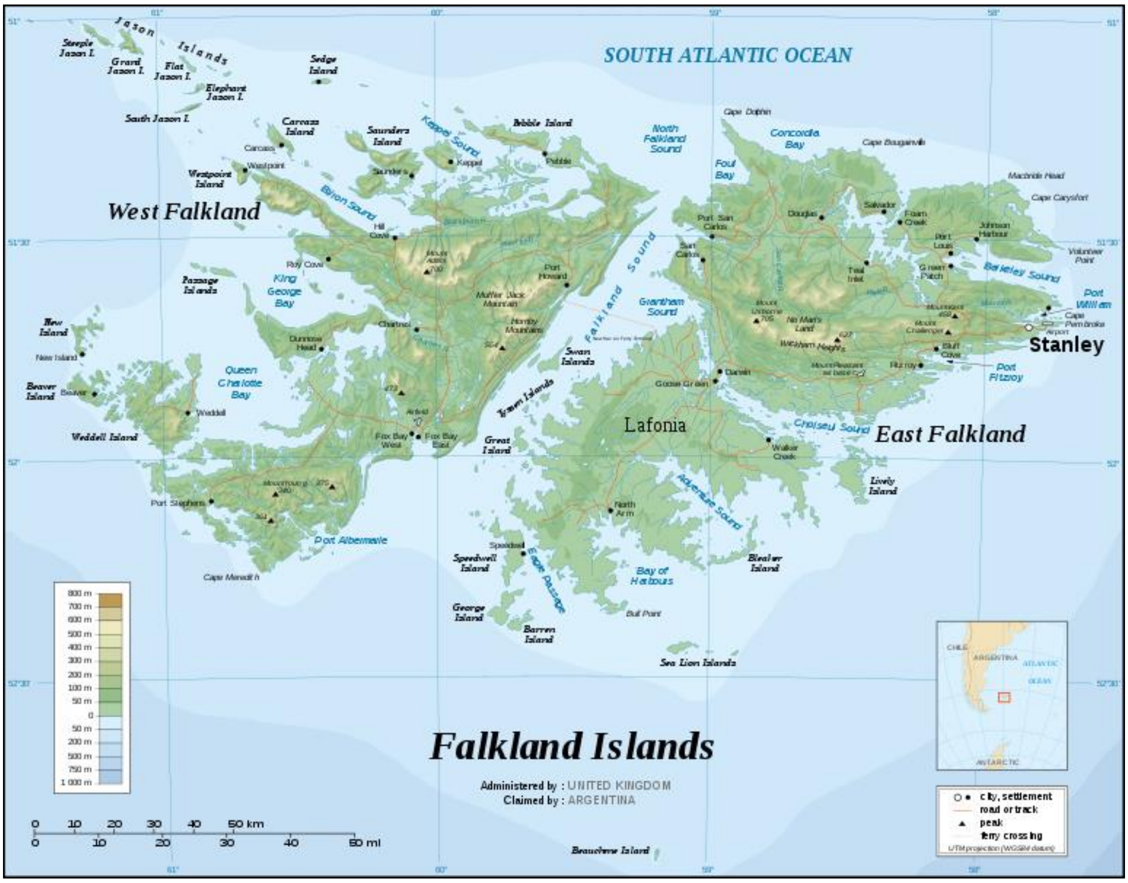

Figure 2 Map of the Falkland Islands

2.1.2. Stanley Power Station/Fossil Fuel Power

Stanley Power Station located within the town itself has an installed capacity of 6.6MW, provided by eight diesel generators. These generators range in size from 320kW to 1,500kW, and are between 30 to 50 years old. The old generators feature none of the modern emissions control systems nor the sound and vibration proofing features that are demanded by the UK standards of today. As they approach the end of their operational life, engine services and failures are becoming a more common occurrence. This has put increasing strain on the power station's ability to provide a reliable source of power to meet the current demand, and as the demand for electricity continues to rise, this growing uncertainty prompted government planners to act. In 2018, plans were confirmed for the development and construction of a new full-diesel power plant in Stanley which would replace the current station. While the Falkland's government have acknowledged the requirement for renewable energy sources to be more heavily adopted in the future, the replacement diesel Power Station "remains necessary…to provide a reliable power source to meet current and future demand." (Falklands.gov.fk, 2018)

2.1.3. FIDC & Rural Wind

The Shackleton Report, written by Lord Shackleton in December 1977 (Drewry, 1977) set out a number of recommendations for the continued economic growth of the islands. This prompted the establishment of the Falkland Islands Development Corporation (FIDC), and since 1996 they have worked alongside the Falklands government to maximise the use of renewable energy systems on the islands. As an island community still reliant on outdated infrastructure, the Falklands are primarily a fuel-based economy. The population is too widely dispersed for there to be an island-wide power grid. Homes rely on kerosene for heating, and diesel generators provided the only source of electricity for the hundred or-so farms scattered across the islands, and even then, only for a few hours of the day. (FIDC, 2019a) The Rural Energy Grant scheme was established to help farms and businesses outside of the Stanley catchment area to invest in a standalone power system incorporating a renewable energy source which would provide them with access to electricity 24-hours a day. (FIDC, 2019b)

2.1.4. Sand Bay Wind Farm & Urban Wind

Further honouring their commitment to the increased use of renewable energy systems, in 2006 the Falkland's government commissioned the Sand Bay onshore windfarm, located just 8km west of Stanley. The initial installation of three Enercon E33 turbines, each with a 330kW capacity, was enough to reduce the price of electricity on the island by 6 pence per kWh. In 2010 three more E33 turbines were added, bringing the total capacity of the Sand Bay windfarm to 1.98MW. (Thewindpower.net, 2019) The windfarm's output on average covers around 40% of the islands' demand and has been known to contributed up to 50% on days with particularly favourable wind conditions. However, as with all wind turbines, the issue of storage of surplus electricity that cannot be absorbed by the grid has plagued the Falklands as much as any other isolated island community. (Carlosstjames.com, 2019) Like many isolated island communities, the Falklands have yet to decide on a suitable solution to combat the dispatchable limitations of wind energy as a fully flexible and controllable energy source. In order to achieve the highest possible yield from the windfarm, a storage solution must be devised to store the surplus electricity generated that cannot be absorbed by the small and outdated grid on the islands. Discussions amongst the islands' development committee have confirmed large-scale battery storage to be an expensive solution. The adoption of more electric vehicles (EVs) around the island was suggested, which would act as a 'driveable' micro-grid of micro-storage banks to absorb some of this otherwise wasted electricity. However, uptake has been almost non-existent as most vehicles on the island are larger more rugged off-road trucks designed to handle the highland terrain and carry out the duties expected of a farm vehicle. Investigation into the use of Hydrogen storage, involving the conversion of wind-generated electricity into Hydrogen through electrolysis, was short and inconclusive. Yet the islanders remain open to the concept if it is proved to be a viable and cost-effective energy solution.

2.2. The Hydrogen Economy

The term 'Hydrogen economy' refers to the use of hydrogen as the main source of fuel to deliver a low-carbon future. (The hydrogen economy, 2004) Hydrogen is an extremely versatile and abundant fuel source, and as the lightest element in the periodic table it also offers the highest energy density per unit mass between 120-143MJ/kg. (Hypertextbook.com, 2005)

A hydrogen economy utilises hydrogen to produce electricity through hydrogen fuel cells. (UKHFCA, 2019) Similarly hydrogen is used as a fuel in Hydrogen Fuel Cell vehicles that are becoming increasingly popular. (Lane, 2017) Crucially, however, hydrogen is able to bridge the gap between clean and sustainable renewable energy sources as it can be produced sustainably, with the ability to store and transport energy in the same way that other solid fuels can.

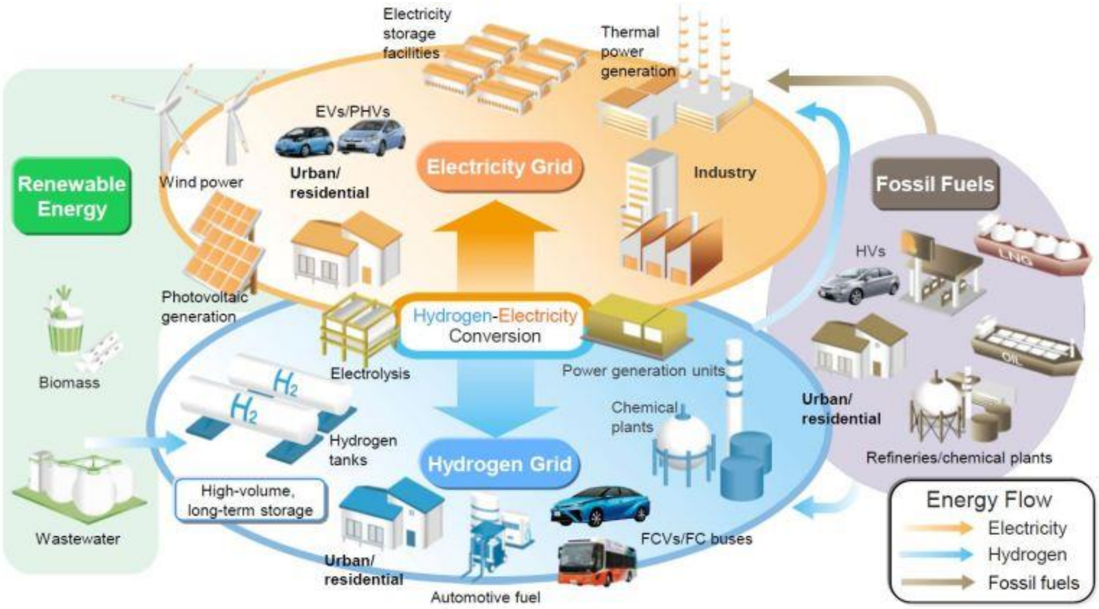

Figure 3 Hydrogen Economy Roadmap (newenergytreasure.com, 2019)

A hydrogen economy is in direct competition with a purely electric economy, where electricity is the medium for power, heating, and transportation in the form of electric vehicles (EVs). The downfall of a purely electric economy is in the expensive, inefficient battery storage solutions, and transmission losses which make the transportation of electricity impractical over long distances. Today, the adoption of a purely electric economy has been the more popular choice globally. An appreciation of this is evident in the uptake of low emission transport. In the United Kingdom, there were just under 220,000 registered plug-in electric vehicles, available in over 125 different models, and serviced by 24,000 charge points around the country. With only 3 models of Hydrogen car available globally, and just 16 active hydrogen refuelling stations in operation in the UK, the poor uptake of Hydrogen vehicles can mostly be attributed to the higher initial vehicle purchase and fuel costs compared to their purely electric counterparts. EVs appear to be the quick fix alternative to reduce carbon-based fuel emissions for now, however the relatively short operating ranges and long charge times are an inconvenience alongside concerns for the life and recycling of the batteries are factors that may discount them as a long-term solution for low-emission transport provision. (The Week UK, 2019)

2.3. Hydrogen Fuel Cells

A hydrogen fuel cell (FC) is an electrochemical device which converts chemical energy from a fuel source, Hydrogen, and an oxidising agent, Oxygen, into electricity through a pair of redox reactions. In hydrogen fuel cells, the waste product is water and the by-product is heat. Fuel cells are more like an engine rather than a conventional battery in that they require a continuous supply of fuel and oxygen in order to sustain the reaction. (Hydrogen.energy.gov, 2019)

The basis of all fuel cells is a pair of electrodes; the cathode which carries the negative charge and the anode which carries the positive charge, and an electrolyte which separates the electrodes whilst still allowing the transfer of electrons between the two. The hydrogen fuel is fed to the anode, whilst air is fed to the cathode. A diagram of a basic hydrogen fuel cell can be seen in Figure 4 below.

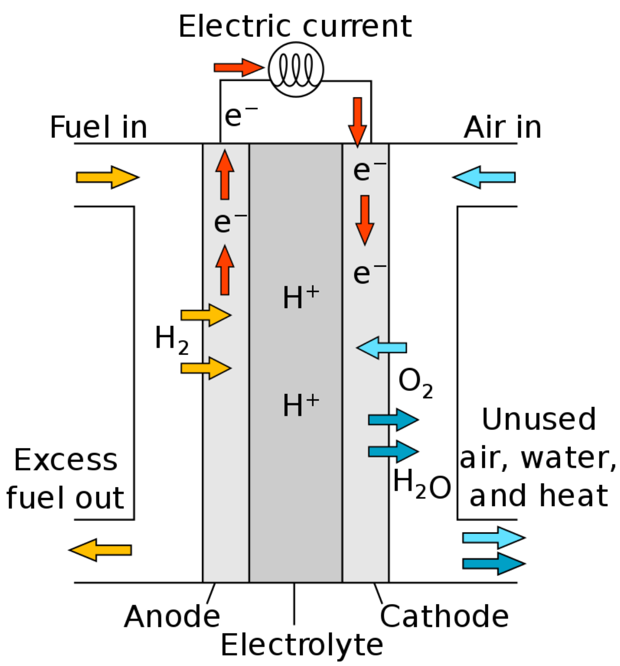

Figure 4 Diagram of a Hydrogen Fuel Cell

The ‘redox reaction’ that takes place is a combination of atomic oxidation and reduction. (Esru.strath.ac.uk, 2019)

Anode: $H_{2(g)} \rightarrow 2\ H^{+}_{(aq)} + 2\ e^{-}$

Cathode: $1/2\ O_{2(g)} + 2\ H^{+}_{(aq)} + 2\ e^{-} \rightarrow H_2O_{(g)}$

Cell: $H_{2(g)} + 1/2\ O_{2(g)} \rightarrow H_2O_{(g)}$

The oxidation reaction occurs at the anode and is the loss of electrons from the Hydrogen atoms. A catalyst is used to help split the Hydrogen molecules into protons and electrons, which take different paths to the cathode. The flow of electrons from the Hydrogen fuel source to the cathode provides the electricity current from the fuel cell. The protons from the Hydrogen atoms travel through the electrolyte to the cathode, where they pair with the Oxygen atoms in a reduction reaction which produces the waste water and some waste heat. The water and any unused gases are exhausted from the cathode, whilst any excess Hydrogen is recycled around the anode.

Temperature levels must be carefully monitored and regulated within a fuel cell, and many systems use waste heat to preheat the hydrogen fuel and air supply. Operating temperatures are high enough to be useful in other heating applications (See Section 2.8).

The described fuel cell acts as only a single cell, which only produces around 0.6V. However, a number of these cells can be combined in fuel cell stack. Chaining fuel cells in series increases the voltage produced by the fuel cell stack and combining in parallel will increase the current. Similarly, increasing the effective surface area of a fuel cell will help to increase the current developed in each cell. An effective fuel cell design will have the reactant gases uniformly distributed over each cell to maximise the power output.

Fuel cells generate a direct current (DC) supply of electricity, yet a majority of consumer applications demand an alternating current (AC) supply. An Inverter is required to convert the DC supply from the fuel cell into AC before it can be used. A transformer is also required to increase the voltage from the fuel cell stack output to 240V which is the same supplied as the UK grid. The inclusion of these devices increases the capital cost of the fuel cell, as well as resulting in a small hit to the overall efficiency of around 2% to 6%. (UKHFCA, 2019)

There are six main classes of fuel cell:

1. Proton Exchange Membrane Fuel Cell (PEMFC)
2. Alkaline Fuel Cell (AFC)
3. Direct Methanol Fuel Cell (DMFC)
4. Phosphoric Acid Fuel Cell (PAFC)
5. Molten Carbonate Fuel Cell (MCFC)
6. Solid Oxide Fuel Cell (SOFC)

Proton Exchange Membrane fuel cells (PEMFCs) are the current focus of research for fuel cell vehicle applications due to their short “start-up” time of around 1 second. PEMFCs use a proton exchange polymer membrane such as Nafion 117 to separate the two electrodes as well as a catalyst, Platinum. In contrast, Solid Oxide fuel cells (SOFCs) use a solid oxide material such as doped zirconia or ceria as the electrolyte material and have a start-up time of around 10 minutes. (Cooper & Brandon, 2017)

This report shall consider findings collected using a PEMFC, as their relatively low operating temperatures, between 80-250°C make them easier to integrate with other mechanical components, and their quick start-up time and longer operational life make them a more practical and cost-effective option.

2.4. Combined Heat & Power (CHP) Systems

Combined Heat and Power systems are extensions of conventional power generation systems as they make use of the waste heat from the chemical reaction to supply heat to nearby loads, thus increasing their practical efficiency to between 60-80%. (USEPA, 2019) The conventional power generation unit, in this case the hydrogen fuel cell, produces electricity in the usual manner. Waste heat from the fuel cell is captured in a heat exchanger which transfers as much of the heat as possible to a hot water storage system. This hot water is transferred to a nearby heating load, for example, to contribute towards the heating of hot water, or for the space heating of a building or district of houses. The cool water is recycled to the storage tank to be reheated. A diagram of a basic CHP system can be seen in Figure 5.

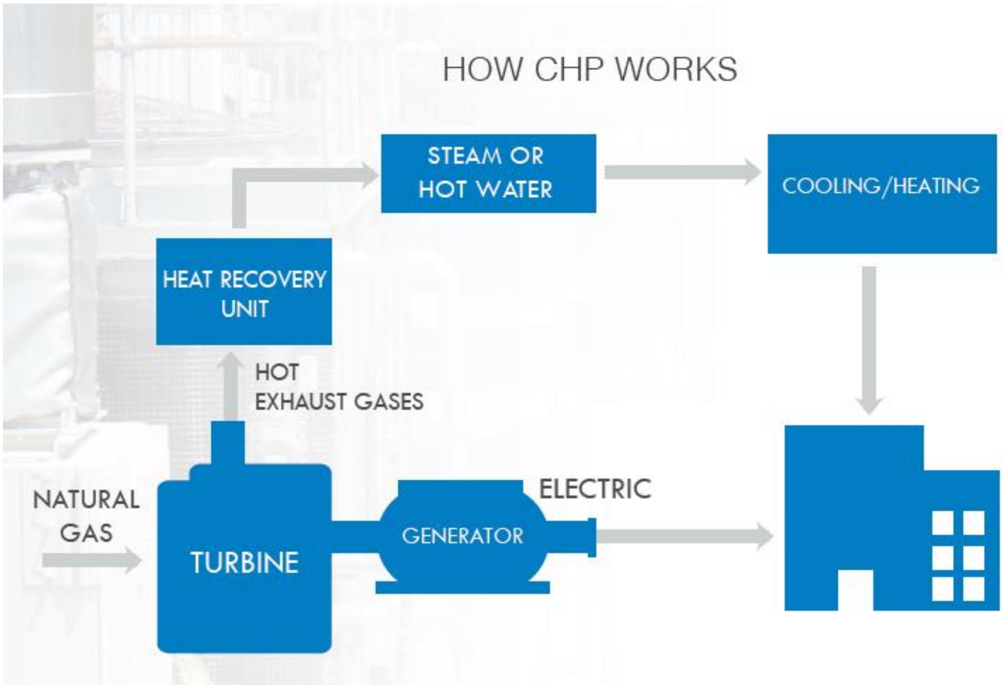

Figure 5 Main Components of a Combined Heat & Power system (PGW, 2019)

Such technology is already commonly used in large buildings such as hospitals, including an active system employed by the University of Strathclyde on John Street, supplying hot water and heating to buildings on the John Anderson campus. (strath.ac.uk, 2019). Other applications in the Netherlands feature district heating to the surrounding neighbourhood of houses. In the Falklands, a CHP system is installed at the Stanley power station which takes the waste heat from their bank of eight diesel generators to heat the local community centre swimming pool & hospital.

3. Modelling

This section describes the process in which the modelling software and process was decided.

3.1. Modelling Software

Appropriate modelling software was required to execute the aims and objectives of this thesis. The primary software would be used to carry out the modelling and analysis of the CHP systems. For this, EnergyPRO was selected; it specialises in energy generation systems, specifically CHP systems, offering a wide selection of energy sources and generation technologies and can provide detailed technical and economic analysis of such systems.

The capacity of hydrogen fuel cell required must be able to service the peak electricity demand from Stanley, which would be calculated by EnergyPRO according to the appropriate demand profile. The demand profiles for both heating and electricity were obtained from HOMERpro.

The climate database offered by EnergyPRO was used to provide the appropriate weather data; air temperature and wind speed, to assist with the assessment of the heating demand of Stanley and generation potential of the wind farm at Sand Bay.

3.2. Climate Data

It was necessary to obtain climate data, primarily for the windfarm site to understand the wind profile over a year, but also for the site of the CHP system, in order to evaluate the heating demand against ambient temperatures. EnergyPRO features an online database of global climate data to choose from. The dataset is from the Climate Forecast System Reanalysis (CFSR) model, a third-generation reanalysis product, of which there are two versions. CFSR provides data from 1979 to 2010 at an hourly interval in a grid with a horizontal resolution of 0.5 degrees. CFSR2 is an extension of CFSR data and as such is only available from 2010 to present. CFSR2 also operates on a tighter horizontal resolution of 0.2 degrees. Both datasets provide the following parameters:

- Air Temperature (°C)
- Solar Radiation (W/m^2)
- Wind Speed (m/s): modelled at a height of 10m
- Precipitation (mm)
- Humidity (%)

All values are taken as the mean over the hour interval. For the purpose of this thesis, only the Air Temperature and Wind Speed were required. (Use of solar radiation data for future work with solar panels.)

A map of East Falklands featuring climate data points can be seen in Figure 6

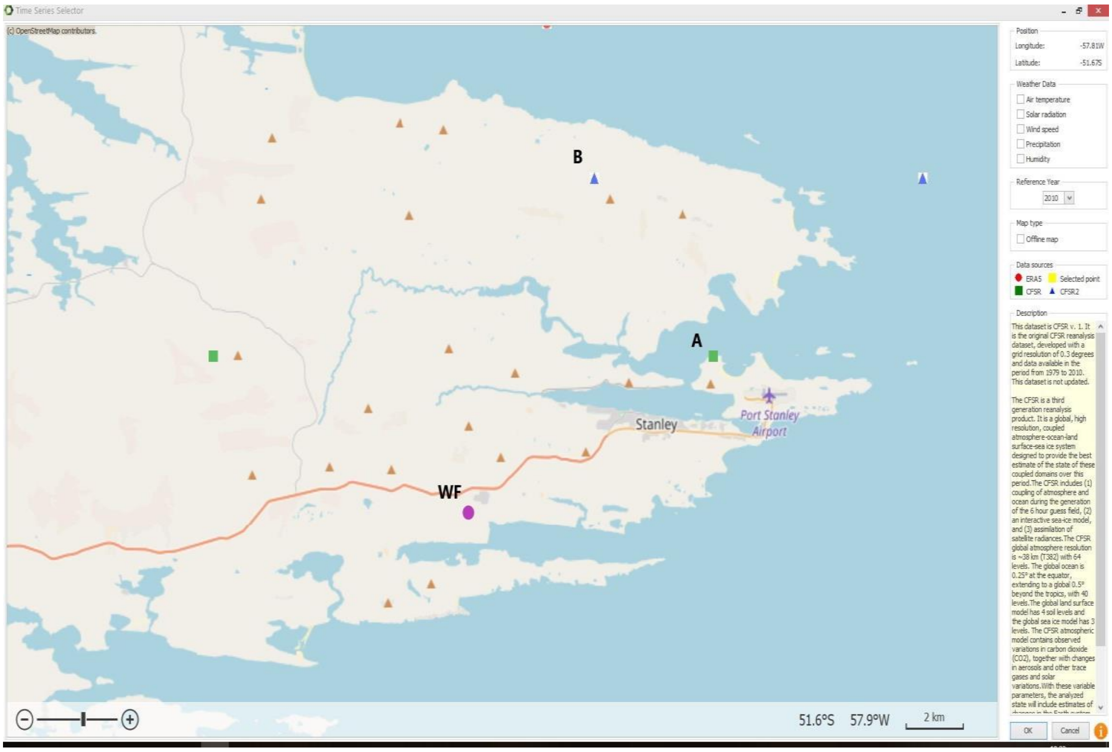

Figure 6 Map of Climate Datapoints in the East Falklands (EnergyPRO, 2019)

The capital, Stanley, and the location of Sand Bay wind farm (WF) are shown. The two closest data points are also highlighted. Point A at Gypsy Cove is the nearest data point to both Stanley and Sand Bay; around 3.5km North East of Stanley and 12.5km North East of Sand Bay. However, this is a CFSR data point and as such only features data up to 2010.

Point B is a station on the North side of Mount Beagle, 9km North of Stanley and 13.5km North East of Sand Bay. This is a CFSR2 data point, meaning that it provides the most recent climate data from 2010 to 2019.

As generation data provided by Stanley Power Station and Sand Bay wind farm is only available from the financial years 2012 to 2019, the use of climate data from the same time period was required. Thus, for this thesis, climate data obtained from Point B was considered.

Figures 7 and 8 show the variation in wind speed and air temperature captured at Point B for 2018-19.

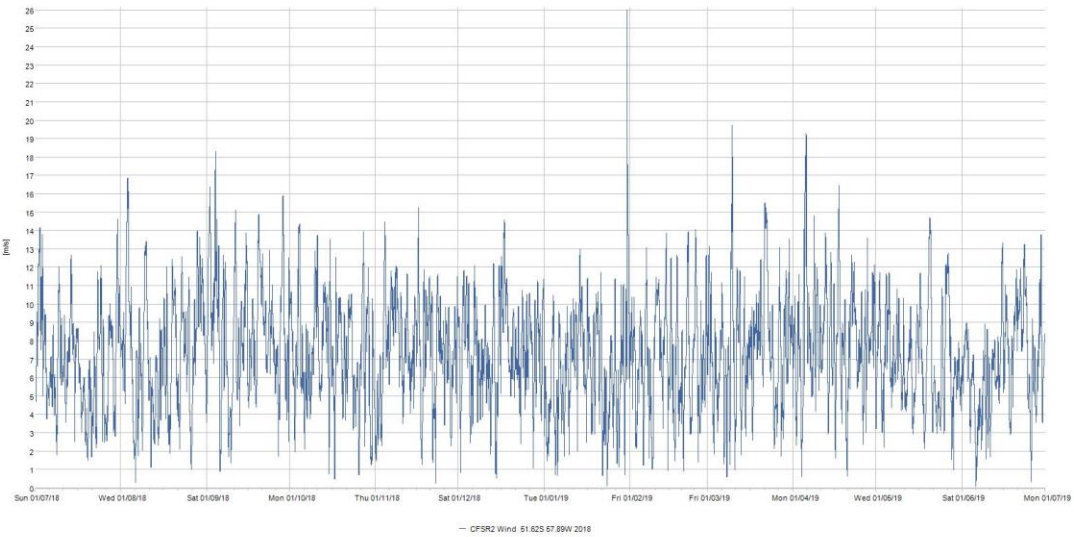

Figure 7 Annual Wind Profile for Data Site B (EnergyPRO, 2019)

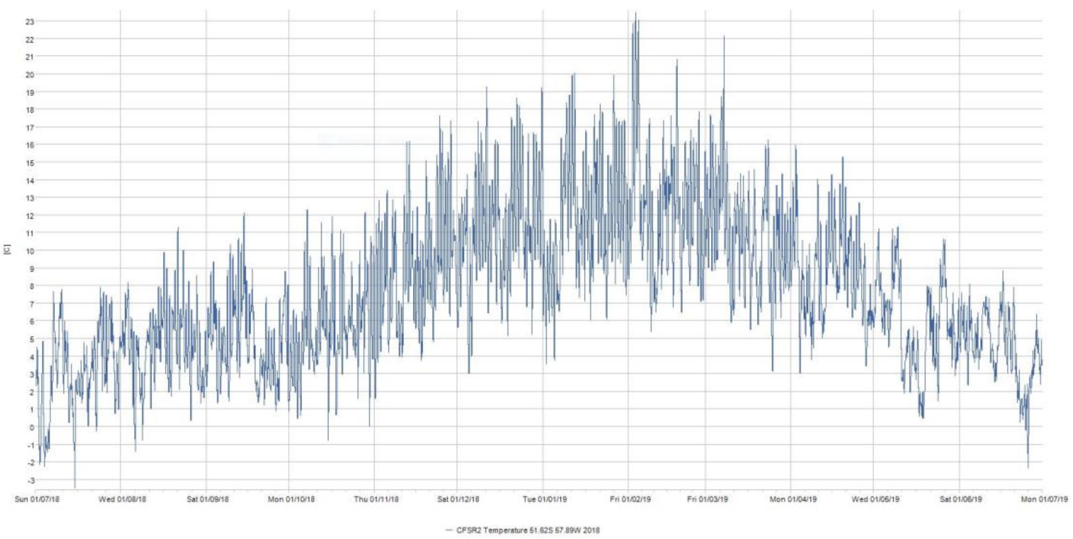

Figure 8 Annual Air Temperature Profile for Data Site B (EnergyPRO, 2019)

Air temperatures throughout the year mirror the southern hemisphere climate, with the warmest temperatures over January and February, and the coldest in June and July.

The wind speed profile (Figure 7) shows predictable variations in wind speeds throughout the year, with minimal influence from the colder or warmer seasons.

The distance between both data points and both Stanley and Sand Bay was assumed to have a negligible impact on the results obtained.

3.3. System Configurations in EnergyPRO

EnergyPRO is a very visual software package and allows for model components to be placed in the modelling window, and then linked to each other similar to a flowchart. The main components required to produce a complete model in EnergyPRO are described below.

3.3.1. Fuel Source

The two fuel supplies considered in this thesis were diesel and hydrogen; diesel for System Config. 1 used by the Stanley power station, and hydrogen for System Config. 2 & 3 for the incorporation of the hydrogen fuel cell CHP systems.

Calorific Heating Values

EnergyPRO requires the calorific heating values for the fuel in use. Values for both fuel sources can be seen in Table 1 below.

Calorific heating values are displayed in both MJ/kg & MJ/L.

Table 1 Calorific Heating Values for Fuel Sources

Fuel	Calorific Heating Value	
Diesel	45.6 - 42.6 MJ/kg	38.6 – 36 MJ/L
Hydrogen	141.7 – 120 MJ/kg	-

The lower heating value was used in all calculations to form a conservative evaluation of generation.

Emissions

The primary emission from the combustion of diesel is carbon dioxide (CO_2), as well as nitrogen oxides (NO_x), carbon monoxide (CO) and unburnt hydrocarbons from the fuel itself, which vary in percentages depending on operating conditions within the combustion engine. The CO_2 emissions per kg of combusted fuel are given in Table 2 below. It was necessary to convert this value from kg_{em}/kg_{fuel} to kg_{em}/L_{fuel} for modelling purposes. This was achieved by adjusting for the density of diesel fuel; 0.846kg/L.

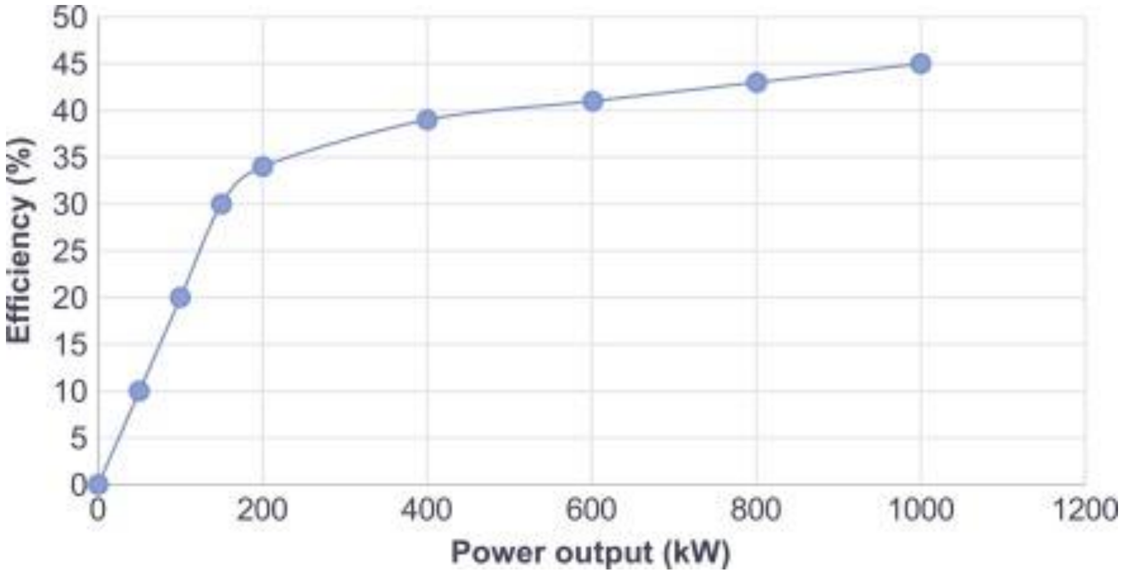

Figure 9 Efficiency of a Diesel Generator against Power Output (Adefarati et al, 2019)

NO_x emissions vary greatly depending on the operating temperatures and air-fuel ratio used. The nitrogen monoxide (N_2O) emissions for diesel is listed in Table 2 below.

Table 2 Emissions for Diesel

	kg_{em}/L_{fuel}	kg_{em}/kg_{fuel}
Carbon Dioxide (CO_2)	2.66	3.15
Nitrous Oxide (NO_x)	0.03717	0.04438

Costs

The operational currency in EnergyPRO is Euros, therefore the conversion rate of 1 GBP equivalent to €1.094 present at the time of writing was applied. The diesel fuel is supplied to the Falklands by Stanley Services Ltd at a price of 0.57FKP/L at the time of writing. The conversion rate from FKP to GBP is 1:1.

For this thesis it is assumed that the price of hydrogen is comparable to that of diesel, specifically the price per kWh.

3.3.2. Diesel Generators

The eight diesel generators in operation at the Stanley power station could have been modelled as an electric generator. However, this would only provide analysis of the electricity generation of the power plant. As the power station provides heating for the community centre' swimming pool, it was necessary to choose a generation model which also provided a heating component for analysis. For this, a CHP component was used. The size of the diesel generators at the current Stanley power station vary in capacity from 320kW to 1500kW, giving a total capacity of 6.6MW. These generator models offer differing electrical efficiencies; from 35% for the lower rated models up to 55% for the higher capacity models. The energy yield of the diesel generators was provided by Stanley power station (Appendix 1) and was calculated by taking electricity generated minus the station consumption, divided by the fuel consumption. Over the period investigated in 2018-2019, the power station produced 3.81kWh of electricity per litre of diesel. The electrical efficiency was calculated as the ratio of the power station's specific electrical generation versus the calorific heating value of diesel fuel; 36MJ/L or 10kWh/L. (3.81kWh/L 10kWh/L x 100 = 38.1%) This electrical efficiency was applied to the diesel CHP element of the EnergyPRO model. As described in Section 2.1.2, there is limited information available on the waste heat system in place. The efficiency of the heat recovery system was set at 50%, giving a total system efficiency of 95%.

3.3.3. Fuel Cell CHP

For the hydrogen fuel cell CHP system incorporated in System Config. 2 & 3, a basic CHP component was used. The fuel cell was to be sized to meet the peak electrical demand of Stanley. The electrical efficiency was set to 40% and the heating efficiency was set to 55%. This resulted in a combined efficiency of 95% for the system.

3.3.4. Wind Farm

All system configurations will include the generation capacity of the six Enercon E33 wind turbines described in Section 2.1.4 The windspeed-power curve for the Enercon E33 turbine was entered into the Wind Farm element of the EnergyPRO model, with the power output multiplied by a factor of 6 at each increment of wind speed to account for the total number of turbines in the wind farm. This describes the power output of the wind turbine relative to the prevailing wind speed at the turbine's hub height. The wind data provides data at a measurement height of 10m and the hub height of the Enercon E33 turbine is 49m. A Hellmann exponent of 0.16 was chosen as it most closely describes the state of the wind in the environment surrounding the wind farm; "neutral air above flat open coast". A view of the wind farm site can be seen in Figure 10.

Figure 10 View of surrounding environment of Sand Bay Wind Farm (Falklands Govt, 2017)

The annual production of the wind farm was calculated by EnergyPRO according to the wind profile recorded at the site described in Section 3.2.

3.3.5. Thermal Store

A thermal store was required to provide a link between the waste heat from the CHP systems and the heating load. The pre-sets provided by EnergyPRO for tank temperature thresholds were used; 50°C for the bottom of the tank and 90°C for the top. The tank size chosen did not require an exact sizing, as there was no specific heating demand to be met. Nevertheless, a tank volume of 1000m^3 was selected, which would provide a heating capacity of 41.2MWh. This is open to change following planned research in the future to achieve a more detailed understanding of the exact heating load of all of Stanley.

3.3.6. Electricity Demand

As there is no power exported from Stanley to other parts of the island, it can be assumed that all energy generated by the power station was demanded by the town. This total annual load, as well as weekly and weighted monthly loads can be seen in Appendix 1.

The HOMERpro software package offers profiles for 'residential', 'community', 'industrial' and 'commercial' loads available in the Load Creator feature. For the purposes of this thesis, the electrical demand profile of Stanley was categorised as a 'community' load, the profile of which can be seen in Figure 11 below.

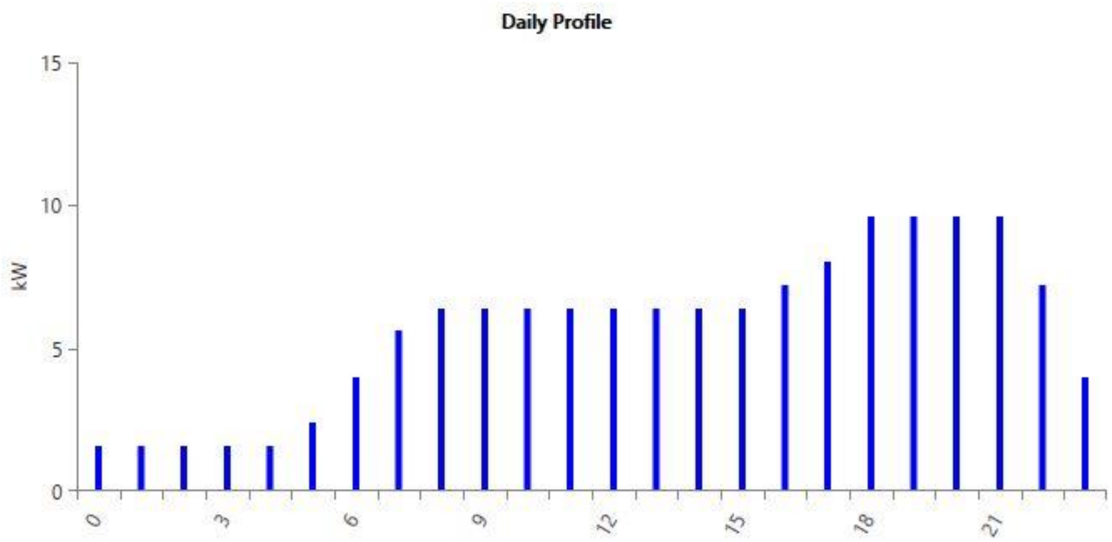

Figure 11 Estimated Electrical Demand Profile for Stanley (HOMERpro, 2019)

The seasonal variation in the electrical demand can be seen in Figure 12 below.

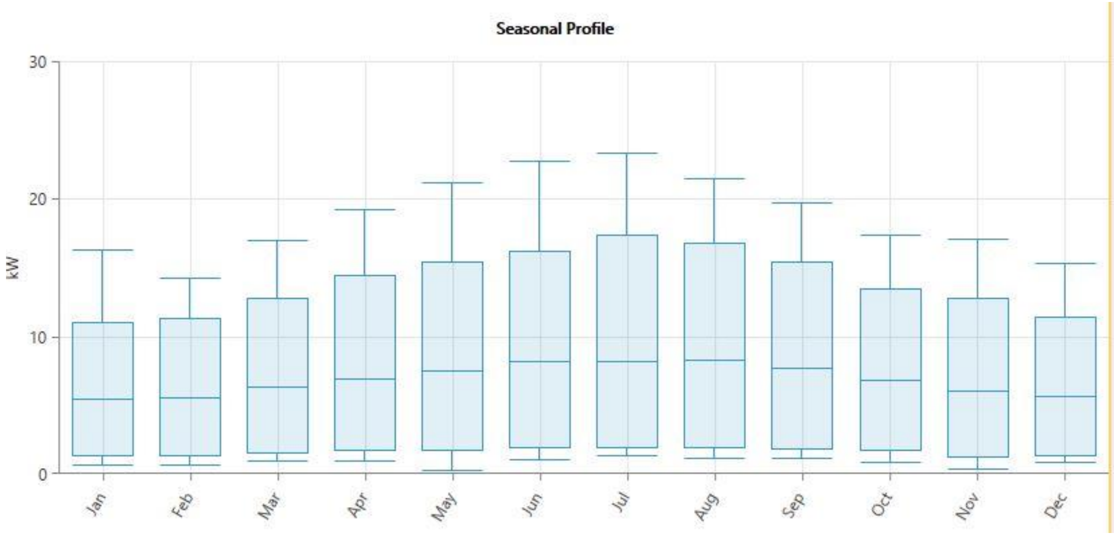

Figure 12 Seasonal Variation in Electrical Demand (HOMERpro, 2019)

3.3.7. Heating Demand

A generic heating demand profile was created on HOMERpro for Stanley. Similarly to the electricity demand, HOMERpro offers profiles for both 'residential' and 'community' loads. The 'community' profile was chosen for this thesis and can be seen in Figure 13 below.

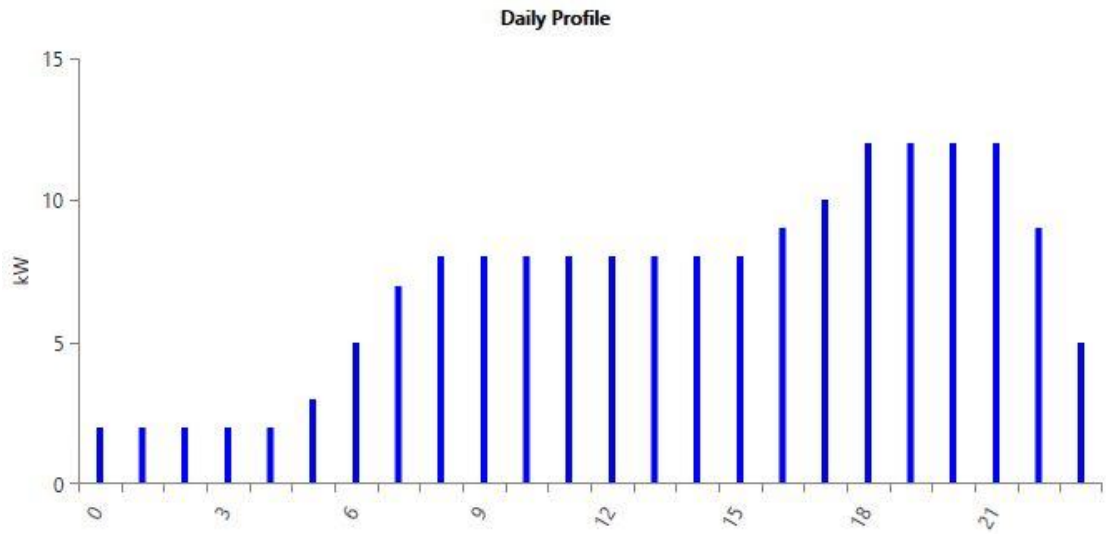

Figure 13 Estimated Heating Demand Profile for Stanley (HOMERpro, 2019)

This shows a similar peak heating demand to that of the electricity demand, with a peak load between 19:00 – 21:00hr. The ratios of heating load were entered into the heating demand field of the EnergyPRO model for each system configuration. As the electricity demand was the primary demand on the model, the heating demand profile was only necessary to evaluate the heating potential of the system, and therefore is not required to be met. A total annual heating demand of 12,000MWh was selected to give a reasonable benchmark for the heating load of Stanley. The monthly variation of this load can be seen in Figure 14 below.

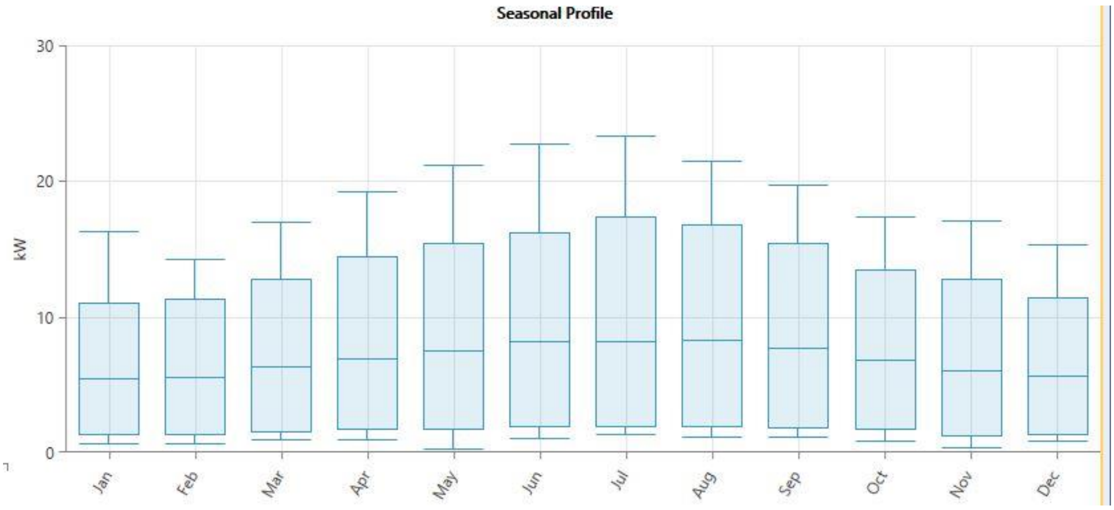

Figure 14 Seasonal Variation in Heating Demand (HOMERpro, 2019)

4. Results

This section details the results obtained for the three systems configurations described in the method.

4.1. System Configuration 1 – Current Diesel & Wind CHP System

This system configuration is an approximation of the currently active power generation system in Stanley. The main components of the system can be seen in figure 15 below.

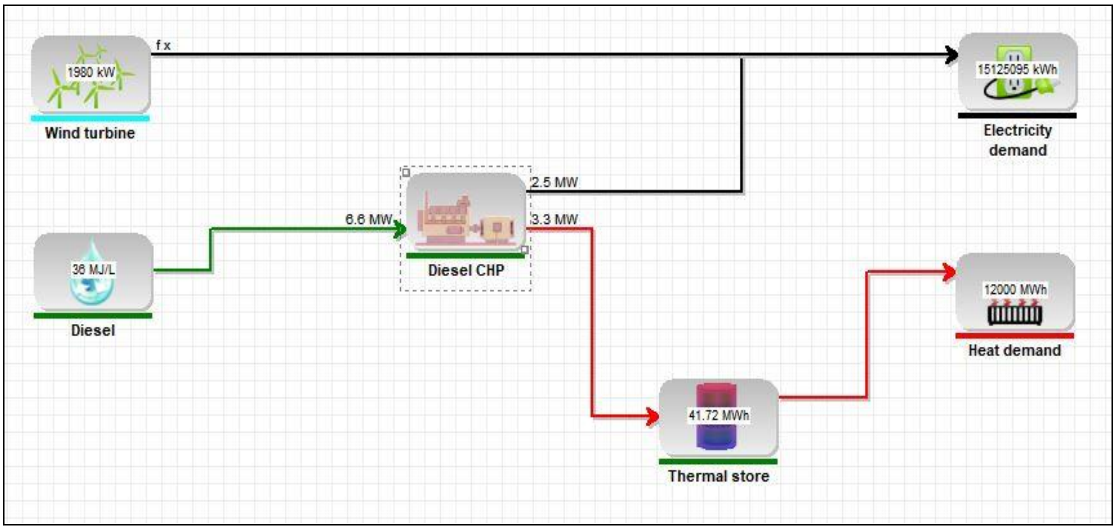

Figure 15 Diagram of System Configuration 1

In this configuration, the electrical demand is met by the diesel generators at the Stanley power station and supplemented by the Sand Bay wind farm. The model is arranged so that the wind farm runs at its peak operating capacity relative to the climate data. The diesel generators also service the heating load via a crude CHP system described in Section 2.4.

The energy conversion results for both electricity and heating can be seen in Table 3 and Table 4 below. Table 3 also features the breakdown in contributions from the wind farm and the CHP system towards the electricity demand.

Table 3 Electrical Match for Configuration 1

Total Annual Electricity Demand	15,125.1MWh	
Diesel CHP Contribution	6,436.3MWh	42.6%
Wind Farm Contribution	8,553.4MWh	56.5%
Total Annual Electricity Produced	14,989.6MWh	99.1%
Peak Electricity Demand	3.3MW	

The peak electrical demand was 3.3MW. This would provide the target peak load to be achieved by the proposed hydrogen fuel cell system, and therefore assist in sizing the hydrogen CHP unit.

Table 4 Heating Match for Configuration 1

Total Annual Heating Demand	12,000MWh
Total Annual Heat Produced	8,495.9MWh
Annual Percentage Match	70.8%
Peak Heating Demand	2.2MW

As stated previously, the heating match was not critical. However, the peak heating demand of 2.2MW and the total annual heat production of 8459.9MWh gives an appreciation of the heating potential of this system and provides a reference point for comparison against the hydrogen fuel cell CHP system.

The annual energy match can be seen in Figure 16.

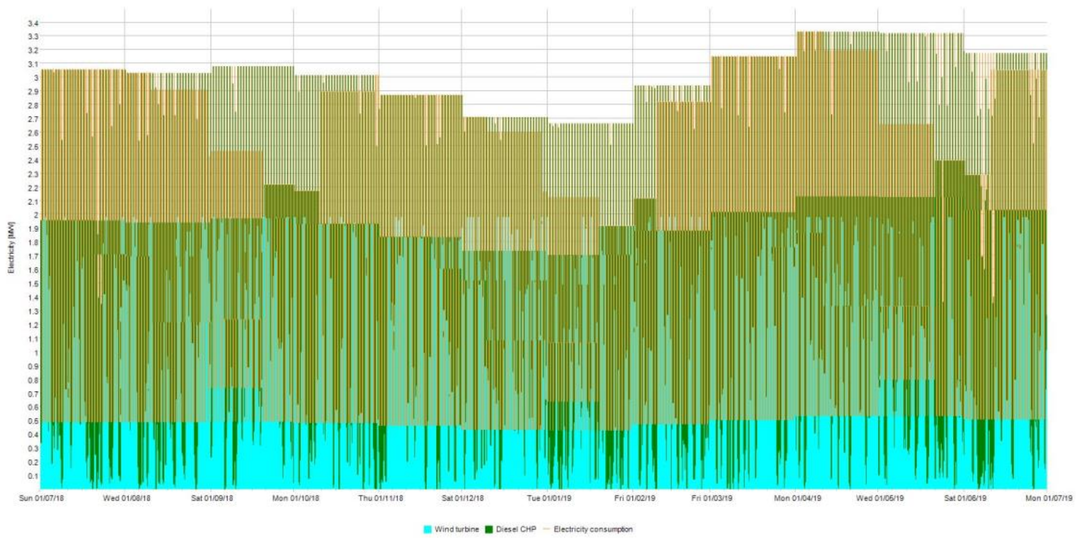

Figure 16 Annual Electrical Supply and Demand Match for Configuration 1

Seasonal variation in electrical and heating demand and production can be seen in Figures 17 and 18 below, which show the demand match for the month of July 2018.

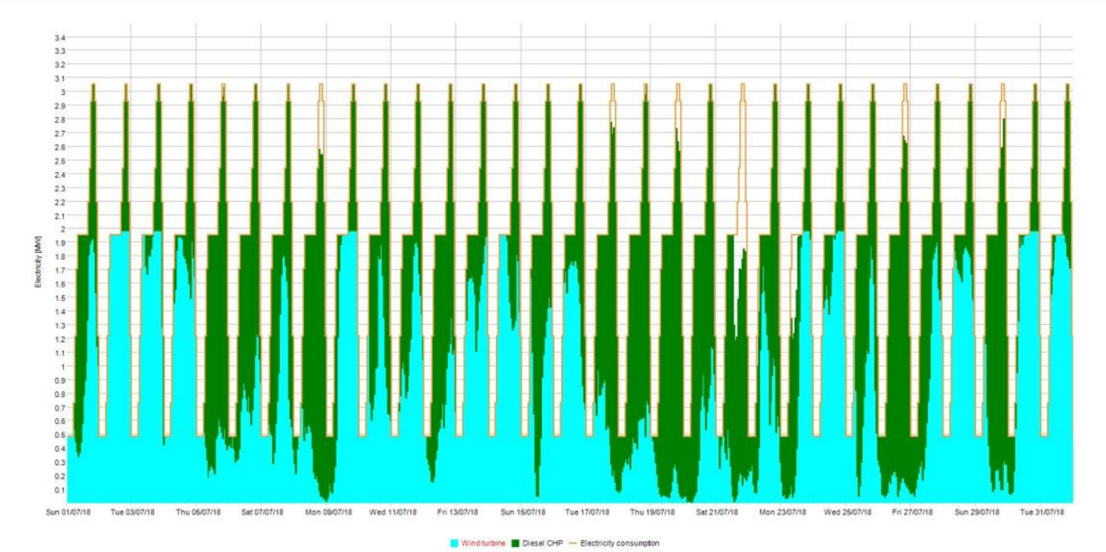

Figure 17 Month Electrical Contribution Match

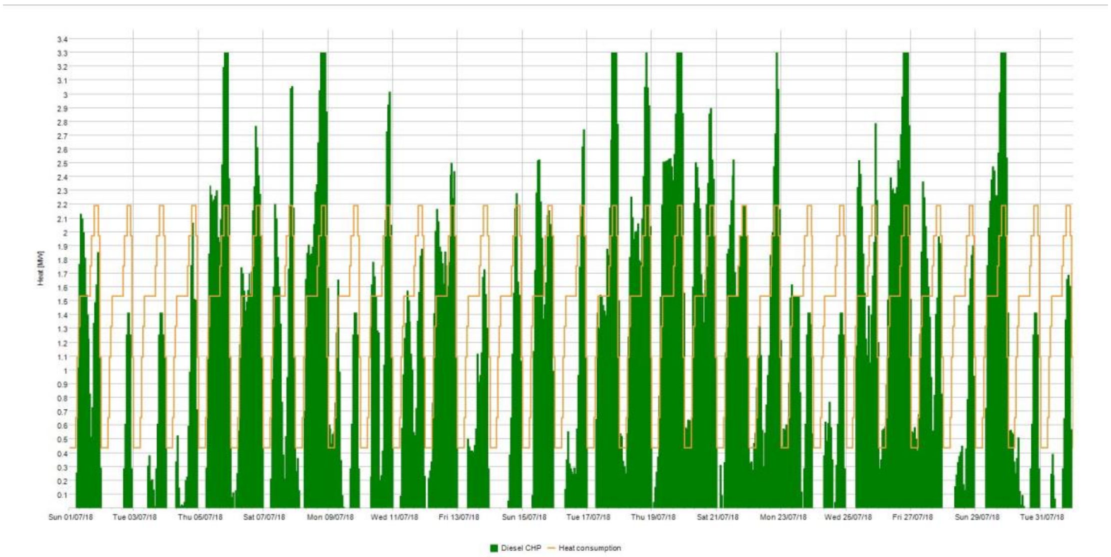

Figure 18 Month Heating Contribution Match

A more detailed look at the electrical and heating demand can be seen in Figures 19 and 20 which show demand for the week commencing 1st July 2018.

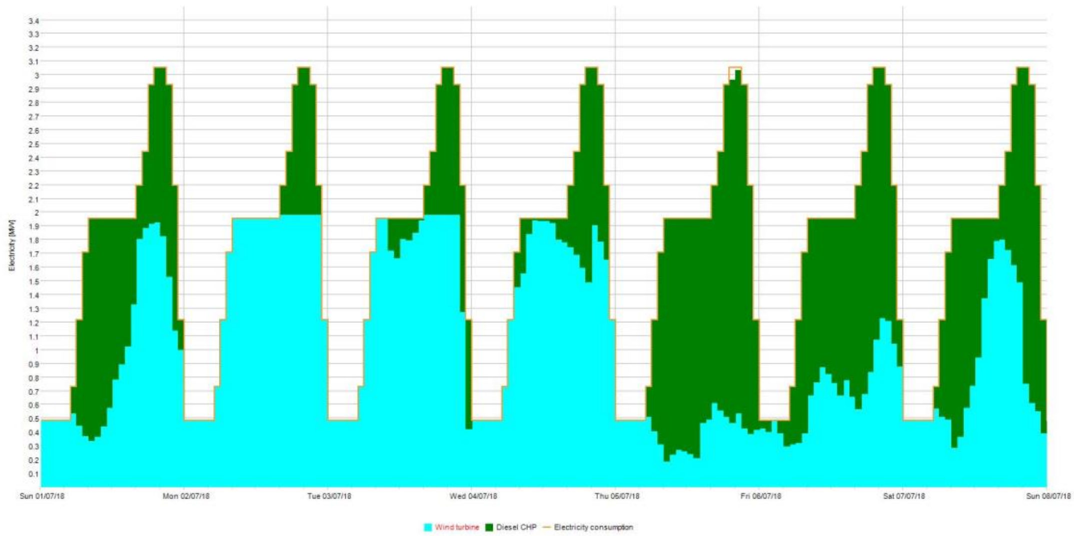

Figure 19 Week Electrical Contribution Match

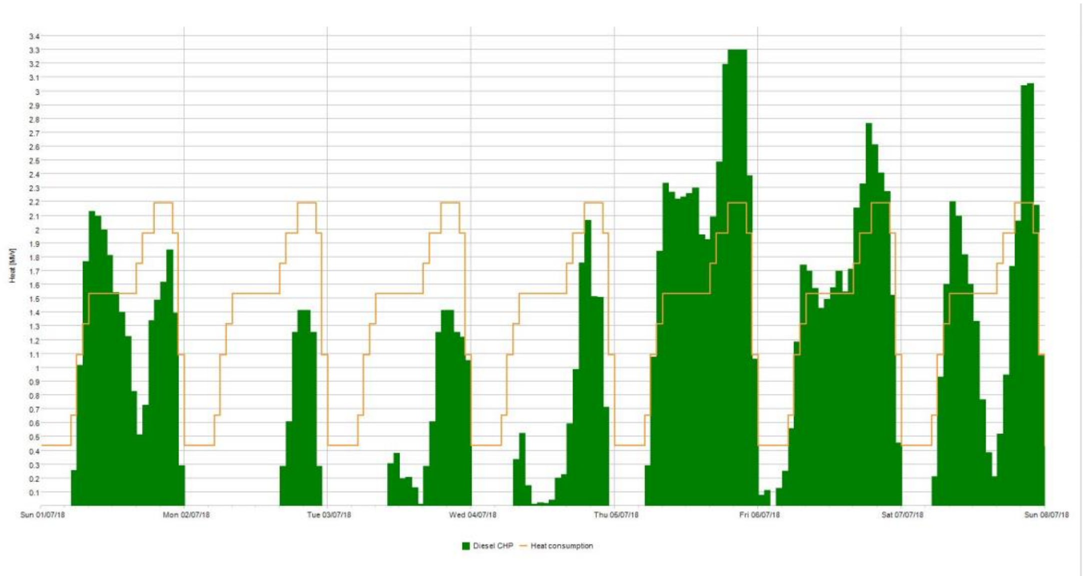

Figure 20 Week Heating Contribution Match

EnergyPRO calculated the annual fuel consumption to be 1,699,175.7L of diesel, annual variation of which can be seen in Figure 21 below.

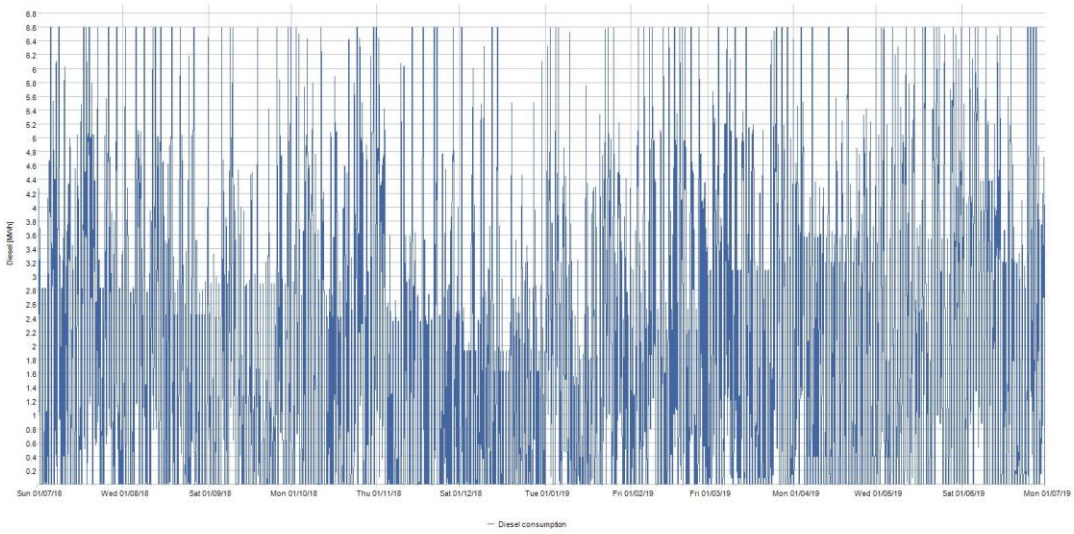

Figure 21 Annual Fuel Consumption Profile

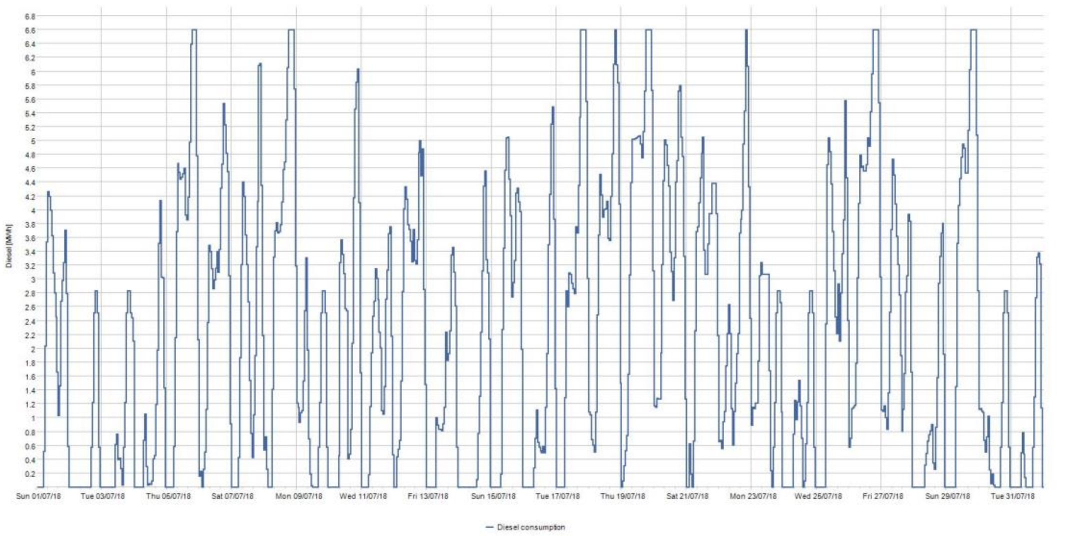

Figure 22 Monthly Fuel Consumption Profile

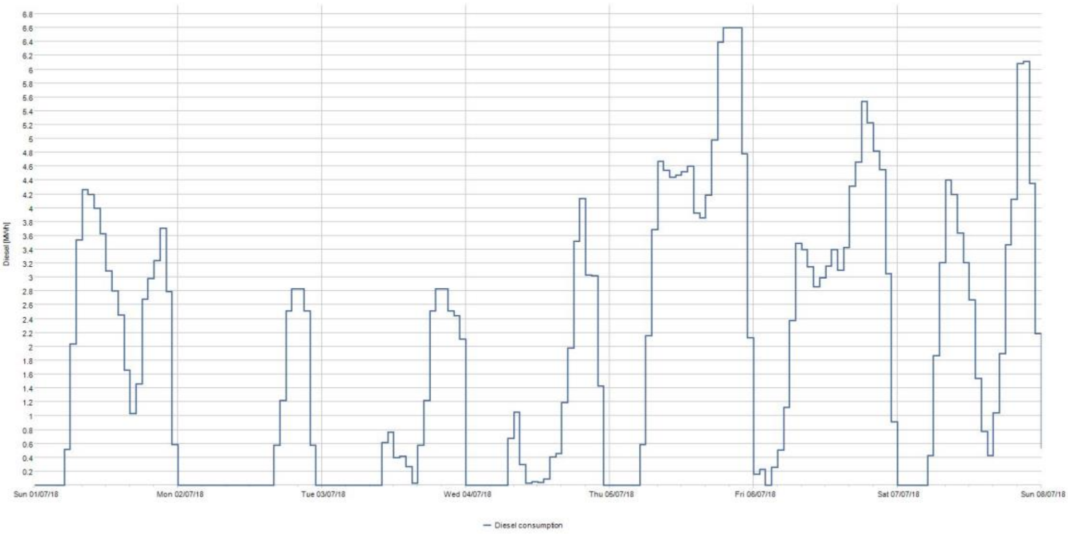

Figure 23 Weekly Fuel Consumption Profile

The associated running costs and emissions can be seen in Table 6 and Table 7 below.

Table 5 Annual Fuel Consumption

Annual Fuel Consumption	1,699,175.7L
Annual Fuel Costs	£951,430.15

Table 6 Emissions for Configuration 1

Emissions	**2018-2019**
CO2	**[tonne]**
Emission	4,520
CO2 Total	**4,520**
NOx	**[kg]**
Emission	63,209
NOx Total	**63,209**

The operational up-time of both the wind farm and the CHP system is detailed in Table 7 below.

Table 7 Operational Up-Time

Hours of operation:	Total [h/Year]	Ofannual hours
Windturbine	8,624.0	98.4%
Diesel CHP	6,311.0	72.0%
Out oftotal in period	8,760.0	
Turn ons:		
Windturbine	50	
Diesel CHP	370	

4.2. System Configuration 2 – Hydrogen Fuel Cell CHP System

This system configuration represents the basic hydrogen fuel cell CHP system to be used in place of the diesel-fuelled power station system, complemented by the electricity generation capacity of the Sand Bay wind farm. The main components of the system can be seen in Figure 24 below.

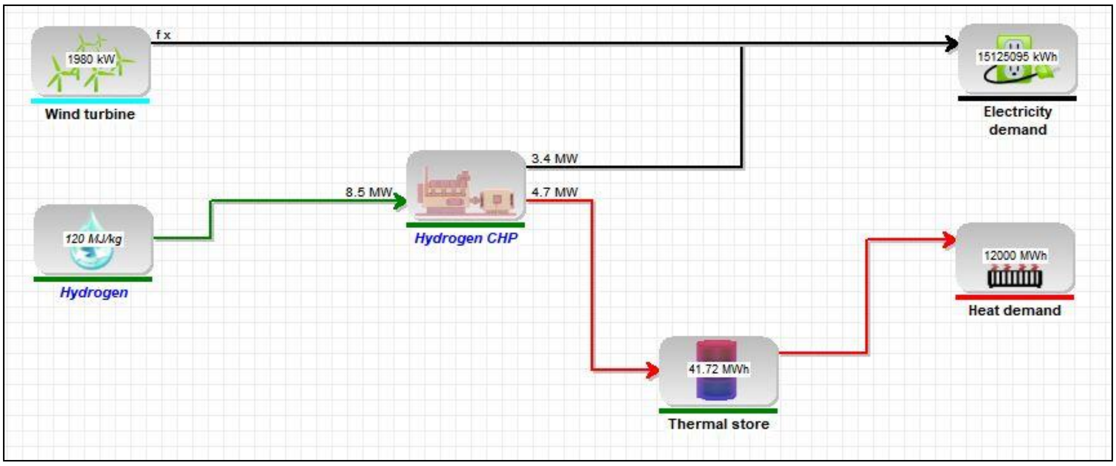

Figure 24 Diagram of System Configuration 2

In order to meet the peak demand of 3.3MW, the fuel cell was sized to produce an electrical capacity of 3.4MW. Taking into consideration operational efficiencies, a fuel cell with a nameplate capacity of 8.5MW was required.

The energy conversion results for the hydrogen fuel cell system can be seen in Tables 8 and 9 below.

Table 8 Annual Electrical Demand Supply Match

Total Annual Electricity Demand	15,125.1MWh	
Hydrogen CHP Contribution	6,451.6MWh	43%
Wind Farm Contribution	8,553.4MWh	56.2%
Total Annual Electricity Produced	15,004.9MWh	99.2%
Peak Electricity Demand	3.3MW	

Table 9 Annual Heating Supply and Demand Match

Total Annual Heating Demand	12,000MWh
Total Annual Heat Produced	8,918.3MWh
Annual Percentage Match	74.3%
Peak Heating Demand	2.2MW

The annual energy match can be seen in Figure ?.

Figure 25 Annual Electrical Match for Configuration 2

A detailed look at the weekly energy match can be seen in Figures 26 and 27 below. These show the seasonal variation in the energy match for a week in July which shows the peak electrical and heating loads in the year.

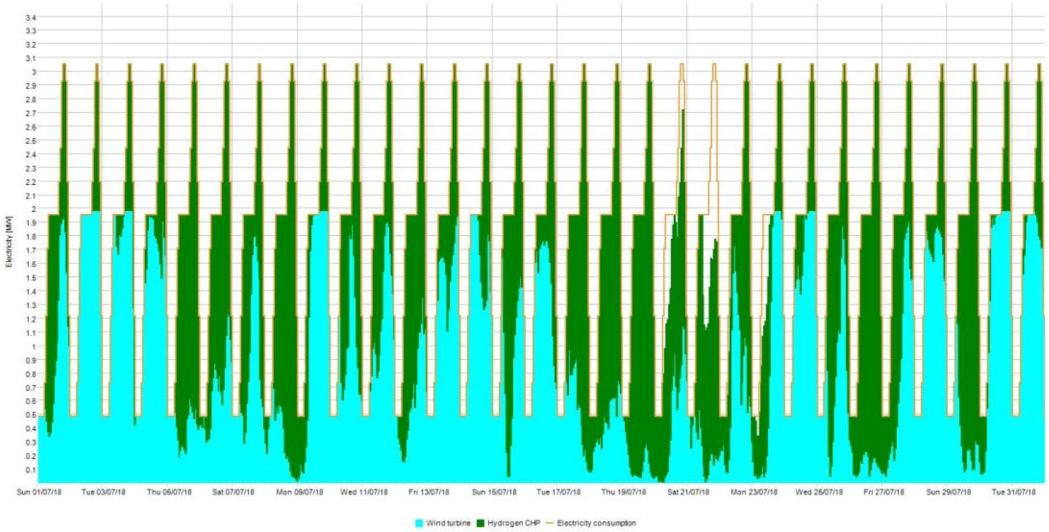

Figure 26 Monthly Electrical Match

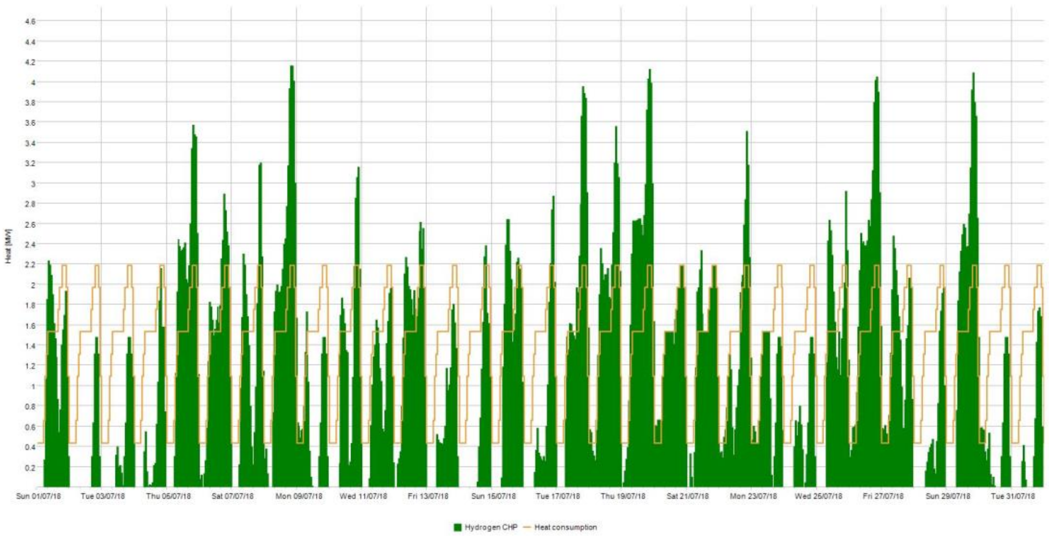

Figure 27 Monthly Heating Match

EnergyPRO calculated the fuel consumption of the hydrogen fuel cell CHP system to be 483,867.2L, annual variation of which can be seen in Figure ? below.

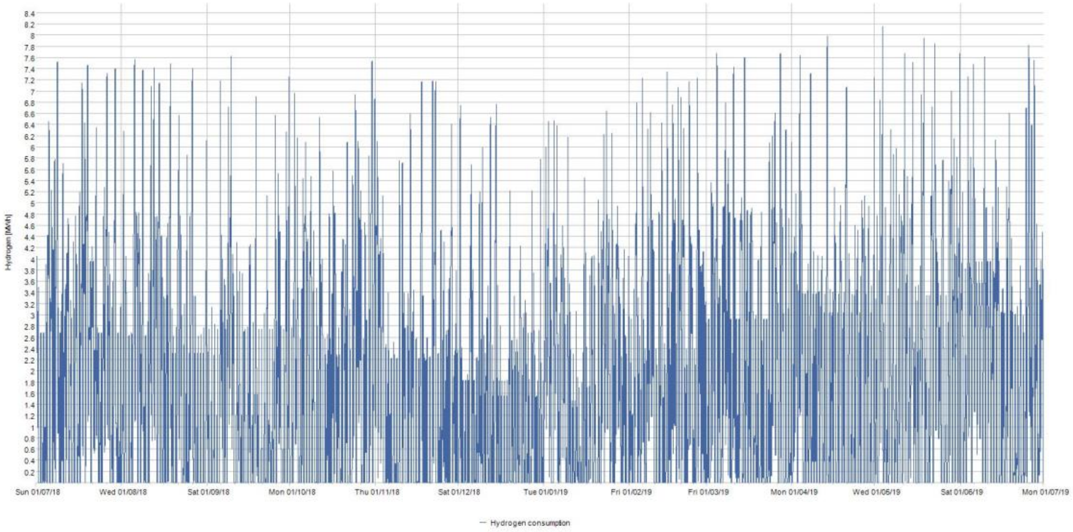

Figure 28 Annual Hydrogen Consumption Profile

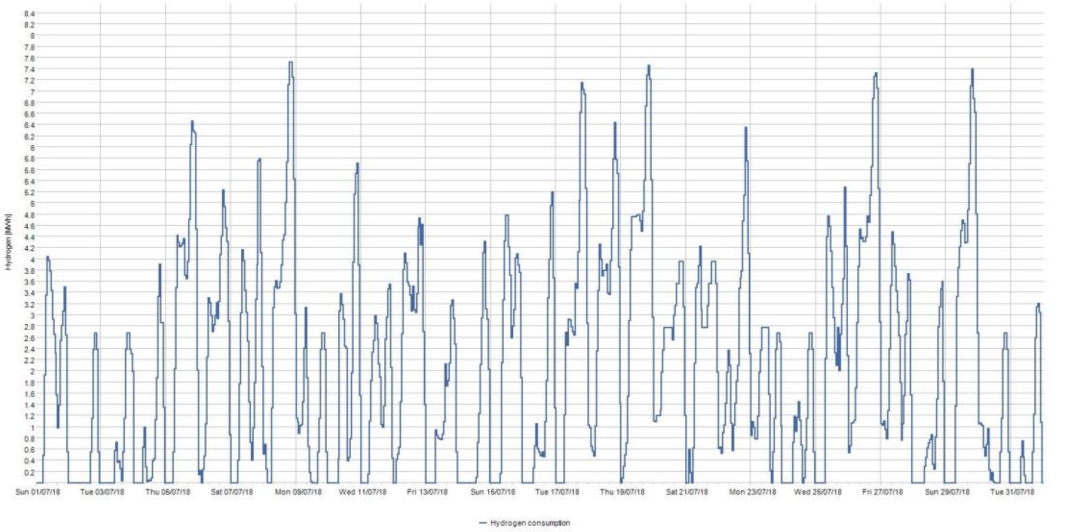

Figure 29 Monthly Hydrogen Consumption Profile

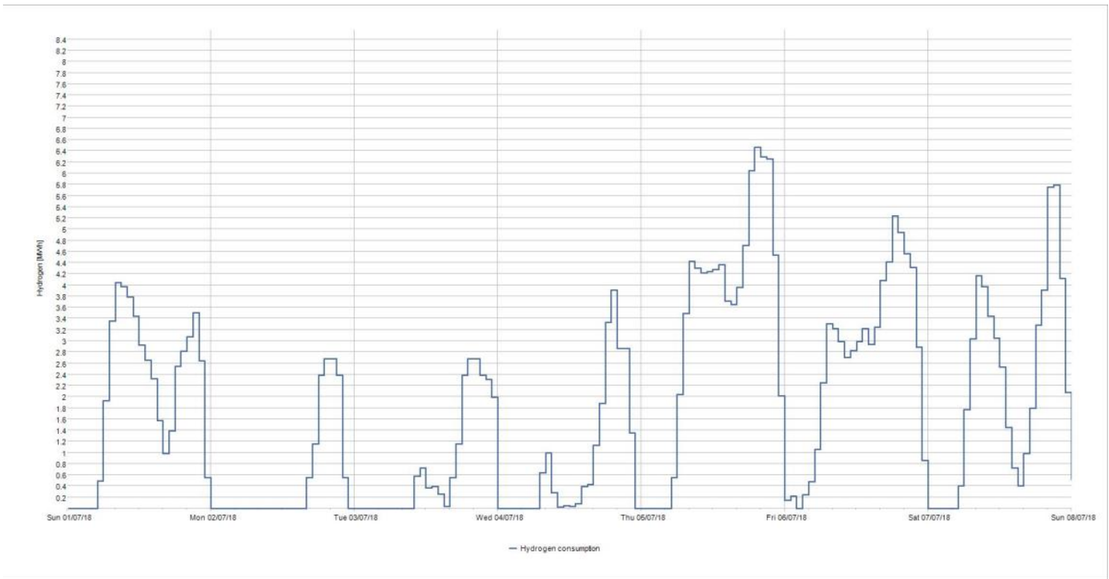

Figure 30 Weekly Hydrogen Consumption Profile

As it is assumed that purified hydrogen fuel is used, there are no associated emissions from the hydrogen fuel cell system.

Table 10 Annual Hydrogen Consumption

Annual Fuel Consumption	483,867.2kg

The operational up-time of both the wind farm and CHP system is detailed in Table 11 below.

Table 11 Operational Up-Time

Hours of operation:	Total [h/Year]	Ofannual hours
Windturbine	8,624.0	98.4%
Hydrogen CHP	6,309.0	72.0%
Out oftotal in period	8,760.0	
Turn ons:		
Windturbine	50	
Hydrogen CHP	370	

4.3. System Configuration 3 – Hydrogen Fuel Cell CHP System w/ RES Integration

This configuration is an iteration of System Configuration 2 and represents the proposed system which would allow the Falkland Islands to become self-sustainable. In this configuration, the electrical generation capacity of the Sand Bay wind farm is used to generate a supply of hydrogen fuel through the electrolysis of water. The main components of the system can be seen in Figure ? below.

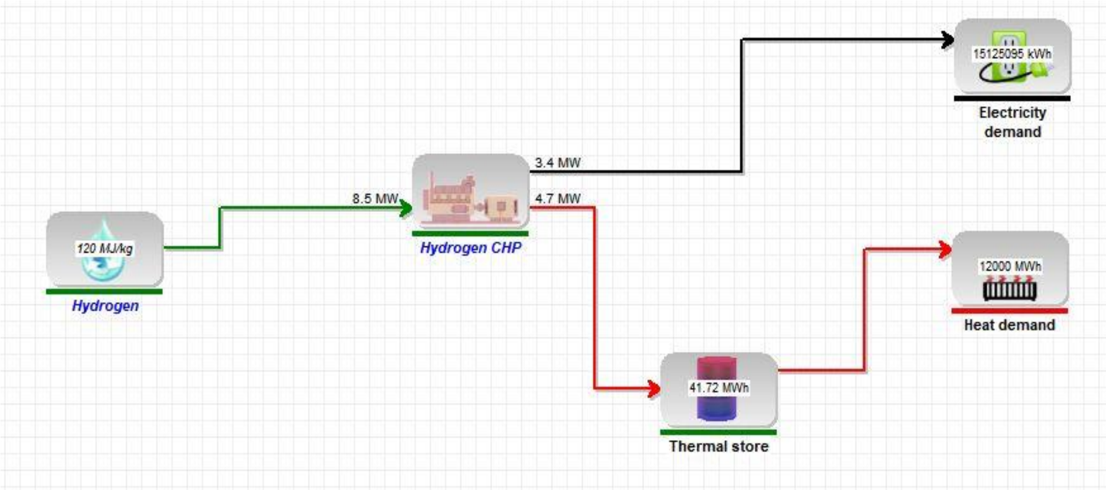

Figure 31 Diagram of System Configuration 3

Results obtained for the annual heating and electrical match of the hydrogen fuel cell CHP system(Table ? and ?) showed that the 8.5MW capacity system was able to meet the peak electrical demand of 3.3MW but was unable to meet the total annual electricity demand.

A number of hydrogen fuel cell capacities were trialled in order to discern the size of fuel cell CHP system required to make a sufficient contribution to the electrical demand. These fuel cells feature the same electrical and heating efficiencies as described in Section ? The results of these trials are shown in Table ? below.

Table 12 Hydrogen FC Sizing Trials Electrical Match

Nameplate Capacity (MW)	Electrical Capacity (MW)	Annual Electrical Supply (MWh)	Annual Electrical Demand (MWh)	Percentage Match (%)
8.5	3.4	8,680.9	15,125.1	57.4
12	4.8	8,727.3	15,125.1	57.7
16	6.4	8,727.3	15,125.1	57.7

From this point forward, only contributions from the 8.5MW fuel cell will be discussed. Seasonal electricity match of the system can be seen in Figure 32, which show results for the month of July 2018. Figure 33 shows the electricity demand match over the course of a year.

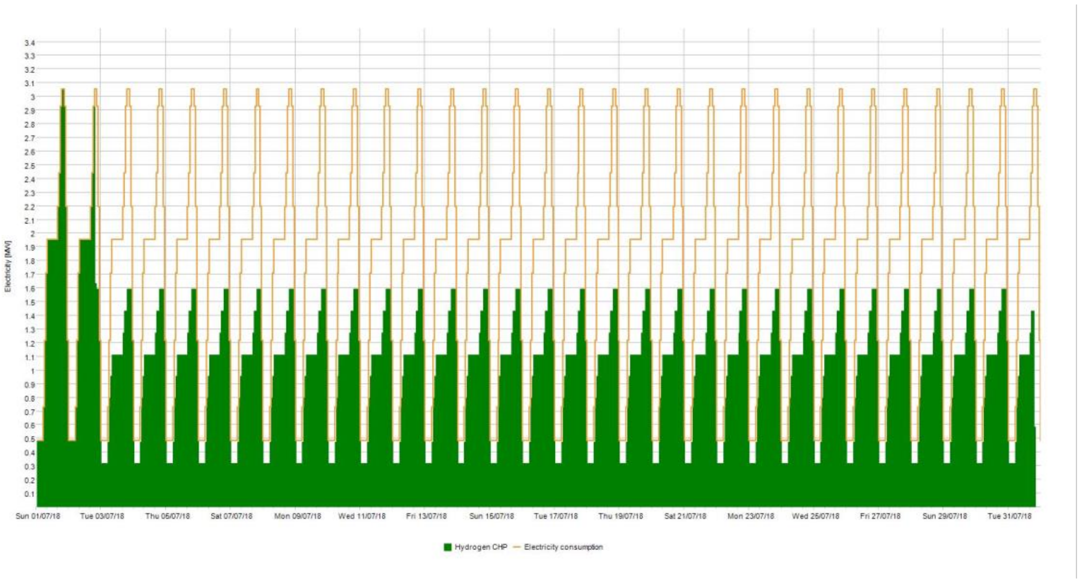

Figure 32 Monthly Electrical Match

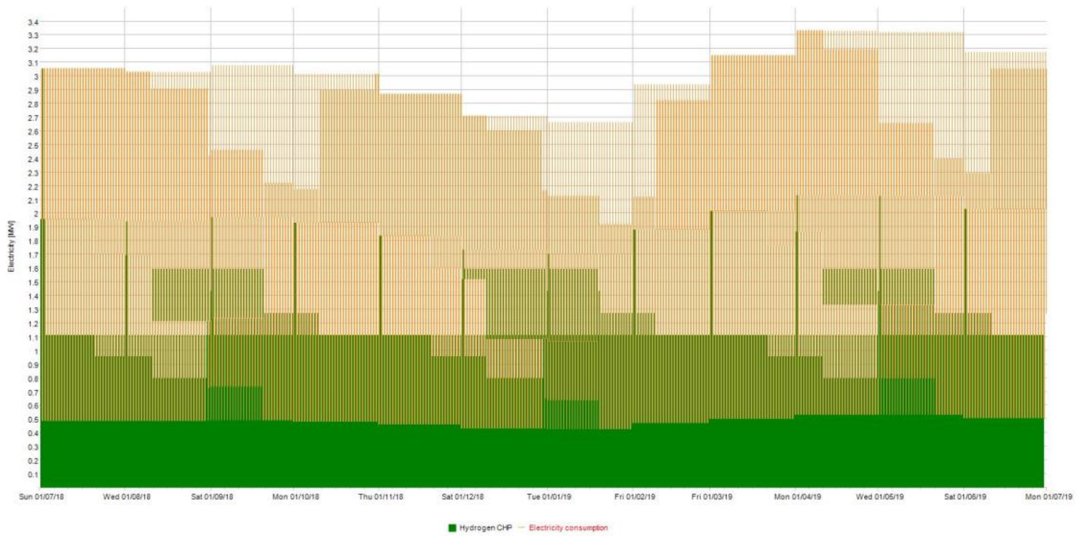

Figure 33 Annual Electrical Supply & Demand Match

The hydrogen fuel consumption profile over the course of the the month of July for configuration 3 can be seen in Figure 34 below.

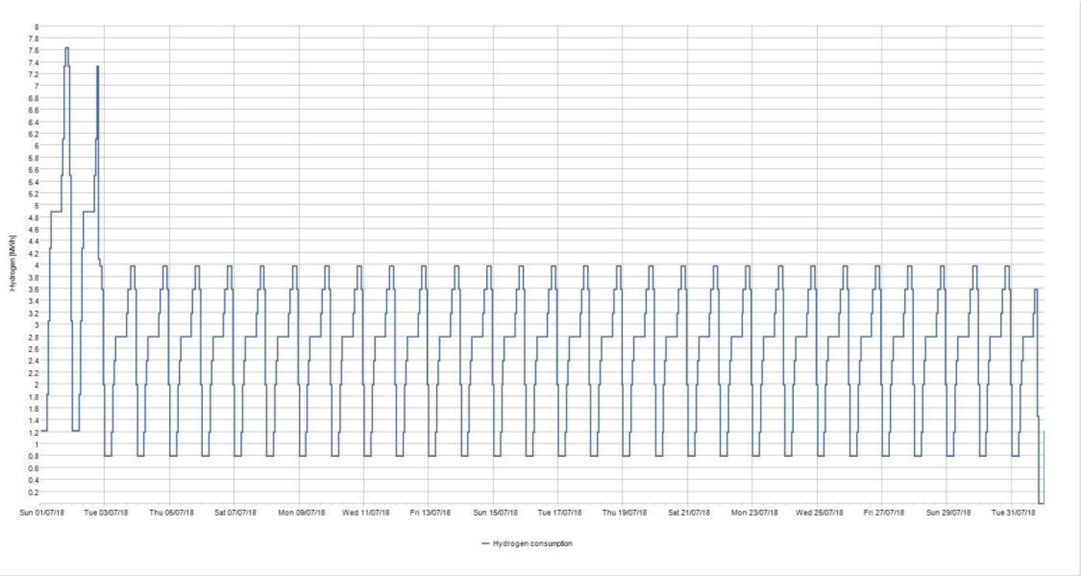

Figure 34 Monthly Hydrogen Consumption Profile

Table ? describes the fuel total annual hydrogen fuel consumption.

Table 13 Annual Hydrogen Consumption for Configuration 3

Annual Fuel Consumption	654,545.4kg

Hydrogen production from the electrolyser was calculated using the same total annual electricity supply from the Sand Bay wind farm as detailed in the results for System Configurations 1 & 2. Using a generic industrial-scale PEM electrolyser with a conversion efficiency of 80%, the total annual mass of hydrogen produced is shown in Table 14 below. The conversion calculations can be found in Appendix 2

Table 14 Estimated Hydrogen Production Yield from Sand Bay Wind Farm

Annual Electricity Production from Sand Bay wind farm (MWh)	Annual Mass of Hydrogen produced (kg)
8,553.4	205,281.6

5. Discussion

This section shall discuss the results obtained and explore potential areas for future work which would supplement the research conducted in this thesis.

5.1. System Configuration 1

As mentioned previously, system configuration 1 was designed to simulate the existing power generation system in Stanley. The model was built using power generation and fuel consumption data recorded by the Stanley power station. Overall, the system was able to supply 99.1% of the electrical demand for Stanley, with a total annual production of 14,989.6MWh. The deficit from the total annual demand can be attributed to the subtraction of the power station electricity consumption and transmission losses approximated by the power station operators. This match, accounting for margin of error, confirmed that the model and its associated data was correct and operating as expected.

The breakdown of annual electrical contribution shown in Table 4 showed that the wind farm at Sand Bay was able to supply an impressive 8553.4MWh of electricity, 57% of the total production. This was made possible by the substantial wind profile of the Falkland Islands over the year (Figure 7) which meant that the Sand Bay wind farm was operational for 98% of the year. However, when compared to the recorded power generation data of the wind farm (Appendix 1) of 30.4% for the period 2018-2019, the model contribution is almost double. This is due to the difference in operational strategy employed by Stanley power station, which currently employs the power station capacity to meet the primary load, with the wind farm used to supplement the load where possible and reduce the fuel consumption of the power plant. In contrast, the operational strategy implemented for the EnergyPRO model uses the wind farm to meet the primary load, with the power station used to cover any disparities in the supply and demand. This is the operational strategy which Stanley power station aims to convert to once construction has been completed on the new power station in Stanley, and would reduce the need for expensive, large-scale electrical storage systems on the island. Furthermore, the EnergyPRO model does not take into consideration transmission losses or any downtime in turbine operation due to mechanical failure or routine maintenance, which may account for a reduction in total power output over the course of a year. This model shows the maximum operational output of the wind farm that may be realised by remedying the issues described above. This is a promising result for the Falklands, as the remoteness of the Islands meant that the Sand Bay wind farm is one of the most expensive wind farms ever installed, with a cost of £2.15m per installed MW. Getting the maximum performance from the currently installed capacity will not only provide energy savings, but also remove the need to install more wind turbines (at great expense) in order to meet increasing electricity demand with clean energy sources.

Total annual fuel consumption of the system was calculated as 1.7m L of diesel. This was significantly lower than the recorded consumption of 3.26m L due to the lower contribution of renewables which demanded higher usage from the diesel generators.

5.2. System Configuration 2

The model for this configuration is mostly similar to that of configuration 1, with the diesel CHP system replaced by that of a hydrogen fuel cell CHP system. Thus the heating and electrical demand and the contribution from the wind farm remain the same. The hydrogen fuel cell was to be sized in order to service the peak electrical demand of 3.3MW. With operational efficiencies of such fuel cells, the nameplate capacity was to be 8.5MW. This system was able to provide a 99.2% match to electrical demand, with the hydrogen fuel cell delivering marginally more electricity than the modelled diesel at 15,004.9MWh.

The renewable energy contribution from the wind farm at Sand Bay is the same as described above and is subject to the same limitations and assumptions.

The hydrogen fuel consumption for the year was calculated as 484T, which would produce net zero emissions from the assumption that only purified hydrogen fuel is used in the system.

The hydrogen fuel cell CHP system produces slightly more heat at 8,918.3MWh, and thus offers more headroom for district heating than the existing fossil-fuel based system.

5.3. System Configuration 3

The model for this system is similar to that of configuration 2, except that all electricity generated by the Sand Bay wind farm was used to produce hydrogen through the use of a PEM electrolyser. Due to limitations in the EnergyPRO software, it was not possible to simulate this hydrogen production system. Therefore total annual electrical supply results were used. The electrical supply from the wind farm was the same value obtained during the simulations of configurations 1 & 2, 8,553.4MWh, as the capacity of the wind farm and the annual wind profile were the same for each configuration. In order to make up for the loss in direct contribution to the electricity demand of Stanley, the hydrogen fuel cell CHP was scaled up. A number of trials were conducted to find the required fuel cell capacity. However, the result of these trials showed a plateau in the annual electrical supply from the fuel cells. This was confirmed by the graphs showing the electricity match over the month of July 2018 (Figure 32) There was no discernible reason for this, and as such these results are assumed to be due to an error in the software, however this is an area for investigation during future work. Nevertheless, from the results obtained for the 8.5MW CHP system, the annual fuel consumption was calculated as 655Tonnes of hydrogen. The annual hydrogen production of the Sand Bay wind farm, coupled with a PEM electrolyser operating at a conversion efficiency of 80%, was calculated as 205Tonnes of hydrogen per year. From the results obtained, and taking into consideration the software errors, it cannot be confidently concluded that the system described in configuration 3 is neither able nor unable to meet the electrical demand of Stanley at present. However, from the results obtained, Sand Bay wind farm and the proposed hydrogen fuel cell CHP system will require significant upgrades to their capacity if they are to meet the electrical demand of Stanley with no support from additional energy generation sources.

5.4. Future Work

There are a number of areas for future research which would supplement the research carried out in this thesis, both for the Falklands and the wider global audience. However, this section shall describe a select few of these potential research paths which would help to fully establish a hydrogen economy on the Falkland Islands and minimise their dependency on fossil fuels.

Firstly, and in direct support of the work carried out during this thesis, research is required into the appropriate technologies and logistics of converting the wider population of the Falkland Islands to use hydrogen as their singular source of electricity, heating and cooling. Around 85% of the wider community spread across the islands are isolated from any sort of grid connect and so currently rely on small-scale wind energy systems, supplied by the FIDC as part of their Rural Development Grant Scheme, which feature a turbine and electrical storage. However, all still rely on a supply of kerosene to supply their heating. Following the successful deployment of a hydrogen fuel cell CHP system in Stanley, an investigation into the use of micro-fuel cell CHP in these outlying settlements is the final step in establishing the viability of a fully-hydrogen economy for domestic energy supply.

Following this, the next step would be to establish a road and marine transport network to transport hydrogen to the outlying villages/settlements/homesteads for the production of renewable electricity.

The basis of this work would be to ascertain which would be the most economical solution:

- transporting hydrogen produced at a central location

- hydrogen production at key locations around the island

Ongoing Projects in the Scottish Islands which are exploring the potential role of hydrogen in Scotland's future energy systems would provide a sound foundation for this work towards achieving a 100% self-sustaining hydrogen economy for the Falkland Islands. This could in time provide not only power and heating but be integrated into their road and marine transport infrastructure generating either a direct clean fuel source for hydrogen powered vehicles or indirectly for EVs. Other countries are already investing in a hydrogen economy infrastructure (REFs) to supplement their renewable energy generation, reducing their fossil fuel dependency and responding to global drive to lower emissions (REFS).

The Scottish Executive (SE) were part of a consortium to commission the UK Hydrogen and Fuel Cell Roadmap (UKHFCA 2016). This independent Report provided a vision and strategy for how hydrogen and fuel cells could play a greater role in the UK's future energy mix.

Further to this Report, the SE have supported a number of world leading hydrogen demonstration Projects. These include the "Surf n Turf" Project in Orkney, an archipelago of some 70 islands some 10 miles north of the coast of Caithness, Scotland. The Surf n Turf Project (Surfnturf.org.uk, 2019) aims to expand the use of hydrogen as a clean fuel for use in road and sea transport as well as for power and heating. Most of the equipment utilised is based on established technology but with innovative integration laying the foundations of a hydrogen network, within the context of a remote Island community setting and associated infrastructure. Hydrogen produced on the Island of Eday is shipped in purpose-built trailers via the Island's roads and inter-island ferry network to Kirkwall where three 25kW fuel cells convert the hydrogen into electricity for use in harbour builds and to provide auxiliary power for ferries, berthed in Kirkwall harbour.

Mobile Storage & Transportation

A key component in expanding the use of hydrogen for the use in road and sea transport has been the development of mobile storage units, capable of safely and effectively transporting hydrogen gas on the island road infrastructure. With the majority of the roads connecting the outlying communities on Orkney being “single track” featuring weight restrictions and limited areas within which to turn articulated lorries, a bespoke transport trailer solution was required.

Calvera, a specialist provider of transport solutions for a wide range of industrial gases was engaged to design and build three specialist trailers sized to transport hydrogen on the island’s roads and inter-island ferries. While conventional trailers are fabricated from steel, to reduce weight these trailers are built of aluminium and carbon fibre. (Calvera, 2019)

The similarity in road network limitations with Orkney offer the potential for these specialist transport vehicles to be adopted by the Falkland Islands as part of their strategy for the expansion of their own hydrogen economy.

Figure 35 Specialised Lightweight Trailer for Transportation of Hydrogen

Finally, no economic analysis was conducted during this thesis. However, as the cost of the technology and fuel supply is the limiting factor to the wide spread adoption of a hydrogen economy, an investigation into capital costs and payback periods would offer an insight into the timeframe before a hydrogen economy can be realised as the future energy solution for the global community.

6. Conclusions

To conclude, through the analysis conducted in the process described by this thesis, a Hydrogen fuel cell CHP system is able to provide a sufficient supply of electricity to fully meet the demand of the city of Stanley in the Falkland Islands when supplemented by the electrical generation capabilities of the Sand Bay wind farm. Furthermore, it can be seen that significant heat can be provided by the system through the incorporation of a heat recovery solution that can be used to increase the district heating potential of the currently operational diesel-fuelled power generation system. All this is achieved with approximately net zero production of CO_2 and NO_x emissions; a significant reduction to the emissions produced by the current diesel system. Following additional research with strategic planning for the integration of hydrogen-fuelled micro-cogeneration systems would allow for the Falkland Islands to fully realise the benefits of a Hydrogen economy, providing a clean and sustainable energy future for themselves and demonstrating its viability to the rest of the world, and particularly to other remote, isolated and under-resourced communities like itself.

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8. Appendices

8.1. Appendix 1 – Stanley Power Station Generation Data

Power Production. July 2018-June 2019

Week	Wind	Diesel	Units Gen	St'n Con	Fuel Gal	Fuel Lit	Oil Gal	Oil Lit	Unit/Gal	Unit/Lit	WD/Gal	% Renewable		Units Sold	Average Daily Load
06-Jul-18	136100	244670	380770	25241	13987	63585	147	668	17.49	3.85	27.22	35.74		319,976	45,711
13-Jul-18	94800	260810	355610	26576	15209	69140	144	655	17.15	3.77	23.38	26.66		296,131	42,304
20-Jul-18	97400	266870	364270	26694	18932	86065	147	668	14.10	3.10	19.24	26.74		303,818	43,403
27-Jul-18	83800	256400	340200	24221	14509	65958	150	682	17.67	3.89	23.45	24.63		284,381	40,626
03-Aug-18	115400	233070	348470	24183	13386	60853	121	550	17.41	3.83	26.03	33.12		291,858	41,694
10-Aug-18	87300	264430	351730	24899	14892	67699	105	477	17.76	3.91	23.62	24.82		294,148	42,021
17-Aug-18	89200	249700	338900	24454	14227	64676	104	473	17.55	3.86	23.82	26.32		283,001	40,429
24-Aug-18	120400	227230	347630	23054	12913	58702	107	486	17.60	3.87	26.92	34.63		292,118	41,731
31-Aug-18	127500	232640	360140	26009	13338	60635	129	586	17.44	3.84	27.00	35.40		300,718	42,960
07-Sep-18	134100	220455	354555	23845	12809	58230	104	473	17.21	3.79	27.68	37.82		297,639	42,520
14-Sep-18	112359	231180	343539	22860	13304	60480	86	391	17.38	3.82	25.82	32.71		288,611	41,230
21-Sep-18	131800	217345	349145	22577	12618	57361	80	364	17.22	3.79	27.67	37.75		293,911	41,987
28-Sep-18	142200	209910	352110	23477	11926	54216	99	450	17.60	3.87	29.52	40.39		295,770	42,253
05-Oct-18	118200	229910	348110	22835	13348	60680	108	491	17.22	3.79	26.08	33.95		292,748	41,821
12-Oct-18	105876	244555	350431	23200	13955	63439	123	559	17.52	3.85	25.11	30.21		294,508	42,073
19-Oct-18	122818	219050	341868	22091	12566	57125	95	432	17.43	3.83	27.21	35.93		287,799	41,114
26-Oct-18	103806	222595	326401	22322	12848	58407	109	496	17.33	3.81	25.40	31.80		273,671	39,096
02-Nov-18	84200	250150	334350	22526	14323	65112	121	550	17.46	3.84	23.34	25.18		280,642	40,092
09-Nov-18	123700	205400	329100	20728	11869	53956	109	496	17.31	3.81	27.73	37.59		277,535	39,648
16-Nov-18	128200	196790	324990	20547	11322	51470	90	409	17.38	3.82	28.70	39.45		273,999	39,143
23-Nov-18	100000	220510	320510	20796	12826	58307	120	546	17.19	3.78	24.99	31.20		269,743	38,535
30-Nov-18	112200	200080	312280	19992	11675	53075	110	500	17.14	3.77	26.75	35.93		263,059	37,580
07-Dec-18	111300	212810	324110	20052	12137	55175	119	541	17.53	3.86	26.70	34.34		273,652	39,093
14-Dec-18	96500	205970	302470	19786	11946	54307	119	541	17.24	3.79	25.32	31.90		254,416	36,345
21-Dec-18	103000	212970	315970	22839	12331	56057	139	632	17.27	3.80	25.62	32.60		263,818	37,688
28-Dec-18	80400	192087	272487	14935	11174	50797	107	486	17.19	3.78	24.39	29.51		231,797	33,114
04-Jan-19	86200	192213	278413	18175	11102	50470	141	641	17.31	3.81	25.08	30.96		234,214	33,459
11-Jan-19	79200	230680	309880	19536	13187	59948	132	600	17.49	3.85	23.50	25.56		261,310	37,330
18-Jan-19	100200	205000	305200	18867	11846	53852	150	682	17.31	3.81	25.76	32.83		257,700	36,814
25-Jan-19	81927	246350	328277	20790	13962	63471	167	759	17.64	3.88	23.51	24.96		276,738	39,534
01-Feb-19	102573	223880	326453	19444	12774	58071	192	873	17.53	3.86	25.56	31.42		276,308	39,473
08-Feb-19	88400	237790	326190	20190	13529	61503	198	900	17.58	3.87	24.11	27.10		275,400	39,343
15-Feb-19	121800	215970	337770	20174	12324	56025	130	591	17.52	3.85	27.41	36.06		285,836	40,834
22-Feb-19	97900	245150	343050	22500	14087	64040	180	818	17.40	3.83	24.35	28.54		288,495	41,214
01-Mar-19	101900	266450	368350	23238	15278	69454	152	691	17.44	3.84	24.11	27.66		310,601	44,372
08-Mar-19	91300	274700	366000	23396	15720	71463	205	932	17.47	3.84	23.28	24.95		308,344	44,049
15-Mar-19	117500	235320	352820	22835	13574	61707	202	918	17.34	3.81	25.99	33.30		296,987	42,427
22-Mar-19	130270	217160	347430	21977	12426	56489	150	682	17.48	3.84	27.96	37.50		292,908	41,844
29-Mar-19	92323	259010	351333	22538	15000	68190	226	1027	17.27	3.80	23.42	26.28		295,916	42,274
05-Apr-19	122530	254640	377170	23826	14522	66017	165	750	17.53	3.86	25.97	32.49		318,010	45,430
12-Apr-19	118670	275030	393700	25095	16157	73450	158	718	17.02	3.74	24.37	30.14		331,745	47,392
19-Apr-19	148000	240740	388740	24455	13890	63144	190	864	17.33	3.81	27.99	38.07		327,857	46,837
26-Apr-19	109700	255910	365610	22619	14941	67922	152	691	17.13	3.77	24.47	30.00		308,692	44,099
03-May-19	95576	288180	383756	23832	16331	74241	180	818	17.65	3.88	23.50	24.91		323,932	46,276
10-May-19	0	383390	383390	21185	22024	100121	275	1250	17.41	3.83	17.41	0.00		325,985	46,569
17-May-19	98609	275685	374294	24418	15929	72413	196	891	17.31	3.81	23.50	26.35		314,888	44,984
24-May-19	138215	232285	370500	23991	13369	60775	154	700	17.37	3.82	27.71	37.30		311,858	44,551
31-May-19	126000	248450	374450	24801	14306	65035	221	1005	17.37	3.82	26.17	33.65		314,684	44,955
07-Jun-19	90200	276690	366890	25747	15762	71654	224	1018	17.55	3.86	23.28	24.59		307,029	43,861
14-Jun-19	67500	296630	364130	26011	16888	76773	237	1077	17.56	3.86	21.56	18.54		304,307	43,472
21-Jun-19	94300	259400	353700	26476	14963	68022	223	1014	17.34	3.81	23.64	26.66		294,502	42,072
28-Jun-19	90700	270590	361290	26431	15438	70181	216	982	17.53	3.86	23.40	25.10		301,373	43,053
Total	5317952	12290210	17608162	1158045	709712	3226351	7661	34827	17.32	3.81	24.81	30.41		15,125,081	

8.2. Appendix 2 – Calculation for PEM Electrolyser Hydrogen Production

Calorific Heating Value of Hydrogen = 120MJ/kg

Annual Electrical Production of the Wind Farm = 8553.4MWh

8553.4 x 3600 = 30792240 MJ

30792240 MJ x 80% = 24633792 MJ

24633792 MJ / 120MJ/kg = 205281.6 kg of Hydrogen