Department of Mechanical and Aerospace Engineering

# Grid optimisation of Isle of Gigha

Author: Faisal Farooq

Supervisor: Dr Paul Tuohy

A thesis submitted in partial fulfilment for the requirement of the degree

Master of Science

Sustainable Engineering: Renewable Energy Systems and the Environment

2016

## Copyright Declaration

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.



Signed: Faisal Farooq Date: 30/08/16

# Abstract

The Isle of Gigha boosts an abundance of wind resource due to its idealistic location. Historically the grid in UK is designed to flow power from transmission terminal stations, at progressively lower voltages, to electricity consumers. It was designed to supply power to low voltage terminals rather than accepting from them. Due to this the subsea cable that connects the island's grid to the mainland has a 1MW limit to export. As a result, renewable power generated using wind turbines on the island has its power constraint. This project looks into the ways energy demands are met on the island and how can they be delivered in an effective and efficient manner using a range of storage and generation options. In order to do that the grid of Gigha was modelled using HOMER. It was concluded that due to the limit of export, a point of saturation was achieved in reducing cost of electricity on increasing renewable capacity. Another important conclusion was that it is financially impractical to run a grid on storage and renewables alone because power is generated at times when it can neither be used to serve the load nor can it be used to charge the electric storage system.

**Acknowledgements**

I would like to take this opportunity to thank my parents who have financed my masters in Strathclyde University. I would like to thank Dr Andy Oliver from Gigha Renewable Energy Limited (GREL) who showed interest in my research and helped in providing the basic data required for modelling the grid of Gigha. PhD student Andrew Lyden from Strathclyde University has helped me in solving problems that occurred while using HOMER. I would also like to thank my supervisor, Dr Paul Tuohy whose continued support and valuable advice made this project a success.

**Table of Contents**

**List of figures**

**List of tables**

# 1. Introduction

Increasing global demand for energy and exhausting fossil fuel resources are posing a risk to the security of supply of energy. Researchers around the world are facing the challenge of delivering reliable, affordable and clean energy by utilising the principles of energy autarky.

Energy autarky means having energy generated locally for a community that relies on its own resources for meeting energy demands. One example of such a community is on a small island located off the west coast of Kintyre in Scotland called Isle of Gigha. The islanders meet most of their electric demands by four community-owned grid-connected wind turbines of a total installed capacity of 1.005MW. Income is generated by exporting excess electricity to the main grid.

Gigha is progressing towards a greener, more sustainable future with an interest in energy autonomy. Due to the current state of grid connection, the island is facing an issue with an increasing presence of wind power generation. There is a limit to export of 1MW which is preventing the grid-connected island from fully utilising its renewable potential. Power that is generated on-site is transmitted to the grid via a subsea cable from where it is distributed to consumers on the island. This LV subsea cable is one of the longest line in Scotland which is prone to faults and power cuts due to the effects of distant faults occurring over a wide area, such as network stability issues and voltage fluctuations. Due to this, the islander's suffer power blackouts even when the onsite wind turbines are operating.

There lies an opportunity to manage energy generation, transmission and distribution network without relying on the main grid. This project looks into ways of achieving this by investigating the system performance of current grid infrastructure and proposing alternative configurations that are effective, efficient and will increase onsite generation. This involves understanding the energy demand and supply characteristics and creating a better match between them.

A comparative study of different scenarios was done to choose the optimum combination of renewables and energy storage device(s) for meeting electricity demands in a low-carbon, cost effective and reliable way. Financial and feasibility calculations were performed using a software package called HOMER on which Gigha was modelled and different alternatives were presented that maximise the use of renewables.

Lessons learned from this project will create pathways for similar communities to follow and conclusions drawn will help create a better understanding of managing, modelling and optimising an electric grid that meets energy demands for a local community in a cost effective and sustainable manner.

## 1.1. Aims and Objectives

The overall aim of the project is to investigate the possibility of having highly reliable, low-carbon sources of energy for meeting demands of a modern lifestyle on Isle of Gigha. The project objectives are:

- Analysing the current ways in which energy demands are met on the island and identifying opportunities for carbon reduction.
- Modelling the electric grid of Gigha using appropriate software package for analysing the electric network and performing technical and financial feasibility calculations.
- Finding an optimum system configuration that meets all demands and gives lowest cost of electricity per kWh by incorporating renewables and storage technology.

## 1.2 Scope

The core of the project lies in investigating the feasibility of current grid infrastructure and proposing appropriate alternatives that will not only improve system reliability but will also help in achieving energy autonomy.

Areas that require further investigation are:

- Mapping local resources of energy generation.
- Feasibility and financial analysis of producing biomethanol from processing organic waste using anaerobic digestion.
- Comparing air-to-air source heat pumps with electric storage heaters for improving the efficiency of meeting domestic heating demands.

The following areas of research are out of scope for this project but can be used in further work:

- Comparing different types of energy storage systems.
- Applying demand reduction and demand side management strategies.
- Performing sensitivity analysis to see how sensitive the results are to changes in input.
- Validation of HOMER model using similar software.

## 1.3 Methodology

Data required for analysing energy demands and supply was collected by literature review and by carrying out a field visit to Gigha. This involved speaking with residents and interviewing those involved with the electricity network. An energy audit report was used to find out the total energy demands and the ways in which these are met. This helped in identifying opportunities for carbon reduction and modelling the grid.

In order to find an optimum system configuration that is technically feasible, reliable and gives lowest net present cost of electricity, a computational software called HOMER was used. HOMER estimates the performance of onsite wind turbines and PV panels using local climate data and calculates the lifetime of storage systems using its charge-discharge cycles. HOMER performs hour-by-hour energy balance calculations taking into account the uncertainty of power output from intermitted, seasonal and non-dispatchable renewables. It’s because of these features that HOMER offers that makes it the best choice for meeting objectives defined in this project.

The first step was to model Gigha for simulating the existing grid configuration. The next step was to model and analyse the future scenario that includes 1.26MWh of flow batteries. The final step was to optimise the grid by finding a configuration that has maximum use of renewables and minimum cost of electricity per kWh. The effect of incorporating extra storage, PV and wind on the grid was investigated. For each scenario, results were obtained for the share of load served by renewables and the systems respective net present cost.

# 2. The Story of Gigha

Gigha is the most southerly islands of the Hebrides. Seven miles long and a mile and a half wide, it is located off the west coast of Kintyre in Scotland, UK. Because it is low lying and influenced by the North Atlantic Drift the climate is drier and warmer than that associated with other islands on the west coast of Scotland. The land is fertile and most of it is used for grazing farm animals. Figure 1 shows an aerial view of the island.

*Fig 1. Isle of Gigha Aerial View* [1]

Gigha was put on the market for sale in August 2001. A body of elected representatives launched a bid to buy the island, hence establishing the Isle of Gigha Heritage Trust. On 15th March 2002, a sum of £4.15m was paid by the islanders. Out of this sum, £3.5m was paid by the Scottish Land Fund/Lottery Fund. Another £500,000 was granted by Highland and Islands Enterprise. The remaining was paid as a deferment payment by the islanders over a span of 2 years.

On purchase of the island, the first problem that the Heritage Trust had to address was the poor condition of estate housing stock. Out of the 42 trust owned properties, 95% were classed as below tolerable standard. Hence a £6million housing improvement program was embarked for renovation and upgrade of existing properties. By the year 2010, 23 residential properties were renovated with a further 16 to be undertaken. It was soon realised that there was a shortage of housing on the island. Hence the trust allowed the sale of plots to residents. Fyne Homes Ltd was granted a contract to build 18 new homes.

Gigha now boosts a population of 160 people and owns 75 homes out of which 90% are upgraded with double glazing and thermal insulation. There is no gas line supply to the island so heating, hot water and cooking needs are mostly met by electricity. The exception to this are self-sourced wood burners used for heating and a few gas cylinders used for cooking.

Gigha is home to the first community owned gird connected wind farm in Scotland. It comprises of four wind turbines of a total installed capacity of 1.005MW. Income is generated from exporting excess electricity to the main grid. Other sources of income are tourism (Gigha hotel, Boathouse Café, self-catering accommodation), farming (livestock farm, dairy farm, Halibut Fish farm (PumpAshore farm), Salmon fish farm (Scottish Salmon Company)) and limited sea fishing. Waste from livestock and dairy farming is used as a fertiliser for the land which is used for grazing animals. Septic tanks are used for water treatment. The information provided above was collected as part of the field trip. A map of Gigha is attached in Appendix I.

# 3. Energy Infrastructure in Gigha

The energy infrastructure in Gigha was analysed as per the objective of the project. Most of the data given in this section was taken from Gigha's energy audit report of 2014[1].

The average electricity consumed on Gigha on any hour of the day is 342.3kW. Around 50% of this electricity is consumed by the Halibut fish farm as a baseload whereas the remaining is consumed by the domestic and public sector.

Out of all the energy consumed by the domestic and public sector, 40% is electric while the rest of energy demand is met by locally sourced biomass and a mix of fossil fuels.

The island is connected to the main grid via an 11kW subsea cable. The four on-site wind turbines, three Vestas V27 of an installed capacity of 225kW each and one Enercon E33 with an installed capacity of 330kW are a net exporter of electricity. There is a 1MW limit to export but no limit to import of electricity. The E33 wind turbine's power output is constraint to 225kW because the grid operator anticipates that running the wind turbine on full output possess a risk damaging the subsea cable due to a voltage peak.

Planning permission has been granted for installing a 1.26MWh Vanadium Redox Flow Battery that will help relieve this constraint. Furthermore, the National Grid plans to replace the subsea cable with a High Voltage cable in order to avoid bottlenecking of renewable potential.

## 3.1 Energy Demands

The total energy demand on the island is 5.67 GWh per annum out of which 54% is met by electricity whereas the rest is met by local wood and a mix of imported fossil fuels. The pie chart in Figure 2 shows the proportional of energy consumed by individual sectors on the island.

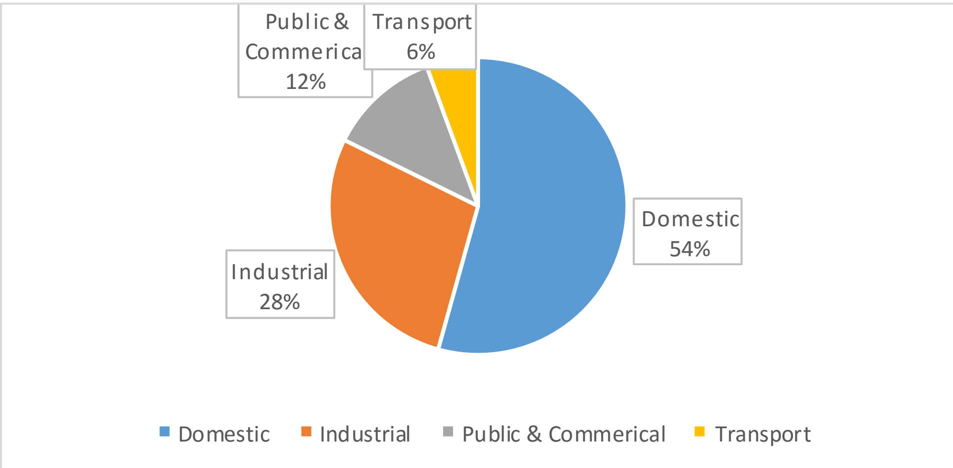


*Fig 2. Contribution of individual sector's energy consumption*

### *3.1.1 Domestic Consumption of Energy*

As shown in Fig 2, 54% of the total energy consumed is contributed by the domestic sector out of which 40% is met by electricity and 60% is met by fuel. Fig 3 shows the contribution of different sources of fuel used in the domestic sector.

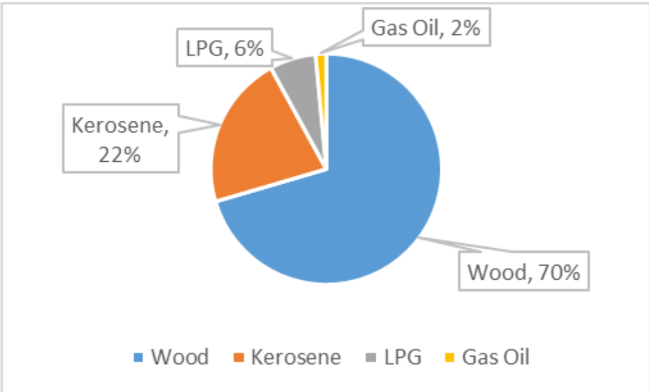


*Fig 3. Non-electric demand of energy in domestic sector*

As it can be seen from Figure 3, 70% of the fuel is comprised of locally sourced, free picked wood. This is used for domestic heating. As the cost of electricity continues to rise, there has been a significant increase in the use log stoves on the island. The use of kerosene, LPG and gas oil for heating and cooking has also mainly been for cost saving purposes.

In order to further reduce electricity bills, approximately 35 homes have installed rooftop solar water heating systems and around 10 households supplement electricity needs with rooftop PV panels.

### *3.1.2 Industrial Consumption of Energy*

The electrical demand for Gigha features a large proportion of industrial consumption. Approximately 51.54% of the total electricity used is consumed by the industrial sector. This is a result of the large, energy intensive halibut fish farm which consumes 95% of the load. The remaining is used by Scottish Water site and a Salmon fish farm. The Halibut fish farm and the Scottish water site own a 1 MW diesel generator for backup power to ensure security of supply during power shortages.

The Halibut fish-farm must continuously draw fresh seawater and pump it through the ponds. 2 out of 3 pumps run at all times (100kW, 100kW, and 75kW ratings) which are used for lifting water to a height of 6m. This results in a baseload of around 180kW for 24 hours a day, 7 days a week.

### *3.1.3 Public & Commercial Consumption of Energy*

The Public & Commercial sector includes a local grocery shop, post office, hotel, café, fire station, surgery, community centre, police station, school and a small selection of B&B’s. This sector is estimated to consume 12% of the total energy used on the island. Out of this, 44% is met by electricity and 66% is met primarily by gas oil used for cooking and a small amount of red diesel used for back-up generation. The tourism sector which comprises of the Gigha Hotel and the Boathouse Café are open from May to November every year.

### *3.1.4 Opportunities for Carbon Footprint reduction*

Kerosene used in the domestic sector and natural gas used in the commercial sector gets imported from the main land via ferry. The Gigha Heritage Trust intends to replace their use with biomethanol produced by anaerobically digesting waste from livestock farms, dairy farms and food waste. This will help in reducing carbon footprint by not only replacing the use of fossil fuels but also by capturing methane released from unprocessed waste dumped to the environment.

There are a total of 7-8 homes on the island (10% of housing stock) that need upgrade at the moment. The remaining have been equipped with thermal insulation and double glazing however around 40% of these homes use conventional electric heating systems. There lies potential of replacing them with more efficient heating systems such as heat pumps and electric storage heaters can drastically reduce energy consumption and lower energy bills. Analysis for calculating the number of payback years and the total carbon saving achieved by undergoing such an upgrade is part of the future work that can be done on this project.

## 3.2 On-site generation

### *3.2.1 The Dancing Ladies*

The ‘Dancing Ladies’ is the first community owned, grid connected windfarm in Scotland. It has been a mainstay of income generation since its installation in 2003. The three Vestas V27 wind turbines have fully paid for themselves of loans and grants since March 2009. Monies generated by the turbines are passed to the trust which are used for undergoing housing upgrades and for wind turbine maintenance. In 2014, an Enercon E33 wind turbine was installed to complement the existing wind farm.

The island boosts a good resource of wind energy due to its idealistic location. The wind turbines have been a net exporter of electricity and are seen as being a source of sustainable income generation. Dr Andy Oliver from Gigha Renewable Energy Ltd suggests that for wind speeds under 10m/s, the wind turbines are importing electricity whereas for wind speeds over 15m/s, the wind turbines are always exporting electricity to the grid.

The three pre-commissioned Vestas V27 wind turbines have an installed capacity of 225kW each. The wind turbines would need some of their components replaced (such as blades, nacelle, gearbox, generator, etc.) in the next 8 years which will cost approx. £160,000. [2]

The fourth wind turbine is an Enercon E33 of an installed capacity of 330kW but it has its power constraint to 225kW. This limitation has been set because that will make the wind farm have a total capacity that is 5kW higher than the limit to export of 1MW. Theoretically, taking turbine losses into account, this limit will never be reached. However, the network operator fears of a damage caused by a voltage rise on the Low Voltage subsea cable. A report [3] by Community Energy Scotland suggests that a total of 3 GWh will be lost in 25 years turbine asset life, which is worth around £300,000 and a carbon saving of 1.5kt$CO_2$ at today’s rates. Planning permission has been granted for commissioning 1.26MWh of Vanadium Redox Flow Batteries that will protect the grid from any excess generation and will allow the fourth wind turbine to operate unconstraint.

Cost estimated for the purchase and installation of the Enercon E33 is approximately £1,025,000. [2]

*Fig 4. Wind Turbines in Gigha*

### *3.2.2 Vanadium Redox Flow Batteries (VRFB)*

1.26MWh of Vanadium Redox Flow Batteries (VRFB) have been commissioned to be installed on Gigha. The VRFB are capable of running for 12 hours at a rate of 105kW. The batteries are sized such that they can store 105kW of constraint power output from the E33 wind turbine. VRFB were purchased from redT Energy Storage Solutions from a grant of £3.6 million received from the Department of Energy and Climate Change (DECC). Researchers from redT Energy conducted experiments for verifying the feasibility of installing VRFB on Gigha [4]. They estimated that the batteries can capture up to 60% of the energy lost due to the constraint over the lifetime of the wind turbine.

The other benefit of using storage on Gigha include:

- Peak shaving by storing excess electricity produced during times of low electric demand and selling it during times of high electric demand.
- Providing a means of operating the grid on islanded mode in the event of network faults.
- Increasing the grid capacity without undergoing upgrades, hence increasing use of onsite generation.

- Providing means for voltage control and frequency control for better power quality.

Out of different storage systems considered for capturing excess power generated on Gigha, VRFB were chosen because they are efficient (80% efficiency), durable (can withstand 10,000 deep cycles), low maintenance and fast responding. [4]

## 3.3 Grid Limitations and Upgrade

The UK grid network has been historically designed to flow power from transmission terminal stations, at progressively lower voltages, to electricity consumers. It was designed to supply power to low voltage terminals rather than accepting from them. When power is exported via a LV cable, transmission losses are huge. Moreover the the amount of power that can be exported is limited. These losses and limitations can be eliminated by connecting sources of electricity generation closer in distance to consumers.

Areas that are best suited for renewable energy generation often tend to be away from population centres like the case of Gigha. Rather than limiting renewable energy ambitions, smaller communities can opt for maximising onsite generation which will not only provide back-up supply of electricity but will also help meet energy demands in a clean, efficient and reliable manner.

If Gigha choses to run as a microgrid, excess energy can still be exported efficiently as Scottish Government plans of replacing the LV sub-sea cable with a high voltage (HV) cable that will improve export quality, reduce cable losses and avoid bottlenecking of renewable potential. [4]

The current LV cable that connects the electric grid to the mainland is prone to faults and power cuts due to the effects of distant faults occurring over a wide area. In March 2013, the islanders suffered from a 5-day power cut due to a blizzard.

However, increasing on-site generation will require a major grid expansion. Moreover, switching reliance from fossil fuel based sources of energy to renewables will increase the electric load. Dr Andy Oliver from Gigha Renewable Energy Limited (GREL) suggests that in order to be fully energy autonomous, on top of a grid upgrade, a total of 2 MW of electric storage will be required. The investment required to do this can be acquired by cumulating the money currently paid on licence charges, distribution and transmission costs, electricity imports and savings achieved from reduced transmission and distribution losses. The Network Innovation Allowance (NIA) allows Distribution Network Operators (DNOs) to spend up to 0.7% of their revenue on Research & Development so that they can plan to test new technologies required for running as a microgrid. [5]

Grid reliability can be maintained by installing fault detectors and rectifiers such as voltage regulators, reactive power compensation equipment and signal communication devices. This will help in facing problems associated with voltage fluctuation, faults and reverse power flow. Another way of improving power quality is by using storage which will help to smoothen the electric output from stochastic renewables, however this method will result in losses incurred due to energy conversion.

If Distributed Generation on Gigha is to be become widespread, then improved monitoring and control techniques will be required for automation and interconnectivity between supply and demand of electricity. Lessons learned from Active Network Management and Demand Side Management applied on similar islands of Scotland such as Orkney can be used on Gigha. If managed correctly, this will provide means for a more effective and efficient way of meeting energy demands, which will not only increase system reliability but will also reduce costs of electricity in the longer run.

# 4. HOMER model of Gigha

A model of the electric grid of Gigha was created using HOMER as per the objective of this project. HOMER is used for modelling micropower systems that generate heat or electricity to a nearby load using a combination of renewables, batteries and generators. [16] HOMER uses local demand and generation data by simulating the performance of renewable energy systems on an hourly time series basis and optimises results to give the best mix of energy resources which have the lowest life-cycle cost of energy.

Simulation results obtained from HOMER include (i) the fraction of renewable output used to serve load, (ii) the amount of power exported to the grid, (iii) the number of times the generator operates, (iv) the number of charge-discharge cycles of storage in an hour and (v) the systems life cycle cost.

The systems life cycle cost takes into account the capital, operating and maintenance costs, annual fuel costs, salvage value and revenues generated over the life span of the system. The salvage value represents the cost of replacing a particular component multiplied by the fraction of the components remaining life over its lifetime.

$$Salvage\ Value = (Replacement\ Cost)\frac{Remaining\ component\ life}{Components\ lifetime}$$

For simplification the systems life cycle cost can be represented as Net Present Cost (NPC) which includes all costs and revenues, with future cash flows discounted to the present using a discount rate. Mathematically, NPC is given as below:

$$Net\ Present\ Cost = (Annualised\ Cost).\frac{(1+i)^N - 1}{i(1+i)^N}$$

Annualised Cost is the systems life cycle cost defined above divided by the project's lifespan. N is the project's lifespan which is set as 25 years for this model. Discount rate 'i' is taken as a UK average of 3.5%.

Results obtained from financial analysis of the system can be used for finding the cost of electricity per kWh. The Cost of Electricity (COE) is calculated by dividing the Annualised Cost by the amount of electricity produced by the system. This amount of electricity produced includes the amount used to serve primary load, the amount of deferrable load and the amount of electricity sold to the grid.

The grid follows a dispatch strategy called the 'load following strategy' in which a generator produces enough power to meet the primary load and batteries are charged using renewable power sources only.

Another important simulation result obtained in HOMER is the 'Renewable Fraction' which is given as below:

$$Renewable\ Fraction = 1 - \frac{E_{non\ renew}}{E_{served} + E_{grid,sales}}$$

$E_{non\ renew}$ = Total non-renewable electric production,

$E_{served}$ = Total electric load served by renewable generation,

$E_{grid,\ sales}$ = Total energy sold to the grid.

This section covers how the grid was modelled using HOMER and the methods used to ensure it is a close representation of the actual scenario in Gigha.

## 4.1 Demand Profile

According to the energy audit report compiled by Gigha Renewable Energy Ltd (GREL) [1] 51.4% of total electricity is consumed by the industrial sector whereas 40.5% is consumed by the domestic sector. The remaining 8.1% is consumed by the public and commercial sector.

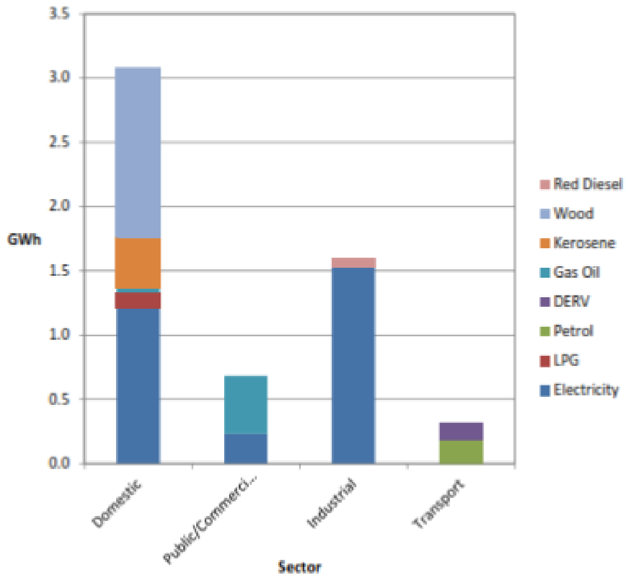


*Fig 5. Individual contribution of energy to each sector [1]*

For simplification purposes, the public and commercial load was assumed to follow the same profile as the domestic sector.

Data for the actual demand profile for Gigha was not obtained, hence in order to approximate how the domestic load varies from one month to another, the profile shown in Fig 6 was used. The graph in Fig 6 shows the yearly pattern in kWh per day starting from the 1st of April to the 31st of March. This was taken from a report compiled by Elexon [6] and it gives the average UK's domestic load over a year.

Data points from this graph were extracted using an online tool called WebPlotDigitizer, represented as red dots on Fig 6.

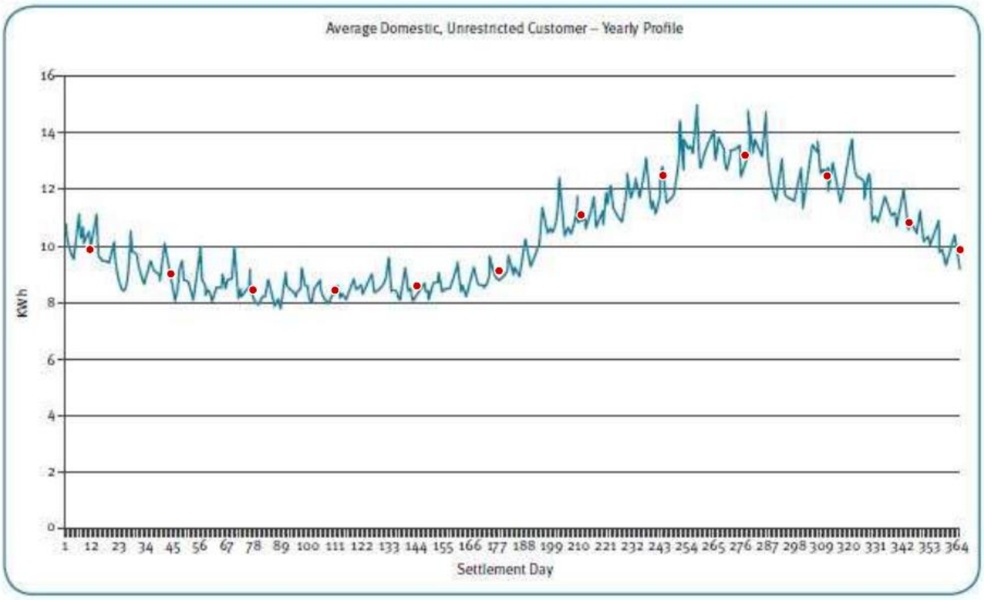


*Fig 6. Daily variation in domestic demand in UK starting 1st of April to 31st of March [6]*

Figure 7 shows the daily pattern in kW per day of an average UK household, each data point represents half an hour time step starting midnight. Energy consumed per hour on the island, on different months of the year, was approximated by using these two UK average profiles.

A baseload of 181.2kW was added to the domestic profile to represent the electricity consumed by the industrial sector. Fig 8 shows the yearly demand profile which has a calculated average annual demand of 8,213.9 kWh/day.

Fig 9 shows the profile for a typical day in the month of January and Fig 10 shows the profile for a typical day in the month of July.

The demand profile accounts for a certain degree of random variability. This allows additional randomness to electric demand for making it more realistic. Because the demand profile created already accounts for changing demands in changing seasons, the timestep (%) was set as zero whereas the day-to-day (%) variability was set to 5% which causes the size and shape of daily profile to change randomly by 5%.

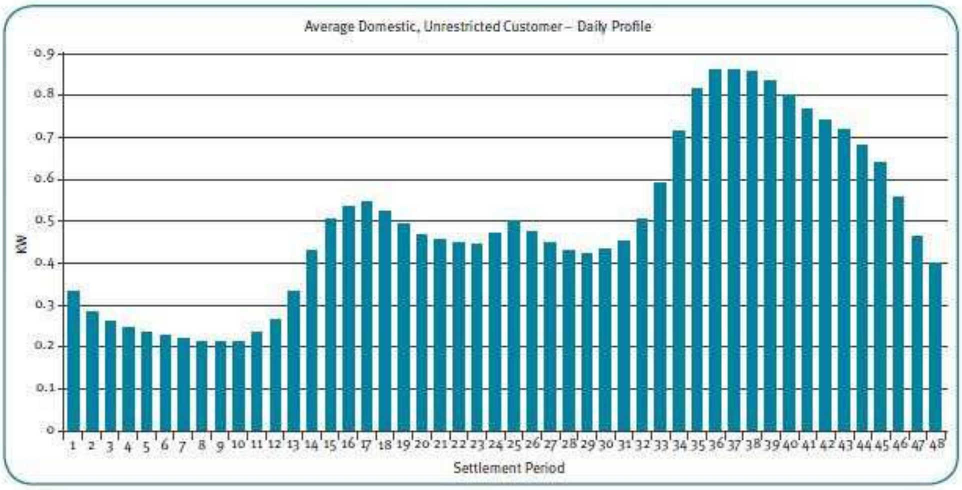


*Fig 7. Daily pattern in kW per day of an average UK household* [6]

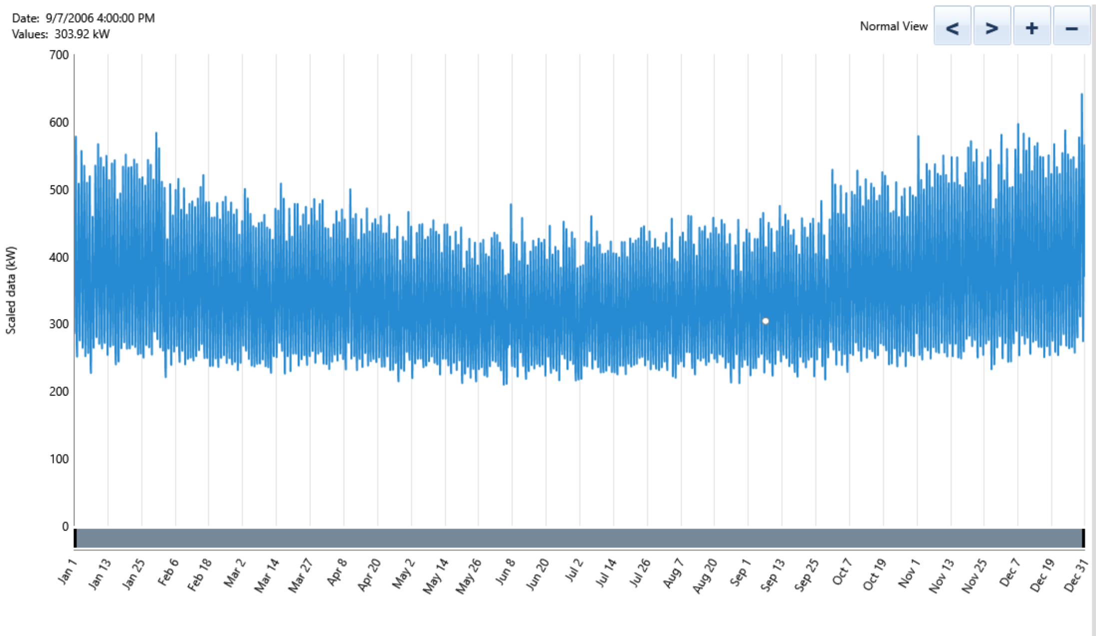


*Fig 8. Yearly Demand Profile of Gigha modelled in HOMER*

According to a DECC article [7], on average, in UK, the electric demand of a typical winter day is 36% higher than the electric demand of a typical summer day. A telephonic conversation with Dr Andy Oliver from GREL revealed that the average load in summers is 350kW and in winters is 550kW which turns out to be an exact difference of 36%. Despite 40% of homes are equipped with electric heating, this trend follows in Gigha partly because of higher load in summers due to tourism.

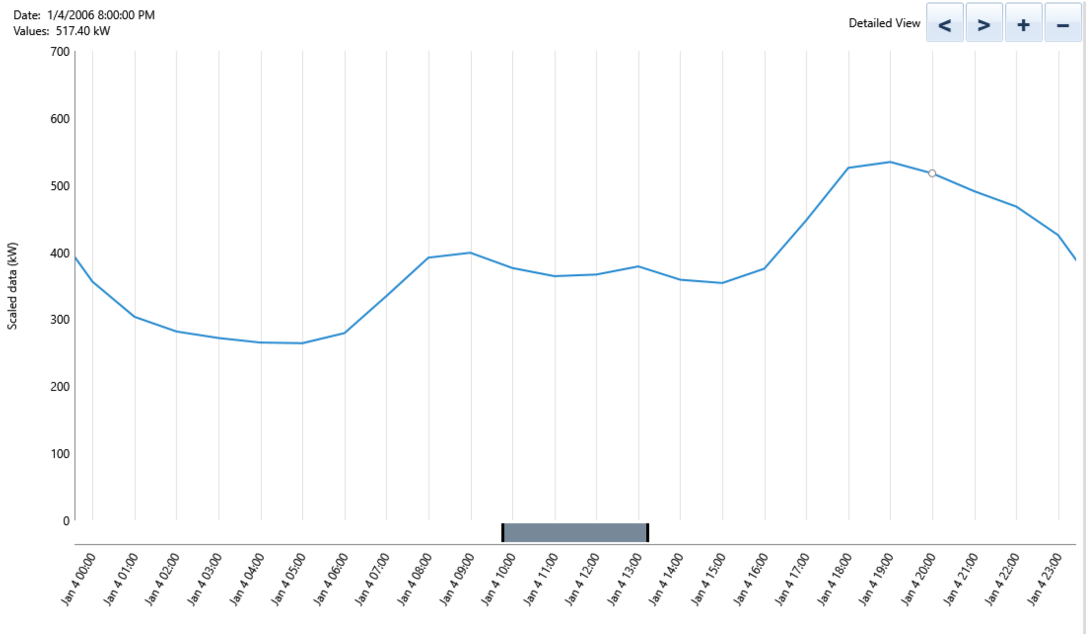


*Fig 9. Demand Profile for a typical day in January*

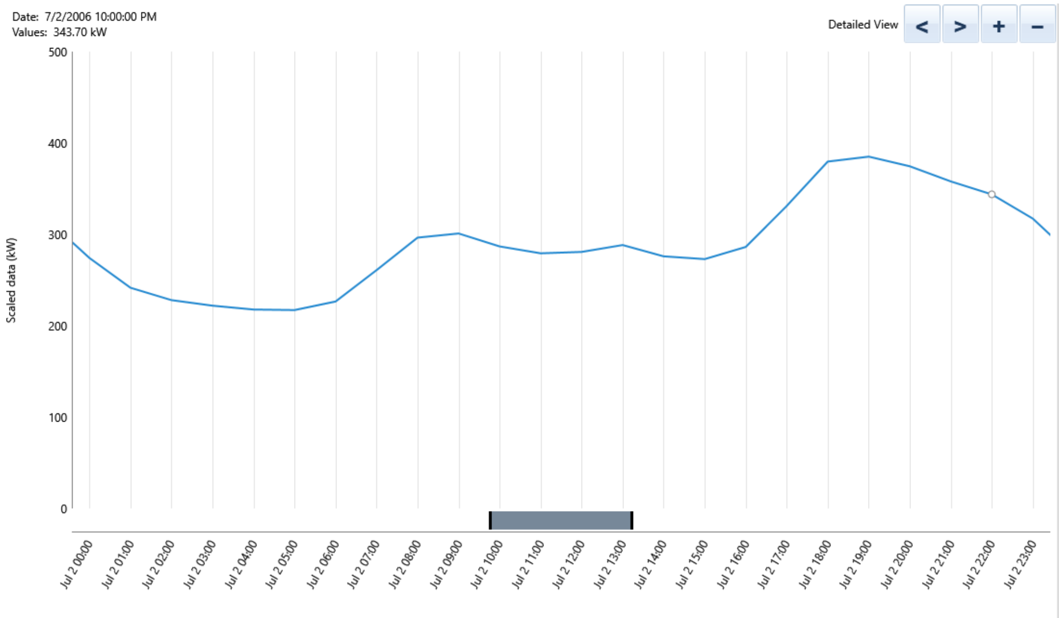


*Fig 10. Demand Profile for a typical day in July*

## 4.2 Wind Power Generation

### *4.2.1 Wind Speed Data*

Data for average monthly wind speeds was added in HOMER using the NASA Surface meteorology and Solar Energy database. In this database, wind speeds are recorded at an anemometer height of 50m above the surface of the earth for a terrain similar to airports. Table 1 gives the monthly average values recorded over a 10 years period (July 1983 – June 1993) for Gigha's location (55.5° latitude, -5.5° longitude).

| Month | Average Wind Speed (m/s) |
| --- | --- |
| January | 9.860 |
| February | 9.240 |
| March | 9.080 |
| April | 7.480 |
| May | 6.920 |
| June | 6.320 |
| July | 6.350 |
| August | 6.600 |
| September | 7.600 |
| October | 8.530 |
| November | 8.890 |
| December | 9.470 |

*Table 1. Gigha monthly average wind speeds (NASA database)*

Hourly wind speed data is synthesised in HOMER from the monthly average wind speeds using four statistical parameters: Weibull shape factor, autocorrelation factor, diurnal pattern strength and hour of the peak wind speed.

The Weibull distribution is a continuous probability distribution which is used for estimating the distribution of wind speeds for every day of the month. The Weibull shape factor is used for finding the ratio of standard deviation to mean wind speed.

A one hour autocorrelation factor is chosen which gives a measure of how strong the wind speed in one hour tends to depend on the wind speed in the following hour. It represents the degree of randomness in hour to hour wind speeds.

The diurnal pattern strength gives the magnitude of daily average pattern in wind speeds. It is a measure of dependence of wind speeds on the time of the day.

The hour of the peak wind speed is the windiest hour of the day. This value helps in indicating the phase of the average daily wind pattern.

All four wind turbines on Gigha have a hub height of 30m. This is because the island ferry cannot transport a wind turbine longer than 30m. The NASA database records wind speeds at a height of 50m above ground, hence corresponding wind speeds (at a height of 30m) are estimated using the logarithmic law. The logarithmic law gives the variation of wind speeds with varying altitude.

### *4.2.2 Vestas V27*

The wind farm on Gigha has three pre-commissioned V27 wind turbines of an installed capacity of 225kW each. The power output of wind turbines changes with changing wind speeds. This is given by the power curve provided by the manufacturer. Data for V27's power curve is given in Figure 11 below. This data is used as an input in HOMER.

2.6. POWER CURVE: (air density 1.225 kg/m$^3$)

| WINDSPEED m/s | OUTPUT kW |
|---|---|
| 3,5 | 1,5 |
| 4,0 | 4,5 |
| 5,0 | 16,6 |
| 6,0 | 31,8 |
| 7,0 | 52,5 |
| 8,0 | 82,4 |
| 9,0 | 114,5 |
| 10,0 | 148,3 |
| 11,0 | 181,0 |
| 12,0 | 205,0 |
| 13,0 | 217,6 |
| 14,0 | **225,0** |
| 15,0 - 25,0 | 225,0 |

*Fig 11. Data for V27 Power Curve [8]*

The three wind turbines have fully paid themselves of loans as of March 2009, hence the capital cost was set to zero. Within the next 8 years, certain parts of the wind turbines would need to be replaced such as blades, nacelles, gearboxes, generators, etc. which are estimated to cost approximately £160,000 [2]. This information is used as part of the financial analysis performed in HOMER.

A value of $31/kW was used for Operations and Maintenance (O&M) costs which was taken from a National Renewable Energy Laboratory (NREL) database [9]. This value is an average of O&M costs of different wind turbines in the range of 100-1000kW. For a V27 wind turbine, the annual O&M cost is taken as £5,390 which is approximated as the total cost for carrying out scheduled maintenance twice a year. Schedule maintenances are assumed to last 15 hours each. [10]

Turbines experience losses which limit them to reach a power output equivalent to their installed capacity. Percentage losses of various types experienced by a wind turbine are taken from a report by AWS Truepower [11] values for which are given in Table 2 below:

| **Typical losses of wind turbines** | **Percentage Loss (%)** |
|---|---|
| Availability | 6.20 |
| Turbine Performance | 4.00 |
| Environmental | 2.70 |
| Wake Effects | 6.40 |
| Electric | 2.10 |

*Table 2. Typical values for Turbine Losses [11]*

Values of turbine losses given in table 2 were inputted to the model. Overall loss factor is calculated to be 19.71%.

### *4.2.3 Enercon E33*

The Enercon E33 wind turbine was added to the wind farm on Gigha in 2014. It has an installed capacity of 330kW but has its power output constraint to 225kW due to grid limitations. This is limit is represented in the model by modifying the power curve for E33 such that the output never exceeds 225kW. Data for original power curve [12] is given in Appendix II and data for modified power curve is given in Appendix III.

It is assumed that $31/kW is spent on O&M [9]. Using this number for the E33 wind turbine, approximately £7,910 will be spent on O&M each year. The E33 wind turbine has a market price of £700,000 [13]. Gigha's official website [2] states that a total of £1,025,000 will be spent on the turbines capital, installation, replacement, operation and maintenance cost over its lifetime, i.e. 20 years.

For finding the turbine's replacement cost, £1,025,000 was subtracted by the sum of capital cost and O&M cost for the 20 year period. This gave a replacement cost of £166,800. Scheduled maintenance occurring twice a year, lasting for 15 hours each, was added to the model. Turbine losses encountered by the E33 wind turbine are given in Table 2.

## 4.3 Grid Specifications

A 1MW limit to export was specified in HOMER model. As there is no limit to import, this number was set to be very large. Electricity consumers on Gigha pay different peak and off-peak rates of electricity. From 7am to 11pm, customers pay a peak rate of 18p/kWh whereas for the rest of the day, customers pay 12p/kWh.

Electricity is sold at a basic rate of 4.6p/kWh but including income generated from Feed-in-Tariff and Renewable Obligation Certificate, the total price turns out to be approximately 12p/kWh. This data was provided by Dr Andy Oliver from GREL and was used as an input to the model.

The model accounts for power shortages that occur 4 times a year, at random intervals and last for around an hour. This information was taken from having a chat with Gigha residents.

## 4.4 Diesel Generator

The island has backup diesel generator of a 1MW capacity. The cost of diesel on Gigha is 112.9p/litre [14]. The grid follows a dispatch strategy called the 'load following strategy' in which a generator produces enough power to meet the primary load. The minimum load ratio was set to 30% which means that the generator operates at a minimum of 30% of its rated capacity even when the demand is lower than that. Running a generator on a load ratio lower than 30% reduces its lifetime. [15]

## 4.5 Simulation Results

Simulation results of the wind-diesel-grid system is shown in Figure 12 for a three day period (starting 12 am on 17$^{th}$ April and ending 11 pm on 19$^{th}$ April). The total renewable power output is represented as the green line on the graph in Fig 12, depicting typical, stochastic nature of electricity generated from wind turbines.

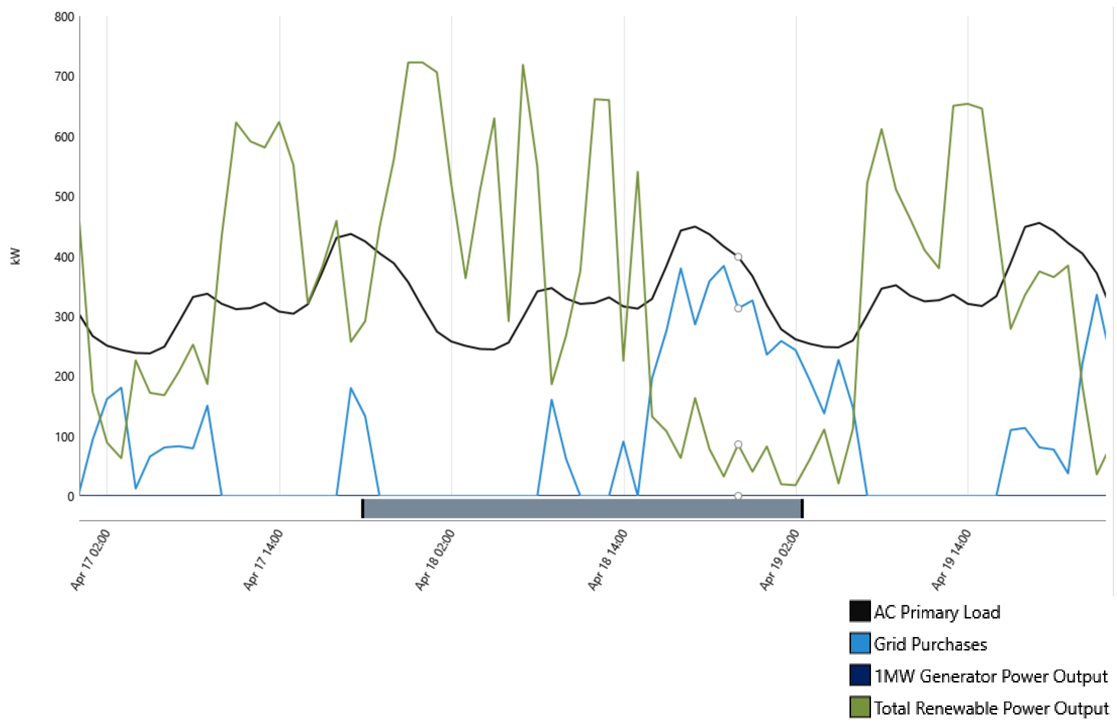


*Fig 12. Power against time of wind-diesel-grid system*

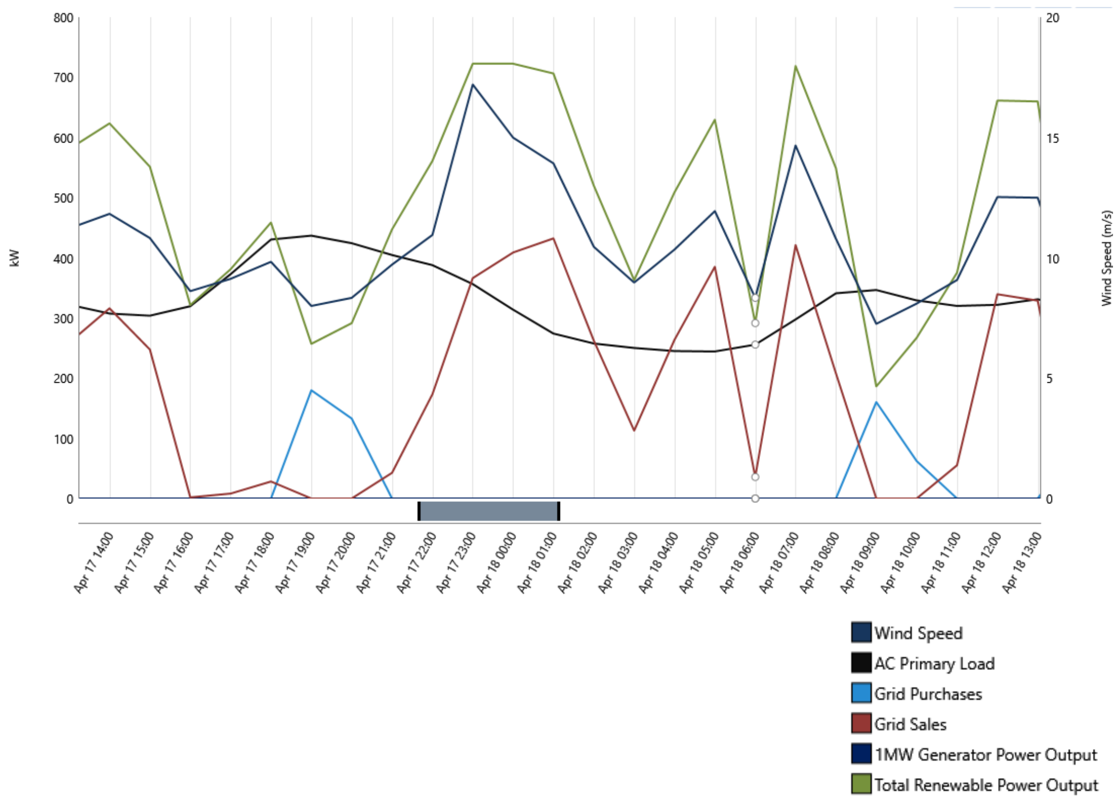


*Fig 13. Graph showing rise in grid sales due to rise in wind speed*

Zooming into the graph (Fig 12), at 9 pm on $17^{th}$ of April, there is a rise in wind speed with a subsequent drop in electric demand resulting in net excess of wind power output which is then exported to the grid, represented as 'Grid Sales' in Figure 13. (Diesel Generator is non-operational at this time).

Similarly, at 6 pm on the $18^{th}$ of April, there is a peak in electric demand, which is followed by a drop in wind speed, electricity is imported to meet demand (Figure 14).

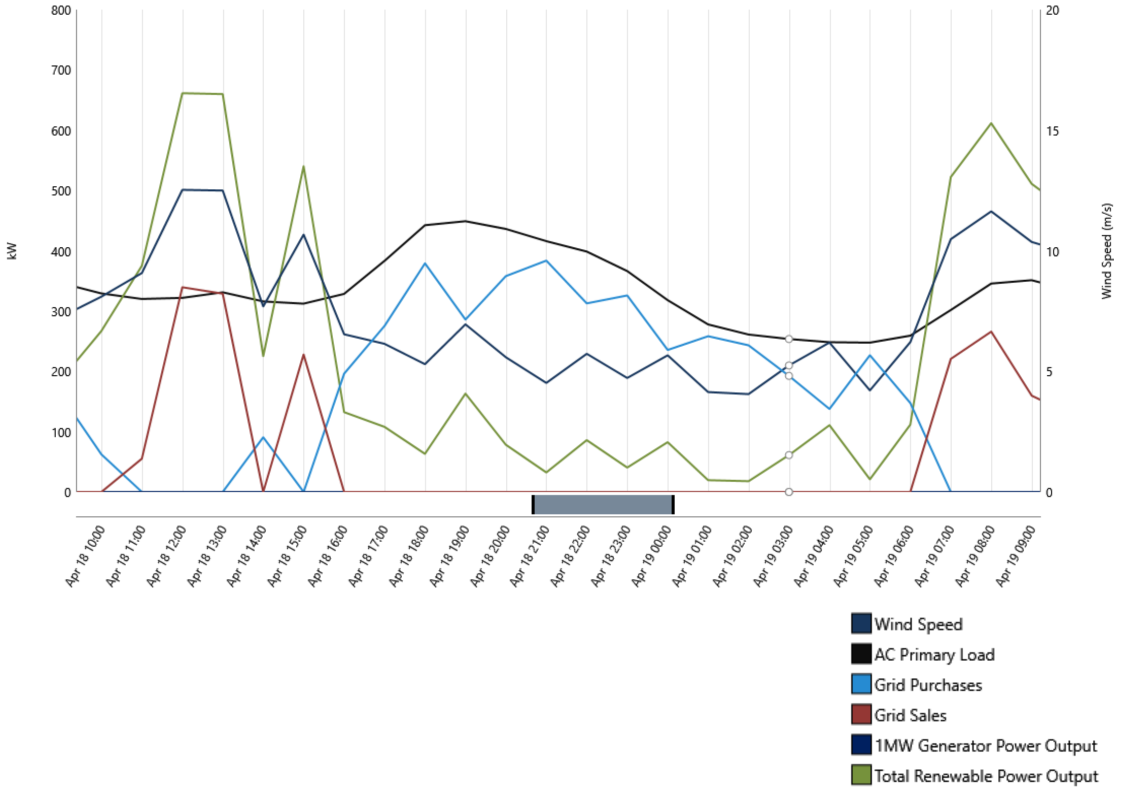


*Fig 14. Net import of electricity on $18^{th}$ of April @ 6pm*

Results show that the diesel generator operates only during times of a power outage. The black dots in Figure 15 show the pattern of grid outages defined in HOMER and Figure 16 shows the operation of the diesel generator during these times.

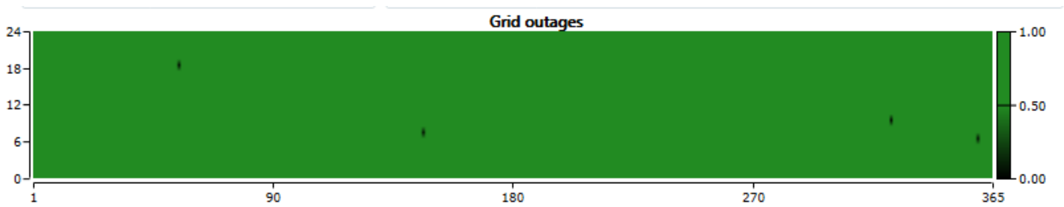


*Fig 15. Grid outages occurring at different times of the year*

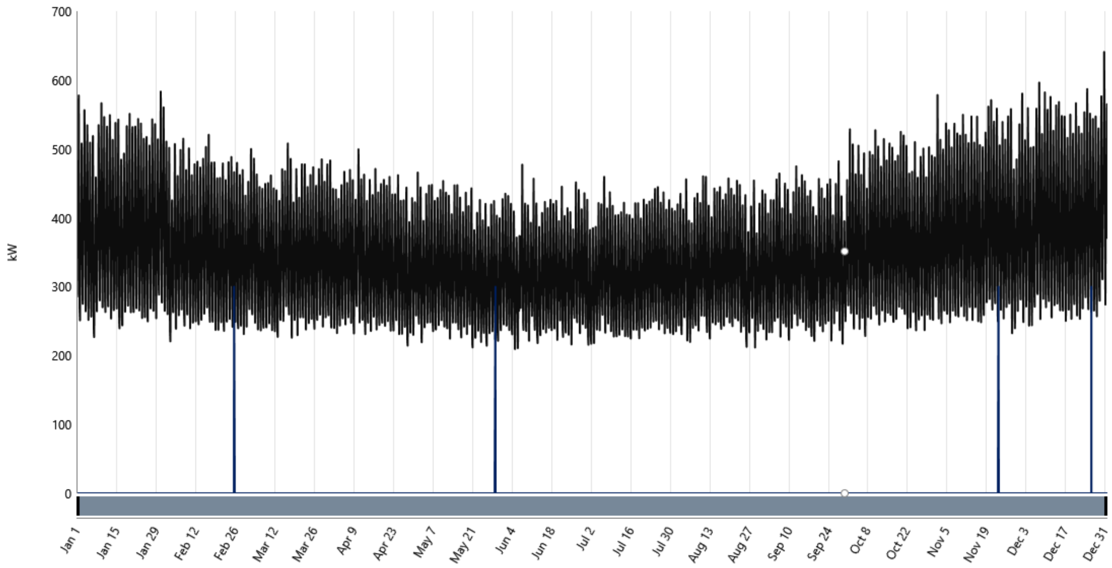


*Fig 16. Operation of Diesel Generator (represented as blue lines) and demand profile*

Zooming into a power blackout that occurs at 6 am on 26th of December, it can be seen (Fig 17) that the power output from the wind turbines is not sufficient to satisfy the load on their own, hence the diesel generators generate enough power to meet the deficit.

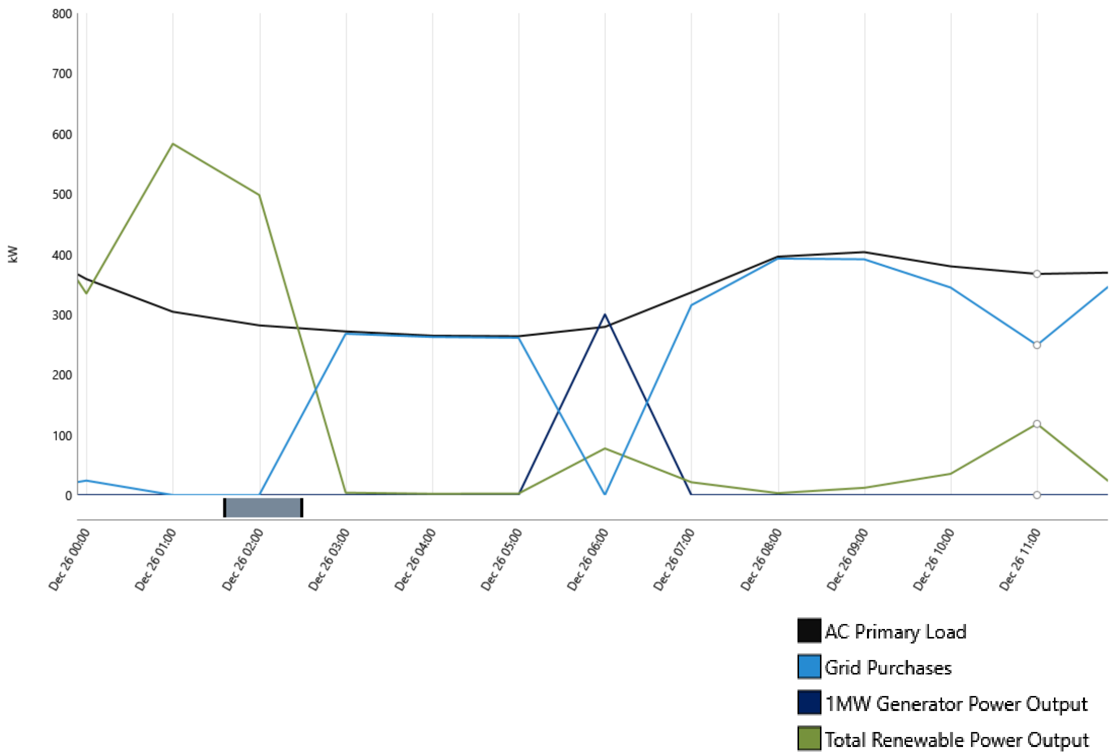


*Fig 17. Diesel Generator operation during power blackout*

### *4.5.1 Operating the E33 Wind Turbine unconstraint*

Simulation results show that, while having the E33 wind turbines power output constraint, the maximum power the four wind turbines generate in any hour is 722.59kW. On removing the constraint, and allowing the E33 wind turbine to follow its natural power curve, the maximum output the wind farm generated was 806.89kW, although the wind farm has an additive installed capacity of 1005kW. This difference in power output is due to losses occurred during wind power generation. Hence it can be concluded that liberating the E33 wind turbine possess no risk to grid integrity as the 1MW limit to export can theoretically never be achieved.

Simulation results show that 66.37% of the total load was served from the electricity generated from the wind turbines. 20.54% of the total electricity generated was sold to the grid. On running the E33 wind turbine unconstraint, 67.7% of the load was served using electricity generated from the wind turbines and 23.63% of total generation was sold to the grid. This decrease in import and increase in export of electricity results in a drop of cost of electricity from 5.13p/kWh to 4.46p/kWh when the E33 wind turbine is run unconstraint. Removing the 1MW limit to export has no effect on simulation results as this limit is never reached with or without the constraint in place.

## 4.6 Flow Batteries

In order to fully exploit renewable energy potential it is desirable to have suitable energy storage systems in place. The Isle of Gigha Heritage Trust received a grant from the Department of Energy and Climate Change (DECC) of £3.6million for installing Vanadium Redox Flow Batteries (VRFB) to supplement excess power produced by the wind turbines and to provide back-up power that will allow to run the grid on islanded mode. [3] The VRFB is composed of two primary parts:

1. Cell Stack: The cell stack capacity determines the amount of power used to charge and discharge the batteries in an hour. This is the component where electrical energy is converted to and from chemical energy of the electrolyte [17]. It has a capacity of 105kW [4]. Manufacturer suggests that the cell stack's cost is 25% of the battery's capital cost. The cell stack needs to be replaced every 10 years [18]. This data was added to the model as part of the replacement and O&M cost of the system.

2. <u>Electrolyte:</u> The electrolyte capacity determines the number of hours the battery can provide power, hence the amount of energy that can be stored. [17] It has a capacity of 1.26MWh [4]. With this capacity the VRFB can serve the load for a duration of 12 hours. Energy is stored in the chemical composites of the electrolytes which in this case are Vanadium ions dissolved in Sulphuric Acid. [17] Manufacturer suggests that the electrolyte has an unlimited life [18] hence its cost was set to zero in the model.

VRFB are easily scalable because power and energy capacity are controlled by their respective components. This is particularly advantageous for the case of Gigha as the storage capacity can be increased easily if they decide to increase onsite generation in future. A converter is used to convert the AC power output from wind turbines to DC, and then to convert DC power output from storage back to AC. Efficiency for the VRFB is in the range of 75 – 82%. [18]

VRFB can withstand 10,000 deep cycles without having any deleterious effect on its lifetime. [18] In the case when excess power from wind energy is used to charge the batteries, VRFB perform fairly well because they can withstand hundreds of shallow cycles in a day. VRFB have the same charge and discharge rate. [18]

A lifetime curve of cycles to failure against depth of discharge was added to the model. Figure 18 shows a comparison of different storage types based on their battery life cycle against depth of discharge.

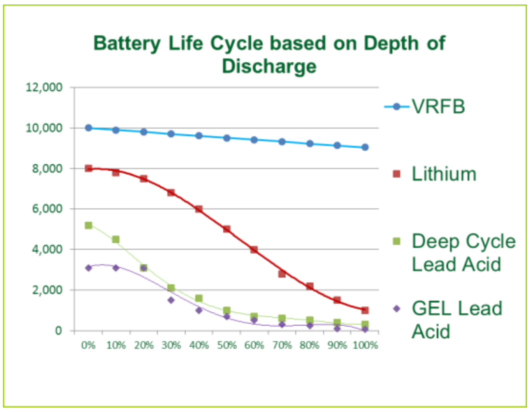


*Fig 18. Comparison of different storage types based on their battery life cycle against depth of discharge [19]*

Data from the graph given in Fig 18 was used as an input to the model. HOMER uses this data to calculate the battery throughput which is the amount of energy that is cycled through the battery over a year. This is used to calculate the battery's lifetime which determines the O&M costs and hence affects the total net present cost of the system. The formula for battery lifetime that HOMER uses is give below: [16]

$$Lifetime\ throughput = (No.\ of\ cycles\ to\ failure).(Depth\ of\ discharge).\left(\frac{Capacity.Nominal\ Voltage}{1000}\right)$$

## 4.7 Simulation Results with Storage

On incorporating VRFB into the model, the percentage of load served using onsite generation increases to 70.97%. The grid exports reduce to 17.37% because part of the excess power is used to charge the storage, as a result, the cost of electricity increases to 6.52p/kWh. Another reason for the increase in cost of electricity is due to the added cost of replacing cell stacks every 10 years. However, adding storage reduces excess electricity by 49%.

Figure 19 shows a correlation of wind speed with the battery's state of charge. From the graph, it can be seen that an increase in wind speed (blue line) results in the storage getting fully charged (red line).

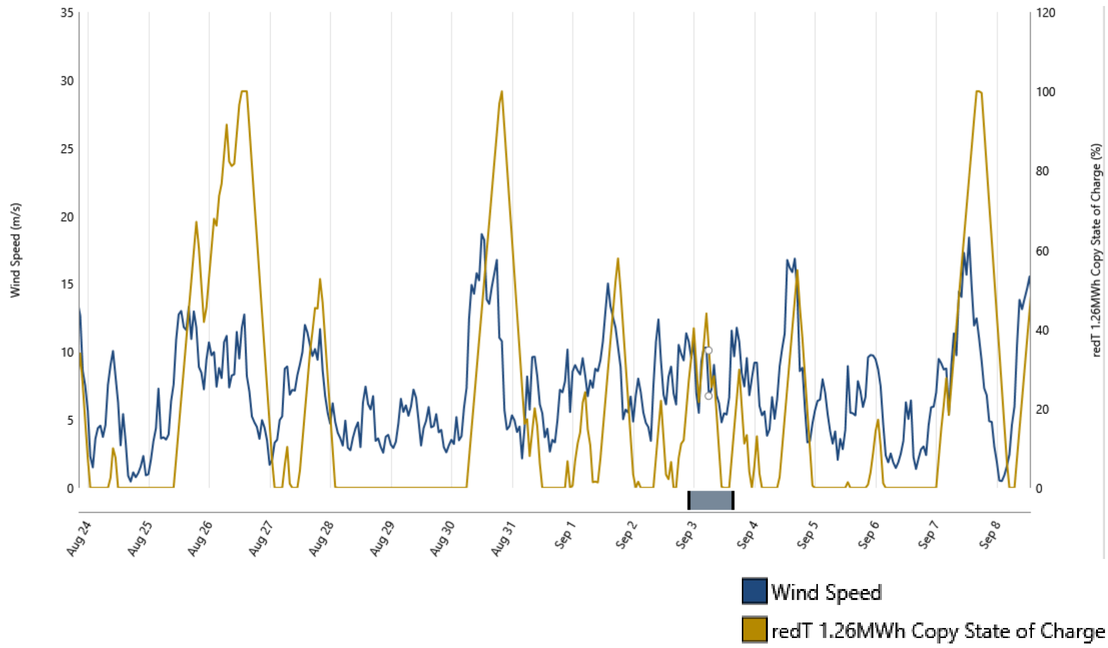


*Fig 19. Effect of wind speed on battery's state of charge*

Zooming into the two day period from 12 am on 28th of August to 6 am on 30th of August, the graph in Fig 20 shows a decrease in power generated from the wind turbines, hence following a drop in battery's state of charge. This results in power being imported from the grid for this duration.

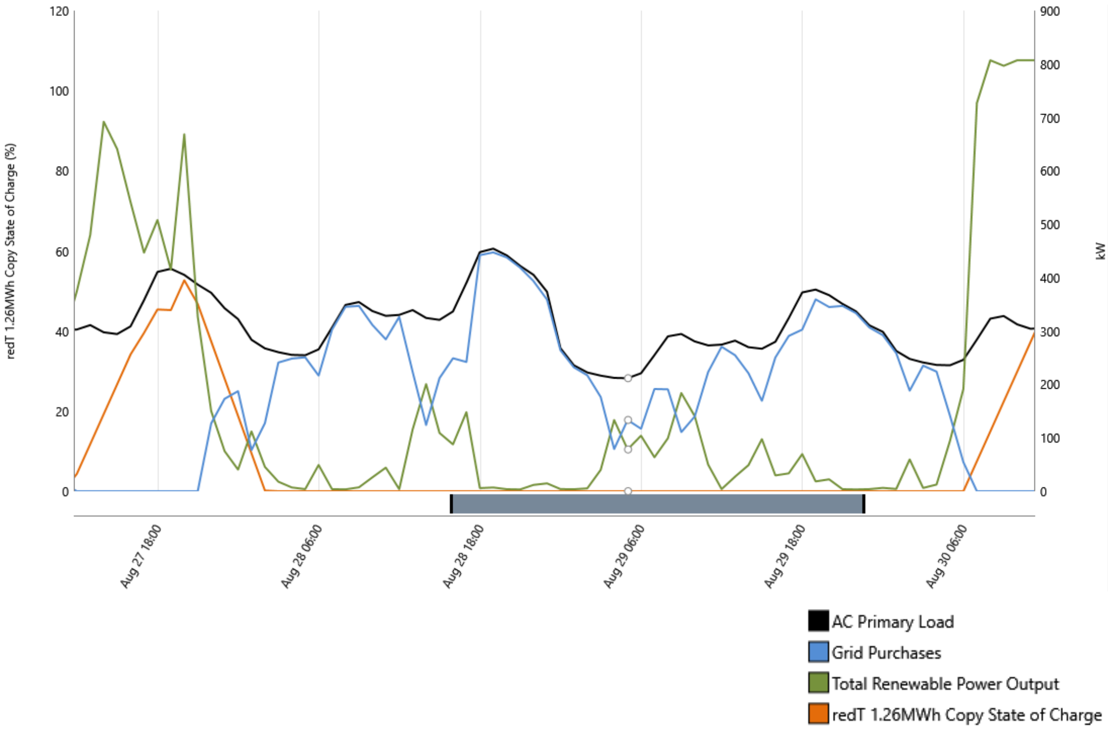


*Fig 20. Grid Imports during times of low power generation*

From 6 am to 8 pm on 30th of August, there is a peak in total renewable power output. This helps in bringing the battery back to its full charge. This is followed by a drop in wind power generation and so the battery gradually losses its charge. Power gets imported from the grid as the grid and storage work collectively to the serve the load after 8 pm (Figure 21).

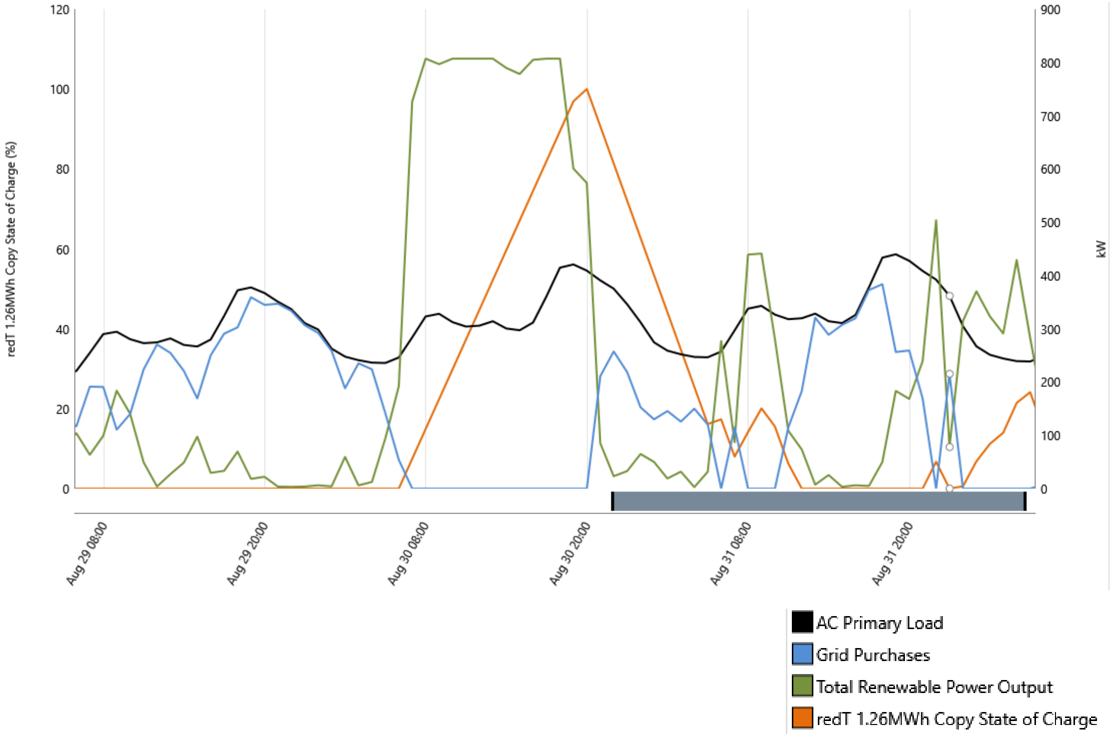


*Fig 21. Power from grid and storage used to serve load after 8pm*

# 5. Grid Optimisation

This section looks into finding an optimum system configuration that increases onsite power generation and gives lowest cost of electricity per kWh. Firstly, the effect of increasing storage capacity was investigated on the grid-diesel-storage-wind system. Secondly, the effect of diversifying the generation mix was investigated. This was done by adding PV and increasing wind power generation to a model with an oversized storage capacity. A range of values for storage and renewables were considered in HOMER simulation to find a system configuration that meets electric demands with lowest cost of electricity.

There lies potential for increasing the share of renewables on the electric grid in Gigha. However the electric company on the island is required permission from network operator to make a grid connection specific to the type of generation. Since the network operator already has the E33 wind turbine constraint, it is unlikely that they will be granted permission for increasing onsite generation without undergoing a major grid upgrade. This includes replacing the LV subsea cable with a HV one. Also there needs to a base for electric transmission on the island so that power can get distributed from closer to the source of generation, rather than going through the subsea cable. Results given below do not consider cost of such an upgrade. All simulation results account for a 1MW limit to export.

## 5.1 Increasing Storage Capacity

The effect of increasing storage capacity up to four times the initial value of 105kW, 1260kWh was investigated. Results are given in Table 3 below:

| Battery Power (kW) and Energy (kWh) Capacity | Percentage of Load Served using Onsite Generation (%) | Percentage difference (%) | Cost of Electricity (p/kWh) |
|---|---|---|---|
| 0 | 67.69 | - | 4.46 |
| 105kW, 1260kWh | 70.97 | 3.28 | 6.52 |
| 210kW, 2520kWh | 73.67 | 2.70 | 8.72 |
| 315kW, 3780kWh | 75.74 | 2.07 | 10.9 |
| 420kW, 5040kWh | 77.00 | 1.26 | 13.1 |

*Table 3. Effect of increasing storage capacity on HOMER model*

It was assumed that the only change in cost that occurs on increasing the storage is the cost of replacing cell stacks and not the capital investment or else the cost of electricity gets so high that the system is not financially viable.

Cost of electricity shows a constant increase of 2.2p/kWh on increasing storage capacity by each fold. However, the percentage difference in the amount of load served using onsite generation becomes smaller on increasing storage capacity. The percentage difference goes from being 3.28% to 1.26% on increasing storage by four times. Results shows that the percentage of load that can be met on increasing storage capacity is limited. The reason behind it is due to (i) Energy losses incurred mainly during AC-DC-AC conversion and because (ii) There is not enough surplus power to charge batteries to their full potential.

Figure 22 and Figure 23 give a comparison of the 105kW, 1260kWh battery's state of charge with the 420kW, 5040kWh battery's state of charge for a year respectively. It can be seen that the 420kW, 5040kWh battery experiences a lower percentage of charge in comparison to the 105kW, 1260kWh battery especially during the summer period when wind speeds are typically low. This situation could be improved by adding PV generation to the model.

It can be concluded that there is not enough power generated to fully utilise the 420kW, 5040kWh battery's potential. The storage system is oversized and hence less effective.

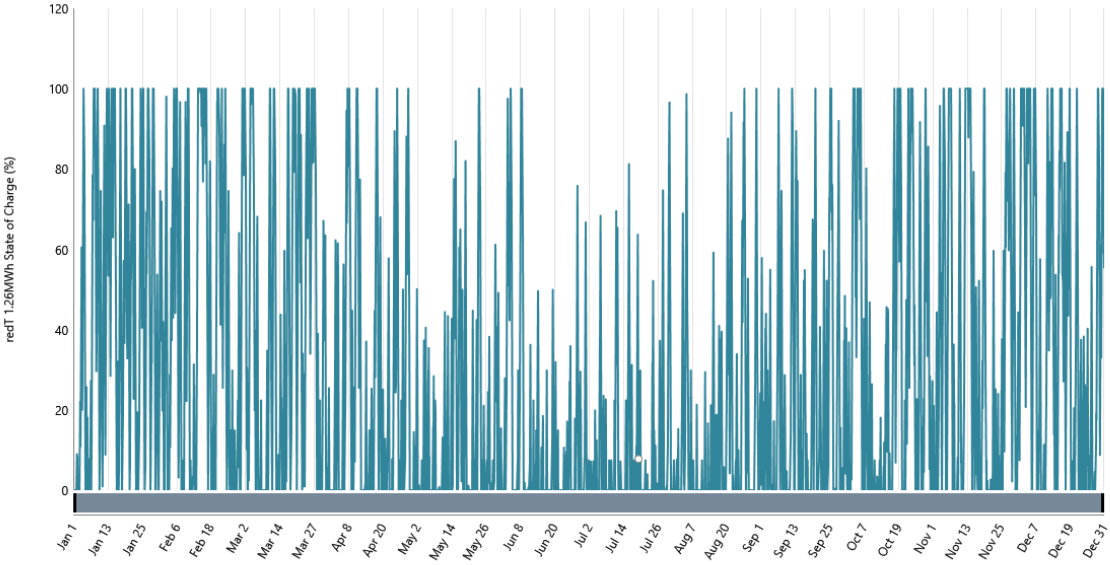


*Fig 22. 105kW, 1260kWh battery's state of charge over a year*

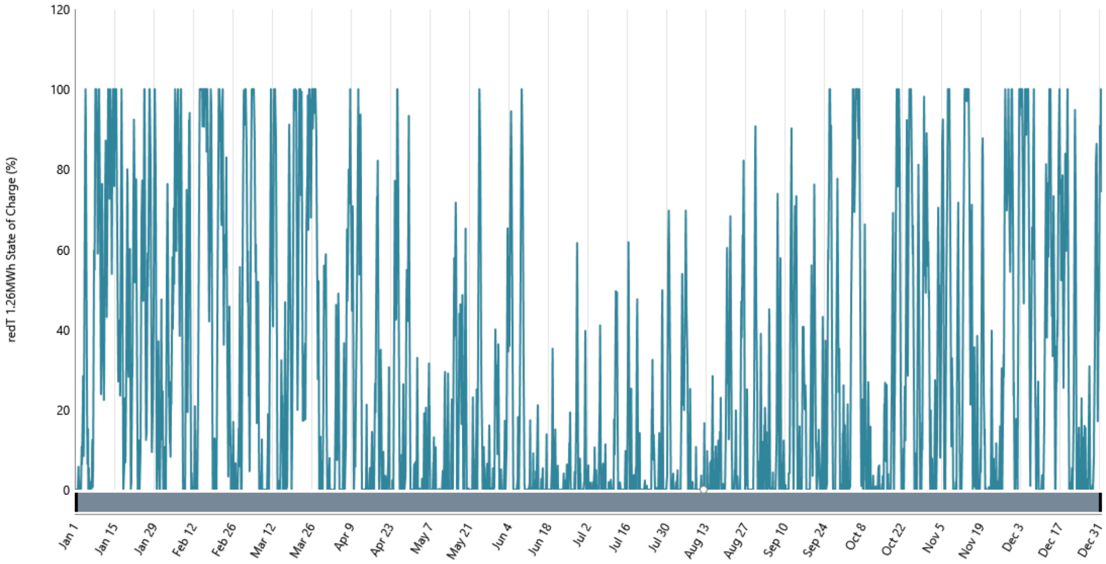


*Fig 23. 420kW, 5040kWh battery's state of charge over a year*

## 5.2 Adding PV Generation

Simulation results from Section 5.1 show that there is a lack in renewable output in the months of summer. As solar resource is higher in summers, the effect of adding PV generation to the model was investigated as this could potentially make up for shortfalls in wind power generation.

Solar resource data for 55.5° latitude, -5.5° longitude (Gigha's location) was taken from NASA Surface meteorology and Solar Energy database which is given as the monthly averaged global horizontal radiation values recorded over a 22 year period. Figure 24 shows the varying monthly radiation and clearness index vales over a year.


*Fig 24. Solar Resource in Gigha (NASA Database)*

Details for SunPower E20 Solar Panel was added to the HOMER model. Online market survey revealed a price of £440 for a 327W E20 Solar Panel. [20]

A single 327W solar panel unit has a surface area of 1.63 m$^2$. [20] An O&M cost of £16/year was estimated for the 327W PV panel from a report generated by NREL. [9]

Table 4 shows the results obtained from increasing the number of PV panels onto a model which has 420kW, 5040kWh capacity of VRFB.

| No. of PV panels | Total PV capacity (kW) | Percentage of Load Served using Onsite Generation (%) | Cost of Electricity (p/kWh) | Area of land occupied by solar farm ($m^2$) |
|---|---|---|---|---|
| 100 | 32.7 | 77.65 | 13.0 | 163.07 |
| 200 | 65.4 | 78.30 | 13.0 | 326.14 |
| 300 | 98.1 | 78.92 | 13.0 | 489.21 |
| 400 | 130.8 | 79.54 | 12.9 | 652.29 |
| 500 | 163.5 | 80.12 | 12.9 | 815.36 |
| 600 | 196.2 | 80.72 | 12.8 | 978.43 |

*Table 4. Effect of increasing PV capacity on HOMER model with 420kW, 5040kWh of storage*

Results show that increasing PV capacity increases the percentage of load served using onsite generation and reduces the cost of electricity. The cost of electricity reduces because power is being generated onsite which reduces grid imports. Any surplus of PV power gets used to charge storage which then plays a role in further reducing grid imports. Simulation results show that on using 196.2kW of PV, the energy input to storage increases by 7.28% and grid imports reduce by 16.15%.

Although increasing PV generation is an attractive option for increasing onsite generation, the area of land required for doing so is considerably high. Cost of electricity given in Table 4 does not account for the cost of land required for setting up a solar farm. For Gigha which is an island of $14km^2$, a kilometre square of land would need to be dedicated to generate less than 200kW of power. Wind turbines on the other hand occupy much less space and can generate more power per square kilometre. As Gigha holds a better wind resource than solar resource, further investigation was done on the effects of increasing wind generation on the island.

## 5.3 Increasing Wind Power Capacity

Table 5 gives the results obtained from increasing the installed wind capacity by 2 × 330kW increments. Simulation was performed on a model that has 420kW, 5040kWh of storage capacity.

| Installed Wind Capacity (MW) | No. of V27 wind turbines | No. of E33 wind turbines | Percentage of Load Served using Onsite Generation (%) | Cost of Electricity (p/kWh) | Percentage of Excess Power Generated (%) | Percentage of Power Sold to Grid (%) |
|---|---|---|---|---|---|---|
| 1.005 | 3 | 1 | 77.00 | 13.1 | 0.0 | 4.69 |
| 1.665 | 3 | 3 | 92.49 | 6.34 | 0.1 | 33.33 |
| 2.325 | 3 | 5 | 96.94 | 3.87 | 7.8 | 47.33 |
| 2.985 | 3 | 7 | 98.55 | 3.60 | 19.4 | 53.01 |
| 3.645 | 3 | 9 | 99.21 | 3.93 | 29.3 | 56.31 |
| 4.305 | 3 | 11 | 99.55 | 4.50 | 37.2 | 58.56 |

*Table 5. Effect of increasing wind power capacity on HOMER model with 420kW, 5040kWh of storage*

Results from Table 5 show a point of saturation is reached in decreasing cost of electricity on increasing wind capacity. This is because of the 1MW limit to export which results in excess electricity produced by the wind turbines. The percentage of excess power increases drastically on increasing the number of wind turbines. This percentage represents the power that is generated at times when it can neither be sold to the grid, serve the load or charge batteries.

The percentage of power sold to the grid reaches its point of saturation as the number of turbines increases. Hence the cost of adding more wind turbines exceeds the benefits obtained from onsite generation.

Simulation results show that even in the case of having 4.305MW of wind capacity, and 420kW, 5040kWh of storage capacity, 0.45% of the electricity was imported from the grid. Hence it can be concluded that because of the non-dispatchable and unpredictable nature of renewables, such as wind, 100% autonomy cannot be achieved.

## 5.4 Lowest Cost Grid Configuration

Simulation was performed of system configurations formed by the several combinations of values of storage and renewable capacity (Table 6).

| Cell Stack Capacity (kW) | Electrolyte Capacity (kW) | Generator Capacity (kW) | PV Capacity (kW) | No. of V27 Wind Turbines | No. of E33 Wind Turbines |
|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 3 | 1 |
| 105 | 1260 | 1000 | 32.7 | | 2 |
| 210 | 2520 | | 98.1 | | 3 |
| 315 | 3780 | | 196.2 | | 4 |
| 420 | 5040 | | | | 5 |
| | | | | | 6 |
| | | | | | 7 |
| | | | | | 8 |
| | | | | | 9 |

*Table 6. Various capacities of storage and renewables that form a combination of system configurations considered for simulation*

For each system configuration, the net present cost of running the system was calculated. A grid system comprised of 3 V27 wind turbines and 5 E33 wind turbines gave the lowest cost of electricity, i.e. 0.174p/kWh. 88.78% of the total electric demands were met using these 8 wind turbines. The remaining 11.22% is met by importing power from the grid. 53.2% of the total power consumed is exported the grid. Due to higher imports, the cost of electricity gets reduced.

In order to verify this result, systems with higher and lower number of wind turbines were analysed. It was concluded that increasing the number of wind turbines results in excess of electricity being generated hence making such a configuration financially impractical. Whereas decreasing the number of wind turbines reduces grid exports hence missing out on the opportunity of income generation.

This system configuration does not require storage or PV. However, it is highly dependent on the grid for meeting electricity deficit. Due to the stochastic nature of wind power generation, grid imports, however small, are very frequent and essential for meeting electricity deficit cost effectively.

In order to see the effect of removing grid connection from this model, simulation was performed by considering the same combinations of renewables and storage as defined in Table 6. Results obtained are given in the screenshot below:

| E20 327W (kW) | V27 | E33 | Gen (kW) | red T VRFB (kW) | red T VRFB (kWh) | Converter (kW) | Dispatch | COE (£) | NPC (£) | Operating cost (£) | Initial capital (£) | Ren Frac (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 98.1 | 3 | 3 | 1,000 | 420 | 5,040 | 10,000 | LF | £0.202 | £9.98M | £470,002 | £2.23M | 85 |

*Fig 25. Results obtained on removing grid connection*

This system is highly dependent on diesel generators and battery storage. 30% of the cost of the system is contributed to the cost of fuel used to run the diesel generator and 36.08% of the system cost goes to replacing storage cell stacks hence making this option financially inefficacious.

# 6. Conclusions

The first step of the project was analysing the individual contribution of energy to each sector on Gigha. In the domestic sector, 40% of households use inefficient electric heating systems and around 20% of households use fossil fuels for meeting domestic heating demands. There lies potential for a housing upgrade by replacing electric heaters with more efficient heat pumps or electric storage heaters. Moreover unprocessed waste from livestock farming is dumped on the fields which could potentially be used for extracting methane which will help shift reliance on fossil fuels exported from the mainland.

The next step was modelling and analysing the electric grid of Gigha using a software package called HOMER. It was in particular interest for this project to investigate the effect that the electric grid has on constraining power output from one of the wind turbines. Simulation results showed that the maximum power output generated from operating the wind turbines unconstraint was 806.89kW. It was concluded that liberating the power output of the E33 wind turbine possess no risk to grid integrity as the 1MW limit to export can theoretically never be achieved. Results showed no change in grid imports or exports on removing the 1MW constraint.

Gigha model was then simulated by integrating 1.26MWh of Vanadium Redox Flow Batteries. This resulted in grid exports reducing by 6.26%. The cost of electricity increased by 1p/kWh due to the added cost of storage and reduced amount of exports.

The final step of the project was to find a system configuration that gives the lowest cost of electricity by choosing from a number of storage and generation combinations. It was found out that a point of saturation is achieved in decreasing cost of electricity and increasing percentage of load served using onsite generation on increasing capacity of onsite generation. This is because of the increasing amount of excess electricity produced on, which cannot be exported due to grid limitations. Also because power is generated at times when it can neither be used to serve the load nor can it be used to charge the electric storage system. Hence it is crucial to allow exports to be unconstraint in order to avoid bottlenecking of renewable potential.

# 7. Future work

1. In order to validate the model created using HOMER, with the actual grid scenario on the island, data for the amount of imports, exports and the share of load served using renewables should be collected.
2. Potential for generating energy from producing methane using anaerobic digestion is worth investigating into. This will provide means for a source of baseload power which is required for better renewable integration on the grid of Gigha.
3. Data for the actual demand profile can be used for creating a better match of loads with generation.
4. Demand side management techniques can be used for improved system utilization.
5. Sensitivity analysis can be performed to assess how changing one parameter affects simulation results, such as changing price of fuel, interest rate, wind turbine lifetime, average electric load, project lifetime, generator minimum load ratio, effects of unpredictable weather etc.

# 8. References


1. Oliver, A., 2014. *Isle of Gigha Island Energy Audit*, Gigha: Gigha Renewable Energy Limited.
2. Isle of Gigha, 2016. *Frequently asked questions about the Gigha Windmills*. [online]Available at: http://www.gigha.org.uk/windmills/TheStoryoftheWindmills.php[Accessed 30 August 2016].
3. Community Energy Scotland, 2016. *Gigha Battery Project*. [online] Available at: http://www.communityenergyscotland.org.uk/gigha-battery-project.asp [Accessed 30 August 2016].
4. Cross, J., Simmonds, G., Ford, G., Samuel, J., 2015. Development of a Vanadium Redox Flow Battery for Renewable Generation Constraint Mitigation, *23rd International Conference on Electricity Distribution*. Lyon, France, 15-18 June 2015. CIRED: Lyon.
5. National Grid, 2016. *Network Innovation Allowance (NIA)*. [online] Available at: http://www2.nationalgrid.com/UK/Our-company/Innovation/NIA/ [Accessed 30 August 2016].
6. ELEXON, 2013. *Load Profiles and their use in Electricity Settlement*. United Kingdom: ELEXON
7. Gavin, C., 2014. *Seasonal variations in electricity demand*, [pdf], pg. 73- 76, Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/295225/Seasonal_variations_in_electricity_demand.pdf [Accessed 30 August 2016]
8. VESTAS, 1994. *General Specification, Vestas V27-225 kW, 50Hz Wind Turbine with Tabular/Lattice Tower*, Item no: 941129, Version 1.2.0. VESTAS
9. National Renewable Energy Laboratory, 2016. *Distributed Generation Renewable Energy Estimate of Costs*. [online] Available at http://www.nrel.gov/analysis/tech_lcoe_re_cost_est.html [Accessed 30 August 2016]
10. Laughlin, J., 2007. *Wind Turbines: Designing With Maintenance in Mind*. [online] Available at <http://www.power-eng.com/articles/print/volume-

111/issue-5/features/wind-turbines-designing-with-maintenance-in-mind.html> [Accessed 30 August 2016]

11. AWS TruePower, 2014. *AWS Truepower Loss and Uncertainty Methods*, [pdf], pg.4, Available at: https://www.awstruepower.com/assets/AWS-Truepower-Loss-and-Uncertainty-Memorandum-5-Jun-2014.pdf [Accessed 30 August 2016]
12. ENERCON, 2007, *ENERCON WIND TURBINES: PRODUCT OVERVIEW*. [pdf] Available at: <http://www.wind-power-program.com/Library/Turbine%20leaflets/Enercon/ENERCON_Product_Overview_Eng.pd> [Accessed 30 August 2016]
13. G2 Energy, *Enercon E33 - 330 kW Turbine*. [pdf] Earthing Design team. Available at: http://westpenninesprotectiontrust.co.uk/wp-content/uploads/2012/06/PDF-101106-Enercon-E33-Flyer-energy-production-return-claimed.pdf [Accessed 30 August 2016]
14. Petrol Prices, 2016. [online] Available at: https://www.petrolprices.com/ [Accessed 30 August 2016]
15. Iverson, J., 2007. *How to size a genset: Proper generator set sizing requires analysis of parameters and loads*. [pdf] Cummins Power Generation. Available at: http://power.cummins.com/sites/default/files/literature/technicalpapers/PT-7007-SizingGensets-en.pdf [Accessed 30 August 2016]
16. Lambert, T., Gilman, P., Lilienthal, P., 2006. MICROPOWER SYSTEM MODELING WITH HOMER. In: F. Farret, M. Simoes, ed. 2006. *Integration of Alternative Sources of Energy*. United States: John Wiley & Sons, Inc. Ch.5.
17. HOMER Energy Support, 2011. *10451 - Vanadium Redox Battery (VRB)*. [online] (11 March 2011) Available at: <http://support.homerenergy.com/index.php?/Knowledgebase/Article/View/453/19/10451---vanadium-redox-battery-vrb> [Accessed 30 August 2016]
18. Green acorn, 2016. *redT – Industrial Scale Energy Storage* [online] Available at: http://www.greenacornenergy.co.uk/#!redt-flow-battery-for-energy-storage/c2k5 [Accessed 30 August 2016]
19. Ward, J., 2015. *REDT Vanadium Redox Flow Battery (VRFB): 'Firming Up' Wind Energy & The DECC Gigha Project in Scotland*. [ppt] Dublin: REDT

Energy Ltd. Available at: <http://documents.mx/documents/john-ward-redt-energy-ltd-dublin-redt-vanadium-redox-flow-battery-vrfb-firming-up-wind-energy-the-decc-gigha-project-in-scotland-meitheal-na-gaoithe.html> [Accessed 30 August 2016]

20. Solar Online, 2016. *327W SunPower E20 Solar Panel*. [online] Available at: <https://www.solaronline.com.au/327w-sunpower-e20-solar-panel.html> [Accessed 30 August 2016]

# 9. Appendices

## Appendix I – Map of Gigha


Isle of Gigha
Giogha
Gigha Golf Club
Ardminish
North Ardminish
Ardminish Bay
Achamore House
Achamore Farm
South Drumachro Farm
North Drumachro
Wind Farm
Airstrip
Leim Farm
Pier
Gigalum Island
Caolas Gigalum
Eilean Liath
Eilean a' Chùil
Dudh Sgeir
Am Pluc
Quern Quarry
Fish Farm
Rubha Dubh
Cara Island

## Appendix II - Data for Original Power Curve E33

| Wind Speed (m/s) | Power Output (kW) |
|---|---|
| 0 | 0 |
| 3 | 5 |
| 4 | 13.7 |
| 5 | 30 |
| 6 | 55 |
| 7 | 92 |
| 8 | 138 |
| 9 | 196 |
| 10 | 250 |
| 11 | 292.8 |
| 12 | 320 |
| 13 | 330 |
| 14 | 330 |
| 15 | 330 |
| 16 | 330 |
| 17 | 330 |
| 18 | 330 |
| 19 | 330 |
| 20 | 330 |
| 24 | 330 |
| 25 | 330 |
| 28 | 330 |

Appendix III – Data for Modified Power Curve E33

| Wind Speed (m/s) | Power Output (kW) |
|---|---|
| 0 | 0 |
| 3 | 5 |
| 4 | 13.7 |
| 5 | 30 |
| 6 | 55 |
| 7 | 92 |
| 8 | 138 |
| 9 | 196 |
| 10 | 225 |
| 11 | 225 |
| 12 | 225 |
| 13 | 225 |
| 14 | 225 |
| 15 | 225 |
| 16 | 225 |
| 17 | 225 |
| 18 | 225 |
| 19 | 225 |
| 20 | 225 |
| 24 | 225 |
| 25 | 225 |
| 28 | 225 |