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# Modelling, Optimisation and the Lessons Learned of a Renewable Based Electrical Network – The Isle of Eigg

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Signed: Lewis Breen Date: 23/07/15

# Abstract

The landscape of electrical supply is changing. There is a pressing need for humanity to wean itself off its reliance on finite fossil fuel resources and switch to sustainable forms of energy capture. This has led to a rapid expansion of the renewable energy sector over recent decades; in the form of both large scale renewable "farms" and smaller distributed generation. Distributed generation is of a much smaller power rating and is sourced much closer to loads – which is against the conventional model of the Megawatt rated power plant located significant distances away from its point of demand.

This report looks into the renewable-based microgrid on the Isle of Eigg – a small non-grid-connected island on the West coast of Scotland. A model of the electrical network is created and validated using the HOMER (Hybrid Optimization of Multiple Energy Resources) software package. The model is then scrutinised to investigate how such a system can be optimised to maximise renewable penetration; which is defined as the ratio of power from renewables (used to meet a load) to the value of the demand load itself. The findings and the 'lessons learned' that can be applied further afield are then presented, discussed and compared with other microgrid configurations.

It was concluded that there is a definitive need for a mix in renewable generation technologies, along with increased storage capacities, when aiming to achieve maximised renewable penetration. Increasing either storage or generation capacities alone works to an extent, but the effect quickly becomes saturated due to numerous limiting factors. Adverse weather and/or climatic conditions should be also considered closely in the design stage of renewable based grids. The importance of "stress tests" on such models is demonstrated as these conditions can act as a severe detriment to the renewable penetration of an apparently autonomous grid.

## Acknowledgements

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I would like to highlight the contributions of John Booth, Maggie Fyffe and numerous other residents of the Isle of Eigg. During the field trip aspect of this project the islanders were extremely welcoming, patient and informative. They are proud of what they have achieved so far with their venture and continue to be a leading example of how a community can maximise their sustainability. Much can be, and will continue to be learned from the community. Their continued support throughout this project was greatly appreciated.

Lastly, but not least, a big thank you to all of my lecturers during this year of study. Your continued support, enthusiasm and knowledge has made the degree course more informative, enjoyable and rewarding than I ever could have hoped for. Thank you!

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## Nomenclature

kW – Kilowatt

W - Watt

$p_{ren}$ – Renewable penetration (%)

$P_{ren}$ – Total renewable electrical power output in a time-step (kW)

$L_{served}$ – Total electrical load served in a time-step (kW)

$P_{hyd}$ – Power output of a hydro turbine (kW)

$\eta_{hyd}$ – Hydro turbine efficiency (%)

$\rho_{water}$ – Density of water (1000 kg/m$^3$)

$g$ – Acceleration due to gravity (9.81 m/s$^2$)

$h_{net}$ – Effective head (m)

$Q_{turbine}$ – Hydro turbine flow rate (m$^3$/s)

$U_{hub}$ – Wind speed at the hub height of the wind turbine (m/s)

$U_{anem}$ – Wind speed at anemometer height (m/s)

$z_{hub}$ – Hub height of the wind turbine (m)

$z_{anem}$ – Anemometer height (m)

$z_0$ – Surface roughness length (m)

ln(..) – The natural logarithm

$P_{PV}$ – Photovoltaic (PV) array power output (kW)

$Y_{PV}$ – Rated capacity of PV array under standard test conditions (kW)

$f_{PV}$ – PV derating factor (%)

$G_T$ – Solar radiation incident on the PV array in the current time-step (kW/metre$^2$)

$G_{T,STC}$ – Incident radiation at standard test conditions (1 kW/metre$^2$)

$\alpha_P$ – Temperature coefficient of power (%/°C)

$T_C$ – PV cell temperature at the current time-step (°C)

$T_{C,STC}$ – PV cell temperature under standard test conditions (25°C)

$E_{kinetic}$ – Kinetic energy (Joules)

$K$ – Flywheel rotor geometric shape factor (dimensionless: $0 < K \leq 1$)

$RPM$ – Spinning speed (Revolutions per Minute)

$I$ – Moment of Inertia (kg m$^2$)

$P$ – Power Output (Watts)

$V$ – Electrical Voltage (Volts)

$I$ – Electrical Current (Amperes)

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# 1. Introduction

The world today is very much shaped by electricity - modern economies and many aspects of society would cease to function without it. In the developed world electricity is the backbone of everyday life. From entertainment to work, from transport to security, from cooking to communications; the list is endless as technology develops in the digital age. Security of supply is therefore a crucial element of the electricity networks of today. The electrical landscape is continuing to change, however, and with this there needs to be innovative change in order to sustainably provide electricity into the future.

The conventional mode of electricity supply has been for power stations to provide electricity to the masses through an extensive electrical grid system; stepping voltages up and down during distribution to minimise losses in the system. This is known as a displacement system. On trend, the majority of these stations have been fuelled by a fossil fuel source[i], had high capacity factors and provided a "base-load" for the electrical grid. Although this model creates a reliable grid system it also creates a problem; this is not a sustainable model.

Firstly, fossil fuels are a finite resource and, due to supply/demand markets, there becomes a point where economic strategies could affect the operation of such power stations or even close them all together[ii]. Environmentally, fossil fuelled electricity generation performs very poorly. The land required to support it is substantial, fossil fuels often need to be sourced by drilling deep into the earth's surface. Then there is the vast infrastructure of getting that sourced fuel processed and transported to the power plant before combusting it. The combustion of fossil fuels alone has significant effects on the environment; producing gases that are harmful to life (e.g. carcinogens), contributing to the greenhouse effect/global warming, generating smog, facilitating acid rain etc…

In recognition of this many acts such as the Kyoto Protocol[iii] and the Large Combustion Plants Directive[iv] have been produced to try and force governments to "clean up" their electricity supply. The Large Combustion Plants Directive, in particular, has led to numerous closures of conventional power plants throughout the European Union. These, and similar, acts have catalysed increasing investment in renewable technologies. Subsequently in recent decades there has been a surge in their presence[v], especially distributed renewable technologies (which are in far greater proximity to the electrical load and tend to be of a significantly smaller power output rating than conventional generators). If this surge continues there will be a significant shift in how electricity is delivered going into the future.

Microgrids are a potential solution for creating a sustainable electricity network going into the future. These would help to create community-level electricity grids running mainly on distributed renewable technologies; with there potentially being an option to connect to a main grid to export excess electricity, or to import electricity to address shortfalls in generation. Having a modular grid like this could significantly help increase redundancy in the entire network; minimising reliance on a central source such as a large scale thermal power station. However, the concept of the microgrid is indefinitely defined in literature – with many different configurations being classed as a "Microgrid".

Remote communities can also benefit from such technologies. Here, there may not be access to a main electrical network through environmental barriers, political barriers or, simply, just remoteness. The Isle of Eigg, an islanded community situated off the west coast of Scotland, is a prime example of this. The island consists of a microgrid which is currently meeting around 86% of its electrical demand with renewable sources. The backbone of the electrical network is made up with two 64kW Diesel generators (one duty, one standby). Ideally, the community would like to minimise the use of the diesel generators as much as possible as they are expensive to run and the bi-products of their combustion is detrimental to the environment. In doing so, they aim to increase their renewable penetration. This is defined as the power from renewables (used to meet a load) divided by the value of the load itself. A fully renewable system will have a renewable penetration of 100%.

*Equation 1: Renewable Penetration - fraction of Renewable Power to Load in a time-step*

$$p_{ren} = \frac{P_{ren}}{L_{served}}$$

## 1.1. Objective

This report aims to provide a validated model of the Isle of Eigg electrical network using a software package called HOMER (Hybrid Optimization of Multiple Energy Resources). From here, it aims to analyse the current system and provide potential improvements to the network, hence increasing the renewable penetration by minimising diesel generator run-time. The report also aims to highlight, reason and discuss the lessons learned that can be applied in a broader context beyond the Isle of Eigg. The HOMER software package is assessed throughout; with consideration being taken as to its strengths and limitations.

## 1.2. Methodology

To fulfil the objective of this report numerous steps were taken. Initially, in order to gain a better understanding of Eigg a field visit was carried out. This created the opportunity to speak with residents, interview those involved with the electricity network as well as the opportunity to see the components of the network in a real life setting. This was a crucial part of scoping out the project; as there is minimal literature available with regards to the present system on the Isle of Eigg. It was noted prior to the visit that there were many conflicts within the literature which is available, hence this allowed for clarification to be gained over the components and operation of the electrical network. In addition to this, contact was made with those who had access to much of the technical data technical data required for this report.

A literature review was then carried out to gain a sufficient understanding of Eigg's electrical system, electrical supply in other remote communities, microgrids and barriers to renewable penetration. As mentioned, it is very hard to give a definitive configuration of a microgrid due to numerous configurations worldwide being classed as a microgrid. This review was used to improve understanding with regards to Eigg, and where it fits in under the extensive microgrid definition.

In order to model Eigg as per the objective of this report, a tool assessment was carried out initially to ensure the desired project scope could be achieved. The tool in question is HOMER[vi] – a commercially available microgrid design tool. From here, a model of Eigg was validated in comparison with real life data gained through the field visit – before looking into further configurations of the network which could be used to optimise the performance, and thereby increase the renewable penetration, of the island. This resulted in four configurations being highlighted as examples of 100% renewable penetration configurations for the island.

Following this, the results were analysed and compared to see what 'lessons learned' could be pulled from the model. These were discussed in depth and applied to other models (e.g. a model of the Isle of Gigha) to investigate their viability. The 100% configurations were also "stress tested" as part of this discussion. This allowed for an integrity test to be carried out on the configurations – to see how they would perform in extreme adverse conditions. The 'lessons learned' and any further findings obtained from this discursive investigation were then compiled into definitive conclusions and identified areas for future work.

# 2. Literature Review

*Due to the nature of this report, much of the literature review was carried out in respect to microgrid definitions and the technologies investigated as part of the Objective (1.1). Therefore the literature review extends further into the main body of this report.*

Kemsley, McGarley, Wade and Thim investigated the isles of Foula and Eigg in their 2011 paper[vii]. They present their respective power systems – describing the differences and similarities between the two. To be successfully implemented on the islands, the paper stated that the electrical systems should aim to:

- provide a safe, reliable electrical network that could provide 24 hour availability
- prove simple to operate, maintain and repair within the skillset of the local community and available support
- adhere to financial, environmental and aesthetic constraints
- achieve a high penetration of renewable energy
- minimise the operating time of the backup diesel generators – and optimise their efficiency
- make use of standard, rather than bespoke, components where available.

Both designed by Senergy Econnect Ltd and Wind and Sun Ltd, the systems make use of SMA's Sunny Island Battery Inverter systems to generate a 3-phase reference power supply smoothed out by battery technology. The systems also both have wind, solar (PV), hydro and Diesel components in addition to the battery banks. The paper analyses these electrical networks, their challenges and control philosophy in order to obtain 'lessons learned' from these "high-penetration" networks.

These lessons learned detailed that it was of upmost importance to consumers that their electrical supply is secure and reliable – the diesel generators are highlighted as the vital backbone enabling such a grid to be able to do this. The paper also states that "The use of multiple renewable energy sources helps to accommodate seasonal output variations from each source and minimise diesel fuel consumption over the year" and that "Systems with multiple generation sources will require more maintenance than networks supplied from a mainland grid or from a single (e.g. diesel) generator".

The battery component is highlighted as a "key component" in the paper, and it states that increasing storage capacity is "more effective in accommodating variations in load demand and renewable energy input". Pumped hydro storage is mentioned as being a readily available, natural form of storage (with the construction of a reservoir), which could be used to provide significant gains in reducing the burden on the current battery systems.

However, the paper is somewhat out of date with the current configuration on Eigg. Having been written in 2011 it does not account for the 2013 expansion of the photovoltaic capacity on Eigg. In addition to this, the stated photovoltaic capacity at the time of writing is marginally wrong; it would have been 30.9kW instead of the stated 29.9kW.

In line with the objective of this report, Eigg has already been modelled using HOMER in a journal[viii] entry by Chmiel and Bhattacharyya (2014)[ix]. Although this gives a solid analysis of the model produced, the model fails in many aspects to be representative of Eigg. This leads to the renewable penetration of the model being 89%; 3% off the 86% average renewable penetration currently achieved on the island. There is, however, a very stochastic nature in renewable energy sources. Therefore such a computational model is always likely to contain some error as it will not be able to fully accommodate the uncertainties in natural resources.

The diesel generators described in the paper are of the wrong size (80kW instead of 64kW) giving the model an extra diesel generator capacity of 32kW – (i.e. half the capacity of one generator). This error may have been in part to the apparent power of the generators equalling 80kVA.

The battery bank system also has its issues in the paper. Firstly, the battery depth of discharge has been set to 50%, not the 60% used on the island to maintain battery life. A 10% extra discharge can significantly reduce battery life and hence Eigg uses the lower 'depth of discharge' value. In addition to this, the actual set up of the batteries in the model is inaccurate. Assuming that they have modelled the battery as per the manufacturer's technical specification sheet (Section 4), the paper has set up the 4 Volt battery in 4 strings of 24 batteries. This would give the batteries a bus voltage of 96V. On the field trip, the found state of the battery bank was 8 strings (4 set of parallel strings) of 12 batteries; instead giving a bus voltage of 48V. This is also what is stated on the island's website[x].

The other two renewable technologies, wind and hydro, also vary. The wind turbine model used is of a different manufacturer, Kingspan – who purchased the original wind turbine manufacturer Proven[xi] in 2011. Even though the Kingspan turbine used in this report appears very similar, the power curve is slightly different to that of the older model used on Eigg and this may contribute to some marginal inaccuracies in the model. Despite this, the paper does not use the given Kingspan KW6 wind turbine power curve – instead using a power curve of a BWC Excel-R 7.5kW turbine to create a KW6 entity in HOMER.

The hydro resource, the amount of river run available on the island, is also not appropriately described; there is an incorrectly labelled figure presenting hydro resource with no description on how it was sourced. During the field trip it was noted that hydro resource is not recorded – therefore this report used an iterative method, working backwards from the average monthly hydro output, to find out the hydro resource present on Eigg.

Hence this paper, for all of its solid analysis of the model produced, has shortfalls in its representation of the Isle of Eigg. Error is going to be forever present in such a computational model, due to the stochastic nature of renewable energy, but there are several modifications that could be made to the model produced by Chmiel and Bhattacharyya that would allow for increased accuracy in modelling the Isle of Eigg.

Kariniotakis, Dimeas and Van Overbeeke (2014)[xii] provide a fairly extensive overview of microgrid projects across the world – focussing on Europe, the USA, South America, Japan and China. Focussing on the successes and lesson learned, they highlight the recent microgrid research and design investment in Europe; running into the value of tens of billions of Euros (€). One of the success stories describes the Wallstadt Ecological Estate (Mannheim, Germany), which is highlighted as a proof of concept for microgrids operating in both grid-connected and islanded modes. MVV Energie[xiii] ran the project which not only successfully achieved a seamless transition between operating modes, but also installed control logic into the microgrid to manage loads, storage and generator outputs. The control logic is another positive outcome of the project; of the 24 houses involved in the project it was concluded that loads could be significantly shifted to improve the integrity of the microgrid alongside predicted renewable generation output.

The paper also uses Chinese islands to highlight the concept of microgrid use in remote communities. A Megawatt level multiple-energy-source microgrid on Dong'ao Island is described. Although the microgrid island is made up of wind (50kW), PV (1000kW) and diesel generation (1220kW), around 80% of the power required for the island comes from the PV panels in line with a 2000kVAh battery bank.

*Figure 1 – One of Dong'ao Island's PV arrays[xiv]; which provide around 80% of the island's electricity*

Load control and demand response is investigated by Hesser and Succar[xv]. Their paper looks into the concept of demand response (or DR) as a method for increasing reliability in grid applications with significant quantities of integrated renewables. Demand response is growing in potential in electricity sectors, due to technological advantages, and it can aid in "smoothing out" the highly variable output from renewable electricity generators.

In particular, Hesser and Succar look at the possibility of integrating demand response in grids with high levels of wind penetration – concluding that there is "potential (for DR) to take a prominent place in the portfolio of wind integration strategies". When analysing such applications for demand response both reliability and economic concerns were evaluated.

The paper also looks at direct load control – the controlled ramping up and down of electrical loads to accommodate the lack of renewable penetration on a grid. It identifies that moving into the future there is potential to utilise building automation and software developments to integrate industrial, commercial and residential loads into such load controlled electrical grids. Having an appropriate control system in place could increase reliability and allow such a system to run automatically without oversight.

In general, though, the paper favours demand response. Noting that for it to be used successfully it needs the right economic “tariffs” and “market products”, and that the flexibility it provides to the grid as a whole is deemed highly beneficial. Despatchable sources, energy sources that can be ramped up and down, are highlighted as being an integral part of such a “demand response” backed grid.

The Isle of Gigha off the west coast of Kintyre, Scotland is an example of a community owned Island currently addressing the issues with an increasing presence of renewable technologies. Wilson, Samuel and Simmonds[xvi] highlighted the issue preventing the grid-connected island from increasing its renewable generation capacity and therefore its renewable penetration.

Currently, the island has 3 wind turbines, known as “The Dancing Ladies”. A project to install a fourth wind turbine is in progress (at the time of writing of the paper) – but this will be required to be constrained in its power output to ensure that the 11kV electrical network infrastructure does not experience an excessive voltage rise. This is entirely a limitation provided by the network itself. An estimated 3GWh of potential electricity could be lost over the 25 year lifespan of the turbine, significant losses could also be incurred financially as they would lose out on renewable generation subsidies and the opportunity able to sell this electricity back to the main grid. The paper highlights that this is an issue affecting many rural communities throughout Scotland, and that grid capacity is a significant obstacle to realising national goals[xvii] of producing the equivalent of 100% of Scotland’s electricity demand via renewable energy sources by 2020.

The paper looks into how energy storage systems could be used to overcome the network capacity issue on Gigha. A comparison is made with Demand Side Management (DMS) and Active Network Management (ANM) systems but energy storage is chosen as the most desirable option in the short term – though it is stated that in the future a combination of all three solutions may be likely to come to fruition. The energy storage would ideally be located anywhere between the wind turbines and the connection to the 11kV grid – therefore protecting the grid from any excess generation and allowing the fourth turbine to be unconstrained.

The application and sizing of the energy storage required is mentioned as being ideally suited to the characteristics of flow battery technology. The paper makes a final rationale that a 1.2MWh Vanadium Redox Flow Battery could be used to alleviate the current limitation on renewable energy generation which exists. In addition to the generation which exists, it is highlighted that future renewable generation (such as PV or tidal generation) could be added to the island infrastructure using such storage.

## 3. Microgrids

The term "microgrid" is a broadly used term but it tends to be applied to well-defined, interconnected areas of energy distribution networks. These will be made up of both loads and generation – both electrical and thermal. The generation in these networks tends to come from non-conventional or renewable sources; made up of distributed generation in the form of technologies such as small scale hydro, solar, combined heat and power plants (CHP), wind, small scale storage etc…

Some definitions of "microgrid" include the capacity of the defined network area to operate autonomously or as part as a wider electrical distribution network (heat transfer is very inefficient so it is not as desirable to distribute heat on a larger distribution network). This can be described in the terms "islanded" and "non-islanded". This is a very desirable characteristic as it can help secure electrical supplies (i.e. when distributed generation cannot meet demand or when the wider grid has a black-out).

The official definition of a microgrid according to the Electric Power Research Institute, National Grid (UK) and the U.S Department of Energy is:

"*A microgrid is group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and that connects and disconnects from such grid to enable to operate in grid-connected or "island" mode.*"[xviii] [xix] [xx]

Microgrids can have many uses. Although this report looks at their use in remote communities such as the Isle of Eigg, microgrids can be used (to provide a vital uninterruptable power supply) in hospitals, public service buildings, housing districts/eco-villages, prisons, community hubs, stadiums communication/transport networks etc…

Microgrids may also have the ability to control loads through a logic/control system. These can be categorised into sensitive, adjustable and shedable loads as per *Figure 2* – which shows one interpretation of a microgrid:

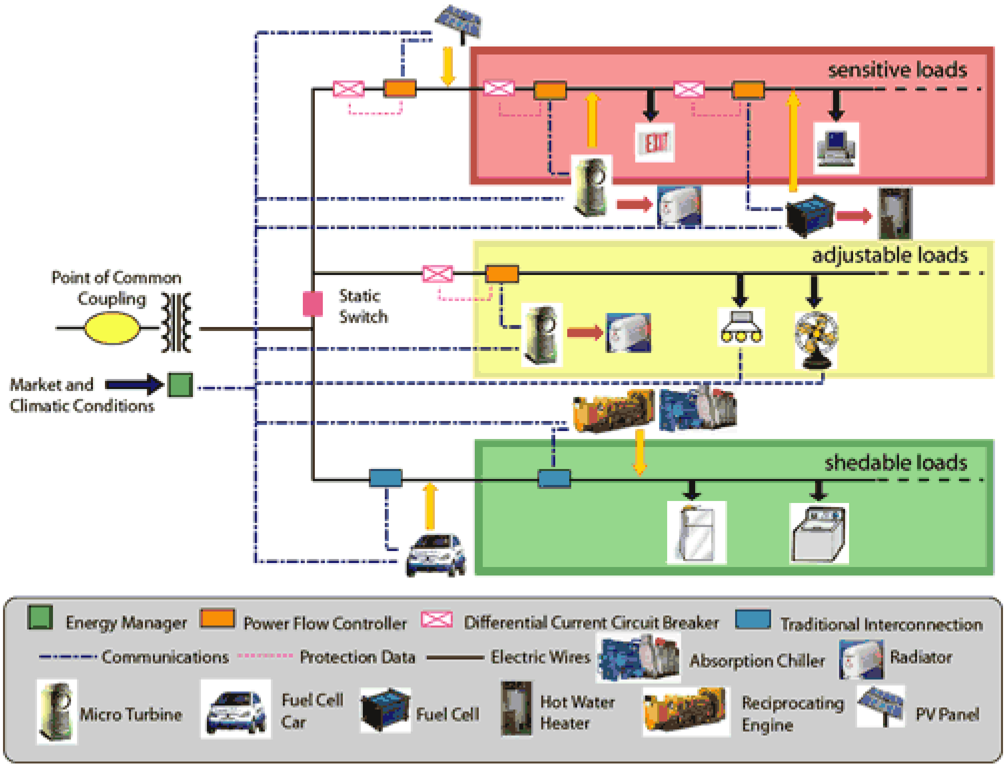



*Figure 2 - Microgrid Schematic*[xxi]

Each load category is based on how crucial the load is for the consumer. For example, it can be seen from *Figure 2* that emergency exit signs and home entertainment systems, such as PCs, are classed as sensitive. "Sensitive" means that it would be very unlikely that these systems would be controlled; either for safety concerns or due to customer demand. "Adjustable" loads can be described as loads which may be altered - albeit with some caution. This is mostly applicable to heating and cooling systems, which are often used ineffectively in buildings. However, controlling these systems could be very dependent on climatic conditions – i.e. it may not be suitable to control a cooling system in the middle of a heat wave. "Shedable" loads are described as loads which can be quickly cut-off from the microgrid. Ideally, this should have minimal effect on the quality of life of the end user. An example of a shedable load could be a washing machine; which could be controlled so it would operate at a time of excess electrical production or a time outside of projected peak demand periods.

It is important to recognise that microgrids are not a complete solution to the current challenges facing the energy frontier today. For the security of supply and opportunities they provide, there are still some considerable drawbacks. Microgrids require high installation costs – mainly due to the high capital costs of distributed energy generators. In terms of remote communities, the initial outlay is also likely to be higher due to the transportation of goods and people (skills) for the construction phase.

Microgrids are also a fairly immature concept. Although well established in some instances (i.e. hospitals) there is a significant lack of experience in this field. Therefore more research is still require to utilise the concept to its full potential. Load control has the potential to be a very significant contributor to the success of some microgrids; but this area is also immature - and is currently being researched as part of the ORIGIN project[xxii].

Despite the current drawbacks, microgrids ultimately can be used to help wean energy supply off fossil fuel sources and provide a greater redundancy in energy supply. They can allow for reductions to be made in the carbon footprint of an energy network and could provide a higher quality of electrical supply (i.e. improved voltage, power and frequency profiles) as the generation source is closer to the load. Small communities may also benefit financially in the longer term from a microgrid system; as they will be producing their own electricity and may not be under as much influence from energy companies.

## 3.1. The Isle of Eigg as a Microgrid

The Isle of Eigg is a small island located in the Scottish Inner Hebrides. Lying to the South of its more famous neighbour the Isle of Skye, the island is home to a population of approximately 100 people. It has a land area of 31km$^2$, much of which is used for crofting. The main industry on Eigg is tourism; it has a vital link to the mainland via a ferry which also brings across supplies to the island such as food, diesel and other consumables.

*Figure 3 - Aerial View of Eigg from the North* *© Copyright of Angus and Patricia MacDonald*[xxiii]

The island was bought in 1997 by the Isle of Eigg Heritage Trust[xxiv] - a landmark community buyout. The Trust is a partnership between The Highland Council, The Scottish Wildlife Trust and the population of Eigg. Prior to 1997 the island had been passed between many owners whom were either disinterested or had poor relationships with the residents of Eigg. This had resulted in a lack of home and business security, unemployment (lack of opportunities for employment), no mains electricity supply and generally poor housing conditions.

The buyout allowed and continues to allow the community to be involved in all major decisions that affect the island. Initially, the Trust set about renovating buildings, setting up a broadband internet network and building a multi-purpose centre for the island. However, the landmark change was how the community developed their electrical supply.

Prior to 2008, Eigg's electrical supply was made up of privately owned diesel generators which ran as and when their owners required power – no electrical grid was present. There was some small-scale, privately owned wind and hydro installations on the island, but these were solely for their owners use. Wind & Sun[xxv] were contracted by the Trust to install a new electrical microgrid system which could provide the island with a secure 24 hour electricity supply. On the 1st of February 2008 this became a reality. The island not only had a secure supply of electricity, but had an electrical network made up mainly of renewable energy technologies that continues to be an inspiring example for electrical networks elsewhere.

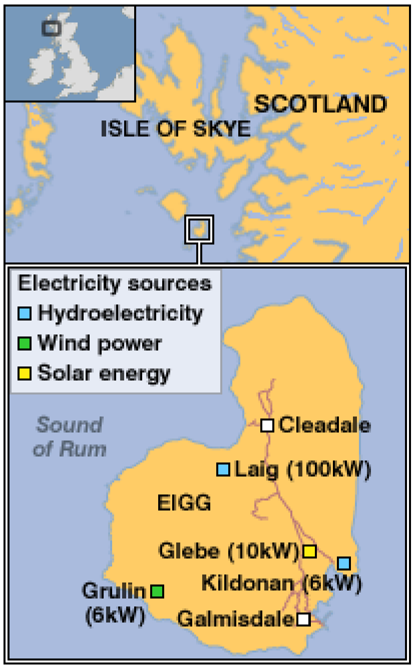



*Figure 4 - Eigg Location and Electricity Network as of 1st February 2008*[xxvi]

The microgrid has been expanded since 2008 to have an increased wind and PV capacity. At present (2015) the grid consists of four 6kW rated wind turbines, three PV arrays (9.9kW + 21kW + 22.5kW) and 112kW of rated hydroelectric capacity (100kW + 6kW + kW). In addition to this, there is a battery storage bank present and two 64kW diesel generators, one duty and one standby, which are run to make up the backbone of the network in times of low renewable and battery output. It should be noted that there is also. This was not considered as part of this report as, due to its experimental nature, any technical information about this is strictly confidential.

Unlike some other microgrids, the Isle of Eigg does not have the capability to connect and disconnect to the main electrical grid. This is a possibility which has been avoided due to the extremely high capital cost of installing an electrical link between the mainland and this island. Instead, the diesel generators fulfil the role the main grid would play in other microgrids; they supply the electricity when there is not enough to be had from renewable generation and energy storage.

Eigg does not have control systems for the microgrid, though there is an instantaneous power consumption limit applied to every premise. Households have a power limit of 5kW and businesses are limited to 10kW respectively. This forces the residents of Eigg to be responsible with their power usage as they are charged a reconnection fee if their supply trips out due to them exceeding this limit.

At peak times of renewable generation, sometimes there is no use for the excess electricity produced. When this occurs on Eigg the community buildings are heated using the excess electricity – this acts as a “heat dump”. If this is not viable, heat will be dumped using open air heating elements located up at the windfarm. Nevertheless, it is undesirable to have to dump energy. Ideally this should be minimised, and the fact that energy dumping occurs on Eigg indicated that there may be a potential for increased energy storage capability.

## 3.2. Eigg's Renewable Performance

*Figure 5* shows the performance of Eigg's renewable technologies, as a percentage of capacity, over the time period of November 2008 to March 2015. Seasonal patterns can be seen amongst the renewable technologies – as the average power outputs vary across the year.

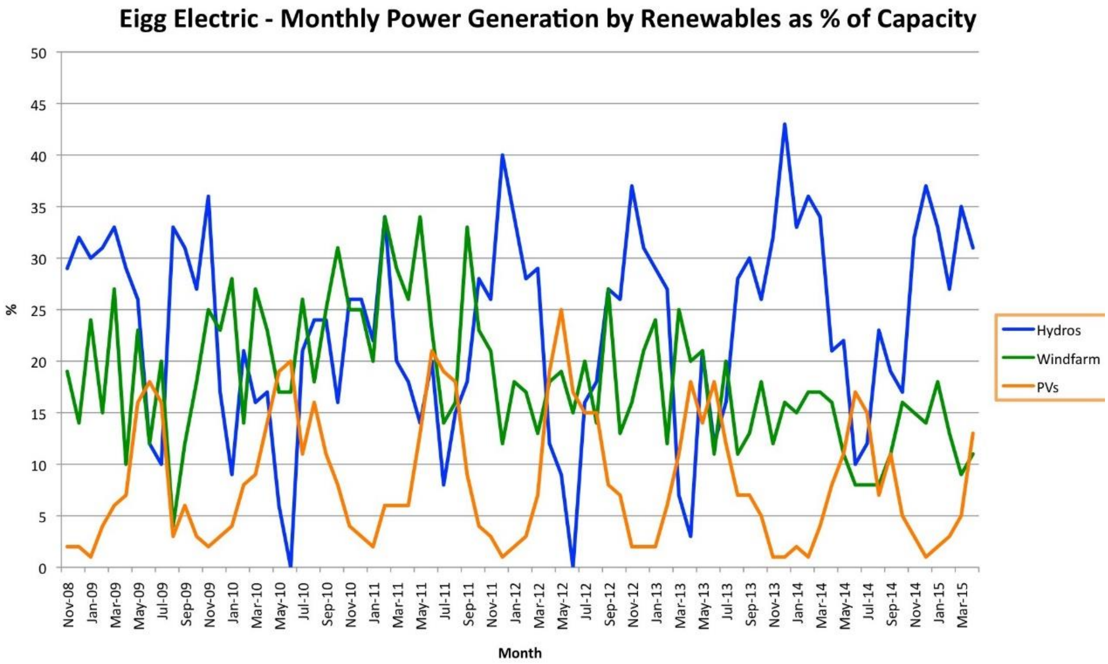



*Figure 5 - Monthly Power Generation by Renewables on Eigg*

The hydro resource output is lower in the warmer months of the summer – in line with less precipitation and, generally, drier conditions. This results in a throttling back of the hydro output due to the lowering of available resource and the need to maintain a residual flow to the stream the main hydro turbine runs off of. The residual flow helps maintain the environmental conditions in the stream and helps to minimise the environmental impact of the hydro installation. The winter months, though, provide a peak in hydro output in line with the expected high precipitation levels at that time of year.

The winter months also provide a lull in PV (Photovoltaic) electricity generation. This is due to the lower daylight levels due to sun position, increased cloud cover and shorter daylight hours; hence less solar radiation being present on the panels. However, the hydro generation at this time can be seen to more than make up for the shortfall in PV output. This "balance" with hydro and PV somewhat continues into the summer months - where PV generation is boosted by longer daylight hours and less cloud cover. This helps to compensate for the diminishing levels of hydro resource (on average).

The wind generation on the island is less affected by seasonal changes, but there is still a slight trend. Still considering *Figure 5*, it can be seen that there is, on average, a slightly higher wind output over the winter months in comparison to the summer months.

From these trends it was hypothesised that the model produced would show an excess of energy generation in the winter months, due in particular to the excess hydro resource available. To the contrary, it was hypothesised that the model would show the lack of hydro resource in the summer months would not quite be made up for by the increase in PV output – essentially because the capacity of the solar array on Eigg is significantly lower than that of the hydro, and that there will still be minimal generation during night time hours.

# 4. Modelling Eigg using HOMER and Validation

A model of Eigg was created using HOMER software as per the objective of the report. HOMER is a simulation software which allows annual analysis (by the minute or the hour) of both islanded and grid-connected microgrid systems. It allows for optimisation studies to be carried out quickly and efficiently, and also allows for many “what if?” scenarios to be carried out in a single simulation (via a sensitivity analysis). After being compared with another software package called MERIT[xxvii] (a supply and demand matching tool), HOMER was selected for this project as it provided a simple, intuitive interface with most of the necessary aspects already included for completing the objective of this report.

As this report will highlight, it is not yet a complete software package; it has its limitations and shortfalls. This has necessitated the need for some ‘workarounds’ or hand-calculations to be used during this investigation.

This section covers how the model was inputted into HOMER and the methods in which the model was assessed to ensure it was a valid representation of the electrical network present on the Island

### Demand Profile

Demand data with a suitable time-step could not be obtained from Eigg Electric – only averaged data from metre readings. Therefore a synthetic demand profile was created using the built-in load generator in HOMER. *Figure* 6 was obtained from Eigg Electric, this shows the monthly generation both for the island's renewable technologies and diesel generators. By summing the generation and dividing by the number of hours, *Figure 6* was used to average out a demand and observe any trends.

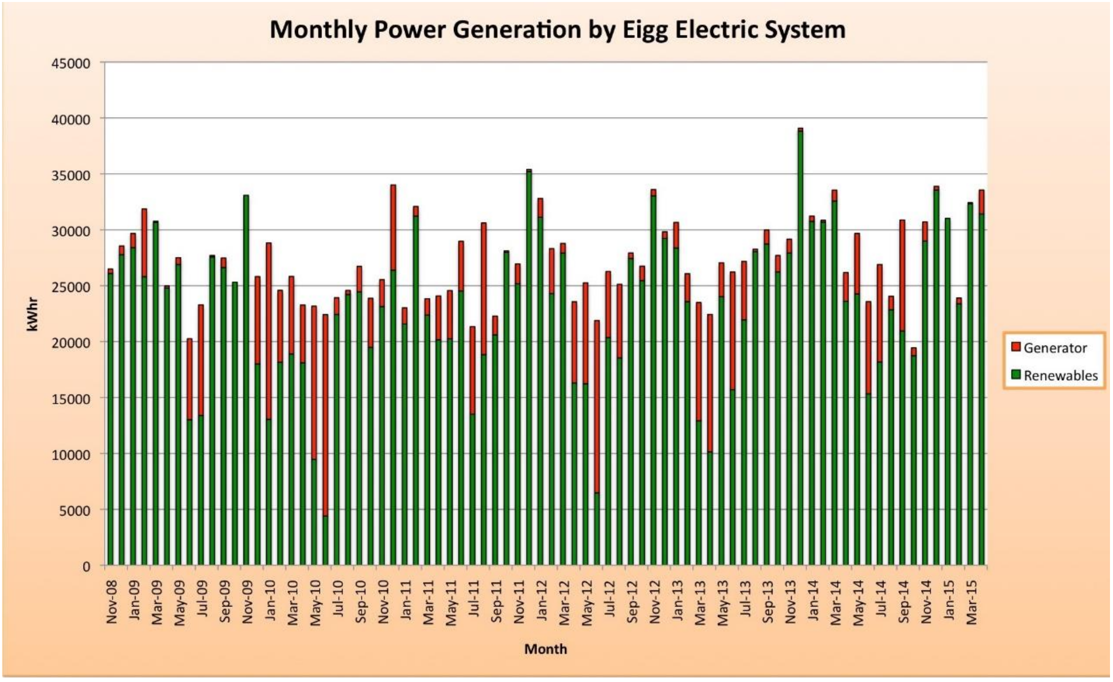



*Figure 6 - Monthly Power Generation (Nov 08 - Mar 15)*

It was chosen to create a "Residential" demand profile with a calculated average annual demand of 856 kWh/day. This is in line with the load inputted by Chmiel and Bhattacharyya (2014)[xxviii]. The load type was selected as Alternating Current (AC) and had the characteristics shown in *Table 1:*

*Table 1 - Load Characteristics*

| Metric | Value |
|---|---|
| **Average kWh/day** | 856 |
| **Average kW** | 35.67 |
| **Peak kW** | 92.3 |
| **Load Factor** | 0.39 |

It is a common trend in western society for daily load profiles for a community to have a drop in demand after around 1000 hours lasting until late afternoon. This is due to residents not being present (i.e. at work). The situation on Eigg differs from this; most residents will still be present in their abode and hence it is less likely that there will be a significant drop in demand during these hours. Considering this, the average daily load profile represented in *Figure 7* was created:

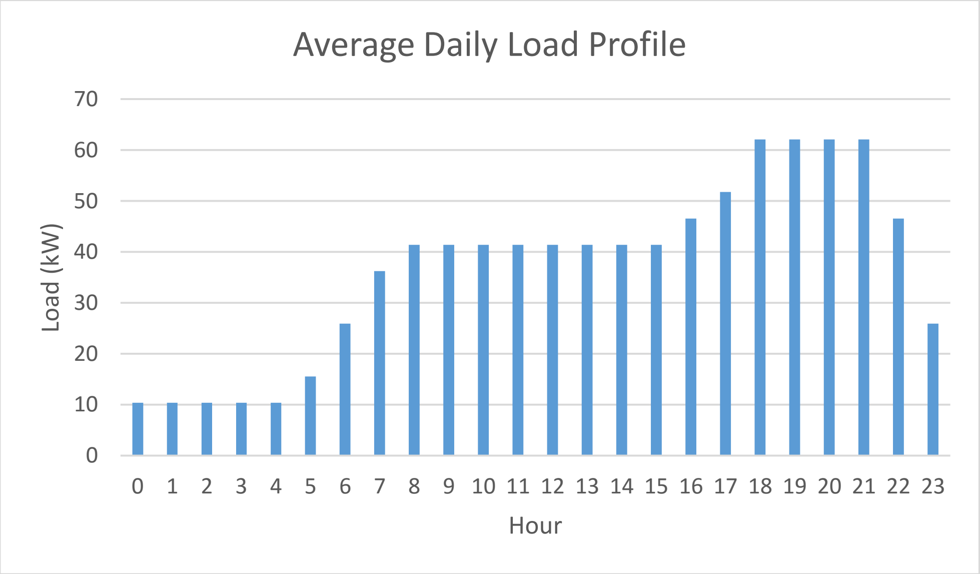



*Figure 7 - Average Daily Load Profile created using HOMER*

The profile predicts that the electrical demand will be low in the early hours in the morning and will rise as the residents wake up and start to use the appliances in their homes. From here it will remain fairly constant as there is not a likelihood that there will be mass commuting. In the evening the profile depicts a further rise in demand in the prediction that more of the population will be using appliances such as televisions, lighting, computers, cookers, and white appliances all simultaneously. The demand then decreases towards midnight as residents go to sleep and therefore tend to switch off electrical appliances.

### Hydro

The electrical grid on the isle of Eigg has three hydro inputs; one 100kW and two 6kW turbines. However, HOMER only allows for one hydro input to be added to the system. Therefore a virtual hydro had to be created that would represent the overall hydro output for the 3 turbines. This was achieved by applying the following criteria to the hydro module in HOMER:

*Table 2 - Hydro Parameters inputted into HOMER*

| Parameter | Value |
|---|---|
| **Available head** | 124 meters |
| **Design Flow Rate** | 130 Litres/second |
| **Minimum Flow Ratio** | 5% |
| **Maximum Flow Ratio** | 100% |
| **Efficiency** | 75% |

The monthly hydro output (for 2014) for the island was obtained during the field trip. This allowed for the hydro resource tab to be adapted so that the simulated data would comply with measured power output data. The prescribed (calculated) resource can be seen in *Figure 8*. It can be seen that the trend is for there to be a drop in the available hydro resource in the summer months on Eigg. This is a real-life issue which results in the throttling back of the main hydro turbine output during drier/warmer periods.

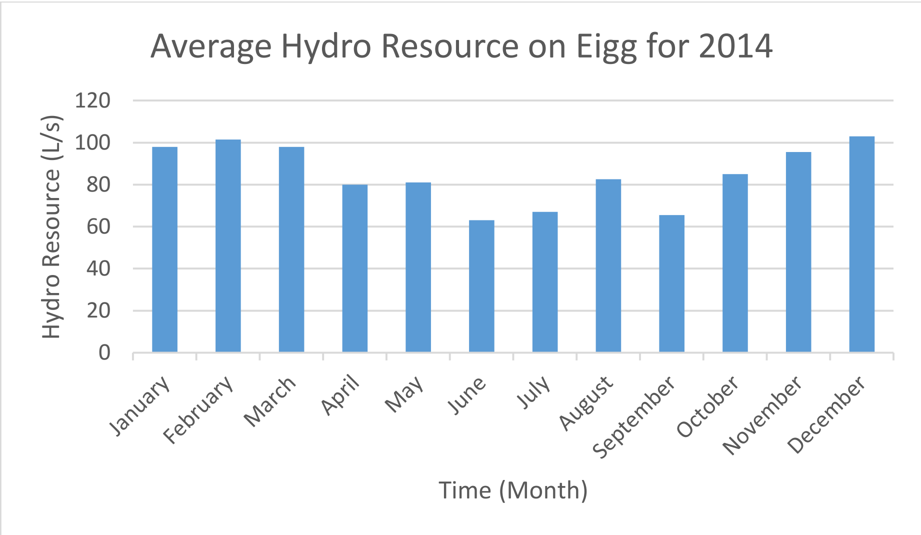



*Figure 8 - Average Calculated Hydro Resource on Eigg for 2014*

In addition to the flow going through the three hydro turbines, a 50 litre per second residual (bypass) flow was created. This was to represent the fact that the hydro turbines on Eigg are “run of river” turbines (i.e. there is still some flow which is bypassed away from the turbine to maintain the river flow – mainly to minimise any environmental impact).

From these inputs, the hydro power output is calculated for each time-step using *Equation 2*. This takes into account the efficiency, density of water (1000kg/m$^3$), acceleration due to gravity (9.81 m/s$^2$), the available head and the hydro turbine flow rate. The flow rate is the variable per time-step, hence this is what will ultimately govern the hydro output. Therefore, the average power output from the hydro will follow the same trend described in *Figure 8*; as the hydro resource falls in the summer months, the power output will fall linearly with this. The same applies for the winter months – it was hypothesised that the excess hydro resource during this period would result in excess electricity in these months.

*Equation 2 - Power output of the Hydro System*

$$P_{hyd} = \frac{\eta_{hyd} * \rho_{water} * g * h_{net} * Q_{turbine}}{1000\ W/kW}$$

*Figure 9 - The hydro dam on Eigg*

## Wind

The wind turbine model used on the Isle of Eigg is the Proven WT6000, which is a 6kW rated wind turbine with a reputation for its robustness and simplicity. There is not currently a standardised model of the WT6000 in the HOMER library, therefore an entity was created to represent it using the manufacturer's installation guide and specification sheet (Section 9.1). This included inputting a power curve for the wind turbine model, which allows HOMER to calculate the generated output per turbine depending on the associated wind speeds over a time period. In total, 4 turbines were added to the model to represent the total wind generation capacity of 24kW for the island.

*Figure 10 - A proven WT6000 on the Isle of Eigg*

A wind resource was added using the NASA Surface Meteorology and Solar Energy Database[xxix]. As there is not any recorded data for the Isle of Eigg, the database uses the "SSE Methodology"[xxx] to calculate a prediction of wind (amongst other renewable) resources at a given point. For this case the wind resource was calculated for 56.893 ° latitude, - 6.153 ° longitude; representative of Eigg's location. The resulting calculated wind resource is based on a 10 year average of the most local monitored data from July 1983 to June 1993).

*Table 3 - Modelled Wind Resource for the Isle of Eigg at 20m Height*

| Month | Average Wind Speed (m/s) |
|---|---|
| **January** | 11.030 |
| **February** | 10.340 |
| **March** | 10.080 |
| **April** | 8.100 |
| **May** | 7.370 |
| **June** | 6.660 |
| **July** | 6.940 |
| **August** | 7.210 |
| **September** | 8.450 |
| **October** | 9.440 |
| **November** | 9.680 |
| **December** | 10.420 |

Using this average wind speed data, HOMER uses a 'synthetic wind speed data synthesis algorithm'. This generates statistically rational time series data for wind speed; "statistically rational" as this accounts for the characteristics of real wind speed data (strong sustained gusts, extensive respites between windy periods, seasonal and daytime patterns).

In this case the algorithm was used to generate hourly time series data. At each hourly time-step, the wind speed at the hub height of the wind turbine is calculated using *Equation 3:*

*Equation 3 - Logarithmic law for calculating hub height wind speed*

$$U_{hub} = U_{anem} * \frac{\ln(\frac{Z_{hub}}{z_0})}{\ln(\frac{Z_{anem}}{z_0})}$$

Once this hub height (9 meters) wind speed is found, HOMER refers to the user-inputted power curve associated with the wind turbine. The power curve for the WT6000 is shown below:

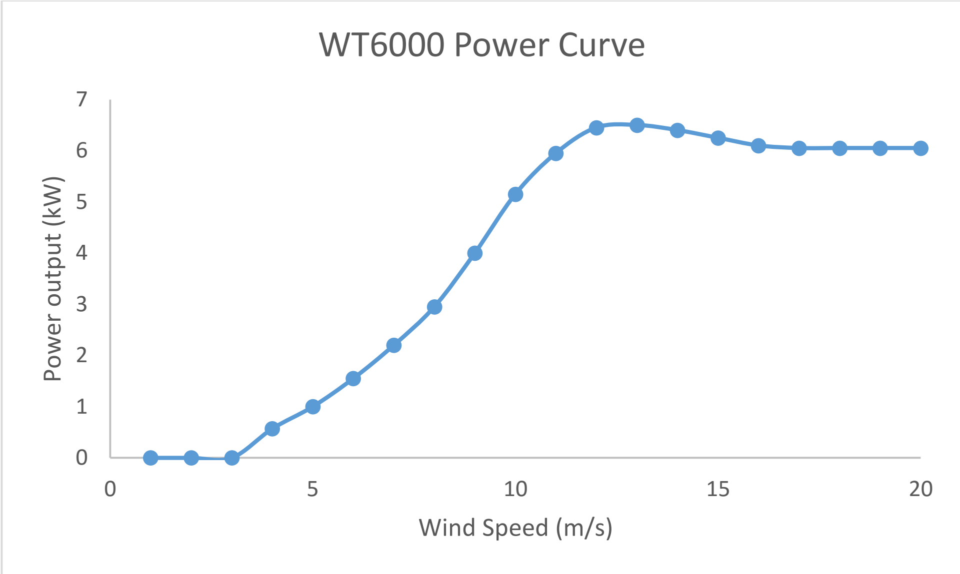



*Figure 11 - Power Curve for Proven WT6000 wind turbine*

Referring to the power curve, HOMER can read the rated output (in kW) for the given hub height wind speed. It will do this for every time-step in order to calculate the overall output of the wind turbine. The power curve is derived under standard conditions of temperature and pressure.

In the case that the turbine hub height wind speed is outside of the defined range in the power curve, HOMER calculates that no power is produced. This is in line with the assumption that wind turbines produce zero power above a maximum "cut-out" or below a minimum "cut-off" speed – which was obtained from the manufacturer's data.

## PV

The Isle of Eigg has three arrays of PV panels. The first array was installed in 2008 and had 9.9kW capacity. Two further arrays of 21kW and 22.5kW were installed in 2011 and 2013 respectively. BP Solar BP4180 PV panels were inputted to the model using the manufacturer's technical specification sheet (Section 9.2). The panels were set up to be South-facing and at an angle equal to the latitude of the Island (56.91°). This helps to maximise the PV contributions in the model.

As per setting up the wind resource, a solar resource was downloaded from the NASA Surface Meteorology and Solar Energy Database[xxxi]. The resource obtained was from monthly averaged values over a 22 year period between July 1983 and June 2005:

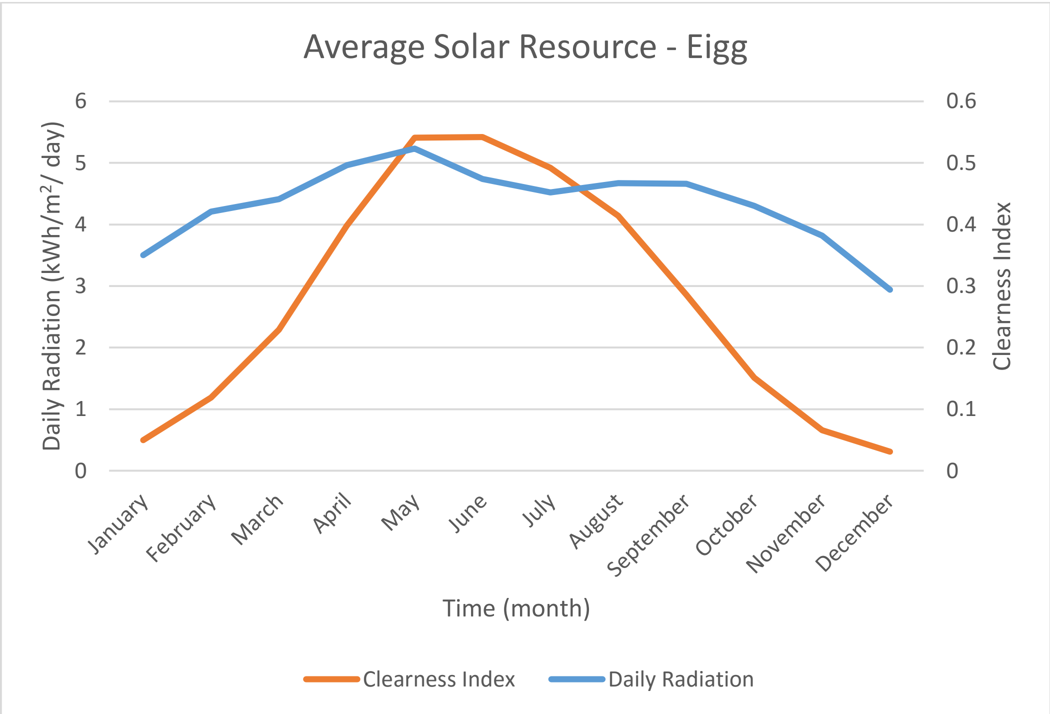



*Figure 12 – Average Solar Resource for Eigg*

*Figure 12* represents the inputted average resource. The daily radiation values can be seen to be significantly higher in the summer months than that of the winter. The clearness index is a fractional representation of the solar radiation transmitted through the atmosphere to strike the earth's surface. It is a dimensionless number with a value between 0 and 1; with higher values representing clearer, sunnier conditions. From *Figure 12* it can be seen that the clearness index is higher in the summer months. This is expected as there will be less cloud cover and the sun's angle in the sky will be lower – hence the solar radiation has a longer distance to travel through the atmosphere and it more likely to be intercepted.

In terms of hourly time-steps, the Graham algorithm[xxxii] is used to generate data from the averaged resource. This takes into account hourly variations, daily variations and identifies patterns to create a synthetic profile which is representative of real data.

The inputted resource and PV specification are used to calculate PV power output as per *Equation 4*. This takes into account the rating of the PV panel, its derating factor (85%), the incident radiation, temperature effects and how it performs under standard test conditions. The various parameters are found using the Duffie and Beckman (1991) methodology[xxxiii].

*Equation 4 - PV power output*

$$P_{PV} = Y_{PV} f_{PV} \left( \frac{G_T}{G_{T,STC}} \right) [1 + \alpha_P (T_C - T_{C,STC})]$$

### Validation of Renewables Model

The finalised model produced 85.4 % renewable penetration. Metered data from Eigg indicates that the real renewable penetration is 86.2% for the current configuration on the island. Therefore this is a fairly accurate outcome considering the random nature of renewable resources.

The simulated performance of the hydro, wind and PV systems is shown in *Figure 13.* Moving average trendlines have been used for the wind and PV outputs to highlight trends and improve the visibility of the data.

It can be seen that the behaviour shown here emulates that of *Figure* 5; the hydro output falls in summer months, the PV somewhat compensates this and the wind power output remains fairly consistent throughout the year except for a slight dip in output over the summer months. This behaviour of the system was used as validation that the renewable output of the model was a reasonably accurate representation of the system in place on the Isle of Eigg.

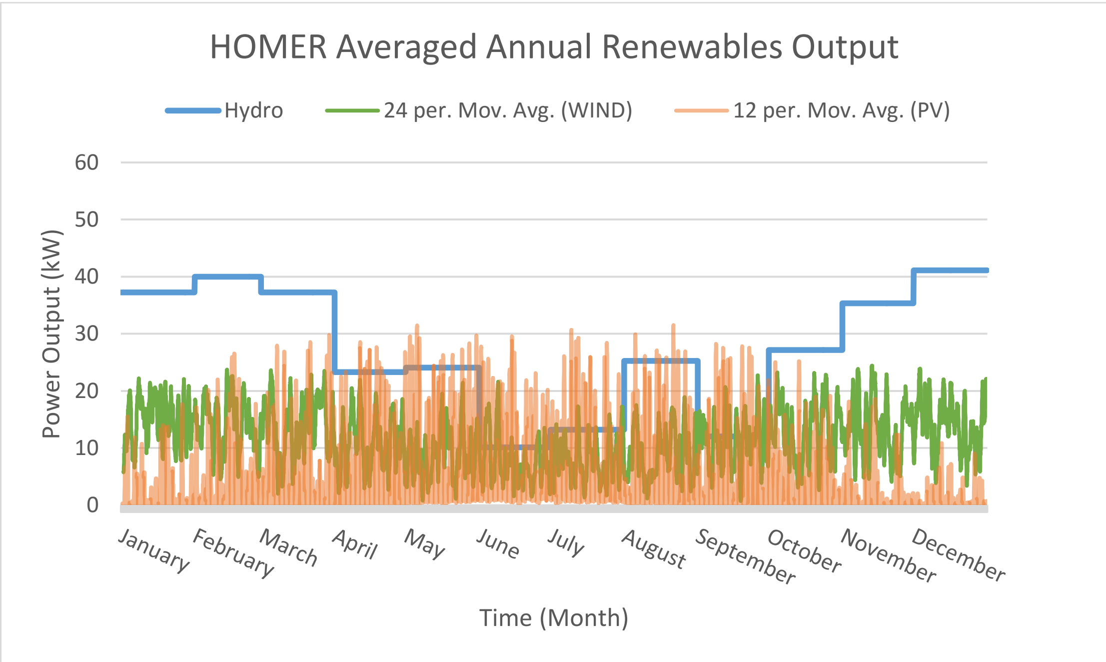



*Figure 13 - Modelled Renewable Output*

In addition to the renewable output in the HOMER model, the output from the diesel generators (as a percentage used to meet demand) was compared with measured data received from Eigg Electric for 2014:

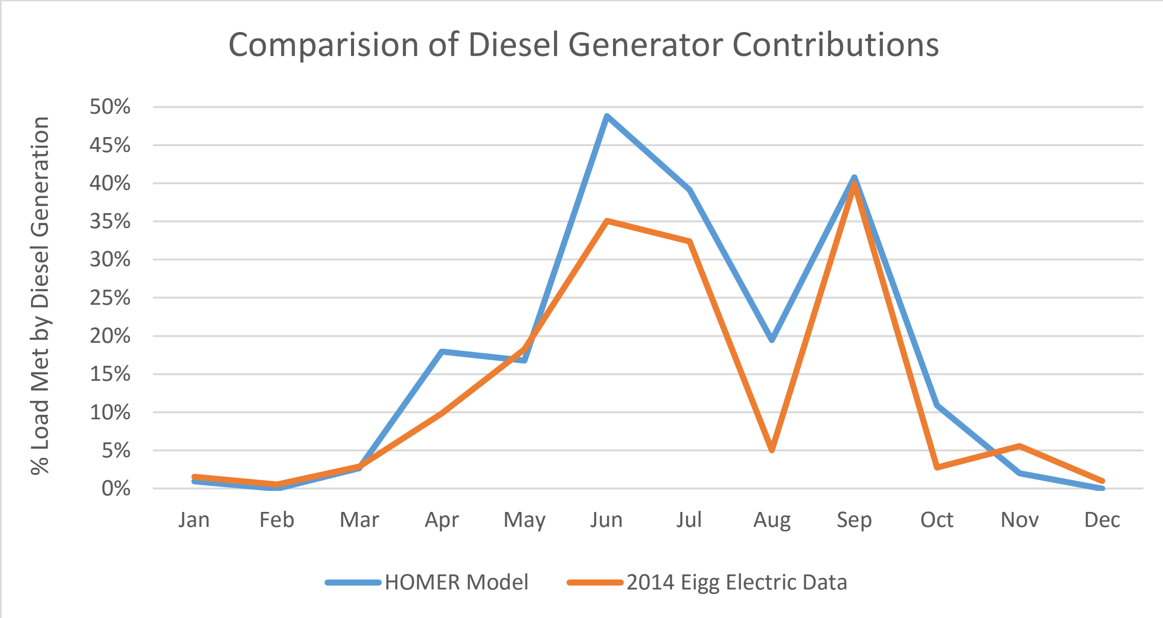



*Figure 14 - Comparison of Diesel Generator Outputs: HOMER Model vs. 2014 Data*

It can be seen from *Figure 14* that there is a general correlation between both the output of the model and the measured 2014 data. The data sets for the winter months very closely imitate one another as there is minimal diesel generation required to satisfy any shortfalls in renewable generation output. The summer months also imitate each other with significant increases in contribution provided by the diesel generators.

However, there still is significant differences between the two sets of data in the summer months. This could be accounted for by the real, measured data only being sourced from 2014 and not as an average contribution over a significant time period (e.g. 10 years). This is unachievable, though, as the current configuration on Eigg has only been in operation since the last upgrade in PV capacity – 2013. If anything, this allowed for the model to be seen as a ‘pessimistic’ portrayal of the setup on Eigg – on the basis that it required more diesel generation to satisfy demand and that the renewable penetration was therefore slightly lower than the actual, measured penetration of the system.

### Batteries

The battery model used for the Isle of Eigg is the lead-acid Rolls[xxxiv] 5000 series 4KS25PS Deep Cycle Solar Battery. Specifically designed for deep cycle applications, these batteries are becoming commonplace in renewable energy systems due to their rugged and reliable nature. They provide a long life expectancy, a 10 year manufacturer's guarantee, adaptability and are simple to maintain – ideal characteristics for a battery used in a remote community with minimal local resource to maintain and repair such technology.

To input this battery into the HOMER model of Eigg, the manufacturer's Technical Specification Sheet (Section 9.3) was used to input the following variables into HOMER for the creation of a new library entry:

*Table 4 - Parameters Required for Modelling the 4KS25PS Battery in HOMER*

| Battery Parameter | Value |
| --- | --- |
| Nominal Voltage | 4 Volts |
| Round Trip Efficiency | 64% |
| Maximum Discharge Current | 459 Amps |
| Nominal Capacity | 1350 Amp Hours |

In addition to these parameters, a kinetic battery model was chosen and a capacity profile was created as per that details in the manufacturer's specification.

The 4 Volt batteries were then inputted to the model in 8 strings of 12 batteries as was observed on the island (*Figure 15*). This configuration maintained the 48V electrical bus described on the island's website[xxxv]. It was also inputted that the batteries would not discharge below 60% charge state – as per operations on the island. This mode of operation aims to optimise battery lifetime in service as doing to deeper depths of discharge is detrimental to lead-acid battery life.

*Figure 15 - The Battery Configuration on Eigg*

## Validation of Battery Model

In order to validate the performance of the battery bank, and the accuracy of the overall HOMER model, the annual state of charge was considered. Eigg Electric Ltd.[xxxvi] has access to an online tool called Sunny Portal[xxxvii]. This allows the view monitoring and assessment of the different inverters on the island and, in particular, the battery performance. The state of charge of the batteries was analysed for an annual HOMER model and compared with the latest available (05/07/2015) measured data gained from Sunny Portal.

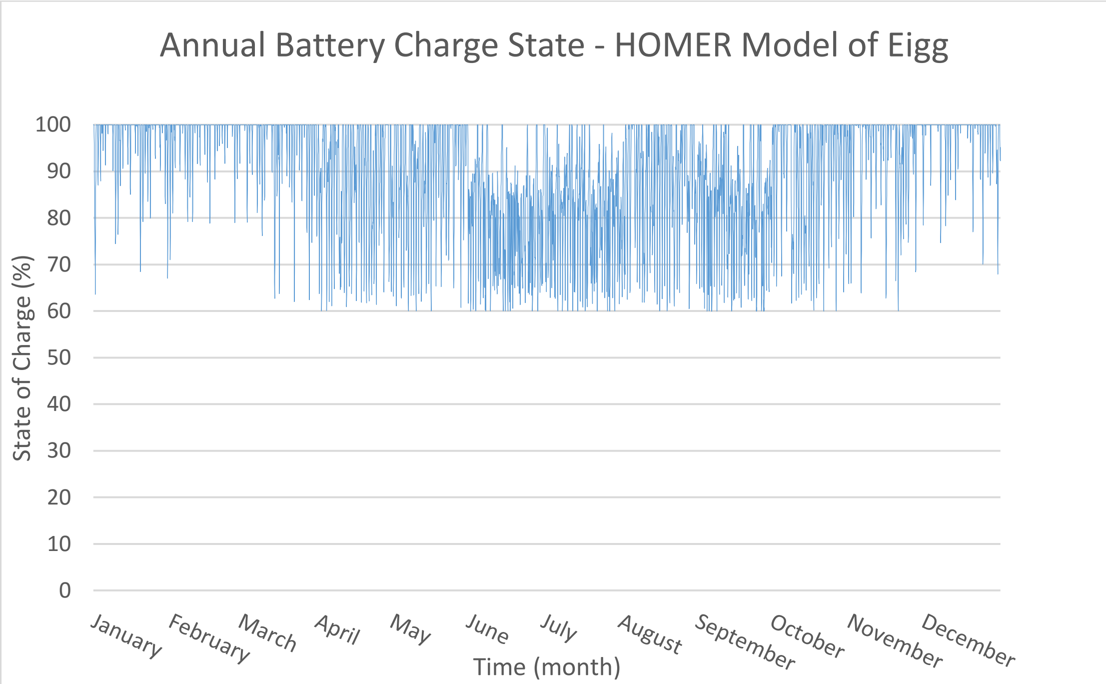



*Figure 16 - Graph Showing HOMER Model Battery State of Charge*

*Figure* 16 shows the annual variation in charge of the battery setup defined in the Eigg model. The defined operating parameter of 60-100% charged can be effectively seen; the charge level "bottoms out" on 60% indicating that the batteries would be providing no more power to the model beyond this. A diesel generator would be likely to be called into service at this point to make up the back-bone of the electrical network – compensating for the shortfall in renewable resource and lack of stored renewable electricity.

*Figure* 16 involves an hourly time-step whereas the Sunny Portal uses a 24 hour one. Hence, for easier comparison, a 24 time-step moving average was applied to the data as per *Figure 17*:

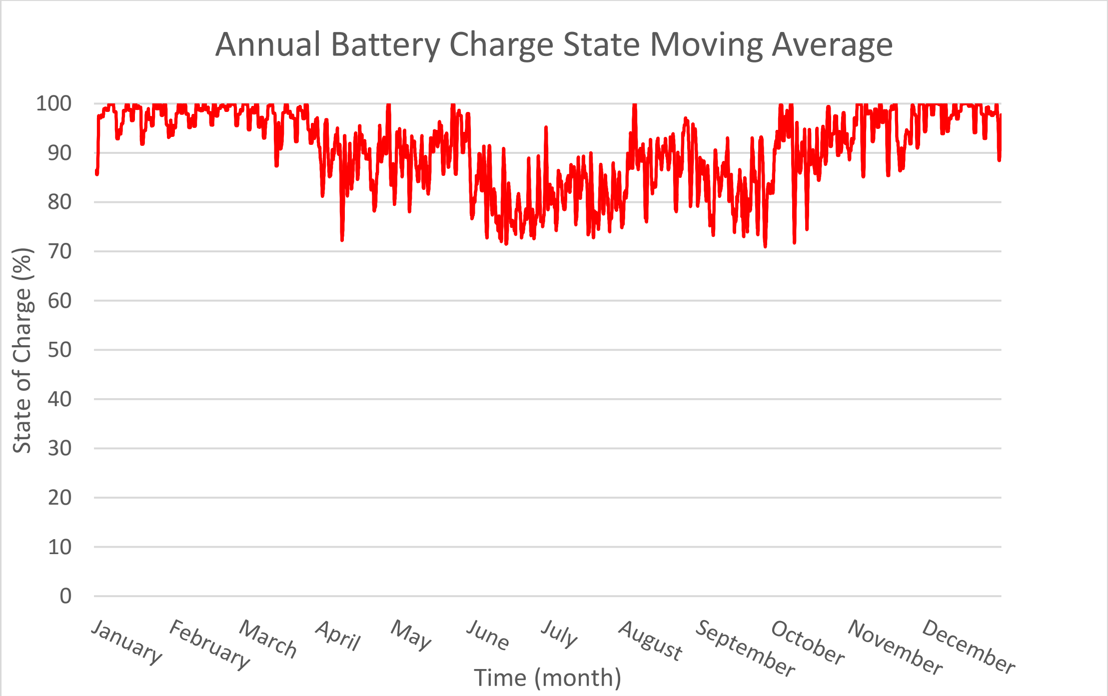



*Figure 17 - Moving Average of HOMER Model Battery State of Charge*

It can be observed from *Figure 16* and *Figure 17* that there is a large variation in the charge state over all periods of the year. It is in the summer months which the batteries are mostly used to supply the electrical system - shown by the lower average state of charge in these months. This is due to the lower hydro resource in these months; the batteries, with the other energy sources, have to make up for the lack of output due to the drier (on average) conditions.

*Figure 18* shows the annual state of charge of the battery system as per measured data in Sunny Portal (time intervals are in 24 hours; Sunny Portal takes a mean value for state of charge over every 24 hour period). There is a small gap in the data, this can be explained by maintenance works on the inverter system associated with the batteries. The orange, dotted line indicates a 4$^{th}$ order polynomial trendline, this shows the overall trend of the data. It is seen that the overall trend is very similar to that of *Figure 16* / *Figure 17*; with there being a lower on average state of charge during the summer months.

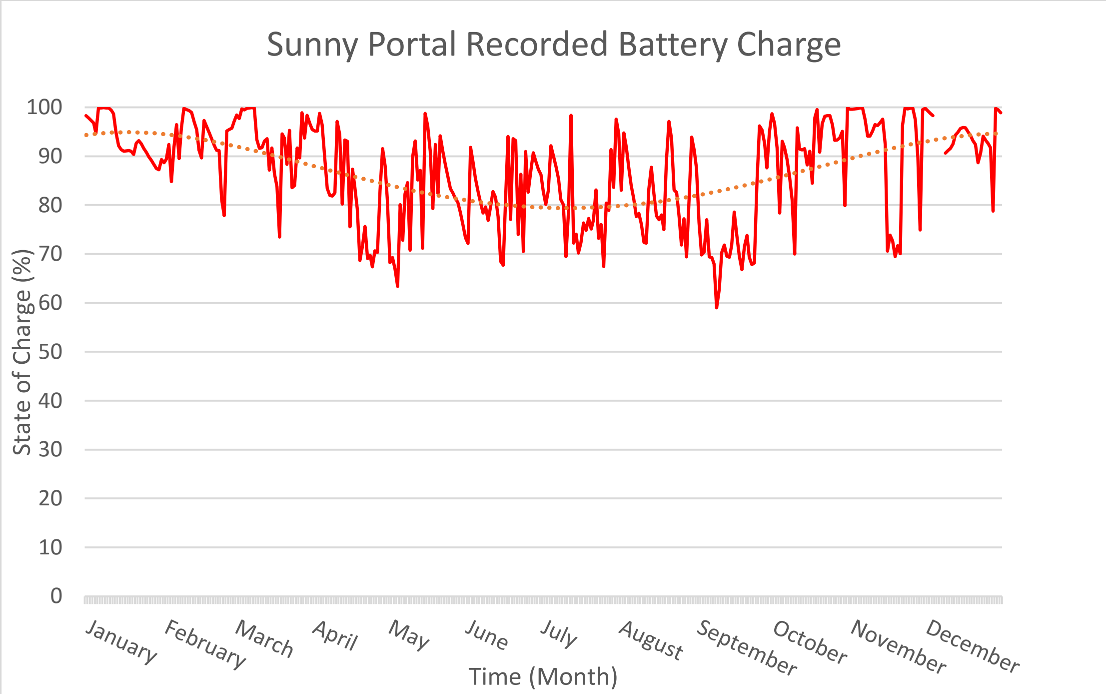



*Figure 18 - Real Life Battery State of Charge from Sunny Portal*

It is also observed that the operating range of the batteries is the same: 60-100%. The longer time step (24 hour mean value) of Sunny Portal will, naturally, show that there is a lower frequency of times where the system reaches a 60% charge level. Hence, it is not surprising that *Figure 18* does not indicated a 60% state of charge as often as *Figure 16*. A long period (24hr) of 60% charge could also represent there being an outage on a component of the electrical network, most likely the 100kW main hydro system.

The nature of renewable technologies is that they are stochastic, and with this they are extremely difficult to model. However - with this battery model emulating the same trends that exist in real, measured data - it was concluded that this was a considerably accurate representation of the battery system on Eigg. The trends also act to prove that the system modelled in HOMER behaves in a similar manner to that of the practical model; further validating its accuracy and integrity.

## Converter

Twelve Sunny Island SI-5048 5kW inverters are used on the Isle of Eigg. These are connected in four three phase clusters to give a total output rating of 60kW. This is not possible to model in HOMER. To overcome this issue a singular 60kW capacity, 90% efficient converter was modelled.

## Generators

Two 64kW/80kVA diesel generators are used on Eigg; one duty and one standby. They operate on a minimum load ratio of 25% when the batteries fall to 60% state of charge and run in a cycle charging mode – this was inputted as the dispatch strategy on HOMER. The fuel cost was set as £1.25/litre[xxxviii]; an inflated price to the national average due to the extra cost of transporting to a remote community. The two generators were scheduled to operate differently. The duty generator was scheduled to run optimally for minimising costs (i.e. minimising the runtime), whereas the standby generator was scheduled to be in "Forced-off" mode unless a capacity shortage occurs.

The generator operation was also set to a cycle charging strategy in line the operating strategy currently used on the Isle of Eigg. This means that when a generator is called to operate it does so at full power. Excess electrical production from this (in this case) is used to charge the battery bank. The system was modelled to charge to a set-point of 80% charge state whenever the diesel generator is operated, once again mimicking the current operation of the diesel generators on Eigg.

## 4.1. Summarised Findings with respect to the Eigg Model

The model of Eigg produced a renewable penetration of **85.4%**, a reasonably close output in comparison to the **86.2%** real-life value. The behaviour of the system is similar to that of measured data received from Eigg Electric and hence the model is deemed reasonably accurate.

*Figure 19* details the average monthly output per generation technology (Hydro, Diesel Generator, Wind Turbines and PV). It is seen that hydro is the main contributor to electrical generation, but it significantly lowers in output over the drier summer months. PV output can be seen to decrease in the darker, cloudier winter months and the wind turbines are seen to give a fairly consistent output with only a slight shortfall in the summer months. Diesel generator output can be seen to be directly linked to the shortfall in the hydro output over the summer months. Hence, the summer period is the “weak link” in the Eigg network and therefore the optimal period for any renewable generation increase.

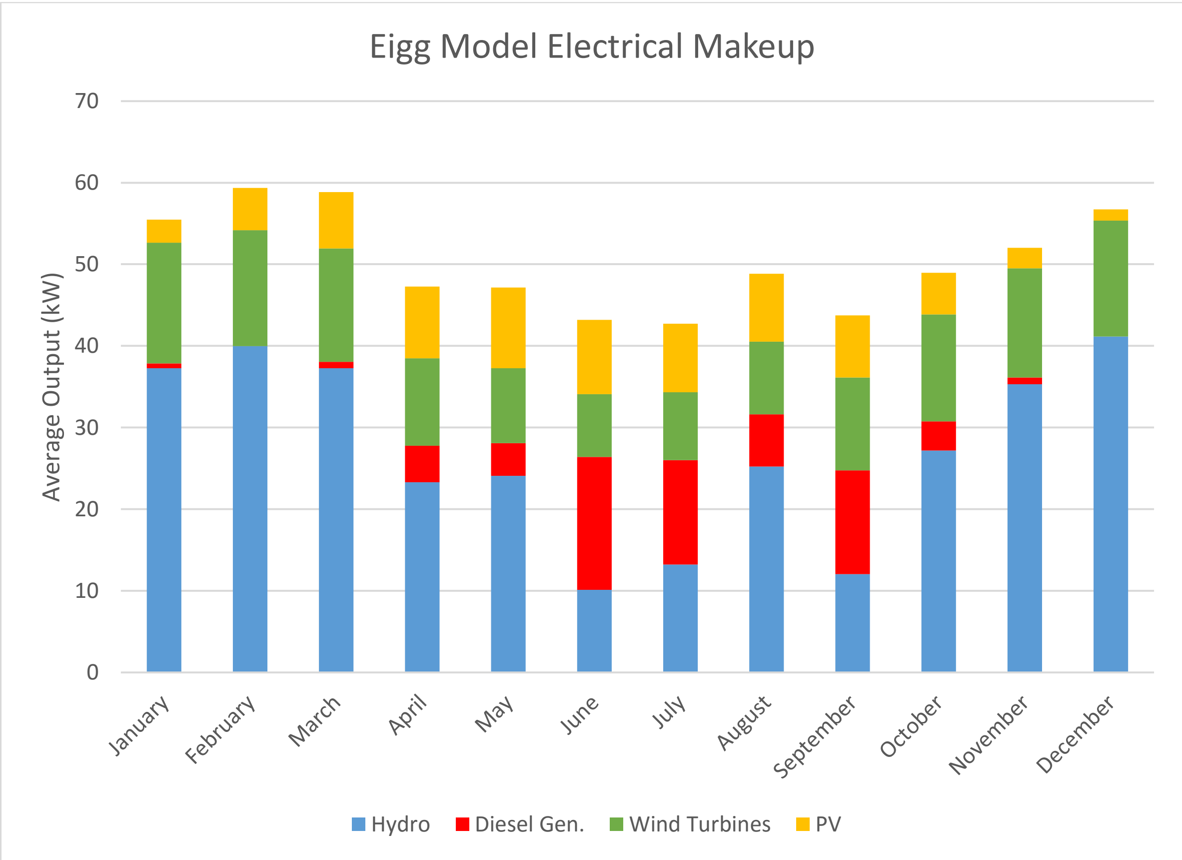



*Figure 19 - Eigg Model Average Monthly Output per Generation Technology*

It was found that an excess **90395kWh/year** of electricity is produced in the HOMER model – **20.5%** of the total electricity generated in the model. The majority of this excess is produced in the winter months. Being almost double the diesel generator output of **45641kWh/year,** if this excess could be harnessed and stored long-term it would minimise the amount of electrical energy going to waste as heat, and ultimately it could lower the diesel generator runtime by satisfying the electrical load at times a low renewable generation.

Hence, the first port of call for this project was to look at possible storage technologies for Eigg. In theory, there is already enough electricity produced annually to satisfy the electrical demand on Eigg. In practice, for this to be used to full effectiveness, a sufficient energy storage technology needs to be installed on the island which can store enough of the excess electricity to minimise (if not totally prevent) diesel generator operation.

# 5. Optimisation of Eigg's Electrical Network

## 5.1. Storage

It is a common conception in renewable based energy systems that storage is the key issue to which a solution needs to be found[xxxix]. Renewable energy, although somewhat predictable, can be very intermittent and variable over small time periods; hence this brings huge challenges to renewable energy based systems. It is not unusual for such a system to have significant amounts of excess renewable energy during some time periods whilst having major shortfalls at others. Hence it is thought that if this excess energy can be successfully stored, then it can be used at a later period and prevent the use of conventional generation, such as the diesel generators on Eigg, to make up the shortfalls.

This section looks at how the model of Eigg would perform with increased levels of energy storage from various technologies. The model simulated 90395kWh/year excess electricity (i.e. 20.5% of the electricity produced is dumped as heat). Therefore it is desirable that this electricity is harnessed and used in times of low renewable generation and/or high demand to increase the overall renewable penetration of the model.

The efficiency of storage technologies is an important aspect with respect to achieving this. It is inevitable that significant losses will be incurred due to the losses during the storage "process". Therefore much of the excess electricity produced will be lost and the 'real' available amount of excess electricity for meeting demands will be much less than the stated 90395kWh/year.

For each simulation a converter size optimisation study was carried out to ensure that this was not limiting the performance of the storage technology. No limitation was found though – hence it was concluded that any limitations were provided by the storage technologies themselves.

### 5.1.1 Increasing Battery Capacity

The first investigation was into increasing the capacity of the current storage technology – the battery bank. The number of batteries was increased in strings of 12 batteries in order to maintain the 48V bus supplied by each string. *Table 5* show the results of increasing the capacity of the current battery technology.

*Table 5 - Increasing Battery Capacity and Renewable Penetration*

| Strings of 12 Batteries | Renewable Penetration |
|---|---|
| **8** (514.8kWh) | 85.4% |
| **16** (1036.8kWh) | 88% |
| **24** (1551.6kWh) | 88.4% |
| **32** (2066.4kWh) | 88.6% |

A doubling in size of the current capacity will increase renewable penetration by 2.6% according to the model. A further doubling will only increase this by 0.6%. This indicates that there is limitations on the energy which can be stored; whether it be due to the technology or the lack of a capacity to generate electricity from renewable sources in certain, prolonged, time steps where the battery bank is available to charge. *Figure 20* shows how the original battery bank charges against renewable output; 24-point moving averages are displayed to aid in improving the visibility of the data.

The maximum charge power (the maximum power of charge the battery bank can accept) increases over the summer months. This indicates that the batteries are running down their charge to compensate for a shortfall in renewable generation output – which also is displayed by the figure. The renewable shortfall is, in most part, due to the shortfall of hydro resource – normally used to make up the baseload of the microgrid.

The charge power (the actual power of charge the battery bank accepts) is seen to be at its highest in the summer months and lowest in the winter months. This can be explained by the batteries being fully charged during the winter months and not having significant amounts of charge capacity available – denoted by the lower maximum charge power available during this period. Whereas in the summer months, as the batteries charge down, there will be periods of high enough renewable output to charge the batteries to an extent. *Figure 16* and *Figure 17* confirm this, as the state of charge, on trend, is at full capacity during winter months and frequently at a lower threshold (60%) during the summer.

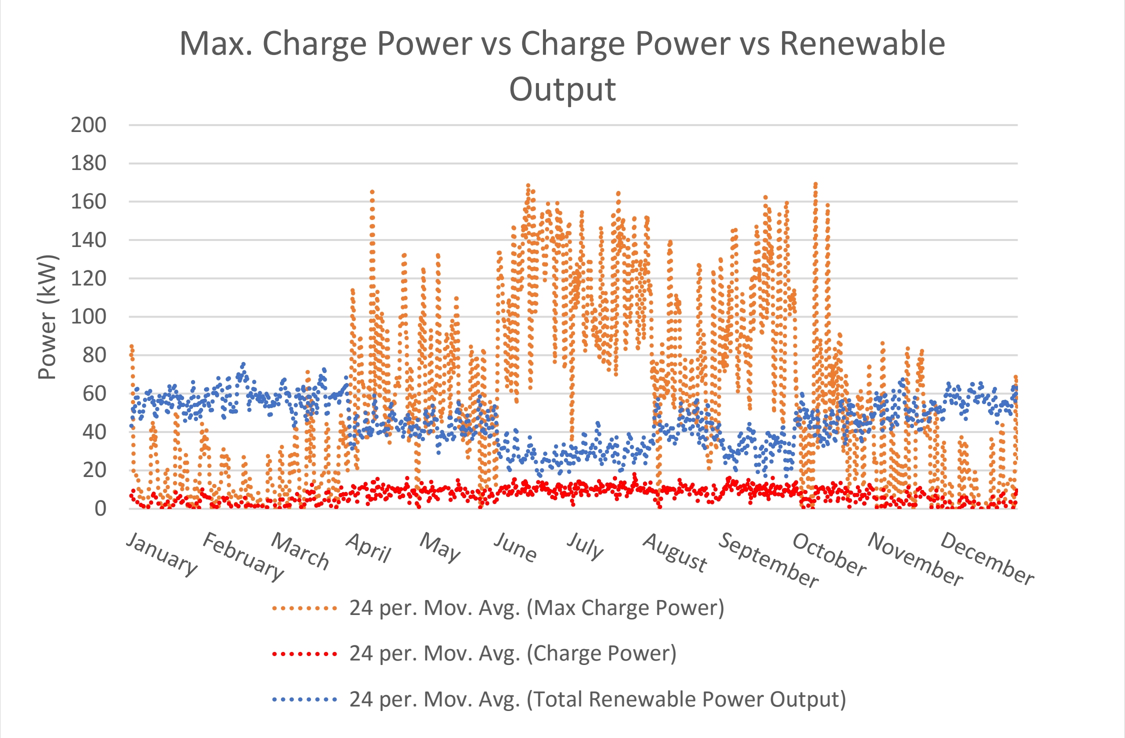



*Figure 20 - Max. Charge Power vs Charge Power vs Total Renewable Output*

Therefore it can be concluded that the batteries are limited by their maximum capacity in the winter months and the lack of renewable generation in the summer months. As the batteries discharge going into the summer months the lack of generation means the effectiveness of the batteries is reduced – as they cannot frequently be fully charged to make enough electrical energy available when it is needed to make up for shortfalls in generation. This would be crucial to avoid the diesel generators from being operated.

The efficiency and charge rate of the batteries may be also be detrimental to their performance – this would cause a lot of energy wastage ( in the form of heat ) and would prevent the battery from making the most of the available charging potential per time-step. A high charge rate is a very desirable characteristic in a renewable energy battery storage system; due to the highly variable output of renewables it is most efficient to be able to store energy as and when it becomes available. A low charge rate might not allow a battery to make use of the all the available energy, hence forcing to go to “waste” as excess electricity.

### 5.1.2 Li-ion Batteries

The performance and presence of Lithium-ion batteries progressed dramatically over recent decades due to the rise in portable electrical equipment. First commercialised in 1991 by Sony[xl], Li-ion batteries have a very high energy density in comparison to lead-acid batteries. They also take up less room, have a significantly longer operating life and require minimal maintenance. An impressive characteristic of these batteries, unlike conventional batteries, is that they can maintain a very long operating life even with high depths of discharge per cycle[xli xlii].

The efficiency of li-ion batteries is also significantly higher than that of lead-acid batteries. Lead acid batteries tend to have an efficiency ranging from 60-80% whereas li-ion ones are around 92% efficient[xliii]. This saves a lot of electrical energy from being wasted as heat during charging/discharging.

To assess the effectiveness of Li-ion batteries in the model a LG Chem RESU 6.4 EX battery was modelled. This battery is compatible with the current SMA Sunny Island inverter system present on Eigg and therefore was seen as an ideal replacement for the current lead-acid battery bank. No entity existed for the battery model within HOMER therefore a new library file was created using the manufacturer's technical specification sheet (Section 9.4) (*Each battery module can be expanded to a 12.8 kWh rating – the expanded module was the option defined in HOMER*). Most notably, it was inputted that the battery efficiency was 95% over the previous 64% for the Rolls lead-acid batteries. The lowest allowed charge state was also put at 20% rather than 60% (as per the Rolls battery model), a feasible operating window due to the long life characteristics of li-ion batteries.

The LG Chem battery was initially inputted into HOMER to equal the capacity of the current battery system on Eigg; **514.8kWh**. This required a total number of 43 LG Chem li-ion batteries to be added to the system. By doing so, the performance of the system improved in comparison to that of the original configuration – reaching a renewable penetration of **91%**. The difference in battery performance can be seen in *Figure 21:*

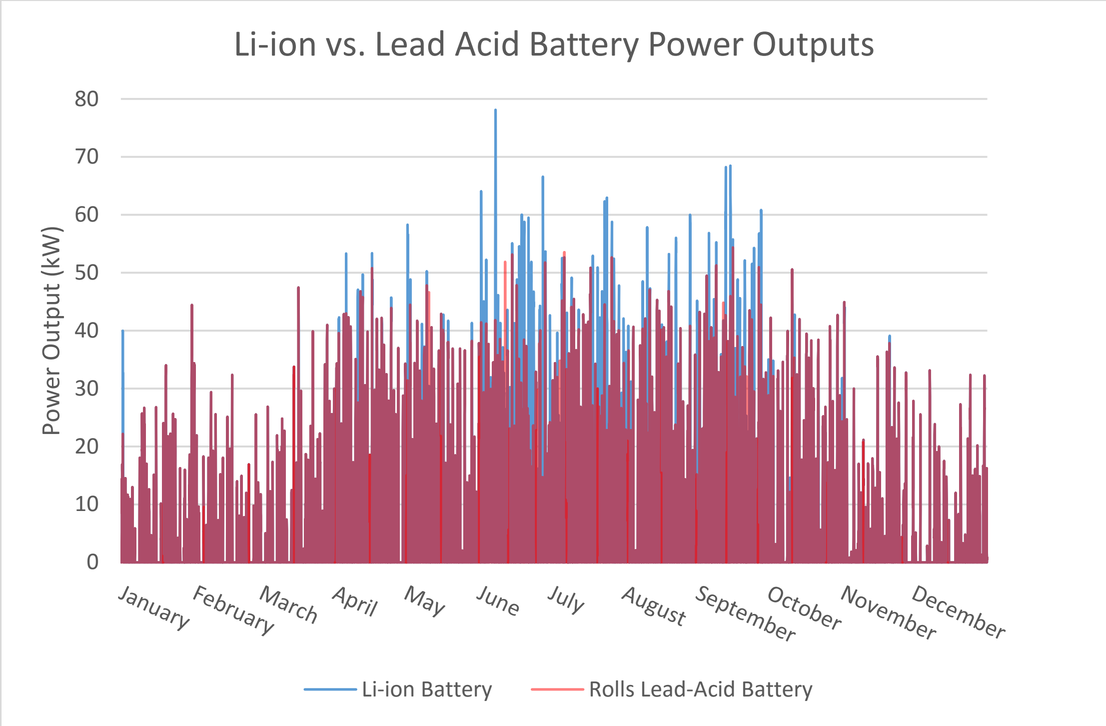



*Figure 21 - Comparison of Power Outputs between Lead-acid and Li-ion Batteries (using the same nominal storage capacity)*

It is seen that the Li-ion battery provides a greater power output over the year; hence contributing to the increase in renewable penetration. The summer months, in particular, show much higher levels of output from the battery; this will help to somewhat ease the need to run the diesel generators to make up the renewable generation shortfall experienced in these months.

Two factors have a big role in the improved battery performance. Firstly, the li-ion batteries are modelled to allow an 80% depth of discharge. This means that in situations where the Rolls batteries are limited by its 60% state of charge limit, the LG Chem batteries will continue to discharge until they reach 20% charge state. This allows for a very significant quantity of stored energy to be available in comparison to the Rolls battery setup. Secondly, the higher efficiency of the LG Chem batteries allows them to store excess electricity more effectively and minimise losses. Therefore, the throughput of energy is higher than that of the Rolls batteries for the same nominal capacity.

If the number of batteries continues to be increased, then the renewable penetration "saturates" at **93%.** This occurs at a doubling of capacity – 1036.8kWh or 86 batteries. The performance of the batteries is demonstrated in *Figure 22:*

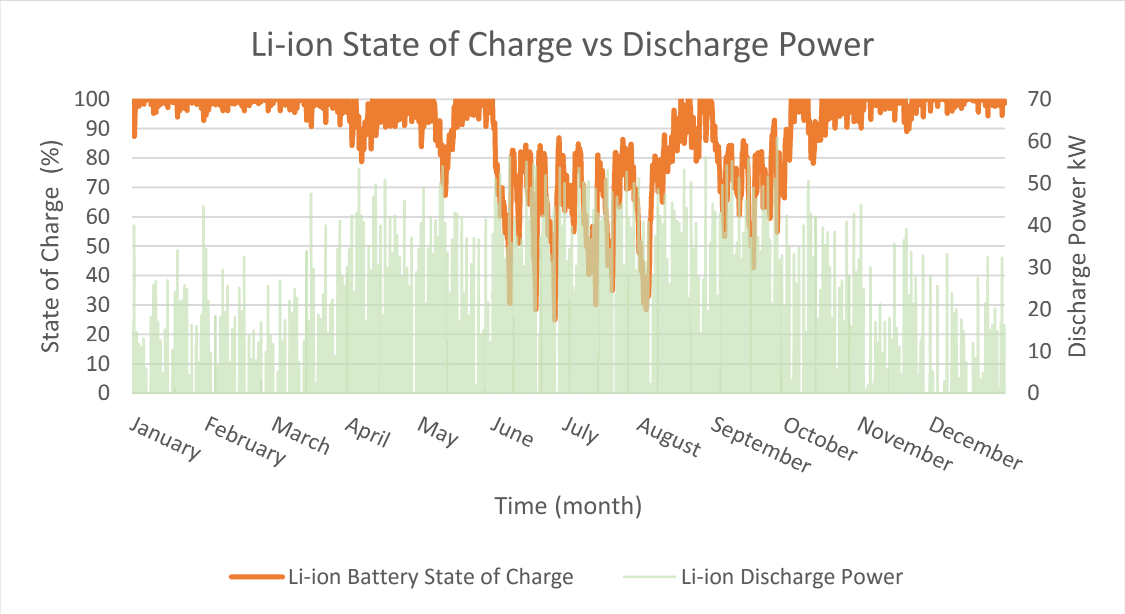



*Figure 22 - Li-ion Battery State of Charge vs Discharge Power*

As per the Rolls batteries, the state of charge follows the same general trend – where there is a lower state of charge on average in the summer months. The discharge power also is higher on average during these months as expected; this will be due to a shortage in renewable generation and therefore the batteries will provide more power to the grid to compensate for the shortfall. As defined for the inputted Li-ion battery library file, it can be seen that the state of charge falls to much lower levels than that of the Rolls batteries. This (as discussed), must contribute to the fact that there is a higher renewable penetration involved with the li-ion battery set-up. This could also be explained by the number of batteries, but as seen in *Table 5*; 384 (or 2066.4kWh of) Rolls batteries still would not provide this return. However, if the same set-up, storage capacity and discharge level, is applied with Rolls batteries, the renewable penetration is decreased at **87.9%.** Therefore it must be assumed that the efficiency difference (31%) must be a very significant aspect in the difference in performance of the batteries; by using lead acid batteries the energy available is effectively reduced.

Looking at diesel generator operation against Li-ion battery charge state in *Figure 23*, it is seen that diesel generator operation is required mostly in the summer months. This is in line with the lower renewable output; and coincides with the lower hydro output in these months. It can also be noted that, there is minimal operation of the diesel generator during the month of August – where the hydro resource is at its highest for the summer months as per *Figure 8*. The solar and wind resources (*Figure 12* and *Table 3* respectively) for this month do not differ greatly from other months. Therefore this indicates that there may be significant impacts on renewable penetration depending upon the hydro resource.

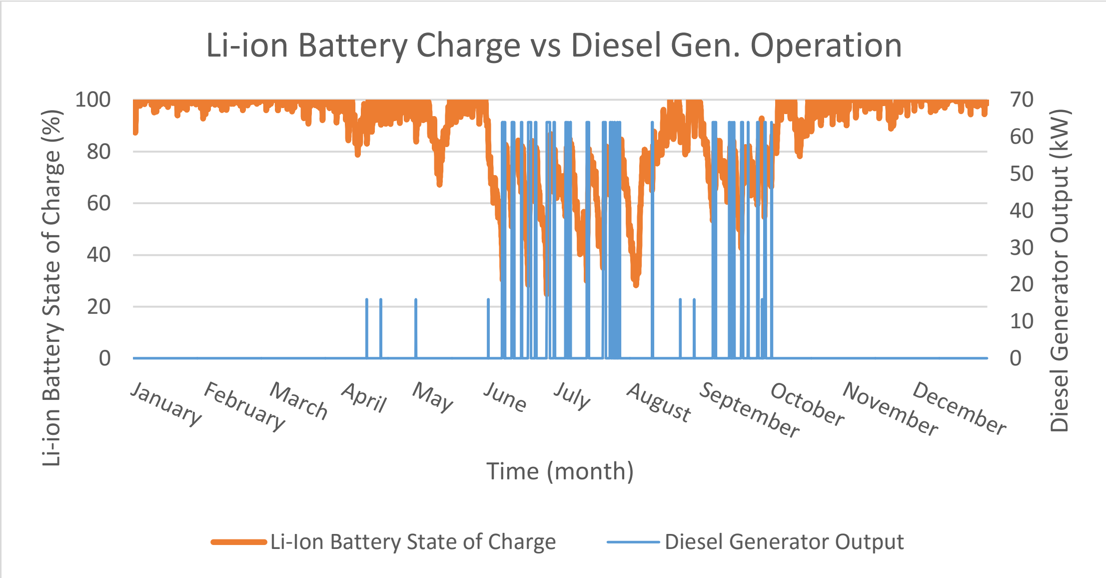



*Figure 23 - Li-ion battery charge state vs diesel generator operation*

For a model with the same battery capacity, but using the Rolls model battery *Figure 24* is produced (the model also includes an 80% depth of discharge to enable a valid comparison). For the same summer period it can be noted that the diesel generator requires to be operated much more frequently – hence there is a lower renewable penetration of 87.9%. This is explained by the lower efficiency of the Rolls Battery and the faster charging rate of the Li-ion battery – i.e. it is more effective at storing excess electricity when it is available.

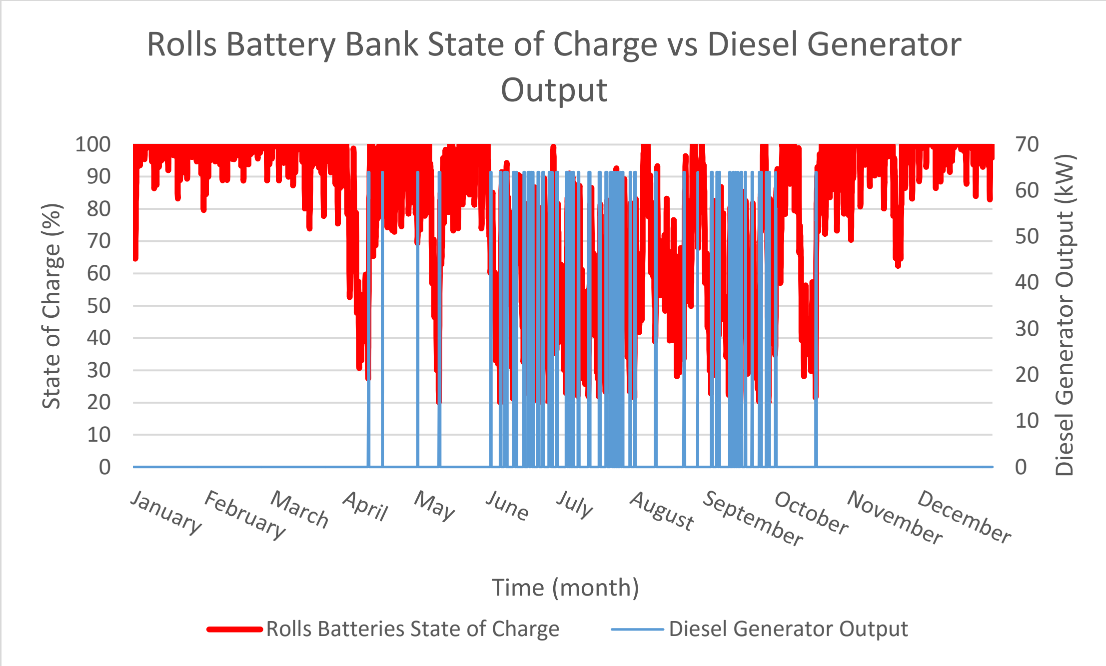



*Figure 24 - Rolls (Lead-acid) battery charge state vs diesel generator operation*

Despite the greater performance of li-ion batteries in comparison to the Rolls battery model. The high cost of such a battery (£3750 vs £845 respectively[xliv]) is a barrier to why these batteries would not be chosen initially for such an electrical network. However, the cost of this technology continues to decrease with technological advances in portable electronics. Therefore it could be a legitimate option for replacing a lead acid battery system in the not too distant future.

### 5.1.3 Flow Battery

As per the Isle of Gigha, it was decided to investigate how a flow battery would perform in comparison to the Rolls and Li-ion configurations. To stay true with what is used on Gigha a Vanadium Redox Flow Battery (VRFB) was chosen as the desired candidate for modelling in HOMER.

Vanadium Redox Flow Batteries operate on the principal that vanadium can be contained in four different oxidation states: $V^{2+}$, $V^{3+}$, $V^{4+}$ and $V^{5+}$. The positive side (half-cell) electrolyte of the battery contains $VO^{2+}$ and $VO_2^+$ ions whereas the negative side electrolyte contains $V^{2+}$ and $V^{3+}$ions[xlv]. The electrolytes are separated by an ion exchange membrane in the central cell as seen in *Figure 25:*

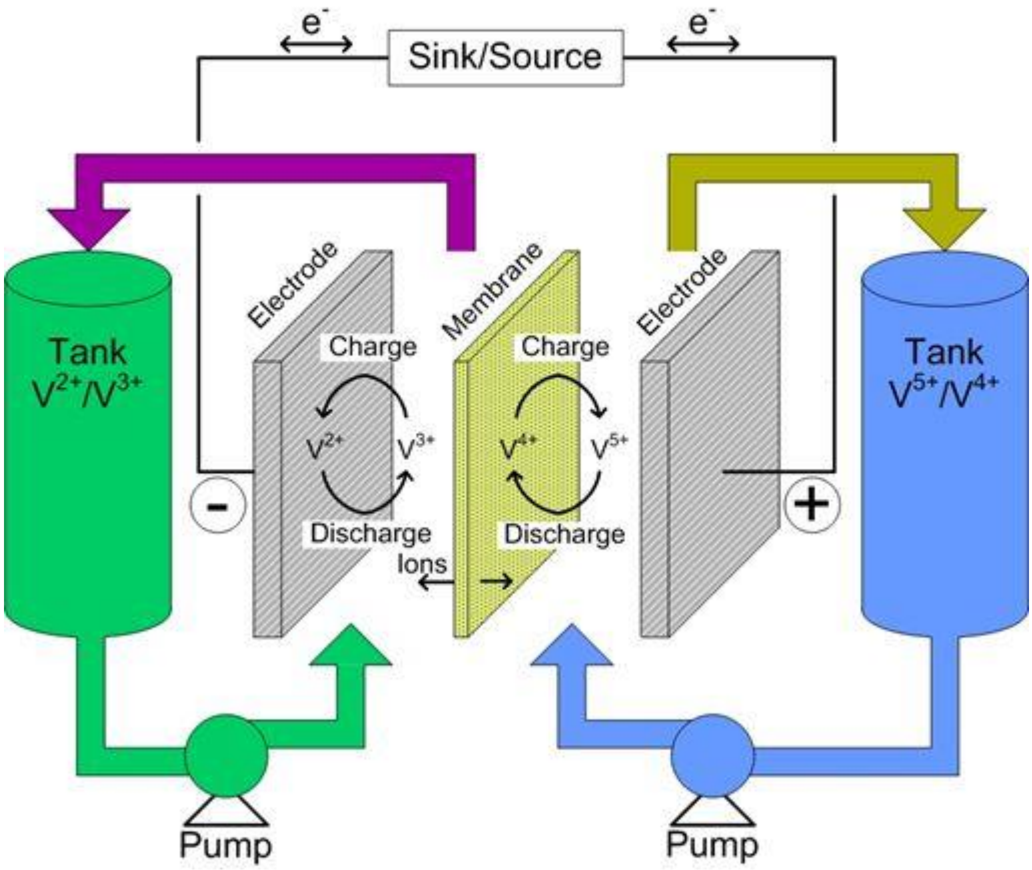



*Figure 25 - Vanadium Redox Flow Battery Schematic*[xlvi]

The storage tanks containing additional electrolyte; it is from here that the electrolyte is pumped round into the fuel cell in order to generate electricity. In the cell itself, the ions are attracted, by charge, to pass through the membrane. The electrons, however, as per a fuel cell (*Figure 28*) are forced to take an external circuit, hence creating an electrical current.

Vanadium Redox Flow Batteries would appear to be a highly advantageous storage system for microgrids. Firstly, they can offer extremely high storage capacities –simply by utilising large storage tanks. They offer minimal maintenance, long-life characteristics (minimal deterioration of the electrolyte on recharging cycles) high electric efficiency and the ability to be discharged for sustained periods with no detrimental effect on the battery performance. Unlike conventional batteries, they also allow for full discharges without any effect on projected life of the battery. Despite this, they can be somewhat bulky to store, they tend to be fixed technologies due to the required pumping (though gravity fed technologies exist), they have been known to be a fire risk as they operate at high temperatures and the electrolyte has a relatively poor energy to volume ratio . There is ongoing research into this area; instead of using pure sulphuric acid as the electrolytic solution researchers at Pacific Northwest National Laboratory[xlvii] used a sulphate ($SO_4^{2-}$) and chloride ($Cl^-$) solution that can hold over 70% more vanadium ions – a dramatic increase in energy to volume ratio.

To input a Vanadium Redox Flow Battery into HOMER a new library entity had to be created. Using the REDT 5-30 battery specification sheet[xlviii] a flow battery was created maintaining the 48 Volt electrical bus already present on the Isle of Eigg. The battery created would not truly represent the REDT 5-30 model; as this required to be scaled up to be sufficient for Eigg (margin for running autonomously on the battery).

A sizing exercise was carried out to measure the optimal storage capacity for the system. Increasing the storage capacity of the battery lead to an increase in renewable penetration. However, the increase becomes saturated at a capacity of approximately **700kWh**; where the renewable penetration is **90.5%.**

*Note: for this part of the sizing the rating of the battery was set to 100kW. This value was large enough not to put a limiting effect on the sizing of the electrolytic storage.*

In addition to this, the rated capacity was also investigated to ensure that an optimal value had been chosen. The 30kW rating as per the REDT 5-30 was initially inputted as per the specification sheet. This was then increased in 10kW increments until a maximum renewable penetration was found. This, once again gave an expected renewable penetration of **90.5%** but instead of a 100kW output it was found that an **80kW** rated flow battery would be sufficient to maximise the renewable penetration of the model.

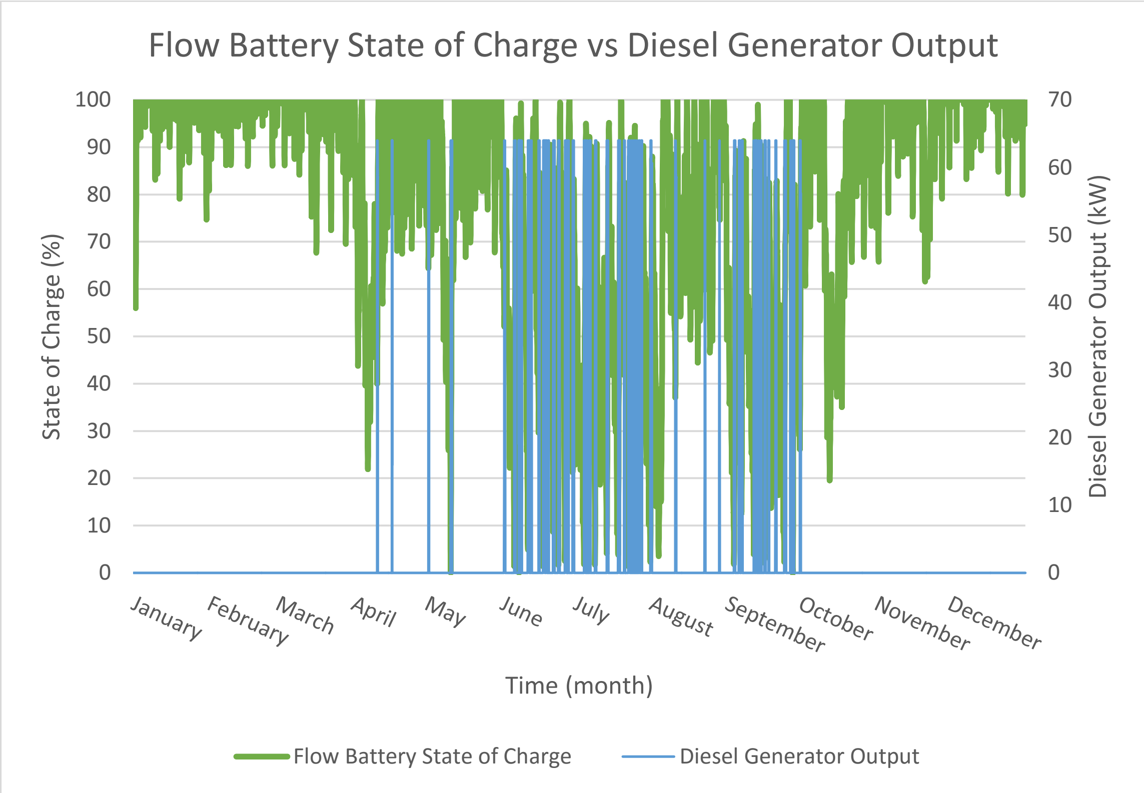



*Figure 26 - Flow Battery State of Charge vs Diesel Generator Output*

*Figure 26* shows the resultant flow battery state of charge against diesel generator output. In comparison to *Figure 23* and *Figure 24*, it is seen that the battery discharges completely on numerous occasions. The diesel generator operation also operates in the same periods as before. It does not operate as frequently as it does in *Figure 24* (Rolls Lead Acid batteries) but it does more frequently than that in *Figure 23* (Li-ion batteries). This is as expected according to the renewable penetrations achieved with modelling the other battery technologies. The fact that the state of charge is hitting 0% indicates, once again, that there is a shortfall in generation capacity in the summer months. This shortfall is shown in *Figure 27*:

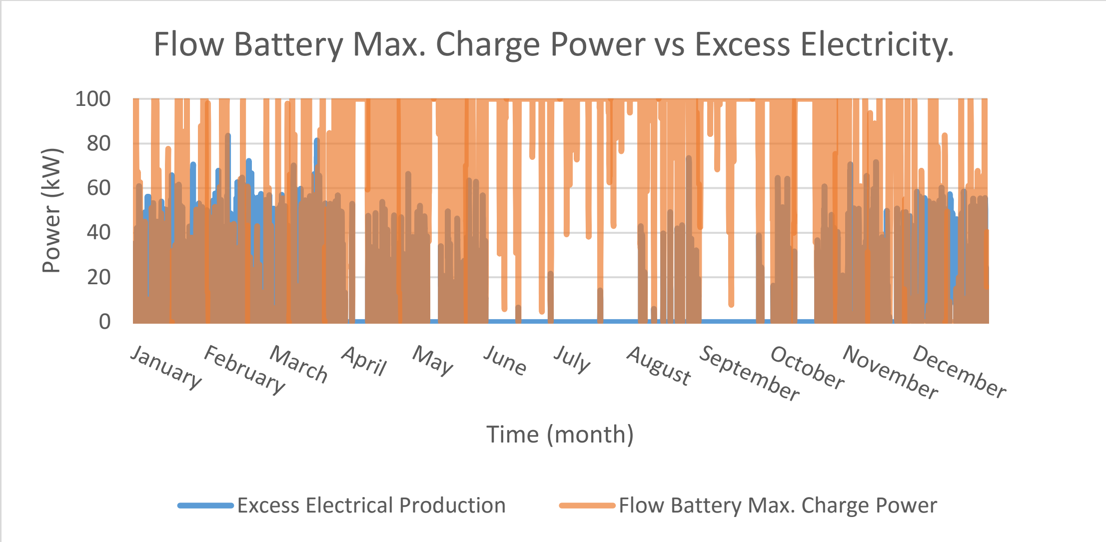



*Figure 27 - Flow Battery Max. Charge Power vs. Excess Electricity*

It is seen that during the summer months there is extended periods of no excess electrical production. This will not allow for charging of the battery and hence, once the state of charge reaches 0% the diesel generator will have to operate in order to meet demand. The maximum charge power of the battery is maximised in these months, hence showing that the battery is spending long periods of time without high charge levels.

An excess electricity generation of **77951kWh** still occurs using the flow battery. This can be explained by the maximum charge power of the battery decreasing in the winter months – where most of the excess electricity generation occurs due to excess hydro resource and wind turbine output. This is still a limitation of the battery, where it cannot accept any more charge.

One advantageous quality of flow batteries is that they can be recharged simply by replacing the electrolyte. This would be a possibility for Eigg if they could stockpile the electrolyte somewhere to "refuel" in the summer months. However, the battery would be likely to deplete its charge very quickly due to the lack of excess electricity. This would likely end up being a wasteful and expensive exercise; it is, in essence, the same logic as increasing the size of the storage tanks – which will not have a worthwhile effect beyond a capacity of **700kWh**.

This investigation into the use of a flow battery highlights that there is a significant shortage of renewable generation output in the summer months. From this, it can be concluded that short-term storage is not a sole solution for maximising renewable penetration – even though it can improve the penetration considerably in some respects. Instead, seasonal storage could potentially be a solution. If the excess electricity can be successfully and efficiently stored in the winter months, then there is potential to use it in the summer to make up for the shortfalls. To achieve this different types of storage technology need to be explored.

### 5.1.4 Hydrogen Fuel Cell

Another form of energy storage is hydrogen storage; using excess electricity to generate and store high pressure hydrogen gas. When needed, this hydrogen can be passed through fuel cell technology to generate electricity. Hydrogen fuel cell setups can be used for longer term storage; dependent upon on the size of the individual components and cost restrictions.

The first stage of the process is called electrolysis[xlix]. Using a water solution, electrolysis produces hydrogen by creating a sufficient voltage between two electrodes immersed in the solution. The voltage potential splits the water into its $O^-$ and $H^+$ building blocks (negative oxygen ions and two positive hydrogen ions) and these form at the electrodes. The negative electrode (Cathode) attracts the $H^+$ ions and the positive electrode (Anode) attracts the $O^-$ ions. These form with identical ions at their respective electrodes to produce $O_2$ and $H_2$ molecules (oxygen and hydrogen gases). The hydrogen produced can then be stored at high pressure until required for use via a fuel cell.

Proton Exchange Membrane (PEM) fuel cell[l] operation is detailed in *Figure 28.* Pure hydrogen and oxygen (in the form of air) are delivered to the fuel cell through different channels. Here, the gases meet two electrodes which are separated by a PEM; the platinum anode (negative) on the hydrogen side and the cathode (positive) on the oxygen side respectively. The platinum anode acts as a catalyst for a reaction which splits the hydrogen gas into its constituent parts as per *Equation 5:*

*Equation 5 - Splitting of a Single Hydrogen Atom into Two Hydrogen Protons and Two Electrons*

$$H_2 \rightarrow 2H^+ + 2e^-$$

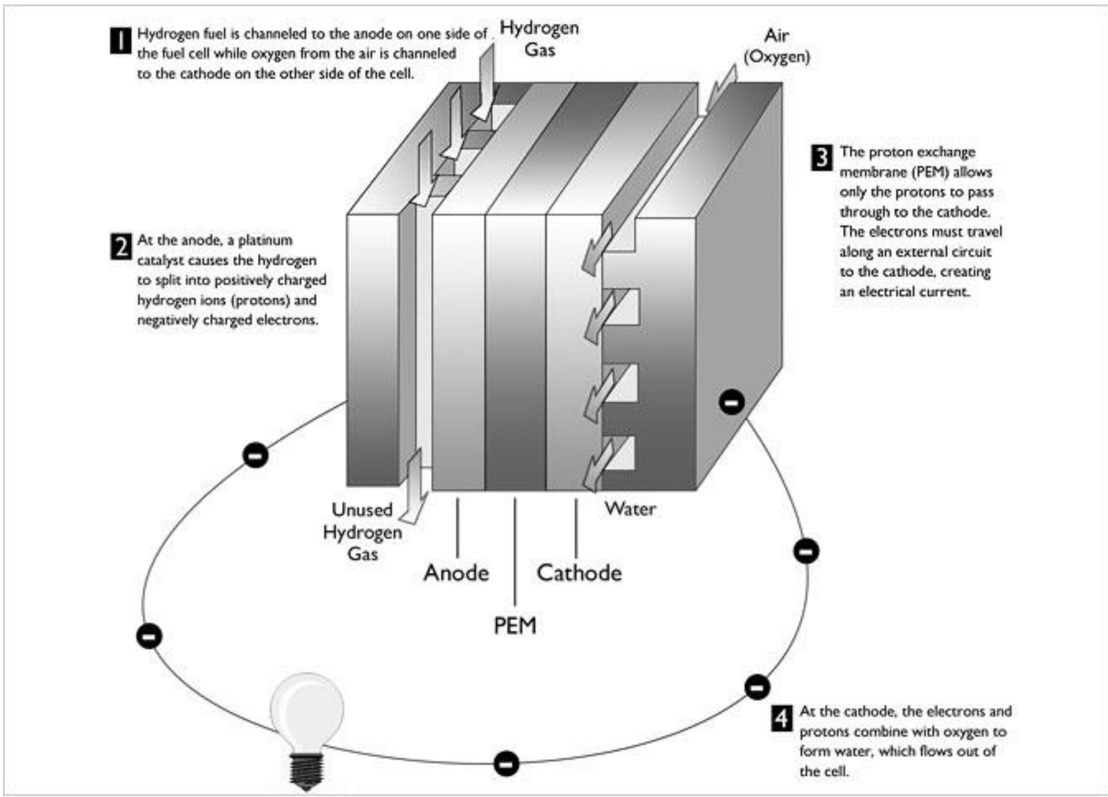



*Figure 28 - A typical Proton Exchange Membrane (PEM) Fuel Cell*[li]

The resultant positive hydrogen protons and negative electrons are drawn to the cathode on the other side of the PEM. However, as the name suggests, only the protons can pass through the Proton Exchange Membrane. Therefore the electrons require to take a route around the PEM - which will be provided by an external circuit. Once the electrons reach the cathode they combine with the oxygen in the air to create water and heat energy; the only two waste products of the process.

*Equation 6 - Recombination of Hydrogen Protons with Oxygen to form Water and Heat*

$$4H^+ + 4e^- + O_2 \rightarrow 2H_2O\ (+\ heat)$$

By passing through this circuit they form an electrical current that can be used for numerous applications. The voltage of single fuel cells tends to be low so numerous fuel cells can be used to step up the voltage of such a system. The current can also be increased by maximising the surface areas of the cathode and anode, therefore maximising the area in which the chemical reactions can take place that produce the current. To generate a greater power output, it is desirable to maximise both of these factors as electrical power is defined as per *Equation 7:*

*Equation 7 - Electrical Power*

$$P = VI$$

Therefore as the power output increases it is likely that the overall size of the fuel cell setup will increase. This can create many engineering challenges with respect to the intended application of the fuel cell – especially when such technologies may be used for electric transport where space is at a premium.

To input a fuel cell into HOMER, a generator was initially added. The fuel source was then altered to "Stored Hydrogen" (i.e. from a hydrogen tank, which was also required to be added to the model separately between the AC and DC buses). In addition to this, the fuel curve had to be calculated in order to represent a fuel cell with higher accuracy[lii]. Therefore the intercept coefficient for the curve was set to zero, the gradient was set to 0.06kg/kWh to give an efficiency of approximately around 50%. In addition to the fuel cell and hydrogen tank, an electrolyser was added to the DC bus of the model. It was defined that this had an efficiency of 85%.
An optimisation study was then carried out using HOMER's inbuilt algorithms to deduce an optimal sizing of the different components of the hydrogen storage system. The results from this study are given in *Table 6:*

*Table 6 - Optimisation study results for hydrogen storage system*

| Component | Optimal Size |
|---|---|
| **Electrolyser** | 45kW |
| **Hydrogen Tank** | 2000kg |
| **Fuel Cell** | 70kW |

It was initially thought that the hydrogen tank would require a larger capacity. Examining the annual levels of stored hydrogen, though, it could be seen why the HOMER algorithms chose 2000kg for the current setup as per the Eigg model.

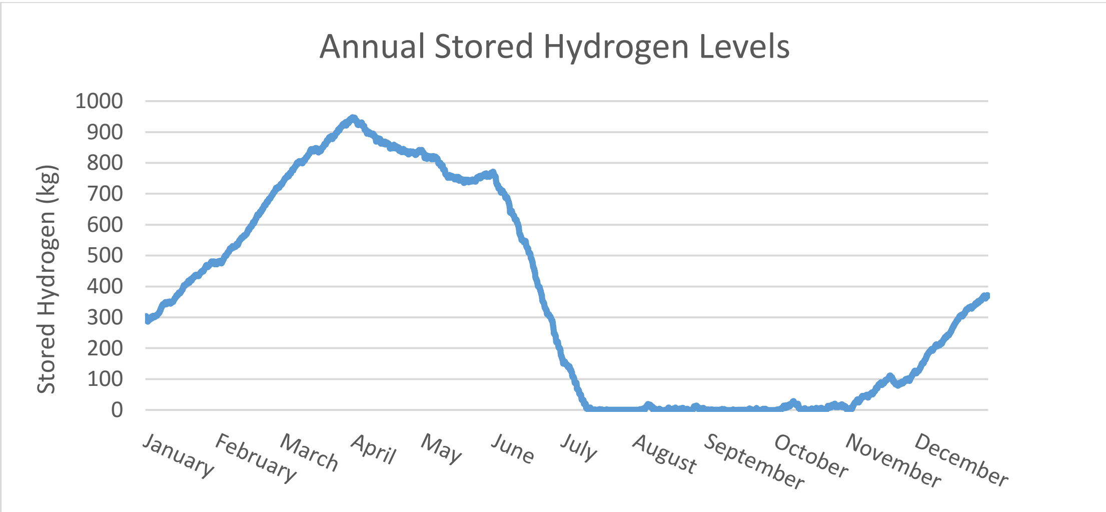



*Figure 29 - Annual stored hydrogen levels for the Eigg model*

*Figure 29* demonstrates the mass of stored hydrogen in the tank over the simulated year. The maximum level of stored hydrogen does not go above 1000kg therefore the optimal tank size is seen to be more than adequate for the current system.

The gradient of the line shows how quickly the hydrogen tank is charging or discharging. This will be limited by the specific consumption of the electrolyser; which was defined as 46.405 kWh/kg of hydrogen. This was a resulting characteristic of the defined electrolyser efficiency of 85%

However, despite the hydrogen storage levels being minimal in the summer, the calculated renewable penetration of **94%** was the highest of all the technologies modelled in HOMER. The excess electricity for this model decreased to **3196.7kWh/year**, which is **0.7%** of the total electricity generated – considerably lower than the initial value of 20.5%.

### 5.1.5 Pumped Storage

Pumped hydroelectric storage is a well-established technology, especially in the UK[liii]. For renewable energy systems, pumped storage can be used to utilise excess electricity by using it to run a 'pump turbine'. This pumps water to a high level storage reservoir (i.e. giving it potential energy). This potential energy of the stored water can then be used for hydroelectric power generation by emptying the storage reservoir, letting the water run down a penstock (hence giving it kinetic energy) and then through a turbine-generator. In conventional grid networks, pumped storage is used to transfer water to the high level reservoir during off-peak hours –i.e. night time. As well as renewable technologies, larger grids are more likely to have non-despatchable generators such as nuclear and older fossil fuel power plants in addition to renewables.

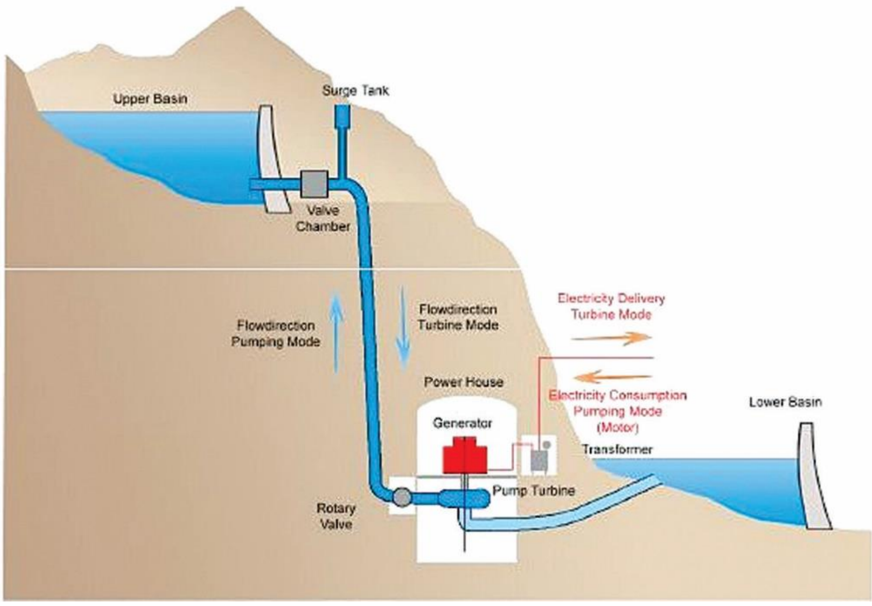



*Figure 30 - Pumped Storage Schematic*[liv]

*Figure 30* shows a simple schematic of a pumped storage system. It shows the directional flows in operation when the facility is either in 'pump' or 'generator' modes and that both a lower and upper reservoir are required. A vital capability of such a system is that the turbine can be reversed to act as a pump; this is what makes pumped storage schemes differ from a standard hydro scheme.

In the case of the schematic, the turbines and pipelines are located within the hillside beside the lower reservoir. This can be very advantageous, but it is not necessary; larger installations which give several megawatts of output can be mostly hidden from view.

Therefore the 'seen' environmental impact is less and the likelihood of public opposition to the development of such a scheme is less. This can be offset by the creation of an upper reservoir – which sometimes can result in vast amounts of land being deliberately flooded – affecting livelihoods, geology and environmental diversity[lv].

Pumped hydro installations have very good storage characteristics. Modern systems will have 80% overall efficiency[lvi] and they have a very quick response time to demand loads (a matter of seconds). Their broader environmental credentials are good too – with their main drawback being how the reservoirs are created. Pumped storage stations produce minimal pollutants, have a very long life expectancy and are able to accommodate large amounts of renewable energy – further boosting their 'green' credentials.

As with every technology, there are drawbacks. Initial construction costs are very expensive; more expensive per output than thermal generation plants, the visual impact on the environment is permanent and can be of significant size, and wildlife can be affected if the plant is designed without due care and process. Despite these drawbacks the technology has become very well established over the last century. It has become somewhat crucial to many electrical networks due to the "black-start" capability it provides – the ability to restore grids following a blackout.

Using HOMER, it is not possible to model a pumped storage module onto the Isle of Eigg. Instead a battery must be modelled running on the DC bus of the grid to be representative of such a system. It was not possible to adapt this to the model of Eigg; as when doing so everything else in the model requires to be connected to the AC bus; hence the model produced would not be representative of Eigg.

Instead of aiming to model Eigg with the pumped hydro, the figures of **80%** efficiency and excess electricity (according to the original Eigg model) of **90395kWh/year** were used to carry out a scoping exercise for the island. In theory, if the efficiency is applied to the excess electricity then, using pumped storage, there could approximately be **72316kWh/year** of useable, stored energy. Minus from this the amount of electricity generated by the diesel generator (**45641kWh/year**) and there could still be an excess of **26675kWh/year.** Even if the pumped storage efficiency was as low as 70% there would still be, in theory, an excess of **17635kWh/year.**

As mentioned, one of the biggest impacts of such an installation would be provided be from creating the reservoirs. For Eigg, the lower reservoir could always be avoided; instead using the sea as a reservoir and running a salt water system such as that in Okinawa, Japan[lvii]. This does require special precautions to ensure that the saltwater does not affect the local environment – both on land and in the sea. If not, a freshwater system could be achieved using the natural run of river present on the island to create a lower reservoir near the output of the existing 100kW hydro installation.

To size the upper reservoir, a method using *Equation 8* was used*:*

*Equation 8 - Potential Energy*

$$E_{Potential} = mass * g * h$$

Assuming the hydro scheme is 80% efficient and frictional losses are negligible, it is taken that it is approximately 89.5% efficient to pump water up, and then 89.5% efficient to generate electricity when it is released from the reservoir (i.e. $0.895^2 = 0.8$). This also assumes that the pump turbine is equally efficient in both generating and pumping modes. Therefore the equation can be set to equal 89.5% of the energy of the excess electricity defined in HOMER (**80904kWh/year** hence **797406kJ** of energy is stored in the upper reservoir). Since we are interested in looking at the volume of the upper reservoir, the mass can be expressed as the density of water multiplied by its volume.

*Equation 9 - Potential Energy (II)*

$$797406(kJ) = (Volume * \rho) * g * h$$

Rearranging and solving *Equation 9* for volume gives a required reservoir volume of **813m³.** A gross head was of **100metres** was applied – in line with the current hydro system in place on Eigg.
It was defined in the model of HOMER that the peak load for demand would equal **92.3kW.** This was used to find the maximum usable flow rate using the equation below:

*Equation 10 - Flowrate of a Hydroelectric System*

$$Q = \frac{P}{\eta * H * g}$$

The maximum usable flowrate for this configuration is **0.105m³/s.** This results in a minimum operating time, for a full reservoir, of **2 hours 9 minutes** using Equation 11

*Equation 11 - Operating Time of Pumped Storage*

$$Operating\ Time = \frac{Volume\ of\ resevoir}{Q}$$

On the other hand, the reservoir capacity for supplying an entire day's demand could be considered. This was scaled as **856kWh/day** as per Section 4, which equals **3081600kJ.** Applying this to *Equation 9*, the required volume is considerably more; **3144m³** (equal to a 25m², 5m deep reservoir).

Pumped storage would not be an instant fix, it would take considerable time to plan, to ensure its environmental credentials, to build and to fill the upper reservoir. However, there is the possibility that it could be a viable option for Eigg to maximise their renewable penetration. The technology is proven, it has a long lifespan, requires minimal maintenance and some extra storage could be gained from the extra hydro resource present on Eigg during the winter months; which takes the form of rainfall. It is likely however that the battery technology would be kept in line with a pumped storage system –as it is used to smooth out the fluctuations produced in renewable generation.

### 5.1.6 Flywheel

Another (short-term) option is to store energy in the form of kinetic energy using flywheel technology. This has been used in some locations to successfully increase renewable penetration to 95%[lviii]. It involves spinning a mass (a flywheel) in a low-friction environment – normally a vacuum. The flywheel is connected to a motor-generator which links into the localised electrical network. Electrical energy is transformed into kinetic energy by the motor-generator and put into the flywheel. At times of power requirement, the flywheel's inertia will keep it spinning, but it will lose some of its kinetic energy as this is transformed back into electrical energy by the "generator side" of the motor-generator.

*Equation 12 - Kinetic Energy of a Flywheel*[lix]

$$E_{kinetic} = K * mass * radius^2 * RPM^2$$

The kinetic energy of a flywheel is proportional to the mass, the radius of the flywheel squared and the square of the rotational speed. A dimensionless constant, *K*, is used as a shape factor to define the location of the bulk of the mass from the centre of the spinning axis. It can be seen that is the radius increases the kinetic energy will increase. From this it can be noted that if the mass is further away from the point of rotation then it must have a larger kinetic energy (for a constant rotational speed).This is because the flywheel will have a larger moment of inertia:

*Equation 13 - Moment of Inertia of a rigid body*

$$I = K * mass * radius^2$$

Flywheels tend to be low-maintenance, long-life technologies; desirable characteristics for remote communities without masses of technical expertise. They also are able to be set up in banks or "farm" configurations to give various levels of output as per the demand requires. However, a main disadvantage of a flywheel is that it will introduce a parasitic load onto the electrical network; the load required to keep it spinning and hence allowing it to maintain its kinetic energy.

To input a flywheel into the Eigg model, the Powerstore 500 model[lx] was selected. This is a 4717kg flywheel with peak capacity of 500kW and a parasitic load of 12kW. Such a size was chosen to maximise the potential of storage via the flywheel, and so that it could operate in 'generation mode' for prolonged periods.

The addition of the flywheel reduced the excess electricity in the model to **30731kWh/year (6.1%)** and the renewable penetration of the model fell to **66.4%**. This suggests that the parasitic load provided by the flywheel will be limiting generation capacity in order to keep the flywheel spinning, hence affecting the ability to meet demand.

HOMER does not give the user the opportunity to assess flywheel performance in either graphical or data form. Therefore to analyse the effect, and as to why the renewable penetration had decreased, it was best to look at the other storage technology – the batteries.

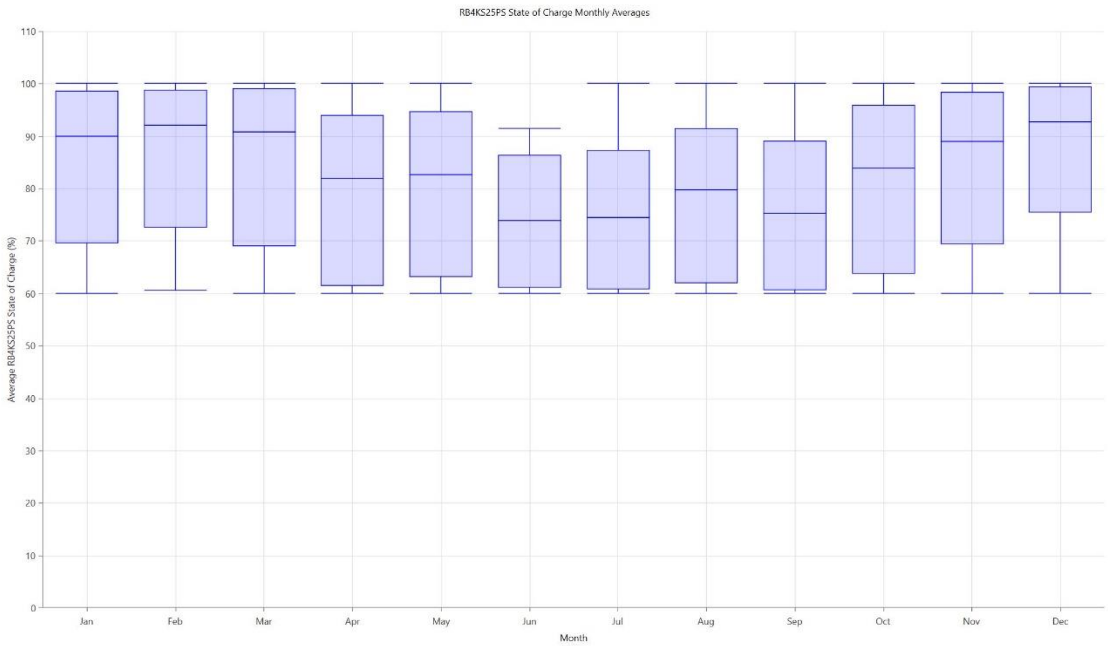



*Figure 31 – Battery monthly state of charge with flywheel storage*

*Figure 31* and *Figure 32* show the monthly battery state of charge with and without flywheel storage respectively. With flywheel storage, the battery state of charge can be seen to fall to the lowest limit of 60% every month. Whereas that is only true for eight months for a simulation minus a flywheel. It can also be seen that in the month of June the battery charge does not go above 93% for a configuration including a flywheel – minus the flywheel 100% battery charge is present at least once every month. On average, it can also be seen that with flywheel storage battery that the state of charge tends to be lower.

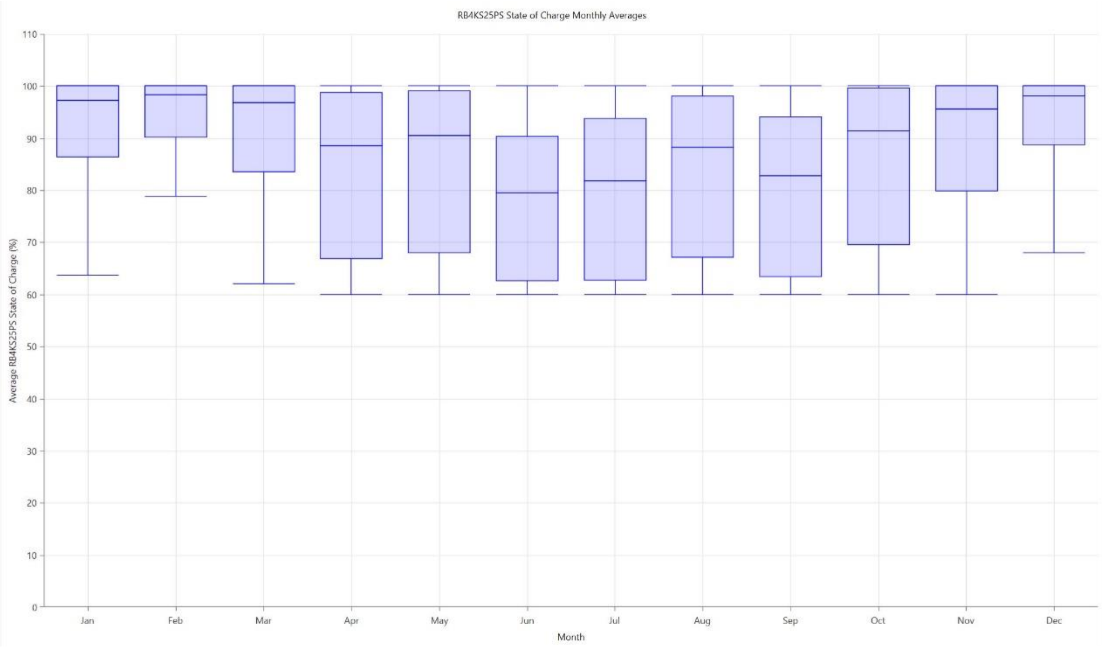



*Figure 32 - Battery monthly state of charge without flywheel storage*

This is conclusive evidence that the hindrance on renewable penetration by the addition of the flywheel is caused by its parasitic load. The lower battery charge levels indicate that the batteries are being discharged in order to feed an extra load; and the only extra load present on the system is that needed to keep the flywheel spinning. Hence, it is not recommended that flywheel technology be used for longer term storage in small communities such as Eigg. Instead it could be used on a smaller scale for somewhat smoothing out renewable supply; where it might have a niche market.

## 5.2. Increased Renewable Generation Capacity

It is clear from analysing the different storage technologies that despite masses of excess electricity, there is a limitation preventing renewable penetration reaching 100%. The limitation is the lack of renewable generation in the summer months – the majority of excess generation is produced in the winter months.

The capacities of the storage can be effectively increased to an extent, but a "saturation" point (a point of diminishing returns) is met where there are minimal gains from increasing the capacity further. In reality, it would not be financially (and possibly spatially) viable to keep expanding the capacity beyond this point with the aim of storing all excess electricity. Pumped storage could potentially combat this, but further investigation should be carried out to ensure the feasibility for this in Eigg (i.e. sites for development, the available head etc.).

Instead it is desirable to try and increase renewable generation, where possible, in the time periods where there is a lull in output, and hence minimal or zero excess electricity generation. In this case it is the summer months that are of interest for increasing renewable generation. A capacity increase in hydro generation is not a viable option for this. The current system uses pretty much the maximum hydro resource that would be available for use under environmental protection procedures. Plus, it is the fall in hydro resource in the drier, warmer summer months that contributes the most to the drop in renewable generation during these months. Increasing PV capacity was chosen to be investigated due to the increase in solar resource over the summer months, it was thought that this would somewhat increase the effect shown in *Figure 5* – that PV generation could make up for shortfalls in hydro generation and vice versa. A wind capacity increase was also considered due to the fairly consistent wind resource annually. The turbines currently in place make up a totally wind generating capacity of 24kW, this is fairly low when a community such as Gigha had a capacity of 675kW with its original three turbines; the aforementioned "Dancing Ladies".

### 5.2.1 Wind Capacity Increase

A small community such as Eigg is unlikely to have much financial resource to purchase new, leading edge technologies when it comes to wind turbines. Instead, they are more likely to make use of very low rated turbines (e.g. the current Proven WT6000s) or make use of second hand, refurbished turbines (such examples are those used in Findhorn and the "dancing ladies" on Gigha). (SNH) released a report[lxi] in 2013 looking at decommissioning of wind turbines, restoration of wind farms and how turbines (and their various components) can be recycled.

Scottish National Heritage highlight that increasing technological efficiency is causing older models to be replaced at an increasing rate. This means that there will be surplus of unwanted second hand turbines, and subsequently they emphasise the significance it could have for remote communities and community owned wind farms. With this in mind, a 75kW Vesta V17[lxii] entity was inputted into HOMER using a defined power curve and parameter data. This was chosen due to its high reliability, good reputation, long life expectancy and that it is a widely available model second hand.

*Table 7 - Current Wind Turbine Configuration Results*

| Number of WT6000 Turbines | Power Rating (kW) | Renewable Penetration | Excess Electricity | |
|---|---|---|---|---|
| | | | kWh/year | % of Total Electrical Generation |
| **4** | 24 | **85.4%** | 297,741 | 46.8% |

The model of Eigg was altered to incorporate the new V17  turbine instead of the four Proven WT6000 models (which provides the results shown in *Table 7* as a reference point). The number of turbines was increased until renewable penetration became saturated at approximately 98.4% as seen in the following table:

*Table 8 - Increasing Wind Capacity Results*

| Number of V17 Turbines | Power Rating (kW) | Renewable Penetration | Excess Electricity | |
|---|---|---|---|---|
| | | | kWh/year | % of Total Electrical Generation |
| **1** | 75 | **95%** | 297,741 | 46.8% |
| **2** | 150 | **96.8%** | 632,913 | 65.1% |
| **3** | 225 | **97.2%** | 951,979 | 74.1% |
| **4** | 300 | **97.6%** | 1,279,175 | 79.4% |
| **…** | **…** | **…** | **…** | **…** |
| **8** | 600 | **98.4%** | 2,588,443 | 88.7% |

Due to the saturation *Table* 8 shows, and the capital cost of wind turbines, it would not be viable to increase the number of turbines indefinitely until (if possible) 100% renewable penetration is met. Instead it shows that there is some gain in having an increased capacity; as they renewable penetration jumps from 85.4% to 95% just by having one 75Kw V17 turbine in place of the original 24kW WT6000 configuration. However, the effectiveness of increasing the capacity reduces exponentially – other factors must be limiting this.

*Figure 33* shows a stacked column chart depicting the power output from increasing wind capacity. The blue columns represent the current 24kW, four turbine configuration on Eigg, whilst the orange and grey columns show outputs from 75kW and 150kW configurations (using Vesta V17 wind turbines) respectively:

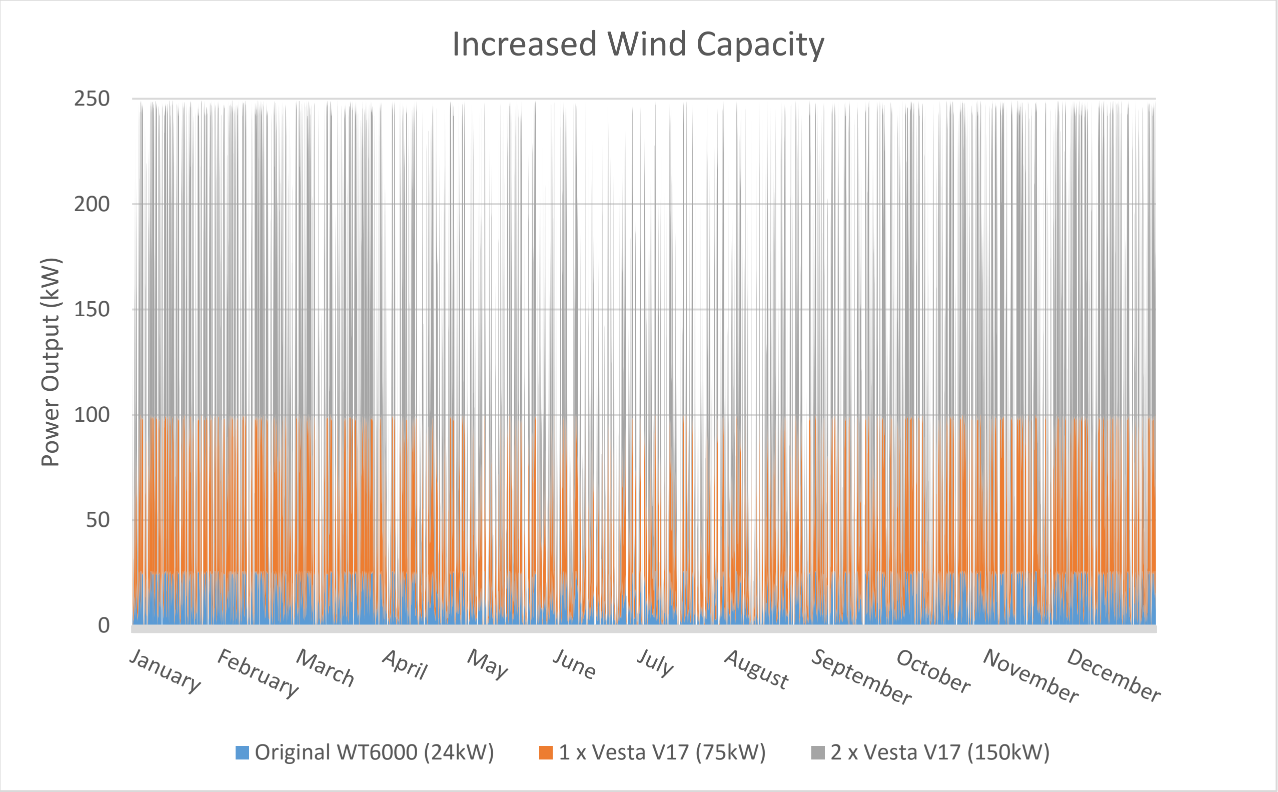



*Figure 33 - Increased Wind Capacity (24kW, 75kW& 150kW)*

It is seen that no matter how big the capacity is there will still be periods of next to no output - especially in the summer months where the wind resource is lower. August in particular has a sustained period of low wind output for the given climate model. Despiute this, as *Figure 8* shows, there is an increased hydro output for this model at this time of year and hence diesel operation is not too frequent; a prime example of two renewable energy systems working together to give redundancy in supply.

Nonetheless, such a period could be very detrimental to the renewable penetration of the island. This is a good example of how capacity can be increased to good effect, yet output it is ultimately reliable on a very unreliable and random resource – wind speed:

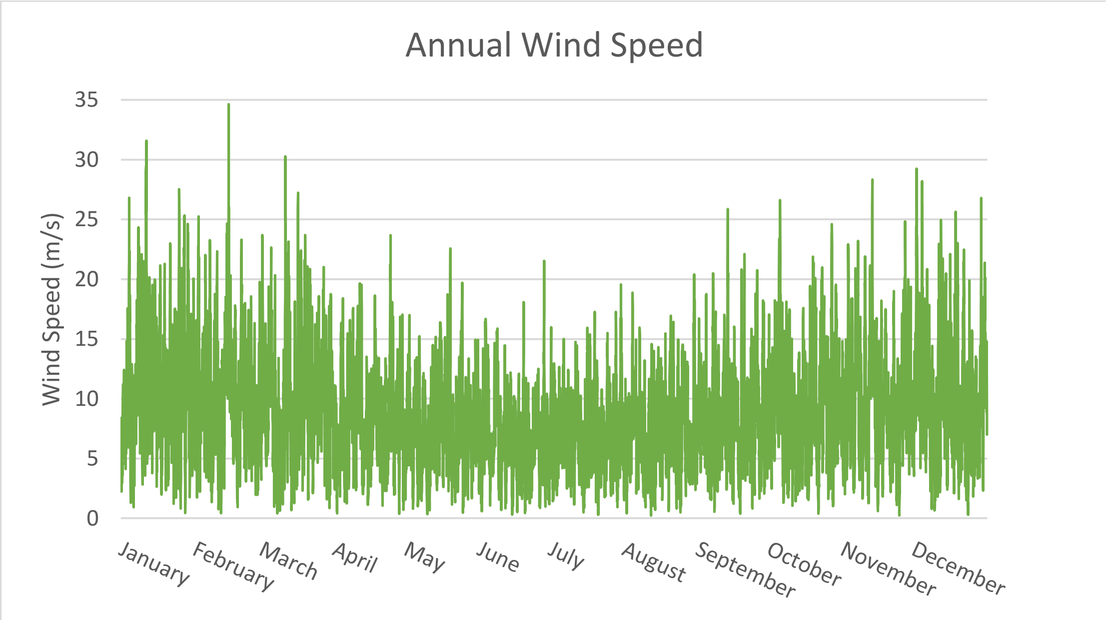



*Figure 34 - Annual Wind Speed for Eigg Model*

The variable nature of wind speed shown goes somewhat to explain the renewable penetration saturation experienced when increasing wind capacity. It is seen that the wind speed reaches approximately 0 m/s on multiple occasions and hence wind power output will be nil, no matter what the capacity is. This is when some other generator, or storage technology (or both) will be required to meet the electrical demand. Otherwise, the diesel generator will be required if the current battery system runs low on charge, or is unable to make up the shortfall in meeting demand.

*Table 8* also shows that there is a significant increase in excess electricity if wind capacity is increased to such levels. This may create its own problems such as voltage/frequency issues on the 3.3kV grid present in Eigg. Hence appropriate electrical dumps would be required to combat this.

### 5.2.2 PV Capacity Increase

Whereas the other renewable resources deplete in the summer months, solar resource becomes more abundant. It is a common misconception that PV arrays are not worth investment in Scotland. This is largely due to neighbouring countries in Europe having much higher levels of solar radiation in general:

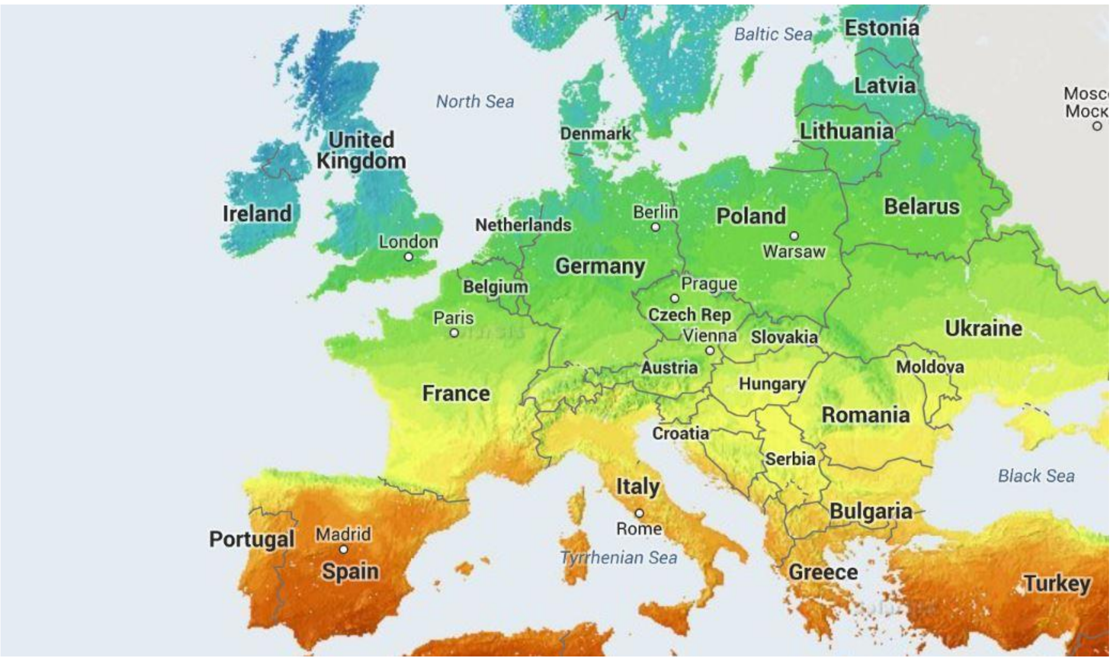



*Figure 35 - Solar GIS Map of Europe*[lxiii]

*Figure 35* shows an annual "heat map" of solar radiation in Europe. It can be seen that as one moves closer to the equator one experiences higher levels of annual solar radiation. The West of Scotland is seen to be a cyan/blue colour indicating its lack of solar radiation in comparison to its European counterparts. However, despite this, there is still more than sufficient light levels to obtain significant outputs from PV arrays[lxiv].

For Eigg, the PV network has already been expanded twice; originally having a capacity of 9.9kW, then 30.9kW before a final 22.5kW was added to give the current capacity of 53.4kW. This points to the success they have already had with increasing PV capacity. Any further addition needs to be divisible by 0.3kW to match the inverter system, therefore it was chosen to investigate the effect of increasing the PV capacity further by an increment matching that of the last expansion – 22.5kW.

*Table 9* shows the results from increasing the PV capacity in 22.5kW increments. As the capacity increases the renewable penetration increases, but not to the same extent as increasing wind capacity as in *Table 8*. This is indicative of how the wind resource on Eigg provides greater electricity generation potential than PV. It is also worth noting that around half the time the PV arrays will be generating next to no electricity whatsoever due to night time hours. In a remote community like Eigg however, and as per the model, night time hours have the lowest electrical demand therefore this effect is somewhat compensated for.

*Table 9 - Increasing PV Capacity Results*

| PV Capacity | Renewable Penetration | Excess Electricity | |
|---|---|---|---|
| | | kWh/year | % of Total Electrical Generation |
| **53.4kW** *(Current Configuration)* | **85.4%** | 90,935 | 20.5% |
| **75.9kW** | **87.3%** | 108,147 | 23.6% |
| **98.4kW** | **88.5%** | 128,438 | 26.9% |
| **120.9kW** | **89.3%** | 149,356 | 29.9% |
| **…** | **…** | **…** | **…** |
| **278.4kW** | **92.8%** | 303,411 | 46.6% |

It is also seen that for a similar renewable penetration (~ 93%), the excess electricity produced by increased PV capacity will be much higher than that for an increased wind capacity. It is not the same for a similar value of rated power output. This is due to the 75kW Vesta V17 models having a capacity factor greater than 40% in the Eigg model, whereas the PV panels have a capacity factor of 12%.

As the capacity increases further the renewable penetration saturates at the value of ~93% from a PV rating of 278.4kW upwards. Once again, as per increasing wind capacity, limiting factors come into play.

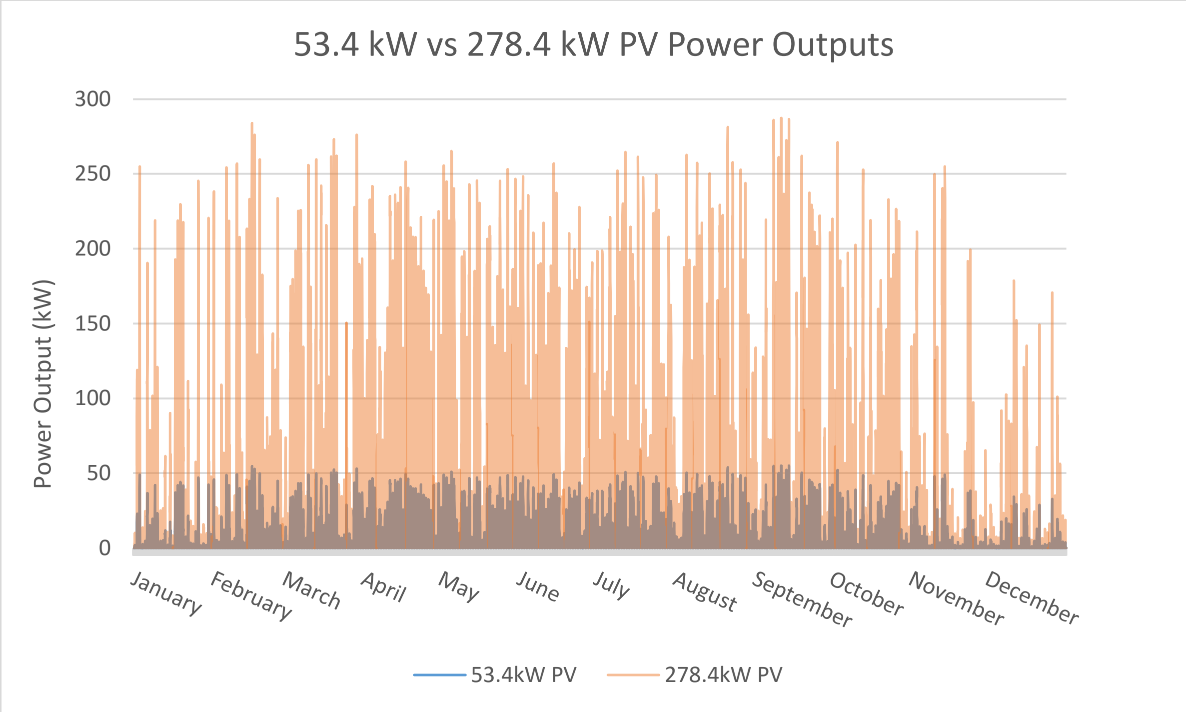



*Figure 36 - Increased PV Capacity Power Output Comparison*

*Figure 36* overlays the output from the modelled 278.4kW PV configuration against the current 53.4kW configuration. It can be seen that the power output is more consistent and higher in the summer months and that there are long periods of minimal generation in the winter months; especially in November and December. Ultimately though, it can be seen that no matter what time of year it is, and whatever the PV capacity is, there will be a lot of variability in the output. Just as with wind resource there are periods where the power output from PV panels cannot be relied upon; the diesel generators will be required to run to meet demand and hence the renewable penetration of the model is lowered. This lack of solar resource is what limits the renewable penetration when increasing PV capacity beyond the "saturation point".

### 5.2.3 Biofuel for Diesel Generators

Another alternative to boost the renewable penetration of Eigg would be to supply the diesel generators with a sustainable supply of biodiesel. Biodiesel can be defined as being carbon neutral – i.e. it provides no net output of carbon in the forms of carbon dioxide/monoxide. This is because the crop used will absorb as much carbon throughout its lifetime as it does when it combusted in the form of diesel.

The carbon neutral "tag" is not necessarily true however, there are many processes associated with biodiesel production (fertiliser production, esterification, solvent extraction of the vegetable oil, refining, drying and transportation) which all have associated energy inputs – usually resulting in some kind of carbon emission. A lifecycle analysis[lxv] carried out by the University of Strathclyde reported that the energy out to energy in ratio of biodiesel is equal to 2.5. Even with the required energy inputs the lifecycle analysis found that there is considerable carbon savings to be had by switching to biodiesel over conventional fossil fuel diesel.

*Figure 37 - Rapeseed Crop*

[lxvi]In the United Kingdom, growing conditions mean that rapeseed is the crop of choice for biodiesel production. Other crop choices are feasible though; elsewhere palm oil, coconut, peanut, sunflower and soybean oils are used[lxvii]. Small scale manufacture of biodiesel is a feasible option[lxviii], and for a small community such as Eigg it could help wean them off imported diesel for their diesel generators. SEPA regulations[lxix] require to be adhered to but as long as the net production is less than 200 tonnes per annum there would be no requirement to seek a waste management license in line with commercial operations.

Therefore a scoping exercise was carried out to assess the land requirement for biodiesel production on the Isle of Eigg. The HOMER model of Eigg calculated a requirement of **14245 litres** of Diesel use per annum. Applying the 2.5 energy out to energy in ratio this means that if the diesel generators were to run on biodiesel the requirement would be approximately **19943 litres** in a worst-case scenario – i.e. where none of the excess renewable generation is used to supplement the extra load incurred by biodiesel production.

The yield of rapeseed is defined as approximately 102 gallons (386 litres) per acre[lxx]. Using this, it was found that a land requirement of **51.72 acres (20.93 hectares)** would be required to match such a demand.

Considering that Eigg has a land area of **3,049 hectares**, one would think that the requirement above is entirely feasible. However, much of this would depend on the type of land and whether it is arable or not. Much of Eigg's current land space is given over to crofting in line with the heritage of the island; it is likely that such a move towards biodiesel production would face some opposition from local residents.

In reality, the land requirement could be much smaller. Load shifting technologies could potentially be used to use excess electricity for the biodiesel production process instead of the production of the biodiesel supporting its own manufacture. In addition to this if renewable penetration increases the biodiesel requirement will be lower; meaning that if there was additional investment in increasing renewable generation capacity there could be a significantly smaller land requirement.

There are other barriers to biodiesel production on Eigg. Firstly, the financials; currently it is more expensive to produce biodiesel than conventional diesel, then there is the fact that renewable subsidies are not something that can be relied upon long term (as seen in the 2015 UK Chancellor's Budget[lxxi]). Therefore it is likely that such a venture into biodiesel would have to be funded by the residents of the Island – possibly in the form of an expansion of Eigg Electric. Ultimately, at the end of the day, Eigg Electric would be the end user of the biodiesel hence it makes logical sense that they produce their own biodiesel if the option is pursued. This would likely produce a levy on the pence/kWh rate paid by the residents on Eigg – such as the levy they already pay to reinvest funds back into the electrical network.

Another barrier requires consideration of the small population of Eigg and the expertise required for such a process. Investment would be required to ensure that enough local residents had knowledge of the system, and that such an asset was not reliant on external (outsider) knowledge or that of one person. Once again, this could potentially be resolved if biodiesel production was ventured as part of Eigg Electric. Finally, it is worth noting that some modifications may be required on the current generators to make them suitable for biodiesel operation – but this is not likely to pose any significant barrier to the feasibility of biodiesel use on the Isle of Eigg.

## 5.3. Maximising the Renewable Penetration of the Model

Even though Eigg has significant amounts of excess electricity, storage alone cannot be effectively implemented into the HOMER model to gain maximum (100%) renewable penetration. The same can also be said about increasing renewable generation capacity in the model. This is due to the variability in renewable resources; on too many occasions there are periods of low renewable power generation. This leads to the storage systems depleting charge and then subsequent operation of the diesel generators.

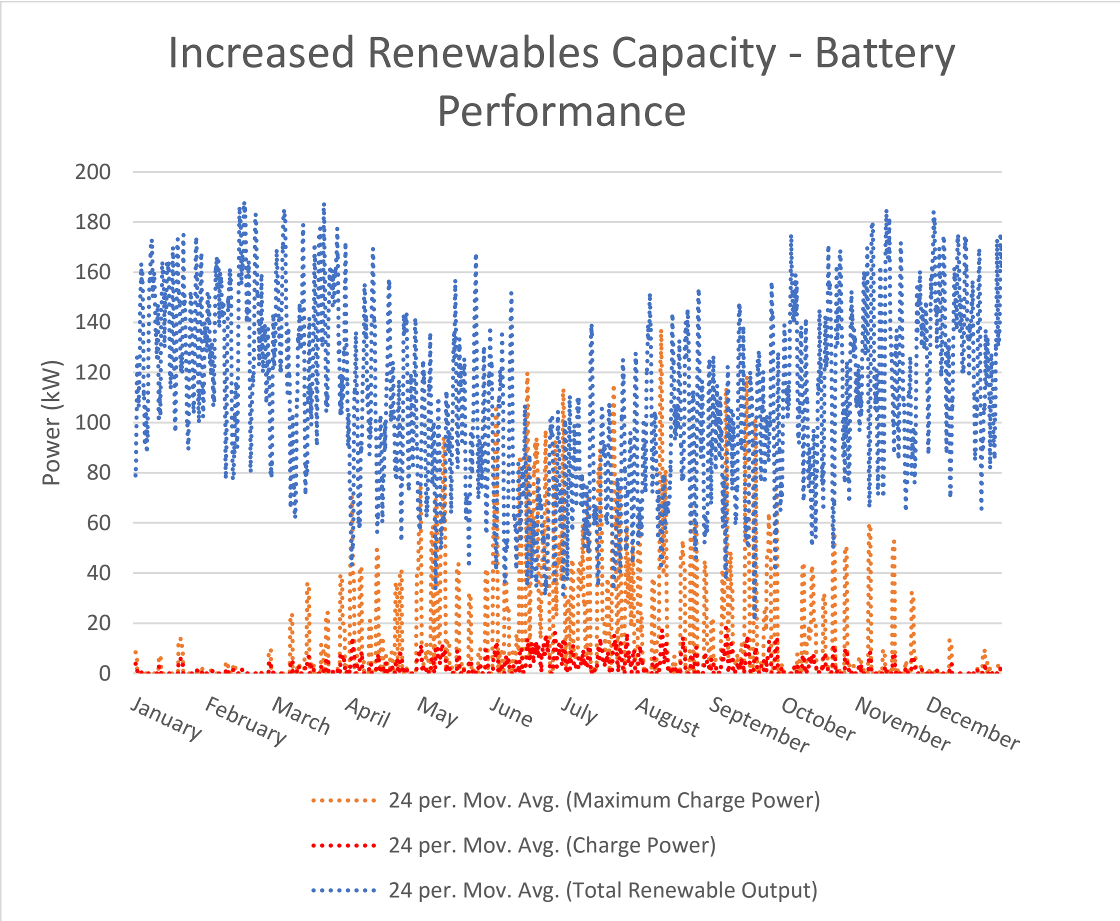



*Figure 38 - Increased Renewable Generation (Two 75kW) V17 Turbines)*

*Figure 38* can be compared with *Figure 20* to see the effect of increasing renewable generation capacity on storage (Rolls Lead Acid Battery) performance. *Figure 38* has an increased renewable penetration of 96.8% with the addition of two 75kW Vesta V17 turbines instead of the Proven WT6000 models in the original, validated model. Firstly, it can be seen that the maximum charge power is much lower on average; this is limited as, in general, the batteries are charged more on average than the original scenario. The renewable output is roughly double that of the original configuration. However, it still follows the same profile as before and hence there are still periods of sustained lulls in renewable output. This is what limits/saturates the effect of increasing renewable generating capacity indefinitely.

In the summer months this occurs with higher frequency, hence the maximum charge power increases as the batteries are willing to accept charge because of their depletion. However, the batteries have to wait until after these periods to charge – when the renewable resource becomes available or enough spare generation comes available from the diesel generator to charge.

It is also seen that the increased renewable generation leads to increased amounts of excess electricity – especially in the winter months. Storage systems have their own limits as to how much excess electricity they can store in a given time-step, hence much of this excess goes to waste. This also, as mentioned in Section 5.2.1, could potentially put too much electricity into the grid; leading to voltage and frequency issues. Hence appropriate electricity "dumps" would be required to be incorporated to the microgrid in addition to the increased capacity.

Therefore, it can be concluded that solely increasing renewable generation capacity is not a worthwhile practice to maximise renewable penetration. Instead, it is recommended that both generation capacity and storage capacity should be increased.

### 5.3.1 Reaching 100% Renewable Penetration

In order to maximise and reach 100% renewable penetration it was chosen to initially investigate the best performing technologies, both storage and generating, investigated in the previous sections. Wind power was chosen as the generation capacity increase of choice, not only because per kW of capacity it increased renewable penetration by a greater margin than PV, but also for the fact that it still operates during night time (lowest-light) hours when the electrical demand is likely to be low. This helps boost the opportunity for any storage technology to charge. PV, though, was not neglected in the search for 100% penetration.

Out of the storage technologies, hydrogen storage and Li-ion battery technology were chosen to be investigated due to their high levels of renewable penetration with sole implementation; 93% and 94% respectively. Due to the desirable long life, low maintenance characteristics of flow batteries, this option was still investigated as these characteristics are highly appealing to remote communities such as Eigg. Lastly, the current storage technology was investigated as this would be the simplest was to increase capacity – minimising the need for further infrastructure works.

The resultant 100% renewable penetration configurations are detailed as follows:

**<u>Configuration 1</u>: Increased Wind with Li-Ion Batteries**

A total of 43 expanded LG Chem RESU 6.4 EX batteries were added to the model in place of the current Rolls Lead Acid battery configuration as this was one of the best performing storage technologies from Section 5.1. As before, 43 batteries were required to provide a storage capacity equivalent to the current battery system on Eigg - **514.8kWh**. The performance, as previously shown, is improved through an increase in efficiency and the ability for the batteries to operate to a lower state of charge; hence allowing for a larger quantity of stored energy to be available to the microgrid when needed.

To this, the current WT6000 wind capacity was removed and replaced with a singular 75kW Vesta V17 turbine. The resulting 100% penetration gave an excess electricity of **297,870 kWh/year** (**48%** of the total electrical production).

**<u>Configuration 2</u>: Increased Wind with Hydrogen Storage**

The current WT6000 wind capacity was removed and replaced with a singular 75kW Vesta V17 turbine as above. An electrolyser, hydrogen storage tank and fuel cell were inputted (as per 5.1.4 Hydrogen Fuel Cell) and a sizing optimisation was once again carried out. The resulting sizes of the components were the same as that of *Table 6* except for that of the hydrogen tank; instead of 2000kg the optimal size was now **2500kg.** This can be explained by looking at the annual stored hydrogen levels in *Figure 39:*

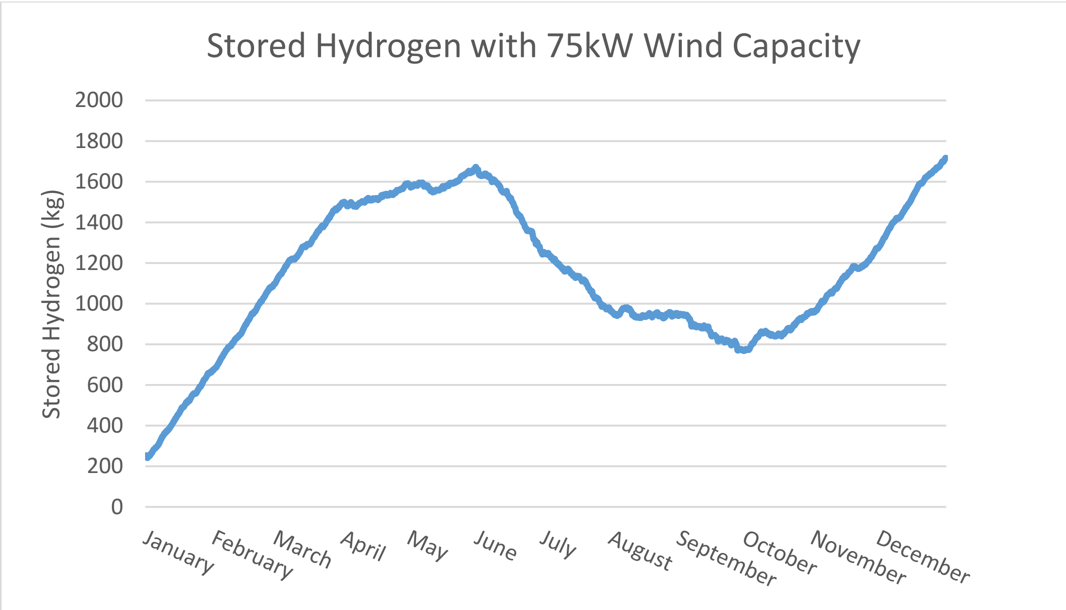



*Figure 39 - Annual Stored Hydrogen with an Increased Wind Capacity of 75kW*

In comparison to *Figure 29*, this shows plentiful volumes of hydrogen storage. This is because the issue with a lack of capacity in the summer months has been resolved by the replacement of the WT6000 turbines with a single Vesta V17. Hence, there is more hydrogen capacity to store and the optimisation study chose a larger storage tank size. It can still be seen, though, that there is a depletion in the storage over the summer months; with roughly steady levels in the month of August when the hydro resource is slightly higher than the rest of the summer months.

The resulting excess electricity equalled **53,800kWh/year – 8.4%** of the total electrical production.

**<u>Configuration 3</u>: Increased Wind and PV with Vanadium Redox Flow Battery Storage**

A Vanadium Redox Flow Battery was added as per section 5.1.3. Initially only a 75kW V17 turbine was included in line with that of Configuration 1 and Configuration 2. However, this only returned a renewable penetration of 98.7%. Therefore an additional capacity increase of 22.5kW of PV was inputted to bring 100% penetration – taking the total PV capacity to 75.9kW.

In addition to this, a sizing exercise was taken at each step to ensure the optimal size of the battery. This was found to be a battery of **100kW** rated capacity and a storage capacity of **900kWh.**

The excess electricity for this configuration was **318,811kWh/year – 49.4%** of the total electrical production.

**<u>Configuration 4</u>: Increased Wind with Rolls Battery Storage**

The WT6000 wind turbines in the validated Eigg model were removed and replaced with three 75kW Vesta V17 turbines. The battery bank was also expanded to include 20 strings (240 batteries). A PV capacity increase was investigated in 22.5kW increments (alongside only two V17 wind turbines), but the renewable penetration would become saturated at **99.5%.** Therefore an increase in PV technology was deemed unsuitable for this configuration

The excess electricity for Configuration 4 was **974,166kWh/year – 75%** of the total electrical production.

*Although three of the above configurations use single wind turbines to reach 100% renewable penetration, in reality it would be optimal to have two turbines. This is to add security and redundancy in supply, to cover for maintenance works and increase the overall robustness of the electrical supply. Even further redundancy could be added by increasing PV and storage capacities in line with this.*

# 6. Lessons Learned from the Eigg Model

The initial aim of this report was to create and validate a computational model of Eigg using a software package. After a comparison with another software packaged called MERIT, HOMER was chosen to progress the project as this had most of the necessary tools/modelling capabilities to complete the objective of this report. The validation step of the investigation proved not only the accuracy of the model, but the validity of the chosen HOMER software package; as the behaviour, the penetration and battery performance matched that of real-life data from Eigg. Confidence was gained from this in order to progress with accomplishing the rest of this report's objectives.
The original model produced significant quantities of excess electricity; 25% of the total electricity produced. The renewable penetration of the model was found to be 85.4% - reasonably accurate to the real life value of 86.2%. Drier months in the summer period had the largest effect on the penetration of the model - lower hydro resources meant that the "baseload" it provided was much lower than the rest of the year. Therefore, the diesel generators were called upon more frequently to match the electrical demand of the model.

By investigation it was found that increasing storage is not necessarily the only required modification to maximise the renewable penetration of a microgrid such as that on Eigg. It was concluded from observations that storage technologies may be limited through efficiency losses or "charge rate capacities" – i.e. how quickly they can store energy at a given time-step. This meant that not all of the excess electricity produced in the model could be stored and significant amounts still went to waste (via heat dumps).

Different storage technologies were tested giving variable results. Li-ion Batteries and Hydrogen Storage technology provided the best performance characteristics – increasing renewable penetration by the largest margins. Li-ion batteries proved to be the most effective battery technology due to their extremely high efficiency and ability to be repeated depleted to low states of charge. This 'frees up' extra stored electricity in comparison to the lead acid battery configuration already present on Eigg. Hydrogen Storage, through efficiency losses and the effectiveness of the electrolyser, produced significantly lower quantities of excess electricity than that of Li-ion batteries. It also created the opportunity for seasonal energy storage – which can be used to compensate for long periods of low renewable electrical production such as the summer months present in the model created for this report.

Flywheel storage (the poorest-performing technology modelled) was seen to be detrimental to the renewable penetration as this requires a parasitic load to keep the flywheel constantly spinning. It was found that such a technology is not suitable in this application. Instead, flywheels should be used on a smaller scale for the smoothing out of renewable supplies over very small time-steps. Having this technology on a smaller scale would minimise the parasitic load, whilst using it for a different function could allow for a long-life, low maintenance technology to be used for immediate voltage and frequency control – maybe one day replacing the battery setups which are currently used for this control.

Pumped storage was scoped out as a possible storage technology for Eigg, but the HOMER software does not have a module for modelling this. In theory such a technology should be able to put the current configuration on Eigg up to 100% renewable penetration. This would depend on a 70-80% efficient pump-turbine being able to use almost all the excess electricity produced by the island. There would also be scope for some natural hydro resource to fill an upper reservoir, therefore some excess resource from the winter months could be stored until summer. This storage option ultimately would require further investigation than that provided in this report; as the isle of Eigg has Special Sites of Scientific Interest (SSSIs) and many geological challenges that may also prevent the implementation of pumped storage capabilities on Eigg.

Like storage, it was found that increasing generating capacity could not be solely used to maximise the renewable penetration of the model to 100%. Ultimately, this was down to a limitation provided by the resources; if there not sufficient renewable resources for a prolonged period, then the storage technology will quickly deplete and the diesel generators will be operated. This occurs no matter how much the capacity is increased as the increased gains will become “saturated” by technological limitations – i.e. if the resource is not there, then increasing the capacity still is not going to combat the shortfall without an appropriate improvement in storage technologies; all the excess electricity needs to be stored as and when it is produced. For Eigg, only wind and PV capacities were increased because the current configuration maximises the use of the island's hydro resource.

In order to maximise renewable penetration it was found that increasing both generation and storage capacities allowed for a value of 100% penetration to be reached. Four feasible and optimised configurations were presented; all but one only using increased wind turbine capacity as the preferred option for increasing renewable generation capacity. It should be noted that wind turbine capacity expansion is becoming an increasingly desirable option for small community-owned grid networks; as technological efficiency advances, many turbines are being replaced creating a second-hand wind turbine market which is easily accessible to community organisations such as Eigg Electric.

*Configuration 1* provided the most efficient result of the four configurations; as it produced the largest quantity of excess electricity per kW increase of capacity. This was largely down to the higher efficiency of the Li-ion battery model, and that such technologies allow the battery to be depleted to a lower state of charge (20%) than the lead acid battery model (60%) with minimal effect on the projected lifespan of the battery.

Whether this is desirable is questionable however. On one hand, this could free up excess electricity to support other processes, or it could be used to start meeting thermal loads on the island – not currently supported by the electrical network but by household gas canister supply. It could, though, be a burden on the infrastructure of the grid; causing voltage and frequency issues. Therefore there would have to be sufficient "energy dumps" – much greater than the current heat dumps that are used to heat community buildings. At the time of writing (2015) Li-ion batteries are a relatively expensive option in comparison to the conventional lead-acid battery. As the digital ages progresses though, and the proliferation in portable electronics continues, the price of this technology is falling in line with its mass market applications. Although maybe out of the price range of a small community enterprise at the present, it may be a viable purchasing option in the near future.

*Configuration 2* on the other hand, uses hydrogen storage technology and leaves an excess electricity of only 8.4%. The model shows a considerably higher end of year hydrogen level than the 200kg initially inputted into the storage tank. This positive net hydrogen production (approx. 1500kg) could futureproof 100% renewable penetration if a larger storage capacity was eventually implemented. The seasonal storage ability of hydrogen could also secure electricity supply in "freak" scenarios involving unprecedented sustained periods of low renewable resource.
The main barrier with hydrogen storage, and the most likely reason that it would not be purchased by a community enterprise like Eigg Electric, is that it is a relatively immature technology. This means that it is relatively expensive in comparison to alternative technologies, and that its reliability in supplying for such a network is not yet known. Fuel cells in the 100kW capacity region have a lifespan of around 60000 hours[lxxii] (6.8 years) and hence this would be a cost which would likely need to be incurred and funded by a levy on the electricity provided to the residents of Eigg. Unless Eigg could get grants for such technologies, the chances of it being a reality are slim. It does, though, provide very impressive performance in simulated model and, as mentioned, opens the potential to seasonal storage – which could accommodate for the generation shortfall during the summer months in the Eigg model.

The other two 100% renewable penetrations required significantly more capacity in order to completely satisfy electrical demand. *Configuration 3* uses a Vanadium Redox Flow battery like that being used on the Isle of Gigha. It was found that complete autonomy was only achieved by using two V17 turbines instead of one as per *Configuration 1* & *Configuration 2.* This may seem undesirable but in reality the likelihood is that a community would wish to have two wind turbines of such a capacity in order to provide redundancy in the case of maintenance or mechanical failure. The issue with this is that it produces 49.4% excess electricity production and a strategy would need to be applied to deal with this (load control, demand response, increased storage or throttling of renewable generators).

The same applies to *Configuration 4*, which produces an excess of 75%. This uses the same lead-acid battery storage technology already in place on the island, but increases its capacity by 250%. The wind output is altered by (again) replacing the WT6000 turbines with three 75kW Vesta V17s. This shows the extent at which Eigg would have to invest in renewable generation technologies to reach autonomy with an expanded version of the current storage setup.

Biodiesel use and production was also investigated to increase the renewable penetration of the island's electrical network. The combustion of biodiesel emits the same amount of carbon-based gases that the crops absorb during their growth; hence biodiesel sometimes gets tagged as being zero carbon technology. In reality, though, there are a lot of associated processes with biodiesel production and these had to be accounted for as a new energy demand in the model. Investigating biodiesel production was carried out by hand calculation and showed that the land requirement is of feasible proportions to provide for Eigg. This was calculated using the current diesel requirement – plus an "energy-in factor" required for satisfying the processes associated with the said biodiesel production.
This requirement could be less in reality though. There is a possibility that load shifting technologies could be used to satisfy the production process during periods of excess electrical production. If biodiesel production could also be implemented with more generating and storage capacity, then the land requirement could decrease even further as the renewable penetration would already be higher; and hence the required biodiesel volume would be significantly lower. This would also allow for the production infrastructure to be minimised in terms of size.

It is apparent from the model that diesel generators will still be required as a backbone for the island if they continue to be islanded from the main grid. Hydro inputs play an essential part in maintaining a baseload for Eigg's network. However, this will need maintenance work carried out on the turbines (and other working parts) and this means outages are destined to occur. Therefore this increases the case for biodiesel production on the island, but it does come with its drawbacks; such as creating a financially sound case, building productions units, obtaining the appropriate skillsets in the local community, being dependant on reliable crop harvests etc.

*The lessons learned here only result from the validated HOMER model of Eigg. These were applied to look at other cases with the aim of validating the findings and discussing how they may be applied elsewhere as per Section 7.2*

# 7. Discussion

*The learnings of this report can be used in a broader context. This section looks at how variability of renewable resource can affect such systems and their design, how the 'lessons learned' are validated beyond the scope of Eigg, the suitability of the HOMER software package and future work that could follow on from this thesis.*

## 7.1. Stochastic Renewables

Renewable resources are renowned for their random nature, their unpredictability and sometimes destructive force. This is a challenge which a renewable network will always face; although forecasting tools are forever increasing in accuracy the dynamic weather system will more than likely differ somewhat from the best forecast.

In the Eigg model created for this report the renewable resources were based on monthly averaged values over a period of up to 22 years. What this does not account for is the "freak" weather scenarios with a detrimental effect; for example, a heatwave causes an exceptionally dry month with very low wind speeds (**Scenario 1)**, or a dark winter month with very low wind speeds (**Scenario 2)**.

To provide an illustrative example of this, both scenarios were simulated in the HOMER system. For scenario 1, the hydro resource in July was lowered to 10 litres/second to represent a very dry month and the average wind speed was lowered to 2.5 m/s. For the original, validated, Eigg model this lowered the renewable penetration from 85.4% to 81%. This led to a capacity shortage so significant that the maintenance (standby) diesel generator had to be operated for 2462kWh in the month of July; a scenario which should ultimately be avoided. Also applying this scenario to *Configuration 1* reduced the renewable penetration from 100% to 92.2%. This also required the diesel generator to run for 2510kWh of electricity during the month of July.

The diesel output for *Configuration 1* is higher than the original Eigg model due to the cut-in speed of the Vesta V17 wind turbines being higher than that of the Proven WT6000 models. This is a good example of how the different system configurations can be affected by different magnitudes to fluctuations in renewable resource. The higher penetration model of *Configuration 1* incurs a renewable penetration "penalty" almost double that of the original model.

Scenario 2 was modelled by lowering the Clearness Index for January to 0.07. In line with this, the Average Daily Radiation was reduced to 0.1 $kWh/m^2/day$. The wind speed data for the same month was reduced to an average of 3m/s. The original Eigg model's renewable penetration, for this example, reduced by 0.3%, whereas *Configuration 1* remained at a penetration of 100%. The reason that the effect on renewable penetration is minimal here is because the Eigg model has redundancy, for this case, in the form of the hydro resource on the island. January is one of the peak months for hydro resource, therefore this can accommodate for a shortfall in the other renewable generation technologies. *Configuration 1* has better resilience than the original model in this scenario, unlike in Scenario 1. This is due to the use of Li-ion batteries instead of the Rolls lead-acid model; less losses are made due to the higher round trip efficiency and therefore an improved storage system is present.

Nonetheless, these two scenarios show that Eigg has some redundancy in the number of renewable resources it uses. It exemplifies the argument for there to be a mix of renewable resources in order to maximise renewable penetration; as it allows for the demand to be met by alternate resources depending on the impending climatic conditions. Scenario 1, in particular, shows that an experimental example of a 100% renewable system can easily be hampered by changes in renewable resource. Therefore, for the design of a system to be truly 100% renewable, it needs to be rigorously stress tested to prove its resilience in periods of a reasonable "worst-case scenario" – not only where renewable resource is low, but where maintenance may be carried out inclusive, where generating units fail etc…

## 7.2. Beyond Eigg

As per the objective, this investigation looked into the lessons from the Eigg model that can be learned and applied to other communities.

### Gigha

As per the Literature Review, the Isle of Gigha was investigated to draw a comparison with Eigg. The grid-connected island was modelled as having the 3 "Dancing Ladies" turbines with a combined capacity of 675kW. Like the Proven WT6000 and Vesta V17 models, these Vesta V27 (225kW) models required a library file to be created in HOMER. This was carried out as per the V27 technical specification sheet[lxxiii]. The new, fourth, turbine was also inputted. This Enercon E33 model also required to be inputted using the manufacturer's specification sheet[lxxiv]. Its power curve was altered to show that the 330kW capacity turbine had been constrained to 225kW as seen in *Figure 40:*

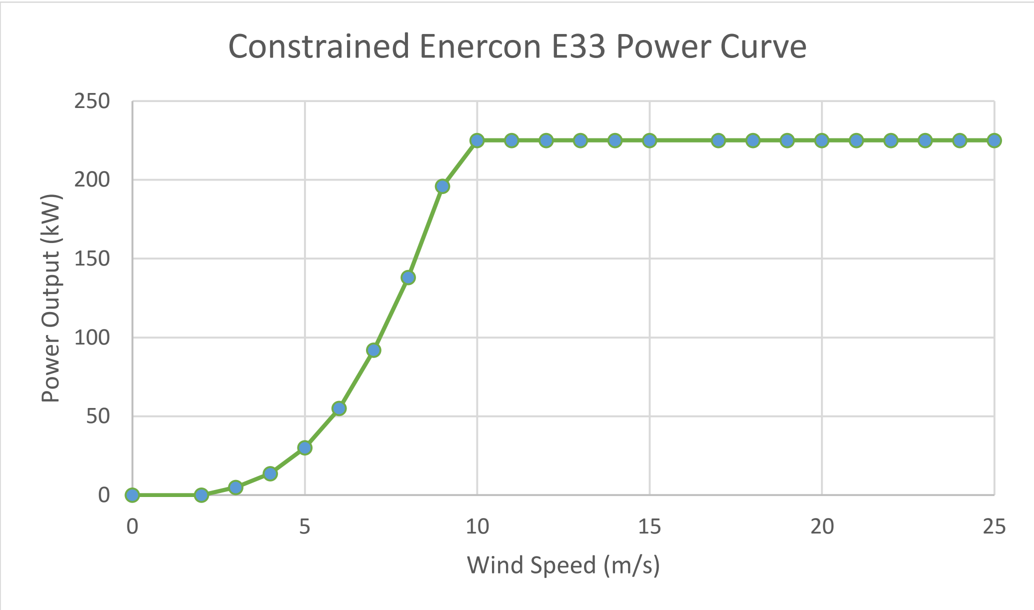



*Figure 40 - Constrained Enercon E33 Power Curve*

The island has a population of approximately 160 in comparison to Eigg's approximation of 100. It is not as simple, though, as just scaling up the demand profile by 160% to match this. Gigha, unlike Eigg, has some industry (farms/fisheries) on the island and therefore the equivalent demand is much higher. As per Eigg, no real-time data was available from Gigha – therefore a synthetic profile had to be created in line with the 3.15Gwh annual electricity demand stated in literature[lxxv]. The natural resources were, as per Eigg, added to the model using the NASA Surface Meteorology and Solar Energy Database.

The final schematic of the island's electrical network was as per below:

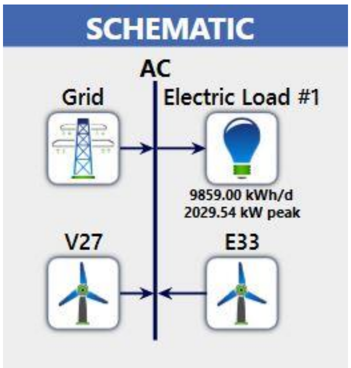



*Figure 41 - Constrained Gigha Model Schematic*

The resulting model gave a renewable penetration of **74%;** without the E33 turbine it equalled **62%.** In reality, the three "Dancing Ladies" are said to provide approximately two thirds of the islands electricity[lxxvi]. Therefore, considering no real time data was available from Gigha, the model was deemed to be a reasonable representation.

To see the benefit of un-constraining the E33 via the addition of a Vanadium Redox Flow Battery the same battery modelled for the Eigg model was inputted – but with a capacity of 1200kWh to match the model being installed on the island[lxxvii]. This increased the renewable penetration by approximately 1%, resulting in a decrease in electrical grid imports of 25252kWh/year.

In terms of Gigha, this does not have a huge impact. What it does do, however, is get rid of a barrier to further proliferation of renewables on the island – i.e. it is no longer constrained by the 11kV network. From here, a simple case study was carried out on Gigha to validate the findings on Eigg.

Increasing storage capacities replicated the results that were obtained from the model of Eigg. It was found that the current sizing (1200kWh) of the battery was the optimal choice for the model and that increasing the capacity further had negligible effect (i.e. the saturation point was reached); the renewable penetration saturated at a value of 75%. Once again, this was due to the fact that there is not enough excess electrical production during the summer months. This can be seen in the 24 point moving averages presented in *Figure 42:*

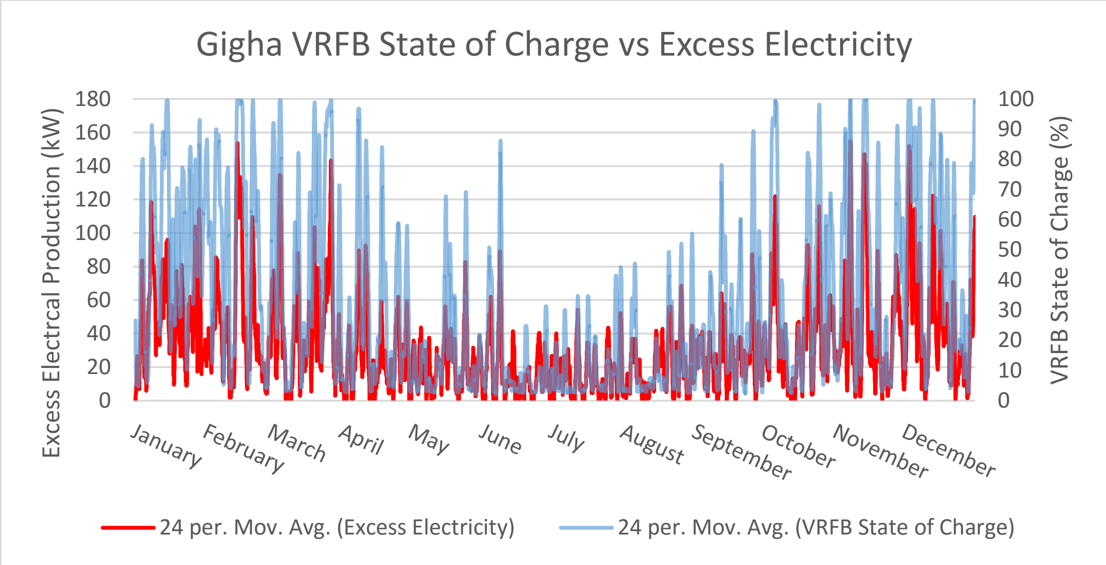



*Figure 42 - Gigha Vanadium Redox Flow Battery State of Charge vs Excess Electrical Production*

The figure shows that the battery state of charge, like Eigg, depletes to its lowest levels in the summer months. At the same time, the excess electrical production on the island is at its minimum, on average, for the year. This is due to the lower wind resource at this time of year as shown by *Figure 43:*

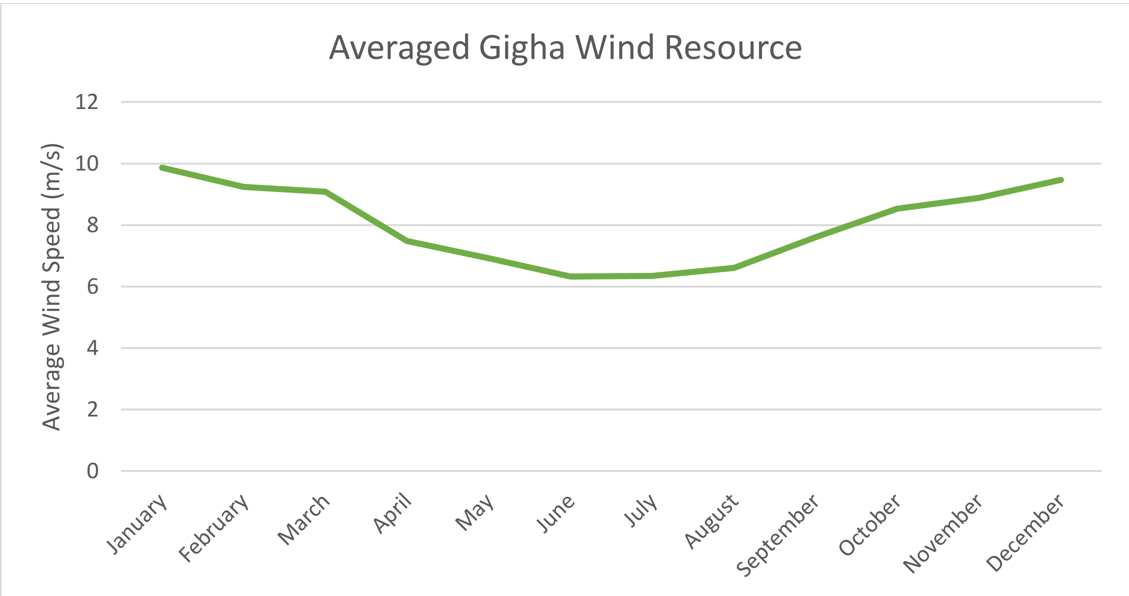



*Figure 43 – Gigha Averaged Wind Resource*

From this, the same lesson can be learned that was learned from Eigg; that **storage capacity cannot be increased effectively unless the seasonal generating capacity (and resource) is there to support it**. In the case of Gigha, increasing the generating capacity is exactly what the addition of storage allows them to do.

To increase the capacity of renewable generation on Gigha, PV was assessed to make up for the shortfall of wind output in the summer months. However, to have any significant effect PV arrays of a rating around 1MW were required. With increasing wind turbine capacity the renewable penetration saturates at approximately 85% - 86% when modelling with 1MW of PV present. This further amplifies that point that **there must be a mix of renewable resources in order to maximise renewable penetration –** i.e. this case shows that if there are periods of low wind and solar resource, the renewable penetration suffers due to too heavy a reliance on wind turbine and PV panel output.

On Eigg, for example, there is a fairly predictable renewable "baseload" in the form of the hydro resource on the island. This is crucial to Eigg, but could also be another crucial factor in maximising penetration elsewhere.

## Other Non-Grid-Connected Islands

Eigg is somewhat unique due to its hydro resource - this effectively provides the island with a fairly reliable baseload to supplement the other renewable technologies. Other islands do not necessarily have the good fortune to have such an asset. Therefore, to highlight the importance of this baseload, the Eigg model was remodelled minus the hydro component to create a generic island with just wind and PV resources.

As soon as the hydro component is taken out of the Eigg model the renewable penetration falls to **28%**, with the excess electricity equalling **850.8 kWh/year.** Not only does this emphasise the importance of the hydro resource to Eigg, but it indicates that for islands without a similar resource the other renewable generation capacities will need to be significantly higher.

Increasing wind (using 330kW E33 turbines) and PV capacity alone, in line with the previous findings, could increase the renewable penetration to a level of **92%** using the same wind and solar resources as the validated Eigg model. From here, the results were once again saturated and further increases had negligible effect. Applying the various storage technologies available in HOMER to this increased capacity could only increase this by a further 1% (most effectively with Li-ion Batteries and a Vanadium Redox Flow Battery). Although there is still excess electricity, at times much of it is not absorbed by the storage systems as they do not have the capacity to make full use of the excess when it is available (i.e. maximum charge rates). Hence, something else must limit this system other than generating capacity.

This limitation comes from the actual wind and PV resource itself. As *Figure 44* demonstrates, the incident solar and wind resource do not necessarily complement one another. There are long periods where both resources are fairly low; meaning low electrical output at these times.

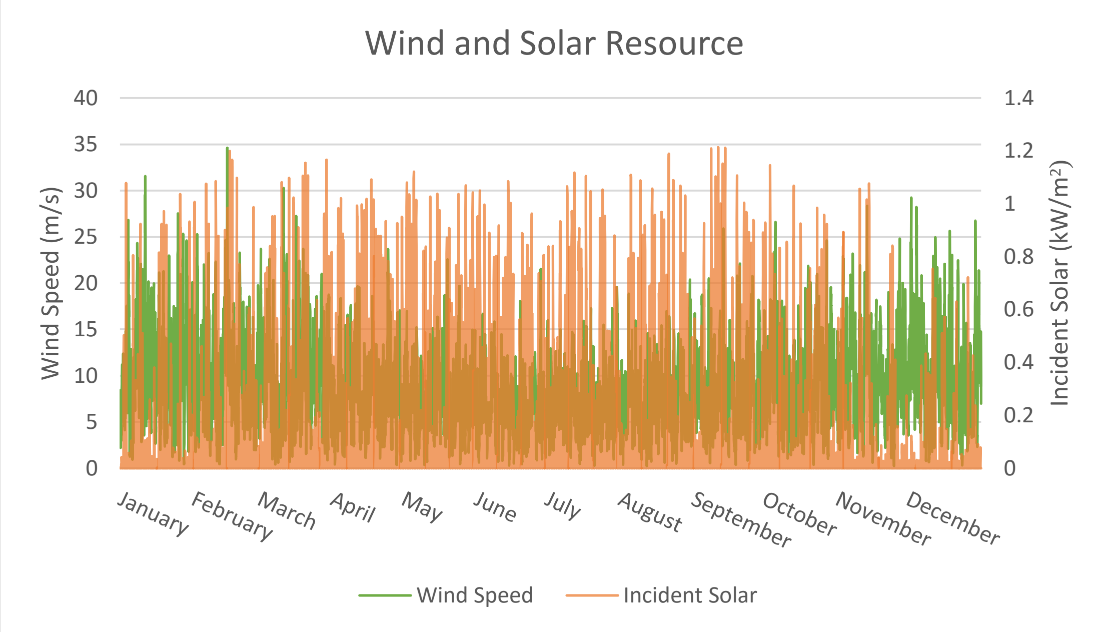



*Figure 44 - Wind and PV Resource*

Hence, it is not desirable to solely rely upon wind and PV systems to maximise renewable penetration. The random nature of their resources means that there can be sustained periods of minimal electrical output. It therefore would be desirable to add another renewable to the mix in order to increase redundancy in the system. Eigg has this in the form of its hydro system, but the geographical nature of other islands means that this could not be feasible.

Another option could be provide a predictable baseload by using tidal technology. Tides can be very predictable, give a consistent output and, once implemented, tidal technologies are a fairly environmentally friendly option as they produce no greenhouse gases[lxxviii].

Tidal technology can be split into two categories; tidal stream and tidal barrage[lxxix]. Tidal stream devices make use of the kinetic energy present in tidal currents – not too dissimilar from the way wind turbines use the movement of air. At present (2015) this is a notably immature technology however, and hence there is very little performance/ reliability data available[lxxx].

A more reliable and established way of harnessing tidal energy is the tidal barrage. This requires a bay or inlet reservoir to which a barrage is constructed across. The operation of such a barrage is captured in *Figure 45* :

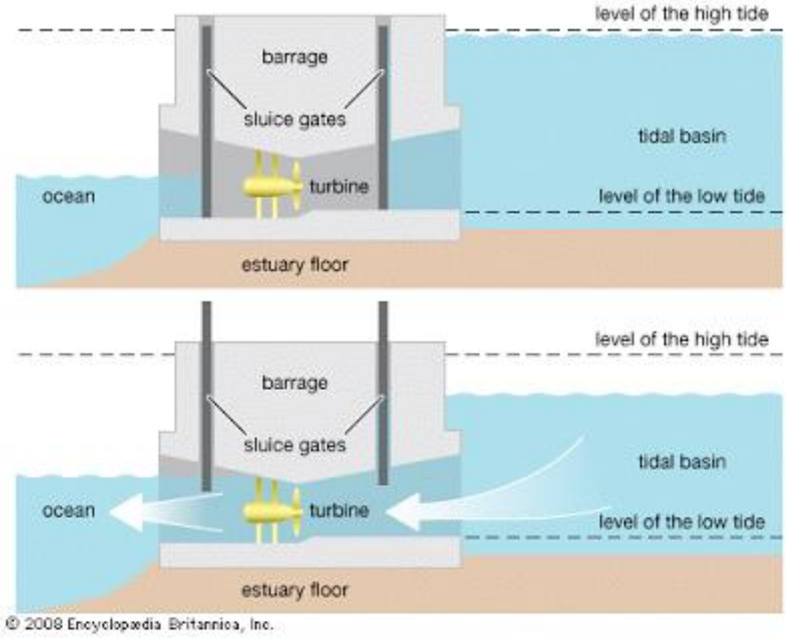



*Figure 45 - Operation of a Tidal Barrage*[lxxxi]

As the tide rises the sluice gates open – allowing for the basin to fill. Once high tide is reached, the sluice gates close for a time period to allow the tide to fall. The water in the basin now has potential energy in comparison to the tide level. This can be utilised, where needed, by reopening the sluice gates, passing the basin water through the turbine and back to the low tide. There is also potential to use such a configuration like a pumped storage unit if a motor generator (or pump turbine) is included – using any excess electricity to fill the basin.

However, the environmental impact of such a scheme can be very significant due to the footprint of the site and the construction involved. It will also only be suitable, in the context of this report, for islands with suitable bays and tidal resource. Otherwise, the tidal stream option may seem more appealing. It is unlikely, though, that there will be a huge uptake in tidal stream technology until its performance and reliability data is proven.

## 7.3. HOMER Software Applicability and Limitations

As per the objective of this report, a computational model of the electrical network on the Isle of Eigg was created. Initially, the HOMER software package was compared with another package called MERIT before being chosen as the software to take this project forward. In comparison to MERIT, HOMER is a more complete package; it has more technological components to choose from, greater reliability (i.e. it does not crash as often), greater flexibility for creating models, an easy access library to create new storage and generation entities, access to an online database for resource data, an online community forum, an effective trouble-shooter etc..

The model of Eigg created in HOMER was proven to be reasonably accurate; the term "reasonably" is used as there is a lot of variation in renewable energy systems (as discussed in Section 7.1). The behaviour of the renewable technologies, the diesel generator operation and the battery 'states of charge' were all compared to real-life data to demonstrate this accuracy. This methodology allowed for the validation of the model; thus validating the accuracy of the algorithms behind the HOMER software. The resulting renewable penetration was also very close to that of measured data (85.4% in comparison to 86.2% respectively); further adding to the validity of the model and hence, once again, the software.

HOMER was not seen to be the "full solution" for completing the objective though. It was found that it did provide some drawbacks. Firstly, two technologies investigated in this report – Pumped Storage and Biodiesel (production and use) – are not covered by the software. This necessitated the use of rough hand calculations for this part of the investigation in order to scope out the feasibility of these technologies.

There is already a biomass resource module on HOMER, but this is solely for use in terms of biogas production. It is thought that this resource could be adapted to model for biodiesel production instead. Currently in HOMER, the biomass resource tab allows for an input of average monthly available biomass. This is then fed to a gasifier to create biogas. Instead of the gasifier stage, HOMER could incorporate the associated biodiesel production processes and the parasitic load it puts on the microgrid. This would allow for a full cycle of biodiesel production to be included in the software.

Pumped Storage can be 'loosely' modelled in HOMER; it is entirely a workaround however. This involves adding a modified battery entity with 80% round trip efficiency to the model, the desired capacity etc., and then adding it to the DC bus of the microgrid via a 100% efficient converter. The one issue with this though, is that it does not allow any other technologies to be present on the DC bus. Therefore this technique was not suitable for this investigation; as it required numerous technologies on the DC bus.

It is thought that Pumped Storage could be an addition to the HOMER software package moving into the future. This would require parameters such as turbine data, reservoir size, reservoir seepage/losses, installation efficiency, etc. Pumped Storage does not solely gain validity from software simulations however. As with many technologies, its feasibility will result from an analysis of environmental concerns in addition to performance concerns – the aspects of which have to be considered outside the realms of modelling software.

In addition to these two technologies, tidal technologies such tidal stream and tidal barrage (discussed in Section 7.2) are not fully accommodated for in HOMER. Tidal stream technologies can be inputted to an extent, but the module for this is 'threadbare'; it only requires a power curve (for the tidal stream generator) and a stream resource (in Litres/second). In short, this HOMER module could be improved. It is also very unlikely that it could be of meaningful use unless measured data was available – like it is for the other resources via the NASA Surface Meteorology and Solar Energy Database.

In conclusion, HOMER was a robust and reasonably accurate modelling tool for many aspects of this report. It did not, however, provide a 'complete package' and this had to be accommodated for by hand calculations when investigating certain renewable technologies.

*Note: There were modules of HOMER which did not necessitate use for the completion of this report; such as thermal loads, deferrable loads, running financial algorithms etc. Therefore no comment will be passed on their accuracy or shortfalls.*

## 7.4. Future Work

There are many areas for further investigation resulting from this report. Firstly, this report only looks at the performance of an electrical grid; with assumptions made to comprehend what "configurations" are reasonable or not. Further investigation could be made into the financial implications behind such set-ups in order to prove/disprove their feasibility for such a community-owned electrical grid. In extension to this, geological feasibility could be considered in more depth and community opinion sought to provide a more rounded feasibility analysis.

Pumped storage and tidal technologies are discussed in this report. There was not the capacity to model them fully using the HOMER software package, hence investigations could be made looking at hand calculations, using other software packages or expanding HOMER to incorporate such abilities accurately. There currently is one method to model pumped hydro on HOMER using an altered battery entity. However, it places restrictions on the rest of the system (i.e. nothing else is allowed on the DC bus) – this prevents such a method being used on the model of Eigg presented in this report.

All models created in this report were based on climatic data sourced off the west coast of Scotland. Future work could look into remote communities with significantly different resources/geological limitations; i.e. no hydro/water resource, abundant PV and concentrating PV resource, low wind resource, high geothermal resource etc. It is hypothesised that many of the lessons learnt with in this report with regards to capacity and storage increases would also apply in this case. It would be advisable to carry out such an investigation before applying these lessons elsewhere.

With respect to the model of Eigg produced in this report further investigations could be made. Firstly, to increase accuracy, it would be desirable to gain real-life data for the demand the island and an hourly time-step output from the hydro for an annual period. Load control (as per the microgrid schematic in *Figure 2)* could be investigated to minimise diesel runtime in periods of low renewable output. Thermal loads could also be investigated – currently electrical heating is not used on the Isle of Eigg other than as a heat dump in community buildings. This would be likely to significantly change the demand profile; causing a peak in the colder winter months.

# 8. Conclusions

From this report numerous lessons were learnt with regards to the model produced. Initially the project aimed to create a validated model of Eigg. This was achieved, with reasonable accuracy, using the HOMER software package and thus it can be concluded that HOMER is suitable for such applications. It is not a complete package though, it lacks the ability to model pumped storage and tidal technologies accurately which, in the case of this report and the wider energy “picture”, are very relevant.
From the Eigg model, increased levels of storage and generation capacity were investigated. It was concluded that there must be a mix of renewable technologies in order to maximise renewable penetration. It was found that increasing both storage and generating capacity alone provided some improvement to the renewable penetration of the model, but the improvement became saturated beyond a certain increase in capacity.

For increasing storage capacity, this saturation either came from prolonged periods of minimal excess electricity generation in the model, or from physical limitations on the technology (such as the efficiency or maximum charge rate). On the other hand, increasing generating capacity produced saturated results due to the renewable resource itself. In simple terms – if the resource is not present then there is no profit to be made in increasing the generation capacity - the gap in output is still going to occur. Therefore a mixture of renewable resources is preferred; the higher the number of resources, the higher the redundancy of the system – as the likelihood of all resources being low at the one time decreases.

In terms of storage, it was found that Li-ion battery technology was the most effective at increasing renewable penetration out of the battery technologies tested. It is a relatively expensive option at present (2015) in comparison to the current storage system and therefore a roll-out of this technology is unlikely unless a feasible pay-back period can be calculated through diesel savings. Looking at generation, the most effective investment (increase in renewable penetration per kW increase in capacity) was found to be wind turbines. This would, though, be dependent on the resource – it is only the optimal choice in the models investigated in this report due to the abundance of wind resource on the Western Isles of Scotland.

In addition to proving that a 100% renewable model can be generated, it can be concluded that such models should be “stress tested” to see how such models perform in adverse conditions. It was shown that seemingly autonomous models can easily lose a significant amount of their renewable penetration in the event of prolonged adverse weather. Therefore, the design process of such electrical networks should consider this – and ensure that there is enough redundancy in place to minimise the impact on the grid if such an event should occur.

Biodiesel was also discussed as a potential option for maximising the renewable penetration of communities. It can have a zero net carbon output as long as the energy required for its production is also compensated by zero carbon electricity generation (perhaps by increasing the biodiesel output itself). Biodiesel production could become more desirable if diesel backup is deemed entirely necessary for a microgrid to have enough redundancy in supply.

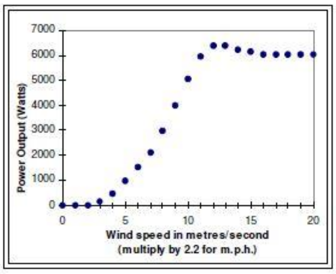
Lastly, it can be concluded that having a predicable baseload on a renewable-dependant grid is highly desirable. Eigg has this in the form of its hydro resource, but this can run fairly low in the drier summer months and thus renewable penetration is affected. Tidal technologies were put forward as a possible solution to islands which are geologically incapable of having a hydro system. However it is likely that this would have to be judged on a case by case basis. Having a baseload (almost) allows for a guaranteed renewable output to be produced. This potentially opens doors for technologies like load control to be used in times of high baseload output.

# 9. Appendices

## 9.1. APPENDIX I – Proven WT6000 Installation Manual Excerpt

PROVEN

PROVEN ENERGY




***Rotor Speed Control***

Above 12m/s (25mph) the blade pitch is automatically adjusted to maintain 200 rpm and full output

***High Build Quality***

All components are hot-dipped galvanised steel, stainless steel or plastic.

***Low Speed Equals Durability***

Low rotor speed (half the speed of comparable machines) ensures extended durability of blades and bearings. It also means that Proven WTs are the quietest in the world!

### Proven WT6000 6kW Wind Turbine<br>Proven TM900 9m (or TM1500 15m)<br>Self-Supporting Mast

| | |
|---|---|
| ***Performance*** | |
| Cut-In Wind Speed | 2.5 metres/second (5.6 mph) |
| Cut-Out Wind Speed | none |
| Rated Wind Speed | 12 metres/second (25 mph) |
| ***Rotor*** | |
| Type | Down-wind, Self-Regulating |
| Number of Blades | 3, Flexible |
| Rotor Diameter | 5.6 metres |
| Blade Material | Wood/Epoxy/PU |
| ***Generator*** | |
| Type | Brushless, Direct Drive, Permanent Magnet (No Gear-Box, Zero Maintenance) |
| Output | 48V/120V/240V/300V 3-phase AC (25Hz nom) |
| Rated RPM | 200 nominal |
| Rated Power | 6000 Watts |
| Annual Output | 7000-18 000 kWh depending on site |
| ***TM900 Mast*** | |
| Type | Self supporting/Tilt Down. |
| Hub Height | 9m |
| Foundations | 35 Newton Concrete Pad 2.5 x 2.5 x 1 m |
| Tube ∅ | 175 mm top A/F<br>350 mm bottom A/F<br>530 mm square mast base |
| ***TM1500 Mast*** | |
| Type | Self supporting/Tilt Down. |
| Hub Height | 15m |
| Foundations | 35 Newton Concrete Pad 3 x 3 x 1.2 m |
| Tube ∅ | 200 mm top A/F<br>440 mm bottom A/F<br>750 mm x 739mm mast base |
| ***Noise*** | (approximate) |
| <45dB | At 5m/s |
| <60dB | At 20m/s |
| 70-80dB | Car 15m away at approx 40 mph. |
| ***Weight*** | |
| WT6000 | 500 kg |
| TM900/6000 | 360 kg (+ 70kg gin pole) |
| TM1500/6000 | 656 kg (+ 240kg gin pole) |

p:\sales & marketing\wt6000\ss\6000 ss 001 rev2.doc

## 9.2. APPENDIX II – BP Solar BP4180 Manual Excerpt

### Electrical characteristics

| | (1) STC 1000W/m² | (2) NOCT 800W/m² |
|---|---|---|
| Maximum power ($P_{max}$) | 180W | 129.6W |
| Voltage at $P_{max}$ ($V_{mpp}$) | 35.8V | 31.9V |
| Current at $P_{max}$ ($I_{mpp}$) | 5.03A | 4.02A |
| Short circuit current ($I_{sc}$) | 5.58A | 4.52A |
| Open circuit voltage ($V_{oc}$) | 43.6V | 39.7V |
| Module efficiency | 14.4% | |
| Tolerance | -3/+5% | |
| Nominal voltage | 24V | |
| Efficiency reduction at 200W/m² | <5% reduction (efficiency 14.1%) | |
| Limiting reverse current | 5.58A | |
| Temperature coefficient of $I_{sc}$ | (0.065±0.015)%/°C | |
| Temperature coefficient of $V_{oc}$ | -(0.36±0.05)%/°C | |
| Temperature coefficient of $P_{max}$ | -(0.5±0.05)%/°C | |
| (3) NOCT | 47±2°C | |
| Maximum series fuse rating | 20A | |
| Application class (according to IEC 61730:2007) | Class A | |
| Maximum system voltage (U.S. NEC rating) | 600V (U.S. NEC) 1000V (IEC 61730:2007) | |

1: Values at Standard Test Conditions (STC): 1000W/m² irradiance, AM1.5 solar spectrum and 25°C module temperature
2: Values at 800W/m² irradiance, Nominal Operation Cell Temperature (NOCT) and AM1.5 solar spectrum
3: Nominal Operation Cell Temperature: Module operation temperature at 800W/m² irradiance, 20°C air temperature, 1m/s wind speed

All solar modules are individually tested prior to shipment; an allowance is made within our factory measurement to account for the typical power degradation (LID effect) which occurs during the first few days of d

# 9.3. APPENDIX III – Rolls 5000 Series Technical Specification Sheet

**4 VOLTS**

| | |
|---|---|
| CONTAINER: (INNER) | Polypropylene |
| COVER: (INNER) | Polypropylene - heat sealed to inner container |
| CONTAINER: (OUTER) | High Density Polyethylene |
| COVER: (OUTER) | High Density Polyethylene snap fit to outer container |
| TERMINALS: | Flag with stainless steel nuts & bolts |
| HANDLES: | Molded |

| | | | | |
|---|---|---|---|---|
| WEIGHT DRY: | 100 kg | | 220 | Lbs. |
| WEIGHT WET: | 143 kg | | 315 | Lbs. |
| LENGTH: | 400 mm | | 15 3/4 | Inches |
| WIDTH: | 270 mm | | 10 5/8 | Inches |
| HEIGHT: | 629 mm | | 24 3/4 | Inches |

| | | | | |
|---|---|---|---|---|
| PLATE HEIGHT: | 432 | mm | 17.000 | Inches |
| PLATE WIDTH: | 143 | mm | 5.625 | Inches |
| THICKNESS (POSITIVE): | 6.99 | mm | 0.275 | Inches |
| THICKNESS (NEGATIVE): | 4.57 | mm | 0.180 | Inches |

POSITIVE PLATE DOUBLE WRAPPED WITH SLYVER

ENVELOPED WITH HEAVY DUTY SEPARATOR

Certified System
SAI GLOBAL
ISO 9001
Quality

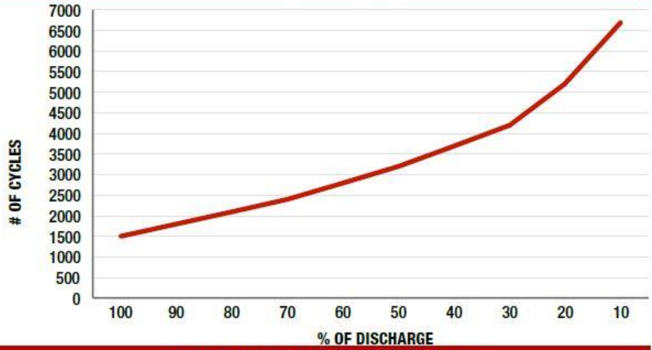
| | | | | |
|---|---|---|---|---|
| CELLS: | 25 | Plates/Cell | 2 | Cell |
| SEPARATOR THICKNESS: | 3 | mm | 0.105 | Inches |
| GLASS MAT INSULATION: | 1 | mm | 0.020 | Inches |
| ELECTROLYTE RESERVE: ABOVE PLATES | 95 | mm | 3.75 | Inches |

| | | |
|---|---|---|
| COLD CRANK AMPS (CCA): | 0ºF / -17.8ºC | 3714 |
| MARINE CRANK AMPS (MCA): | 32ºF / 0ºC | 4643 |
| RESERVE CAPACITY (RC @ 25A): | | 4290 Minutes |

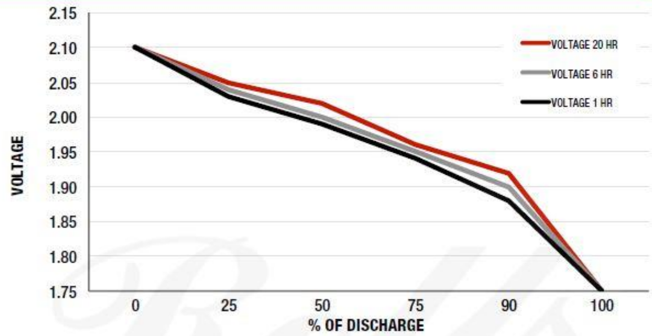
**CAPACITY** **1350** AH

| HOUR RATE: | SPECIFIC GRAVITY | CAPACITY / AMP HOUR | CURRENT / AMPS |
|---|---|---|---|
| @ 100 HOUR RATE | 1.280 | 1904 | 19.04 |
| @ 72 HOUR RATE | 1.280 | 1796 | 24.94 |
| @ 50 HOUR RATE | 1.280 | 1661 | 33.21 |
| @ 24 HOUR RATE | 1.280 | 1404 | 58.50 |
| @ 20 HOUR RATE | 1.280 | **1350** | 67.50 |
| @ 15 HOUR RATE | 1.280 | 1256 | 83.70 |
| @ 12 HOUR RATE | 1.280 | 1175 | 97.88 |
| @ 10 HOUR RATE | 1.280 | 1121 | 112.05 |
| @ 8 HOUR RATE | 1.280 | 1053 | 131.63 |
| @ 6 HOUR RATE | 1.280 | 959 | 159.75 |
| @ 5 HOUR RATE | 1.280 | 905 | 180.90 |
| @ 4 HOUR RATE | 1.280 | 837 | 209.25 |
| @ 3 HOUR RATE | 1.280 | 756 | 252.00 |
| @ 2 HOUR RATE | 1.280 | 648 | 324.00 |
| @ 1 HOUR RATE | 1.280 | 459 | 459.00 |

**CYCLE LIFE VS. DEPTH OF DISCHARGE**




**VOLTAGE VS. DEPTH OF DISCHARGE**




Amphere Hour capacity ratings based on specific gravities of 1.280. Reduce capacities 5% for 1.265 specific gravity and 10% for specific gravities of 1.250

## 9.4. APPENDIX IV – LG Chem RESU 6.4 EX Li-ion Battery Data

Data for RESU6.4EX

Stand: 03.31.15

| Size | | Description | |
|---|---|---|---|
| | | Base unit | Expansion Module |
| Nominal power | | 6.4 kWh | 3.2 kWh |
| Nominal Capacity (CC / CV mode and cut-off: 0.05C) | | 126 Ah | 63 Ah |
| Dimensions (width x height x depth in ㎜) | | 406 x 664 x165 | 230 x 664 x 165 |
| Weight | | 60 kg | 30 kg |
| Max. Continuous discharge | | 110 A (30s) | |
| Voltage (V) | | 51.8 V | |
| DC voltage range (V) | | 45.2 V 58.1 V | |
| Nominal discharge | | 42A | |
| Nominal charge current | | 42A | |
| Max. Power | (25 ℃) | 5 kW | |
| Faraday charging efficiency (25 ℃) | | 99% | |
| Battery Efficiency | (C / 3, 25 ℃) | 95% | |
| Expected lifetime | (25 ℃) | > 10 years | |
| Cycle life | (90% DOD, 25 ℃)<br>(80% DOD, 25 ℃) | > 6,000 cycles (EOL - End of Life: 60%)<br>10,000 cycles (EOL - End of Life: 60%) | |
| Operating temperature range * | | 0 40 ℃ | |
| Optimal operating temperature range | | 15 30 ℃ | |
| Storage temperature | | -30 50 ℃ | |
| Cooling | | Natural convection | |
| Communication | | CAN communication | |
| Certification | Zell Security | IEC 62133 | |
| | Security module | IEC 62619 (Mai 2015) | |
| | UN number | UN 3480 | |
| | Hazard Class | Class 9 | |
| | Transport specification | UN 38.3 | |
| | Protection class | IP 21 | |

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