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HOW TO REDUCE FOSSIL FUEL RELIANCE IN THE SMALL ISLES: A STUDY INTO THE POTENTIAL OF INTER-ISLAND CONNECTIONS

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Abstract

This dissertation looks at the renewable energy potential in the Small Isles of Eigg, Muck, Rum and Canna: these islands are not connected to the mainland's transmission grid network, thus renewable sources, and diesel power generation, are heavily relied on. The feasibility of whether these islands can provide a secure electricity supply from their own renewable resources has been investigated, indicating that it is possible for the Small Isles to be independently sustainable with inter-island connections. This has many benefits and drawbacks, which are discussed in this paper.

In order to measure the feasibility of inter-island connections within the Small Isles, each of the islands was modelled using HOMER software. Additionally, HOMER was used to model the islands as if they were inter-connected, by summing up the loads of each island and using this value as an input. This enabled a comparison to be made between the individual islands, and the scenario of them being connected by a local grid network.

A cost analysis was been conducted: the inter-island connections and additional renewable generation systems' costs have been considered in the context of small-scale communities. In this context, it was appreciated that budgets are small, and therefore major investments are often not possible without major funding grants. Social and environmental aspects have also been considered.

It is hoped that this investigation will be useful in indicating whether or not island connections would be beneficial in matching the electricity demand of islands with local renewable generation supply. The methodology used for this project can be taken and applied to other groups of islands that are isolated from the mainland grid connection to achieve a secure, clean energy supply.

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NOMENCLATURE

DSM	Demand Side Management
CO_2	Carbon Dioxide
HOMER	Hybrid Optimisation of Multiple Electric Renewables
GHI	Global Horizontal Irradiance ($kWh/m^2/day$)
COE	Unit Cost of Electricity (£ per kWh)
PV	Photovoltaic
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
VSC	Voltage Source Connector
kW	Kilowatt
kWh	Kilowatt hour
MWh	Megawatt hour

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1 INTRODUCTION

The Scottish Government aims to implement more renewable, clean energy resources in the foreseeable future to meet set targets:

"Renewable sources to generate the equivalent of 100 per cent of Scotland's gross annual electricity consumption by 2020, provisional statistics show that Scotland has met our 2015 50% interim target." [Scottish Government, 2017]

Scotland boasts the best conditions for generating many forms of renewable electricity. This includes wind, tidal and wave, but also solar and hydroelectric [Scottish Government, 2017]. A way in which these targets can be met is with an increase in the deployment of wind energy, particularly in the Scottish Isles, which are home to some of the windiest conditions in the world [SSE, 2017]. Consequently, the islands are ideal for new wind farm projects; their mountainous topography also makes conditions ideal for hydroelectric schemes.

There would be many benefits and drawbacks in such projects. Of the islands that are inhabited, there are social issues and environmental issues to consider when proposing the installation of wind turbines and other renewable systems. There are also financial barriers, due to the significant capital costs of grid connections to the mainland.

One of the most significant social issues regarding energy in the islands is fuel poverty. These islands, which have huge amounts of renewable energy potential, are also home to the households where fuel poverty is a problem:

"Households in the Highlands and Islands are paying more because of the cost of getting the power to them." [Herald Scotland, 2014]

If the physical distance was less between the supply and end user, the cost of getting the power to the consumer would decrease – and there is potential that fuel poverty could be reduced. This could be by implementing more local renewables energy generation schemes and installing microgrids and smartgrids. With these emerging technologies, it is possible that the Scottish Isles could set an example for the rest of the world in the renewable energy sector.

Despite having abundant wind and other renewable energy potential nearby, the islands in Scotland are still reliant on fossil fuels to meet their energy demands. If there was no reliance on diesel, and islands were able to generate their own electricity locally (on the island or nearby), perhaps fuel poverty could be reduced. This would also help in reducing the nation's overall carbon dioxide emissions, thus helping to meet government targets in accordance with the Paris agreement. Due to the unpredictable nature of wind energy – in combination with the stochastic nature of electricity demand – it is difficult to match demand and supply completely. If nearby islands collaborated and shared their renewable generation – for example Eigg, Rum, Muck and Canna – via the implementation of local grid connections between the islands, there is potential that the overall demand/supply match could be more efficient.

2 AIMS AND OBJECTIVES

2.1 Aim

The aim of this project is to assess the renewable energy potential, and electricity demand, of the Small Isles and evaluate how these islands can remove their reliance on diesel generators for electricity.

This project considers two scenarios: firstly, the islands being independent and utilising battery storage with an abundance of renewable sources to achieve 100% renewable penetration; the second scenario considers the potential of inter-island grid connections to aid in meeting the total electricity demand of the Small Isles with renewable sources. These scenarios will be compared from financial, environmental and social perspectives.

The core of the project is to assess the drawbacks and benefits of inter-island grid connections. It is hoped that this investigation will be useful in indicating whether or not inter-island connections have the potential to aid in matching electricity demand/supply of islands that are not connected to the mainland grid network. While this project looks closely at the Small Isles, the methodology can be applied to other groups of islands as more renewables are deployed.

2.2 Objectives

The project has the following objectives:

- Conduct a literature review to gain background knowledge and insight into the Small Isles;
- Investigate what available technologies are available and are best suited to Small Islands without mainland grid connections;

- Evaluate the energy demand and population of each of the Small Isles and gain an understanding of how the demand varies between them;
- Assess the potential renewable generation source options for the Small Isles, considering wind, solar and hydropower using modelling software (HOMER);
- Compare the Small Isles in the context of two scenarios: being interconnected through the presence of a local grid, or being independent of one another through the utilisation of battery storage. This comparison will be conducted from financial, environmental and social perspectives;
- Explore how local electricity generation could reduce fuel poverty on islands, while encouraging growth in local communities and their economies;
- Recommend whether or not grid connections would be beneficial or not, exploring the benefits and drawbacks of having them.

3 BACKGROUND

Islands are unique in that they can be used as test-sites as “living labs” [Smart Island Initiative, 2017]. They can be used as exemplar energy models for wider scales in social, financial and technical aspects.

3.1 Background to the Small Isles

The Small Isles are a group of four islands that are situated in the West of Scotland, below the Isle of Skye, as shown in Figure 1. The Small Isles comprises of the Isle of Eigg, Muck, Rum and Canna. Compared to the other Scottish Isles, the Small Isles have significantly lower population, with a total population of around 158 people across the four islands [Scottish Isle Federation, 2017].

Figure 1: Map Showing Location of Small Isles [Google, 2017]

3.1.1 Energy Across The Small Isles

There are many types of energy utilised amongst the Small Isles. Having this variety is key for these islands as they are isolated from the main grid, to ensure that there is a secure and reliable energy supply. The islands can have varied and extreme weather conditions, making energy security even more of a necessity [Scottish Isle Federation, 2017].

For heating, coal, peat, wood (briquettes, logs and pellets), kerosene, propane gas, and solar radiation are used. The reliance on fossil fuels for heating is hoped to reduce as more renewable resources become available – such as biomass, which currently accounts for 6% of the Small Isles' total energy consumption, as outlined in the Small Isles Energy Audit. The Isle of Eigg has incorporated some biomass heating (for example the school and some of the islanders' homes are heated using biomass boilers), however there is still a huge reliance on traditional heating systems and scope for improvement:

"The fossil fuels here could be reduced with more properties taking up biomass energy as the major space and water heating energy source." [Scottish Isle Federation, 2017]

For general electricity consumption, wind, water and solar resources are present on each of the Small Isles. Depending on the weather conditions, the output of these can vary however, and therefore diesel generators are still present as back up power generation supply. Figure 2 illustrates the breakdown of the Small Isles' energy consumption.

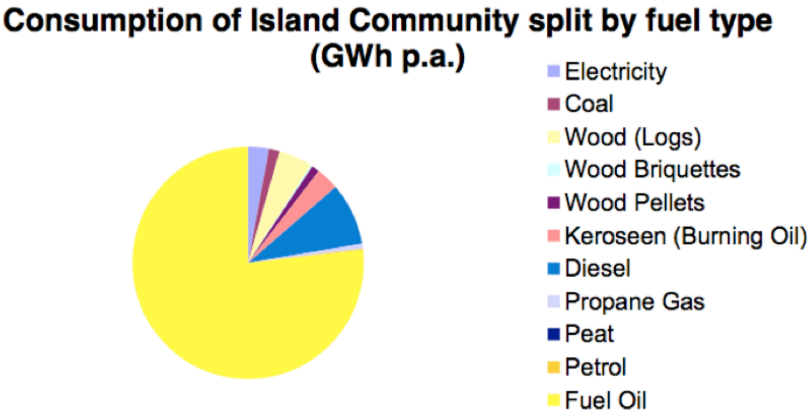


Figure 2: Small Isles' Energy Consumption Breakdown by Fuel Type [Scottish Isle Federation, 2017]

This figure illustrates that fuel oil is a dominant energy resource for the island, accounting for roughly 77% of the total energy consumption [Scottish Isle Federation, 2017]. This fuel oil is used to meet the large transport sector demand, thus does not represent the domestic energy consumption: as illustrated below in Figure 3, the transport sector accounts for 97% of the total energy consumption at 9.3GWh. The commercial and domestic consumption amounts to only 0.12GWh and 0.2GWh respectively [Scottish Isle Federation, 2017].

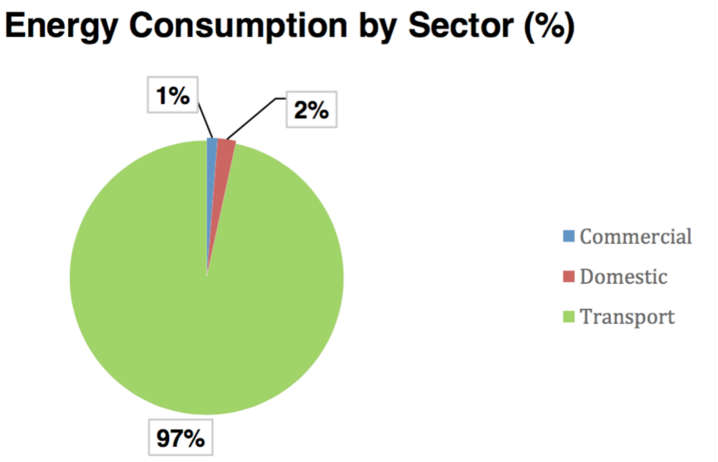
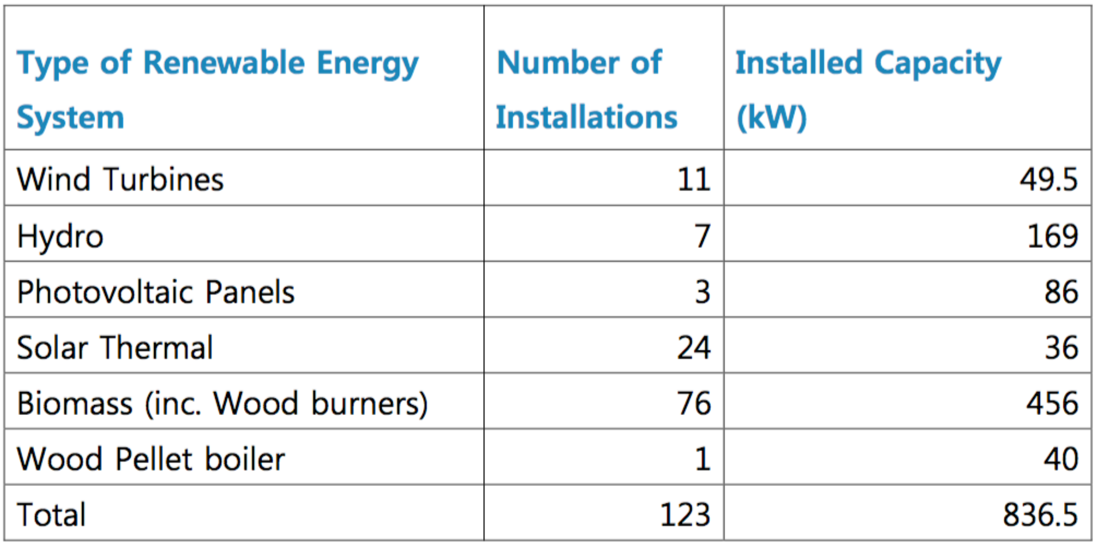


Figure 3: Small Isles' Energy Consumption Breakdown by Sector [Scottish Isle Federation, 2017]

Each isle has different renewable resources. The Isle of Eigg serves as a good example as the island is mainly powered by wind, sun and water energy systems. The Isle of Muck has followed in the footsteps of Eigg, and now has wind and solar energy systems installed. The Isle of Canna does not currently have any renewable energy sources, however there are plans that the island can install a similar system to that of Muck. The Isle of Rum is the largest of the islands, with mountainous landscape, and therefore has more hydropower installations, and there is also potential for more hydro schemes on the island [Scottish Island Federation, 2017]. Table 1 shows the installed renewable capacity across the Small Isles.

Table 1: Renewable Capacity of Small Isles [Scottish Island Federation, 2017]



Type of Renewable Energy System	Number of Installations	Installed Capacity (kW)
Wind Turbines	11	49.5
Hydro	7	169
Photovoltaic Panels	3	86
Solar Thermal	24	36
Biomass (inc. Wood burners)	76	456
Wood Pellet boiler	1	40
Total	123	836.5

The total renewable capacity of 840kW is more than enough to satisfy the Small Isles' shared total annual energy consumption of 2GWhs [Scottish Isle Federation, 2017]. This value accounts for the heating and electricity demands, negating transport demands [Scottish Isle Federation, 2017]. To allow this demand/supply matching, energy storage systems must be considered to allow the renewable resources to be stored when they are generated, and consumed when required.

3.1.2 Isle of Eigg

Eigg is the second largest of the Small Isles at 8km by 6km, as shown in Figures 4 and 5. The Isle of Eigg Heritage Trust, who bought over the island in 1997 in the community buyout, owns the island. Since owning their island, the community have encouraged sustainable developments on the island, including Eigg Electric [Isle of Eigg, 2017]. These developments have aided in supplying renewable energy to the island to meet the 67MWh electrical demand.

Figure 4: Map of the Isle of Eigg [Digimaps, 2017]

Figure 5: Isle of Eigg [Scotland Info, 2017]

Eigg Electric is a community-owned company, which is managed and maintained by residents of the island. The island has the following renewable generation: four 6kW wind turbines; a 50kW photovoltaic array; and two micro-hydro systems installed, one of 100kW capacity and two smaller 6kW systems [Eigg Electric, 2017]. These systems provide power for the 87 inhabitants on the small island, and have significantly reduced the islands' reliance on diesel generators. The renewable installations enable the island to be powered up to 100% from renewables, however the average across the first switch on in 2008 stands at roughly 95% [Isle of Eigg, 2017]. There are back up diesel generators on the island to provide the remaining 5%, for times when the renewable systems are unable to meet the total electricity demand.

There are two diesel generators, each with a capacity of 90kW [Eigg Electric, 2017]. There are also batteries on the island, which allow surplus renewable energy to be stored when there is a surplus of renewable generation.

3.1.3 Isle of Rum

The Isle of Rum is the largest of the Small Isles (see Figure 6) and is the most mountainous, making it ideal for hydroelectric energy schemes. There are currently two hydropower schemes on the island: 15kW and 30kW turbines provide electricity for the 22 residents on the island [Wind and Sun, 2017]. This population means that the demand of the island is around 16.7MWh [Scottish Isles Federation, 2017]. Batteries on the island help to harvest and store hydroelectric energy; when there is a surplus of energy, storing it in batteries allows it to be used at later times when demand may be higher (or supply is less reliable). The low voltage network on the island allows this renewable energy to be distributed to homes and community buildings. There is also back up diesel generation on the island, for when the hydropower schemes are insufficient in meeting the total electricity demand.

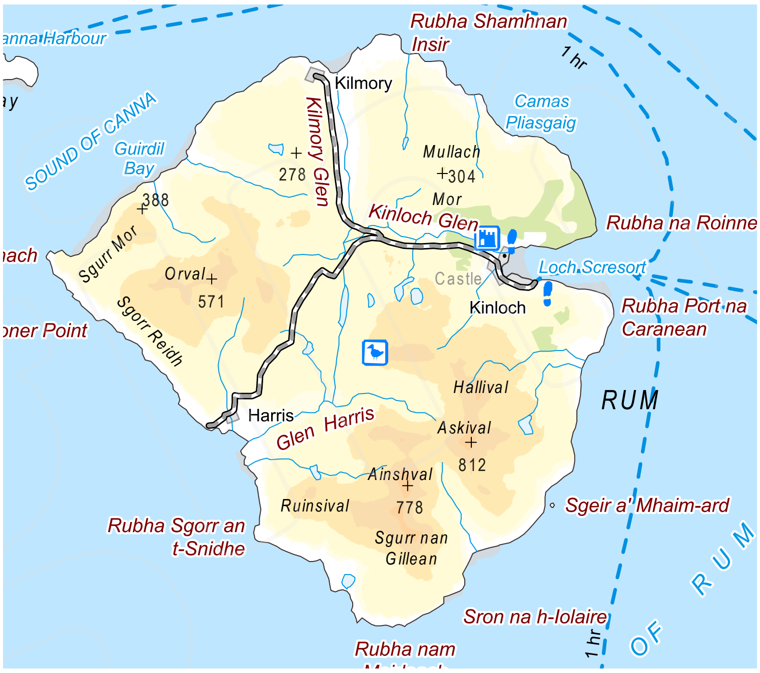


Figure 6: Map of the Isle of Rum [Digimaps, 2017]

The mountains are also ideal for pump storage, which could potentially serve as a means of energy storage for the small isles. Rum doesn't currently have any wind or solar renewable generation, but the island is considering installing photovoltaic arrays in the anticipation of an increasing population.

3.1.4 Isle of Muck

The Isle of Muck is the smallest of the islands, as shown in Figure 7. Despite being the smallest island, measuring at just 2 miles by 1 mile [Wind and Sun, 2017], there are 38 residents on the island with an overall electricity demand of 29MWh [Scottish Isles Federation, 2017]. The island has two 20kW wind turbines installed on the island – in addition to photovoltaic arrays – which allows up to 95% of the islands' electricity demand to be met by renewable sources [Wind and Sun, 2017]. There are batteries on the island, which allow efficient management and control of the renewable sources.

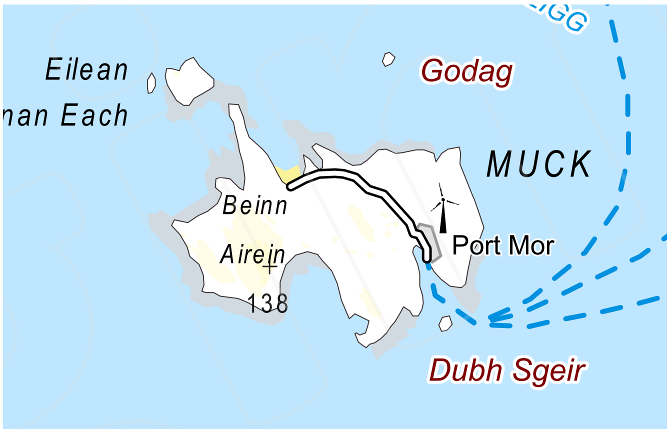


Figure 7: Map of the Isle of Muck [Digimaps, 2017]

The renewable energy is distributed to locals through the islands' high voltage grid. At times when the energy produced by the wind turbines is not sufficient, there is a backup diesel generator (in addition to the battery storage). The diesel generator is essential for ensuring security of supply on the island, as wind and solar energy resources are intermittent and can therefore not be relied on completely without another source of energy.

3.1.5 Isle of Canna

The Isle of Canna is the farthest away from the Scottish Mainland, as shown in Figure 8. With a population of only 11 people, the electricity demand is significantly lower than that of the other Small Isles at only 0.6MWh [Scottish Isles Federation, 2017]. The island's diesel generator is currently the only source of electricity, however there are plans for the island to install wind and solar renewable sources in the footsteps of the Isle of Muck [Wind and Sun, 2017].

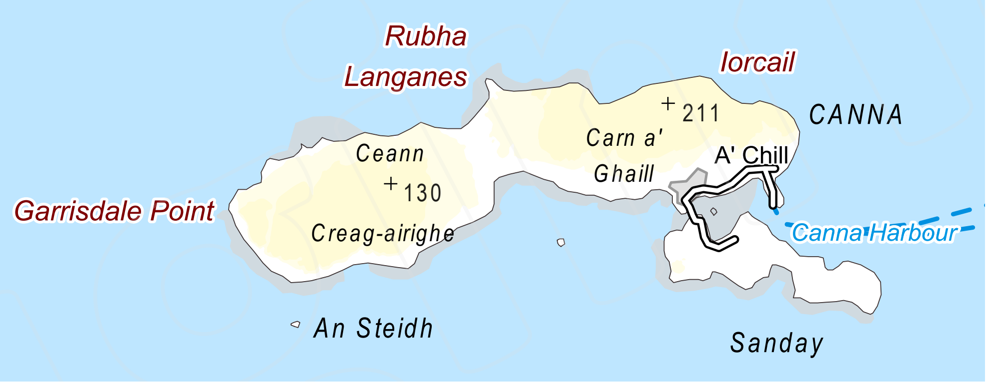


Figure 8: Map of the Isle of Canna [Digimaps, 2017]

3.2 Remote Islands Outside of Scotland

Compared to connecting cities and countries of mainland continents, it is difficult to interconnect remote islands; one example is the Fiji islands [Prasad and Raturi, 2017]. The two main islands of Fiji are connected, but the three hundred smaller islands are not connected to the main electricity grid as shown in Figure 9. This imposes many difficulties for residents of these islands, similarly for those living in smaller Scottish isles such as Muck and Canna. Demand Side Management (DSM) is particularly important for islands [Morales et al, 2017], and can help to reduce the demand of fossil fuels.

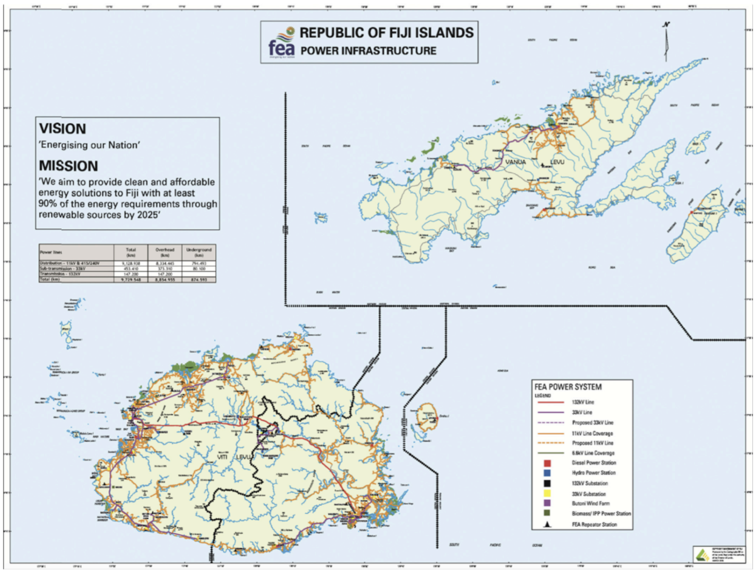


Figure 9: Fiji Islands' Power Infrastructure Map [Prasad and Raturi, 2017]

DSM work has been carried out in the Galapagos Islands (see Figure 10) in the shift towards the Islands' Smart Grid, in combination with renewable generation in the form of thermal, photovoltaic and wind [Morales et al, 2017]. Renewable energy generation has been encouraged since the government of Ecuador enforced a zero CO_2 policy [Morales et al, 2017]. As the renewable generation is of a stochastic nature, DSM has been practiced to optimise the demand/supply matching.

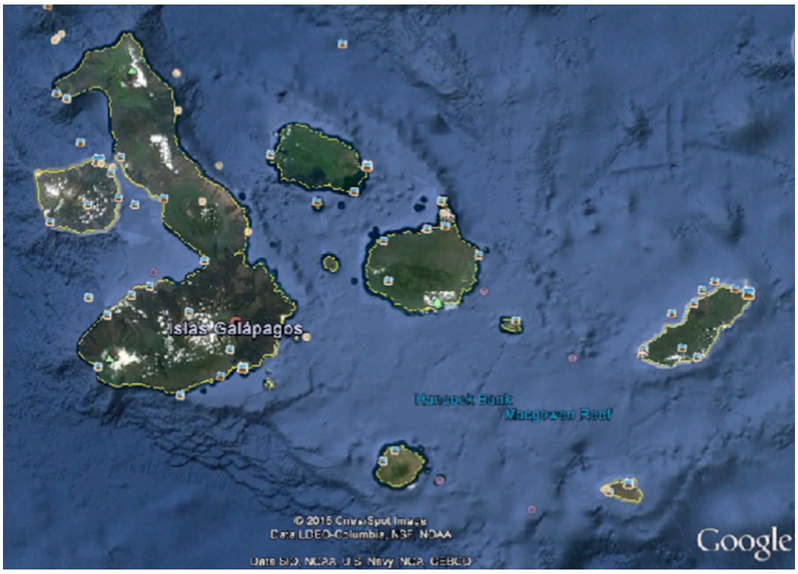


Figure 10: Galapagos Islands Satellite Map [Morales et al, 2017]

The Cook Islands also serve as an example for Scotland, with goals to deliver 100% of energy with renewables by 2020 across the twelve inhabited islands [Nikolic et al, 2016]. With small, medium and larger scale projects (depending on the island size and population), the Cook Islands have different approaches to meeting the islands' energy demand [Nikolic et al, 2016].

The Canary Islands' is an example of a group of islands, which are interconnected to share renewable energy resources [Gils and Simon, 2017]. The approach conducted here can be applied to Scotland, to achieve 100% renewable generation for Eigg, Canna, Rum and Muck. Figure 11 illustrates the different types of grid connections present between the Canary Islands.

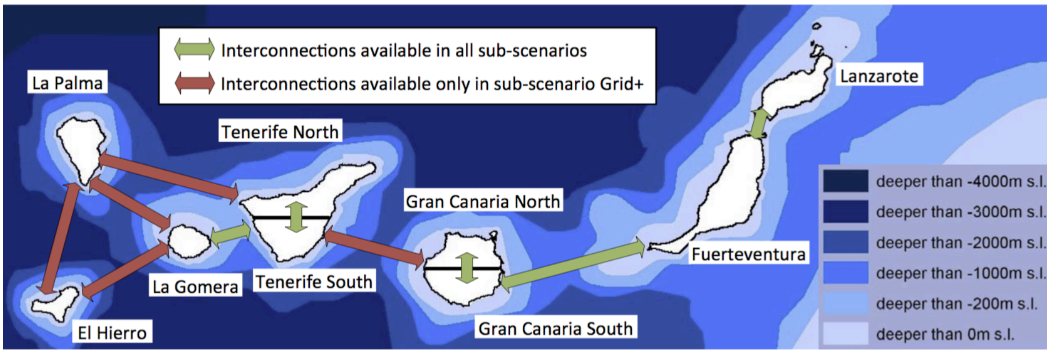


Figure 11: Canary Islands and Interconnections [Gils and Simon, 2017]

3.3 Demand/Supply Matching

There are many factors that contribute to accurate demand/supply matching. As discussed, DSM is something that can be practiced to achieve this [Morales et al, 2017]. DSM is particularly important in islands where there are no connections to the main grid. Consumers are made more aware of their electricity consumption, and electricity may be capped at certain times of the day in order to enforce careful use of electricity. On the Isle of Eigg for example, households are limited to using appliances up to a value of 5kW, whereas bigger buildings (such as schools) are able to use up to 10kW. Instead of taking electricity for granted, consumers are more aware of how they are using their energy. On the Isle of Muck, electricity consumption was limited to only use between 7:30am to 11:30am and 4:00pm to 11:30pm [Wind and Sun, 2017]. Although this can appear to be a drastic method of reducing the demand – restricting users to electricity – it is nonetheless another means of DSM. In the end, all of these measures aid in achieving a close demand/supply match.

Energy storage is another way in which demand/supply can be matched with more precision. As mentioned, the stochastic nature of renewables means that there is a chance that the times when the energy is needed by consumers is not the same time as when the energy is generated. If it were possible to store this energy when it is generated and not required – and have it ready for peak demands – the demand/supply match would be improved. There are many types of storage, some of the main technologies include flywheels, batteries, hydrogen, and pump storage. There are both benefits and drawbacks of each type, for example batteries are very efficient but will not last forever and need to be disposed of correctly. Pump storage is good for large amounts of energy, but requires specific land characteristics which may not be available everywhere.

Another way in which demand/supply can be matched is by implementing a variation of renewable energy sources. Variety is important as when all of the energy systems are operating at the same time as each other, energy can be generated at each point of the day/week/month/year. Solar energy – although it is not the most ideal in Scotland – can generate electricity steadily across the period of a day, peaking at noon when the sun is strongest. Solar energy has an advantage of being predictable. Similarly, hydroelectric schemes can generate a base load. This is dependant on sufficient rainfall, which can vary from month-to-month/year-to-year. Generally, rainfall in Scotland is guaranteed and therefore a valuable electricity output from hydro systems can usually be relied upon. Wind energy is another type of renewable generation in Scotland, however – unlike solar and hydro – it does not have the benefit of being predictable. Wind energy is very intermittent as the electricity generated varies directly upon the wind speed. As the wind speeds vary a lot, the energy output varies accordingly. This makes it difficult to rely solely on wind energy for day-to-day electricity consumption, as the demand/supply match is not aligned. These are some examples of common renewable energy sources, which are all present among the small isles in Scotland. Eigg has all three, and has almost no reliance on diesel generators for electricity. The other isles are not as advanced as Eigg, however are home to some renewable generation.

Currently, fossil fuels are relied on heavily for demand/supply matching. On the mainland, there are gas (and coal, however coal is not as popular) power plants that are able to deliver a base load of energy. Although they are not the most sustainable resources of energy, fossil fuels provide reliable energy for consumers. Unlike renewables, the energy from fossil fuels is predictable and secure. This is one of the main reasons that the UK is still reliant on them – renewable energy resources generally do not bring the same security, without being complimented with sufficient energy storage. Among the islands in Scotland, diesel generators are still heavily relied on. In cases where there are some renewables on the islands, diesel generators serve as back-up energy supplies when either the renewables fail, or if the renewable generation is not sufficient enough to meet the demands.

This study looks to explore the potential of renewable energy sharing amongst the Small Isles. As each island has its own assets – for example, Rum is very mountainous, and therefore ideal for hydroelectric schemes and pump storage – there is potential that the group of islands could be 100% powered by renewables. This could be possible if the Small Isles collaborate, acting as one, and share their electricity. Local grid connections between the islands could allow this to happen, thus reducing the overall reliance on diesel generators as a means of demand/supply matching.

3.4 Technology Available

3.4.1 Generation Technology

As more wind farm projects are deployed, the amount of energy being captured from wind turbines is increasing. Wind generation is suitable to islands as the dimensions can be altered to suit the requirements of the island and the energy demand. Solar energy is also good for this reason, as the size of the photovoltaic array can be altered to suit the client. Hydroelectric power is more difficult to deploy, due to the requirements of differences in elevation required. Due to the topography of islands, where sometimes mountains are not common and thus differences in elevation can be scarce, implementing hydropower can be more challenging.

Tidal technology is an emerging technology and is still very much a futuristic means of generating electricity. For this reason, tidal (and wave) sources of electricity generation are not as common as wind generation. Moreover, when considering new projects for islands, tidal is not as heavily considered due to the obstacles faced. Due to the fact that the technology is not as developed as wind and solar, it is more expensive. This imposes financial barriers, particularly in the context of community-based islands where budgets are lower (in comparison to the mainland).

In summary, when considering renewable developments for islands, wind, solar and hydroelectric (depending on the nature of the islands' topography) have been focussed on. These systems are generally cheaper, easier to maintain and more efficient for communities.

3.4.2 Storage Technology

There are many types of storage available. Batteries, hydrogen, flywheels, pump hydro are some of the most common types. In the context of community-based schemes, like the Small Isles, battery storage is the most suitable. Hydrogen storage requires complex technology, such as an electrolyser and fuel cell. Moreover, as this technology is still not as common (as battery storage technology), it can be more expensive and more difficult to operate/maintain.

Flywheels are a basic form of storage, but are not the most idyllic option for community-based projects. Similarly, pump storage is a larger-scale version of energy storage (compared to batteries), and requires mountainous landscapes with reservoirs. This is very specific, and often the site requiring storage will not have this topography. Taking these options of storage into consideration, it was concluded that batteries would be the most suitable option for the Small Isles.

3.4.3 Transmission and Distribution Cables

There are different types of grid connections, each with advantages and disadvantages. The main determining factor of the most cost-effective is the length of the connection. If the distance exceeds the "critical distance", as shown in Figure 12, HVDC cables become more economic. For projects where the distance is less than this value however, HVAC cables are cheaper.

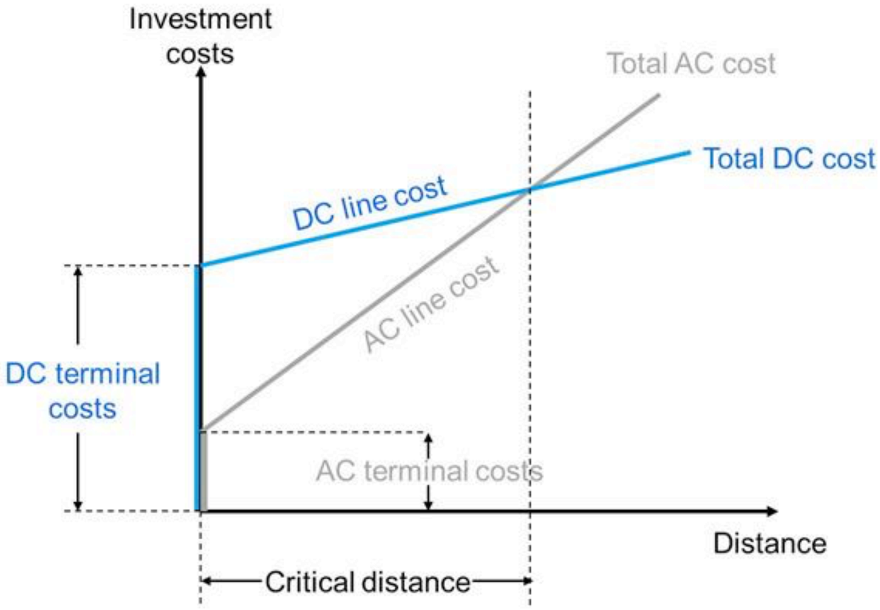


Figure 12: Investment Costs versus Distance for HVAC and HVDC Cables

[http://new.abb.com/images/default-source/p-s-hvdc/illustrations/investment-cost_large.jpg?sfvrsn=1]

There are many benefits of having grid connections, one of the main advantages being that it allows renewable energy projects to feed electricity into the main grid, thus "decarbonising the grid". As more offshore wind – and even tidal and wave – projects come online, more offshore grid connections are required to prevent projects being "stranded", and the energy is not able to reach consumers. As there are more grid connections, it also reduces the need to curtail renewable energy resources, increasing the amount of clean energy utilised and reducing the requirement of energy from fossil fuels. One of the main drawbacks from grid connections is that they are extremely expensive. Additionally, there are environmental and social impacts due to the infrastructure requirements. This exploits the land, imposing social conflict and potentially harming wildlife and the environment.

3.5 Microgrids

There is huge potential for renewables across the UK and other countries, but most of these renewables thrive in locations that are far away from main cities (where most of the energy is required). This imposes a grid connection problem – putting offshore wind farms online, for example, requires new infrastructure to be installed. The offshore wind farm is not likely to be nearby a populated area, thus the energy needs to be transported across the country if it is to be utilised, requiring major changes to be made within the national grid network [Banerji, 2013]. This would cost significant amounts of money, which private renewable companies cannot afford [BBC, 2017].

Alternatively, if the wind farm was to be located in a more densely populated area, and then the energy may not have to be transported as far. This is where the idea of a microgrid is introduced: utilising distributed energy generation from a variety of small-scale renewable resources to power nearby cities and towns [Banerji, 2013]. As this is where the energy demand is, the need to transport the energy disappears. On the other hand however, the capacity of the power plants may not be as high as what it could be in offshore areas – particularly for wind and tidal energy, as they thrive in windier conditions, which tend to be found further away from bigger cities at the coasts. This energy compromise is balanced out however by the reduction in grid connection infrastructure.

Microgrids tend to be made up of small-scale renewable sources [Banerji, 2013], including solar power, wind power, geothermal power, biogas and biomass [Networks Online, 2017]. Some microgrids may contain some form of energy storage, such as a lithium ion battery [Networks Online, 2017], however energy storage is expensive as it is still at a very early stage of development.

These small-scale power sources are connected to each other and to a local community (where the energy is consumed), in addition to being connected to the wider grid. There is communication between these components, in order to meet supply and demand [Fadlullah, 2015]. When there is a surplus/deficit of energy, the main grid can be utilised - if the microgrid is connected to the grid. When the main grid is not required however, the microgrid can be separated. This is the major difference: the microgrid enables the local community to operate independently of the main grid [Energy Department, 2017].

While microgrids have many potential benefits, there are also numerous drawbacks involved. Since microgrids utilise renewable energy sources, it can be said that the electricity produced is cleaner with fewer carbon emissions, in turn helping to reduce global warming. As a consequence, other traditional energy businesses may go out of business. An example of this is the closure of Longannet power station in 2016 [Scottish Power, 2017], which used coal to produce electricity. While this is better for the environment, it is not beneficial for the employees or business owners. They cannot continue to practice their jobs, as their skills in working in fossil fuel power plants grow more redundant. While there are fewer opportunities for these people, consequently there will be more jobs within the renewable energy industry. Unfortunately for those working in traditional power plants, such as Longannet, the skills of the employees are not easily transferable to these new jobs: the skills associated with working in a coal power plant cannot easily be transferred to working in maintenance of wind turbines.

On the other hand, a benefit of microgrids is that they do not require significant adjustments in the national grid network, which saves money [Echevarria, 2017]. This money can then be injected into research and development of optimising renewables, and energy storage. As renewable energy grows to be more popular, the cost of electricity from wind, wave, solar, hydro and other renewables should significantly decrease. Therefore, despite the consequential drawback of having high initial capital costs, renewable energy has the potential to benefit society immensely. Although this may initially be a cause for fuel poverty, as not everyone may be able to afford more expensive energy, in the long run the cost should decrease.

While the grid does not need to be heavily expanded, thus saving money, a drawback from this is that microgrids can add instability to the network. Due to the dispatchable nature of the majority of renewable resources, variability is added to the supply of electricity [Banerji, 2013]. Matching this fluctuation of supply is a challenge, as there are also variations in the energy demand. In turn, this creates instability within the grid. Unlike traditional power plants, which give a base load of electricity and can always be relied on, renewables are instable to some extent.

Another benefit of a microgrid however, compared to the main grid, is that when there is a small problem and it needs to be repaired, the microgrid can still function [Echevarria, 2017]. In the traditional wider grid, whenever there is a small problem, it affects everybody because of the interconnectedness of the system. A microgrid is beneficial in this way, because it can function independently. If there is a fault in the main grid, the microgrid can cut itself away, still providing energy and allowing people to work and enjoy a good quality of life.

Another benefit of microgrid installations is that it will help governments to reach climate change targets. For example, the Scottish Government has a target to deliver 100% renewable electricity by 2020 [Scottish Government, 2017]. Considering the need to reduce carbon footprint, new energy resources have less environmental impact than traditional fossil fuel plants. Renewables are perfect however, for example in Scotland the best conditions for renewables are in areas of natural beauty. This imposes social and environmental conflicts, as despite renewables thriving in these areas, in reality their presence would exploit the natural environment. Locating the renewables within a microgrid, away from these areas, can therefore be seen positively.

Despite the many benefits and drawbacks, microgrids have the potential to make renewable energies realistic resources of energy. While current renewables have the capacity to power the plant, they can be viewed as unfeasible power resources due to their undesirable locations and dispatchable nature. Ultimately, microgrids will play a vital role in the growth of renewable energy.

4 METHODOLOGY

The methodology, as detailed below, was conducted in order to meet the aims and objectives set out.

4.1 Collection of Information and Data

Relevant literature was read to gain the necessary background knowledge for the project. This was essential in assessing the energy (and electricity) demands of Muck, Eigg, Rum and Canna. Insight was given into what different technology options (generation, transmission, distribution, and storage) for the Small Isles are available. It was important to be aware of the relevant technology costs, and how generation/storage/transmission sources can be used in the context of islands to aid in matching supply/demand with local renewable resources.

Island communities were evaluated, which helped in the understanding of how residents would handle this project's proposals. Previous case studies served as good examples to learn about the dynamic of groups of small islands. The Small Isles were studied in great detail to gain essential background information of the culture/social/environmental characteristics.

A site visit was conducted, where residents were interviewed and understanding of life on the islands was gained. This was invaluable in gaining insight into how renewables would affect life of residents of the Small Isles, in good and bad ways. Environmental, social and financial aspects were discussed with locals on the Isles of Canna and Eigg, contributing to the analysis of this project.

4.2 Modelling of the Small Isles

HOMER, RetScreen and Merit were initially considered as options for modelling renewable generation on the Isles of Muck, Eigg, Rum and Canna. After reading literature, and evaluating each of the modelling tools, it was decided that HOMER was best suited to this project. Using input data gained from the wider literature review, and site visits, models were made for each of the Small Isles. Additionally, a model was constructed which represented a scenario where all of the islands are interconnected with a local grid.

4.3 Validation of Model and Results

A thorough evaluation was conducted of the Isle of Eigg, as there is a lot of previous work done on this island. A detailed HOMER model of Eigg was obtained and used to compare results against, as a means of validating the robustness of the results. Assumptions made in the modelling stages have been justified appropriately.

4.4 Evaluation of Results

An economic analysis of the results was conducted. This allowed the financial feasibility to be assessed and evaluated, within the context of the Small Isles. It was taken into consideration that the Isles of Muck, Eigg, Rum and Canna have fragile communities – with small budgets – and therefore may not be able to afford large-scale renewable projects.

Environmental and social aspects have also been taken into consideration. Relevant literature and sit visits highlighted some of the main areas of concern for the Small Isles, which would also be relevant in other groups of islands.

4.5 Conclude and Recommend

After assessing the feasibility of inter-island grid connections, a final recommendation can be made.

5 MODELLING

HOMER models were configured for each of the Small Isles. Additionally, a single model combining all 4 islands was also simulated, to represent a scenario where all islands are connected by grid connections. With these five models, conclusions were drawn as to which are the more effective ways for the small isles to lose their reliance on fossil fuels.

5.1 Background to HOMER Software

In the context of investigating renewables in the Small Isles, HOMER is a suitable software for evaluating which technologies are optimal for the islands. Merit and RetScreen are examples of other software that were considered for this investigation, but it was concluded after a brief software comparison that HOMER would offer the better results.

Hybrid Optimisation of Multiple Electric Renewables (HOMER) is a microgrid modelling software [Bahramara et al, 2016]. The range of renewable components is vast within the software: wind turbines, photovoltaic arrays, fuel cells, hydropower, biomass, converters, batteries, and conventional diesel generators [Bahramara et al, 2016] can be selected as the user desires, as illustrated in Figure 13. The user can choose whether or not the grid network is connected also.

Figure 13: Components Toolbar in HOMER [HOMER, 2017]

HOMER conducts cost analysis, as well as demand/supply matching, to deliver a range of optimal results [Kumar et al, 2016]. Maintenance, capital costs, and replacement costs are considered [Bahramara et al, 2016] within the simulation, thus the final results are more representative of real-life scenarios.

The user can input any load or resource (according to the site that is to be simulated). Within HOMER itself, weather data can be downloaded [Pepper, 2017]. This data can be relevant and accurate depending on the site. In any case where a high degree of accuracy is required, the input data can be modified as required. The load data can be modified within HOMER to suit the load profile, for example community/residential energy usage. Peak months of demand can also be selected, for example summer or winter.

5.2 Assumptions

Due to the time constraints of this project, assumptions were made to simplify the models and scope of the analysis.

5.2.1 Loading

It was assumed that the loading peaked in January. HOMER offers the option of selecting a peak month of loading, as shown in Figure 14.

This assumption was based on the fact that each of the Small Isles' population fluctuates throughout the year [Isle of Eigg, 2017]. In the summer months, the islands receive a relatively large amount of tourism – thus the population can often double, according to islanders – which in turn contributes to the energy consumption of the island. In these summer months, despite the increase in the amount of people using electricity on the island, the heating load will be lower than in the winter. Due to the colder months and shorter days, it was assumed that the energy requirements for both lighting and heating would increase across November/December/January/February. In turn, the average load from month to month across a given year should not vary too much, but still peaks in winter as illustrated in Figure 14.

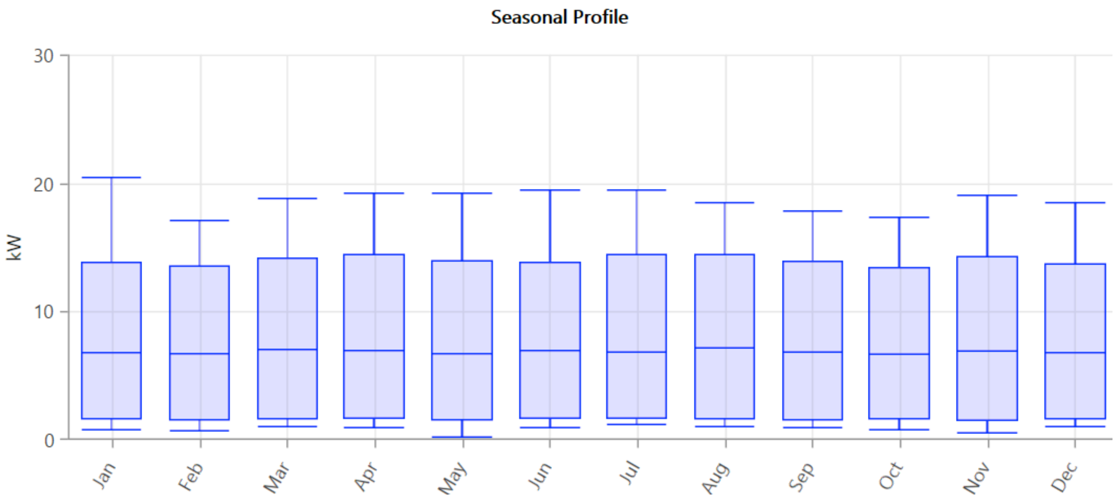


Figure 14: Seasonal Load Profile from HOMER

HOMER also has the option to select the trend of the load. In this case, it was assumed that a community model should be used as shown in Figure 15. This was upon recommendation of previous HOMER users, in addition to the fact that each of the Small Isles operates on a community basis.

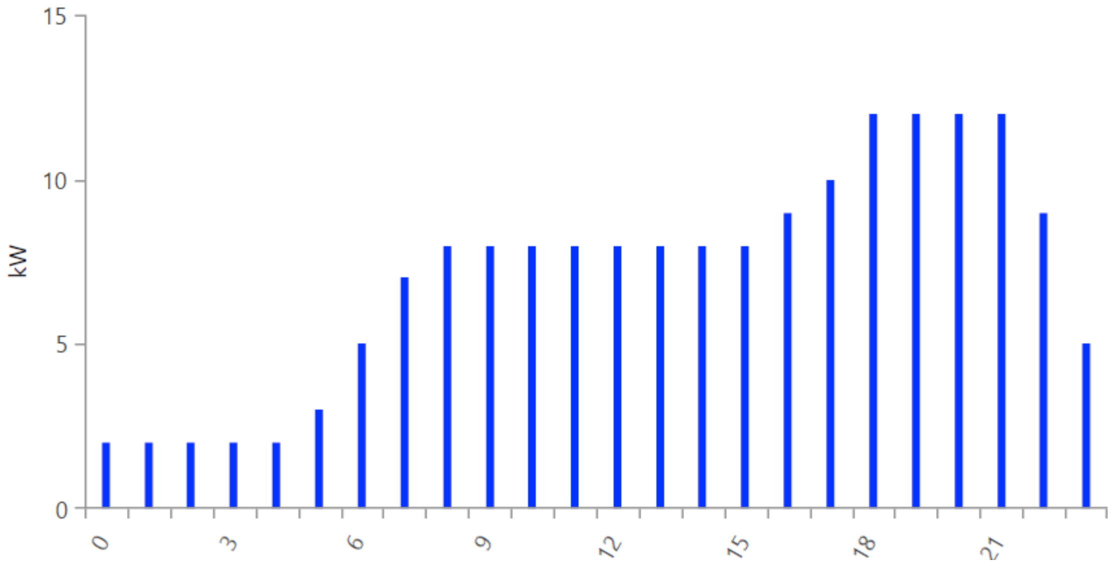


Figure 15: Community Load Profile from HOMER

Population variations were considered due to the nature of population changes within the Small Isles. As the population of each island does not exceed 100 inhabitants – with the smallest population being just 11 on the Isle of Canna – this was an important consideration as a small change in the amount of people correlates to a significant change in the percentage of energy usage.

5.2.2 Heating

Heating systems within the Small Isles – and the majority of the Scottish Isles – are still heavily reliant on coal and gas. When the total energy consumption is considered, the fact that heating is still sourced from fossil fuels impacts the "green status" of the islands significantly. For example the Isle of Eigg can be said to be 95% renewable for electricity, but when heating and transport are considered statistics show that the island is only 25% renewably resourced. This accounts for the huge transport fuel consumption, as well as the general heating fuels.

As the electricity sector alone is still not 100% renewably resourced – more so in the Isles of Rum, Canna and Muck – it was decided to focus on the electricity sector only in the scope of this project. The conclusions of the analyses therefore will be best suited to non-electrical heating systems, as it heating loads were negated in the modelling; the methodology presented in this dissertation could however be applied to a higher loading that considers the electricity that would be required for electrical heating. HOMER also has the options of thermal heating, which could be factored into the model in future work.

Generally, based on the fact that the majority of the heating still comes from fossil fuel resources, it was decided to emphasise this study only on the electricity consumption. In the future, when the Small Islands achieve success in achieving up to 100% renewable electricity status, renewable heating and transport could be considered.

5.2.3 Transport

Transport was not taken into consideration, as this is mostly relevant to the ferry to the mainland. While there are some cars on the islands, their contributions to energy consumption were deemed negligible.

5.3 Renewable Resources

HOMER software has a feature, which allows resource data to be entered manually, or downloaded from the Internet. Figure 16 shows the toolbar within HOMER, where resource data can be inserted.

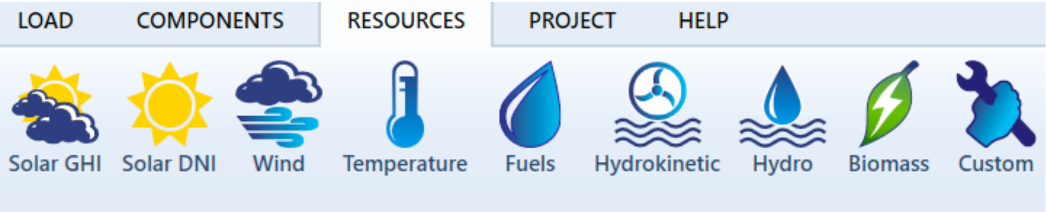


Figure 16: HOMER Resource Toolbar [HOMER, 2017]

In the case of this study, the resources that were given the most consideration were the Solar Global Horizontal Irradiance (GHI), Wind, and Hydrokinetic as these are necessary for HOMER to calculate the amount of photovoltaic, wind and hydro energy produced by different systems. In the cases of the Small Isles, these are the only renewables that were considered.

As the information required for each of the islands was specific, assumptions had to be made as detailed in previous chapters. One of the biggest assumptions made was the wind/solar/hydro resource data. It can be seen from the Isle of Eigg case study that there are sometimes significant differences in the resource data – in this case, particularly the wind resource data. As HOMER uses a location between the Isles of Tiree and Ulva, the resource data can be said to be unrepresentative of the Small Isles. In order to compensate for this, for the Isle of Eigg a more detailed data collection was carried out and input into HOMER to model the island's energy system. Both outputs of each simulation – for different wind speeds – concluded that wind energy was not suitable for the island. For this reason, it was assumed that HOMER's downloaded data was sufficient to use for modelling of the remaining Small Isles (Canna, Muck and Rum). Similarly, the solar data location within HOMER is not a true representation for each of the Small Isles. For this reason, when comparing the results from HOMER it was considered that the actual output of the renewable technologies may differ in real life. Solar and hydrokinetic resource data was configured by calculating from the solar/hydro energy outputs of the technologies installed on Eigg. As this was not possible to replicate for Muck, Canna and Rum – due to time constraints – HOMER data was utilised. Using this data imposed a degree of potential inaccuracy in the results, however the methodology remains useful. There is potential for future work to account for this, and the input data for each island can be easily altered.

5.3.1 Solar Global Horizontal Irradiance Data

Figure 17 illustrates how the average GHI (in kWh per m^2 per day) varies from month-to-month across a year for the Isle of Eigg. This solar data is essential in calculating the amount of electricity that would be produced by solar photovoltaic technologies.

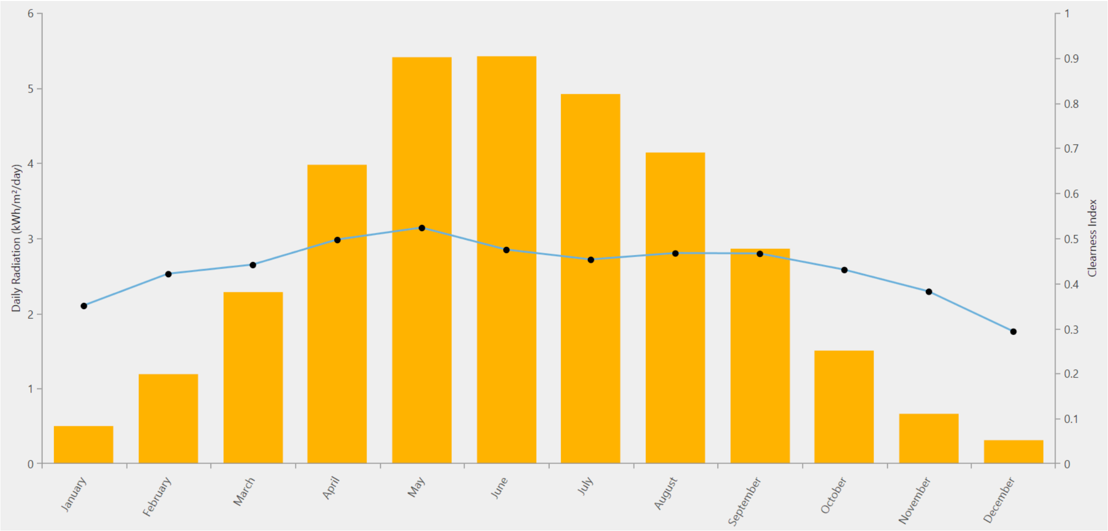


Figure 17: Solar GHI Data Input into HOMER [HOMER, 2017]

This data was compared to other resources, from other academic journals, for validation. Figure 18 shows the solar GHI data for a previous HOMER model of Eigg [Pepper, 2016].

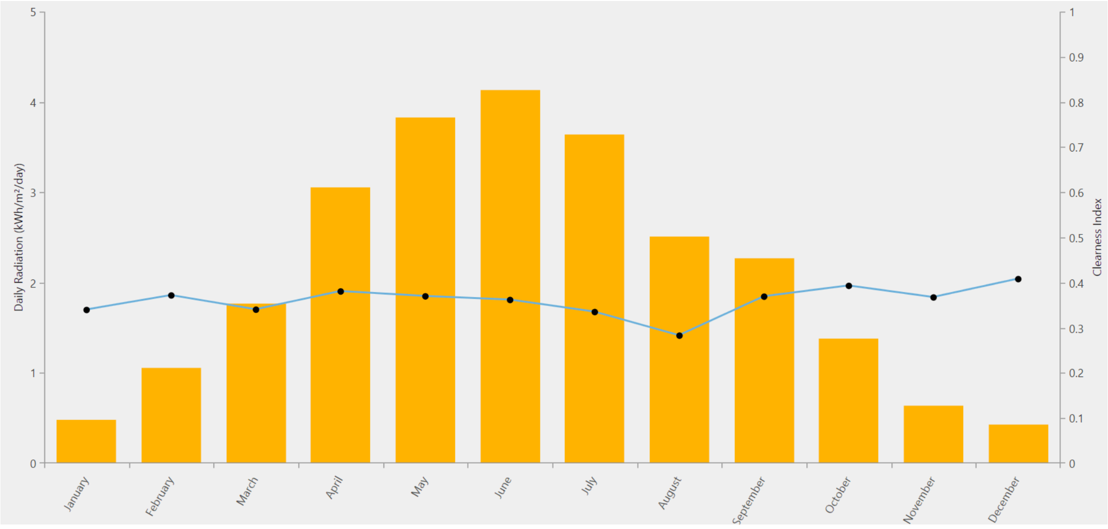


Figure 18: Manually Collected Solar GHI Data for Eigg [Pepper, 2016]

When comparing the magnitudes and trends of the solar data, it was concluded that HOMER's built-in data was considerably accurate. Figure 17 shows the solar GHI data that was manually measured by Russell Pepper in 2016. As this dissertation investigated four islands, there was not sufficient time available to collect this data manually for each of the islands. It was also considered that collecting this data manually would have its own discrepancies, for example due to human error. For these reasons, it was decided to use the HOMER resource data for calculations.

5.3.2 Hydrokinetic Resources

Figure 19 shows the average stream flow (in litres per second) across the months of the year for the Isle of Eigg. As the hydro schemes on the Isle of Eigg are small, this data is required to be localised. This data was taken again from Russell Pepper, who produced a thorough HOMER model of the Isle of Eigg [Pepper, 2016].

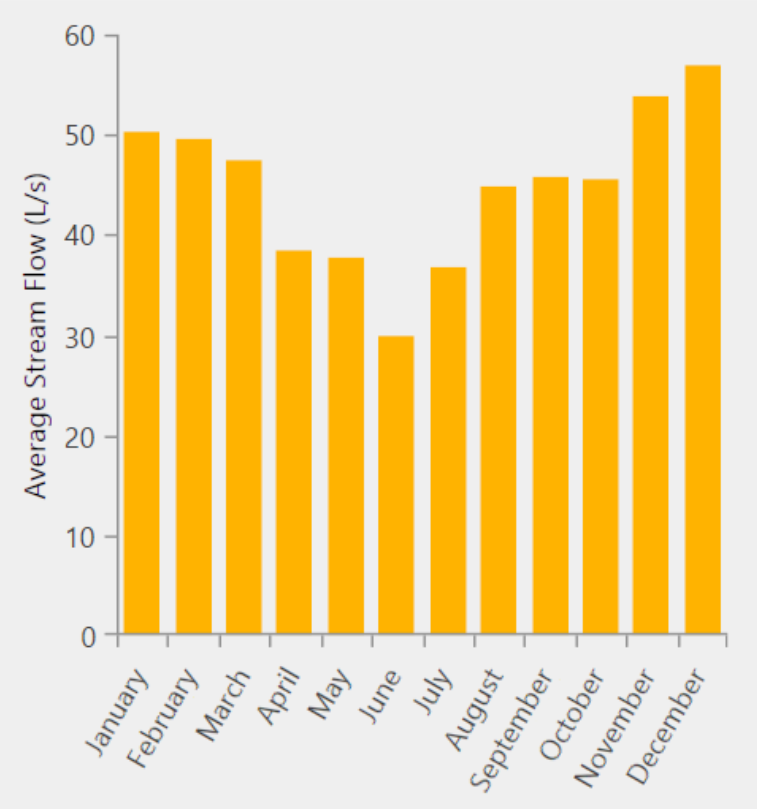


Figure 19: Hydrokinetic Data for Isle of Eigg [Pepper, 2016]

HOMER software is not able to import this data, and therefore if hydro schemes are to be considered this data is required to inputted manually. For this reason, the data is required to be as accurate as possible to ensure that the software accurately evaluates the electricity output of hydro systems. Other resources were investigated - such as the National River Flow Archive - and used to validate the magnitude of this local flow stream data further [National River Flow Archive, 2017]. As no major differences in the data values were found, it was concluded that this data for the Isle of Eigg was sufficient enough to proceed with the analyses.

5.3.3 Wind Resources

Figure 20 shows the HOMER wind data for the Isle of Eigg, whereas Figure 21 illustrates the data obtained by Russell Pepper [Pepper, 2016].

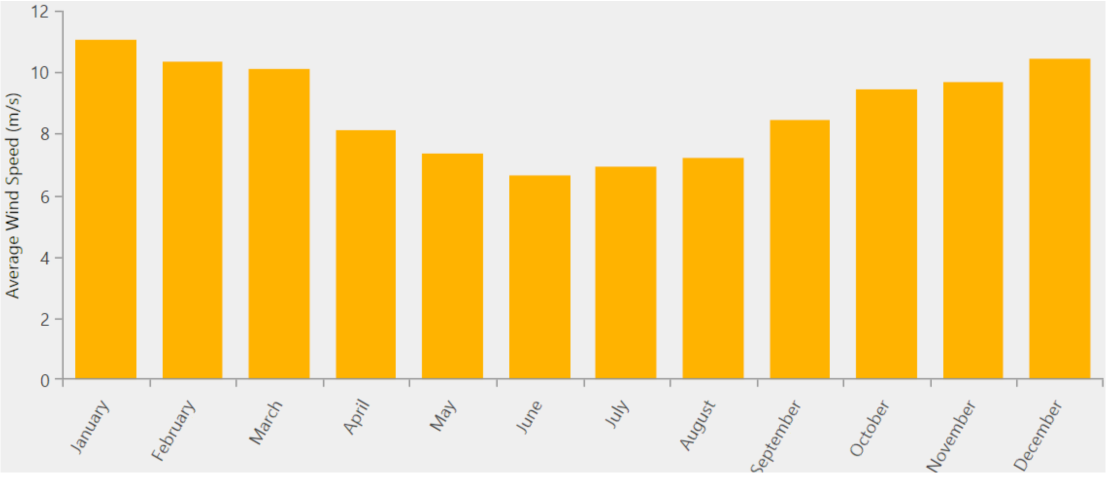


Figure 20: Default HOMER Wind Data for Isle of Eigg [HOMER, 2017]

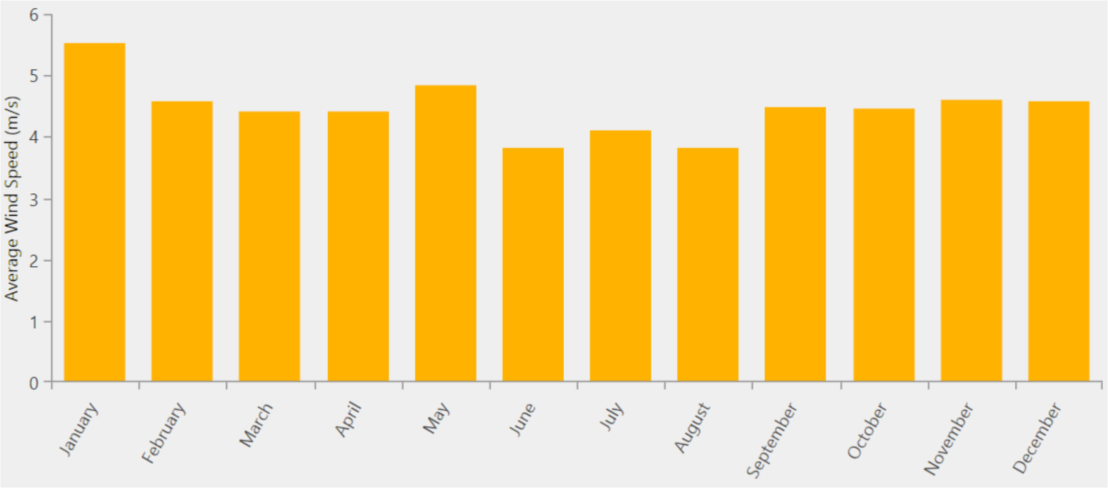


Figure 21: Manually Inserted HOMER Wind Data for Isle of Eigg [Pepper, 2016]

It can be seen that the data is different, and therefore another source was considered in order to validate the accuracy of the input wind speed values. Weather data from the MET Office and BBC Weather was considered. Difficulties arose in obtaining specific wind data however for the Small Isles, due to the fact that the area is very rural.

5.3.4 Technology Selection

Based on the literature review and background studying, it was found that each of the Small Isles is suited to different types of renewable energy resources. This is mainly due to the different landscape types; for example the Isle of Rum is mountainous and therefore more suited to hydro systems. Currently, the Isle of Eigg has installed a mixture of wind, photovoltaic and hydroelectric; Muck has a mixture of photovoltaic and wind; the Isle of Canna does not have any renewables as such yet installed, however due to similar conditions to the Isle of Muck, a similar system of wind and photovoltaic is being considered; the Isle of Rum has only hydroelectric systems in place.

Based on this, HOMER models for each of the Small Isles were composed. Each model considered the renewable resources currently on the island – or in the case of the Isle of Canna, the forecasted renewable generation systems (wind and photovoltaic) were considered.

In terms of the type of technology, the generic type was used as a default. Although the real technology may be different than what HOMER has used in the analyses, it was decided to use the generic systems as it offered a fairer comparison. Additionally, some of the systems (which were provided by Wind and Sun to the islands) have very specific design features, which in turn makes it more difficult to accurately model (financially and technically).

The priority was given to producing results that could be accurately compared, and therefore it was decided to implement the generic technologies.

5.4 HOMER Simulation

HOMER simulations were carried out for each of the Small Isles in order to evaluate the optimum combination of renewable technologies to meet the electricity demand, as detailed below. Additionally, a simulation was conducted which represented the total load of the Small Isles – as if they were interconnected.

First of all, the location was selected as an input. The next step was to input the resources, as explained previously. The technology is then selected, from the toolbar as shown in Figure 13. When the load (see Table 2), resources, and components are in place, a schematic is ready to be calculated in HOMER as illustrated in Figure 22 below. Figure 22 shows the schematic of the Isle of Muck, where wind and photovoltaic components were being considered. Hydro was neglected in this case, as the island does not have this technology implemented yet [Wind and Sun, 2017]. In turn, this schematic can be said to be a truer representation of the Isle of Muck today.

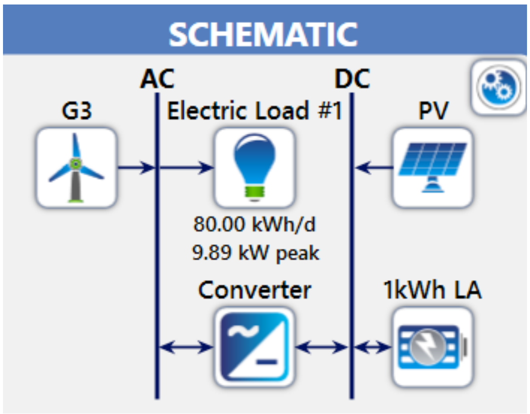


Figure 22: Schematic for Isle of Muck

Now that the simulation is set up, HOMER is able to evaluate the optimum combination of renewables to meet the load, as illustrated in Figure 23.

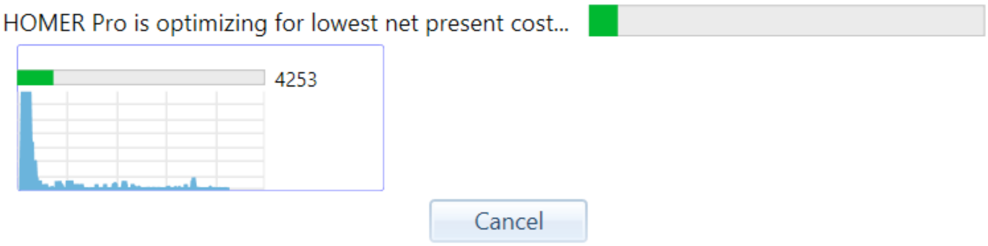
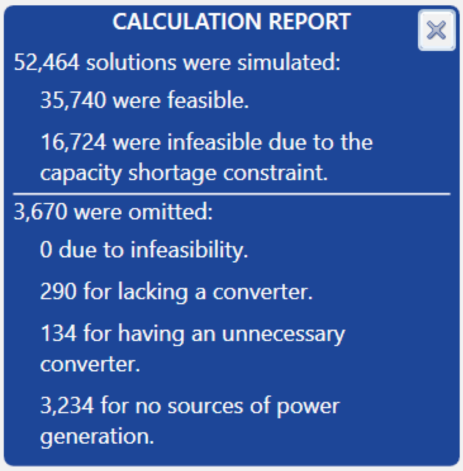

HOMER Pro is optimizing for lowest net present cost...

Figure 23: HOMER Optimization Process

Figure 24 shows the calculation report produced by HOMER after the simulation is complete.



CALCULATION REPORT

52,464 solutions were simulated:

35,740 were feasible.

16,724 were infeasible due to the capacity shortage constraint.

3,670 were omitted:

0 due to infeasibility.

290 for lacking a converter.

134 for having an unnecessary converter.

3,234 for no sources of power generation.

Figure 24: Simulation Calculation Report

6 RESULTS

6.1 Individual Island Models

Table 2 shows the input to HOMER. As the input was required in kWh/day, the conversion was conducted from the given values, which were in MWh/year. This load data was extracted from the Small Isles Audit [Small Isles Federation, 2017]. The total demand of the Small Isles was divided between the islands, according to the population.

Table 2: HOMER Load Inputs for Each of the Small Isles

Island	**Population**	**Load (MWh/year)**	**Load (kWh/day)**
Muck	38	29	79.4
Canna	11	0.6	1.64
Eigg	87	67	183.6
Rum	22	16.7	45.8

Table 3 shows the collected results. HOMER calculated several combinations of renewable technologies, of which the “optimum” combination for each island is shown. This “optimum” was based on some assumptions:

- The model assumed that the load was not connected to any means of main grid network;
- There was no option of having a diesel generator as a backup electricity supply;
- The renewable resources available were limited to wind, solar and hydro (as these technologies were found to already be installed amongst the Small Isles, thus a truer representation could be recreated in the HOMER models);
- There was no limit to the capacity of these renewables;

- Tidal generation was neglected as an option, due to the barriers to deployment and complicated installation;
- Maintenance processes associated with tidal energy; all simulations were set up to achieve 100% renewable penetration;
- Finally, only the electricity demand was modelled, neglecting heat and transport.

Table 3: Summary of Optimal HOMER Output Results for Each Island

Island	**Hydro (kW)**	**Battery (1kWh LA)**	**PV (kW)**	**Wind (G3)**	**Operating Cost (£)**	**Initial Capital Cost (£)**	**COE (£)**
Muck	-	188	15	5	7300	19500	0.769
Canna	-	17	4.03	-	514	17300	3.08
Eigg	112	18	-	-	4900	99400	0.188
Rum	112	-	-	-	4372	92760	0.691
All	112	145	21.7	-	8700	207000	0.219

For all of the simulations, numerous outputs were given from each HOMER model. In Tables 4, 5, 6, 7 and 9, these outputs are labelled “i, ii, iii, iv etc.”. In all cases, “i” corresponds to the optimal result (from a financial perspective), “ii” the second best result, “iii” the third best result etc. Some models had only two feasible results, for example Rum and Muck, whereas the HOMER simulation of Eigg delivered many options, as shown in Table 4.

6.1.1 Isle of Eigg

Table 4 shows the results obtained from HOMER for the Isle of Eigg.

Table 4: HOMER Output – Optimal Combinations of Renewable Sources for Eigg

Case for Eigg	Hydro (kW)	Battery (1kWh LA)	PV (kW)	Wind (G3)	Operating Cost (£)	Initial Capital Cost (£)	COE (£)
Ai	112	478	80.5	-	18950	500000	0.366
Aii	112	337	107	1	15700	550000	0.373
Aiii	112	691	-	53	44000	1280000	0.911
Bi	112	18	-	-	4900	99400	0.188
Bii	112	18	0.054	-	4930	100600	0.189
Biii	112	17	-	1	5252	117200	0.213
Biv	112	18	0.406	1	5400	121900	0.22
Ci	112	18	-	-	4900	99400	0.188
Cii	112	18	0.054	-	4932	100600	0.189
Ciii	112	18	-	1	5218	116600	0.212
Civ	112	18	0.406	1	5368	121800	0.22
Cv	112	-	142	21	13800	902500	1.25

A) Russell's model, modified components to generic and optimised by HOMER, load/resources not modified;
B) Russels resource data, modified load to 185kWh/day, generic components;
C) HOMER resource data, modified load, generic components, comparable to other islands.

A more detailed analysis was conducted for the Isle of Eigg, as previous work from Russell Pepper was obtained. This was useful as the detailed HOMER model of Eigg - as annotated “A” in Table 4 – gave different output results to the standard one, as annotated “C”. This third simulation of the Isle of Eigg was not as detailed as Pepper’s, in order to give a fair comparison with the other Small Island models. The “C” simulation had the assumptions applied to it: using HOMER resource data, opposed to manually inputted data; the load applied was according to data from the Small Isles Audit, proportional to the population differences amongst the Small Isles; and generic technologies were selected, for example the 3kW wind turbines and basic solar photovoltaic panels and generic battery storage. The specifications of the generic wind turbine and PV can be seen in Appendices B and C respectfully.

It is worth noting that the simulation, titled “B”, was conducted to gain an understanding of how the resource data affected the results. This “B” model utilised the same metrological data as “A”, but a different load and component selection. As the results did not vary significantly – particularly the scale of the results – it was concluded that the HOMER resource data was reliable. With this data validated, other models for other islands were composed with knowledge that the data was reliable, as it had been checked against another resource. Having this comparison within the simulations for the Isle of Eigg was useful in identifying potential points of error within the other Small Isle models. This was down to the fact that the weather inputs were slightly different, as discussed previously.

The HOMER results indicated that hydropower is the most cost effective renewable technology for Eigg. From reading literature however, and visiting the Isle of Eigg, it is known that the island actually has various forms of renewables installed: 4 wind turbines, 2 small hydro systems, and a photovoltaic array. This doesn’t match HOMER’s optimal result, thus implied that maybe the HOMER data was not completely reliable. Alternatively, it could be said that the Isle of Eigg would actually be better suited to having only hydro energy systems, from a COE perspective. HOMER does not take into consideration that having a variation of renewable resources can be useful in increasing the security of electricity supply from renewables, as there is less reliance on one certain technology.

6.1.2 Isle of Rum

Due to the geography of the small isles, there are local microclimates and therefore the weather conditions can vary quite significantly between the islands. Rum has a very mountainous landscape, and therefore is prone to more rainfall due to the microclimate. Due to the higher precipitation levels – and the mountainous landscape – the Isle of Rum was hypothesised to be suitable for hydro renewable technology systems. Figure 25 illustrates how the clouds collect around the mountains of rum, as seen from Canna.

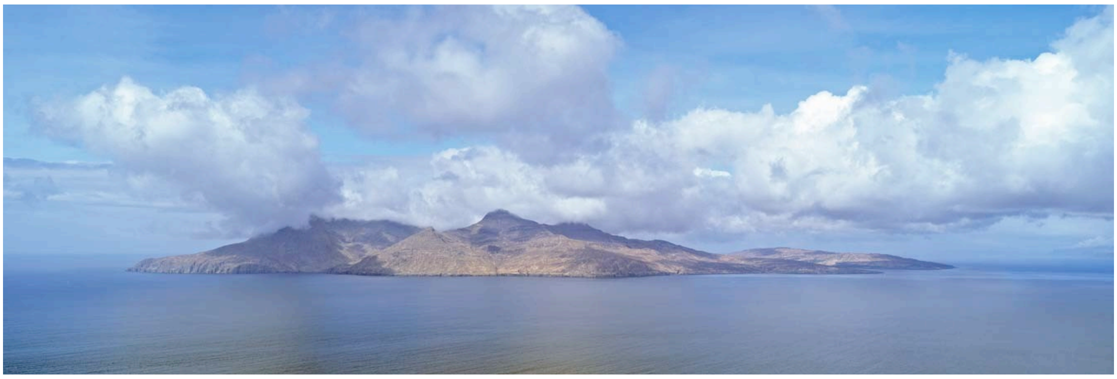


Figure 25: Isle of Rum [http://www.scotlandinprint.co.uk/isle-of-rum]

While the wind speeds are also substantial enough for wind energy, as shown in Figure 26, the nature of the landscape on Rum makes it slightly more difficult to erect and maintain wind turbines. This also applied to photovoltaic power – Figure 27 illustrates the GHI of the Isle of Rum.

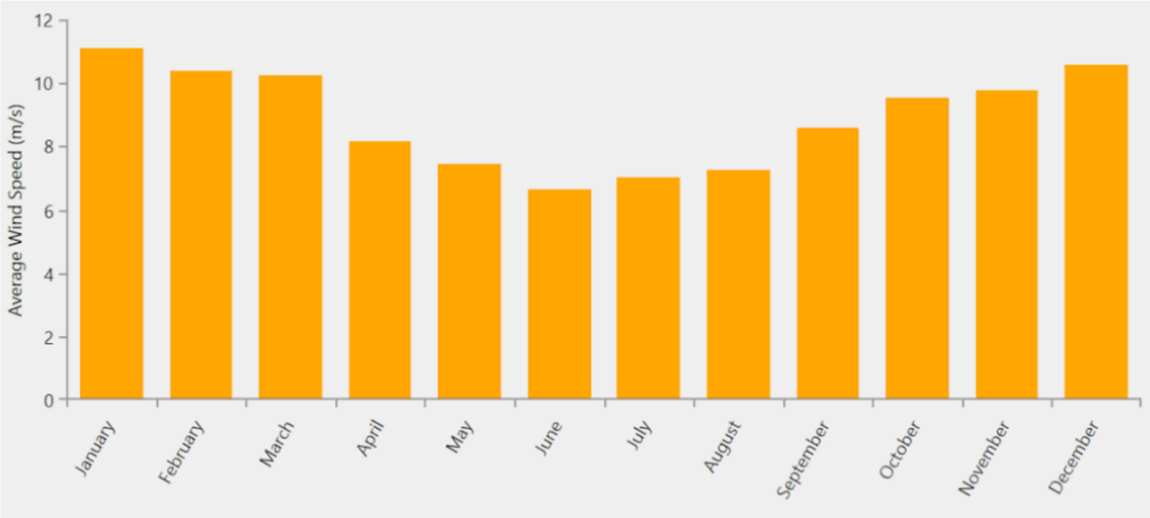


Figure 26: Wind Speed Data for Isle of Rum [HOMER, 2017]

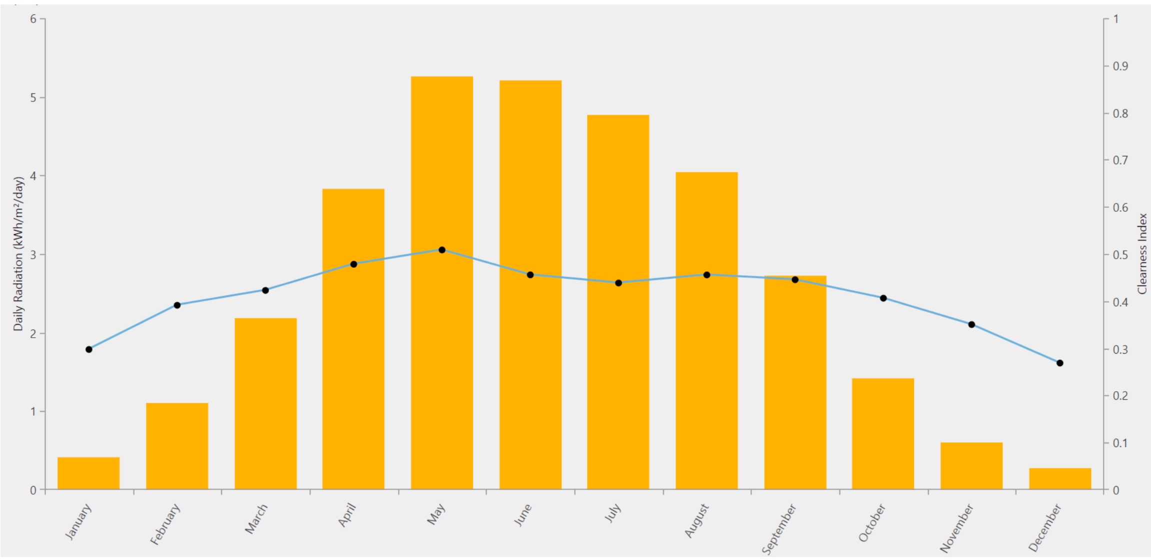


Figure 27: Annual GHI Data for Isle of Rum [HOMER, 2017]

While the deployment of wind or solar energy is feasible, the island is generally better suited to hydropower. Appendix A further illustrates the mountainous nature of the landscape; it can be seen that there are many peaks (up to 812m) on the island, with many valleys and lochs that have potential for hydro schemes and pumped storage.

The output of the HOMER model indicated that hydropower was the optimal option for the Isle of Rum, when coupled with battery storage to allow demand/supply matching. This matches what is currently on the Isle of Rum – the island has hydro turbines of 15kW and 30kW capacity installed, however is still reliant on a diesel generator for back up. As the HOMER model did not factor in the use of a diesel generator, it was recommended that 112kW of hydro power was installed, without the need for a battery.

Table 5: HOMER Output – Optimal Combinations of Renewable Sources for Rum

Rum	Hydro (kW)	Battery (1kWh LA)	PV (kW)	Wind (G3)	Operating Cost (£)	Initial Capital Cost (£)	COE (£)
I	112	-	-	-	4372	92760	0.691
Ii	112	1	-	-	4400	93000	0.694

The simplicity of only having hydropower means that a converter is not necessary, allowing costs to be reduced. Again, this HOMER model is based on many assumptions, thus the outputs are only used for a general evaluation of the island. Nonetheless, it was concluded from the HOMER model that Rum is an ideal location for hydropower, which could be an asset for the Small Isles in providing a solid base load of electricity (if they were interconnected).

6.1.3 Isle of Muck

Muck has an average annual wind speed of 8.5m/s, with velocities of 6m/s in June and up to 11m/s in January. Figure 28 illustrates the variations of the wind speeds across the year, as input into HOMER.

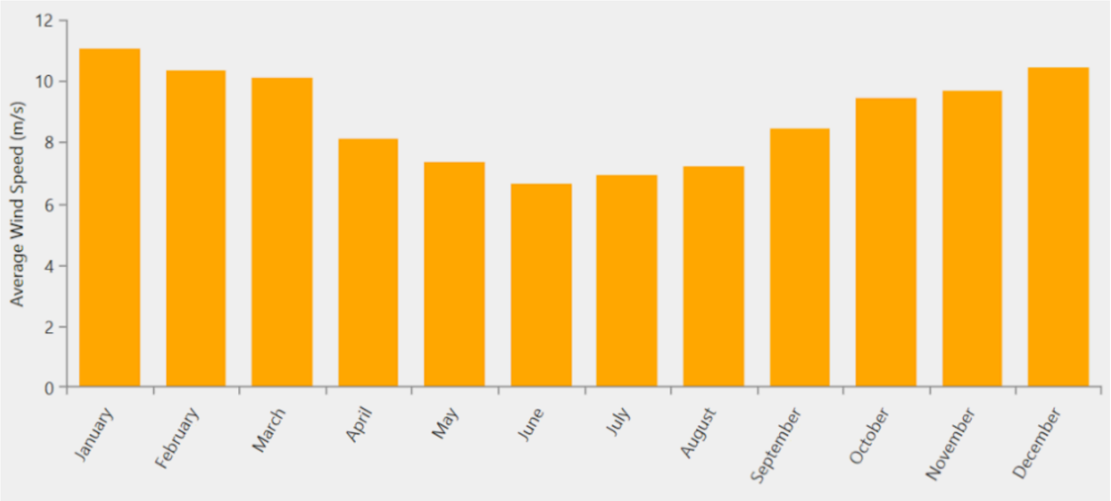


Figure 28: Wind Speed Data for Isle of Muck [HOMER, 2017]

With this wind data, the HOMER outputs showed that 5 3kW wind turbines would give the optimal demand/supply matching when paired with 188kWh of battery storage and 15kW of photovoltaic power. It was predicted that photovoltaic would be a suitable renewable energy technology for Muck, due to the solar input data as shown in Figure 29.

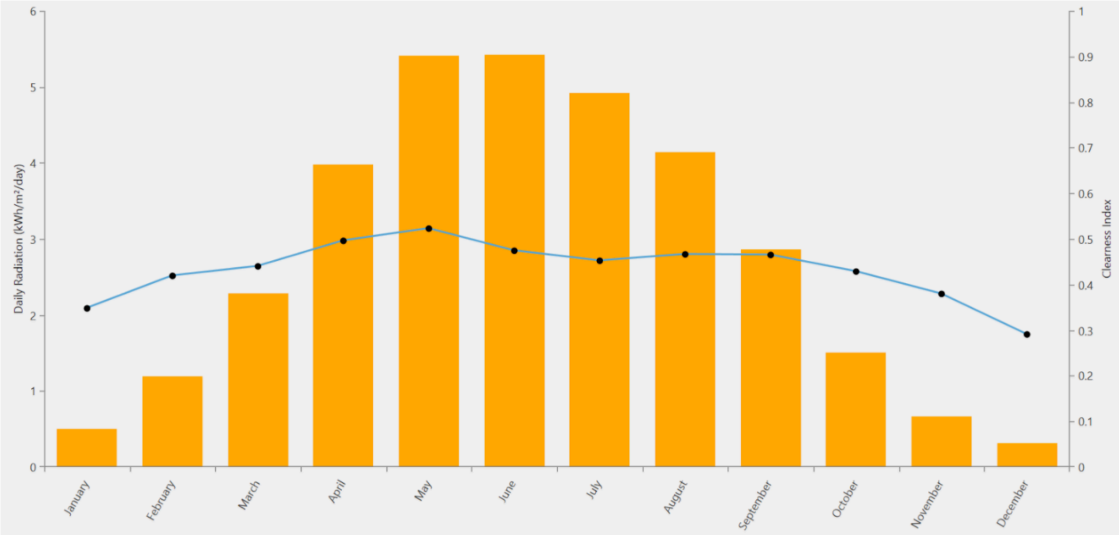


Figure 29: Global Horizontal Irradiance Data for Isle of Muck [HOMER, 2017]

The combination of wind and solar technologies for Muck is ideal, according to the wind and solar data. The lower wind speeds in the summer months is compensated by higher GHI values, thus the reduction in wind energy generated will be compensated by the extra solar energy produced.

The HOMER recommendations were compared to what technologies are currently on Muck. According to Wind and Sun, the island currently has wind, PV and battery technologies installed to power the island's local high voltage grid. The system comprises of 6 5kW wind turbines, 132 250W photovoltaic modules, and 3 battery banks allowing 150kWh of storage. There is also a back-up diesel generator on the island, which is used around 5% of the time according to islanders.

Table 6: HOMER Output – Optimal Combinations of Renewable Sources for Muck

Muck	Hydro (kW)	Battery (1kWh LA)	PV (kW)	Wind (G3)	Operating Cost (£)	Initial Capital Cost (£)	COE (£)
I	-	188	15	5	7300	19500	0.769
ii	-	241	-	13	11800	31800	1.25

The difference between the HOMER recommendations and actual installations was considered to differ for numerous reasons. First of all, for the HOMER model assumptions were made, which would affect the accuracy and reliability of the results to an extent. In reality there will be several inefficiencies to consider. For a more accurate model of the island, these should be taken into consideration - for example, by increasing the load to compensate for losses. The main conclusion from the results was that Muck is best suited to wind and solar technologies to generate electricity.

6.1.4 Isle of Canna

The analysis of Canna proved to be similar to that of the Isle of Muck. With similar wind speeds and GHI values, as shown in Figure 30 and 31, it was concluded that the island is best suited to wind and PV technologies for electricity generation.

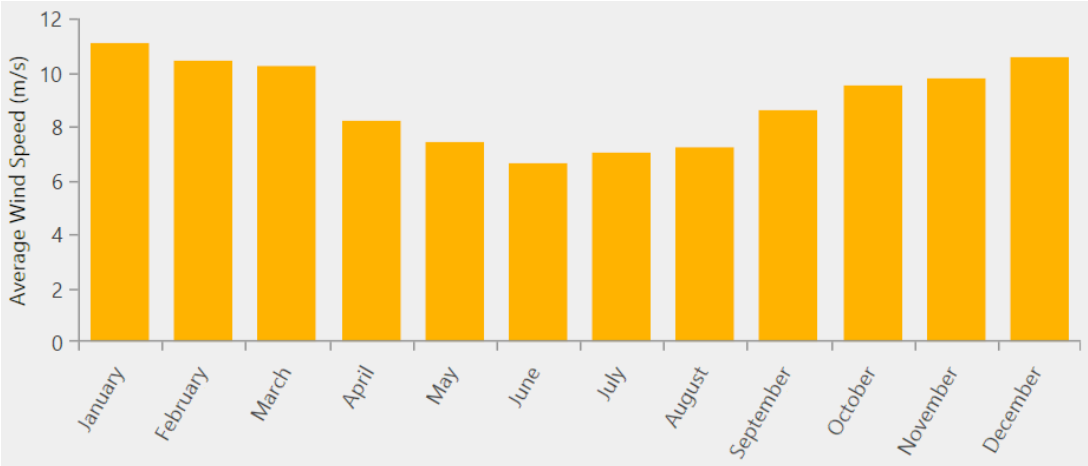


Figure 30: Wind Speed Data for Isle of Muck [HOMER, 2017]

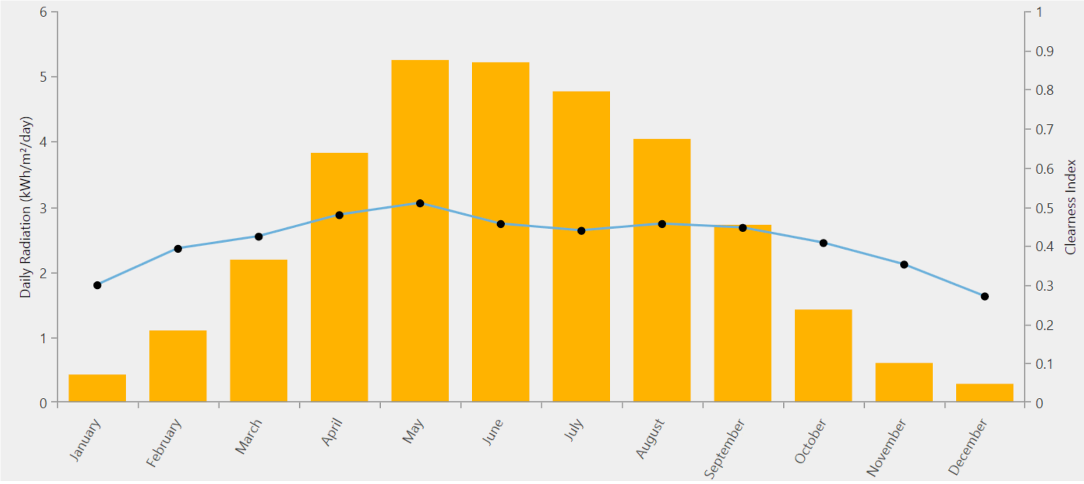


Figure 31: Global Horizontal Irradiance Data for Isle of Canna [HOMER, 2017]

HOMER provided two outputs, one considering wind power and one without wind power. It can be seen from Table 7 that having a single 3kW turbine reduced the requirements of battery storage significantly, which would perhaps be more ideal for the island. Having a wind turbine also reduces the reliance on PV, and only 0.16kW would be required opposed to 4kW.

Table 7: HOMER Output – Combinations of Renewable Sources for Canna

Canna	Hydro (kW)	Battery (1kWh LA)	PV (kW)	Wind (G3)	Operating Cost (£)	Initial Capital Cost (£)	COE (£)
I	-	17	4.03	-	514	17300	3.08
Ii	-	2	0.155	1	433	19100	3.18
Iii	-	3	-	1	458	18900	3.2

Currently on Canna, there are no renewables installed as residents rely completely on the island's diesel generator. The HOMER analysis conveys that there is scope for Canna to have renewables in place of this generator, with or without wind turbines.

6.2 Combined Inter-Island Model

Table 8 shows the results for the model simulation that was conducted, representing the total load of the Small Isles – as if they were interconnected.

Table 8: HOMER Output – (Representative of Island Interconnections)

All	Hydro (kW)	Battery (1kWh LA)	PV (kW)	Wind (G3)	Operating Cost (£)	Initial Capital Cost (£)	COE (£)
i	112	145	21.7	-	8700	207000	0.219
ii	112	144	19.4	1	9000	218000	0.229
iii	112	263	-	3	12900	233000	0.274

The results indicate that the Small Isles may benefit financially if they were interconnected, as the COE values are significantly lower for each HOMER output. This is lower for the majority of the Small Isles – with the exception of the Isle of Eigg, however the variety of renewables and higher population and energy demand allow a cheaper COE to be possible – which indicates that the islands would be better connected. The HOMER analysis does not account for the cost of the grid connections however, which would ultimately cause the initial capital costs and COE values to increase.

Another benefit of connecting the islands is that the amount of generation and storage capacity required decreases. As well as decreasing the costs of generation and storage equipment, this moreover reduces the maintenance costs and time. While grid connections are expensive, they require less time to operate/maintain than a diesel generator. This is useful as some islands currently face challenges in this area, for example on the Isle of Canna where the population is significantly small. The plans to install wind turbines and PV arrays has been questioned by residents, as there is not currently anybody on the island who is qualified to maintain and operate the proposed project. On an inter-island scale, decreasing the amount of technology required would therefore be beneficial.

6.3 Grid Requirements

Figure 32 illustrates what the Small Isles could look like with localised grid connections. The red lines show where undersea cables could be placed, in order to share the renewable resources amongst the different islands.

Figure 32: Plot of Potential Local Grid Connections Amongst Small Isles [Digimaps, 2017]

Using Digimaps, it was calculated that the length of cable required totals at 14.7km. As indicated in Figure 32, the length of the cable from Canna to Rum, measures 3.88km; from Rum to Eigg it measures 6.38km; and from Eigg to Muck, 4.4km of cable would be required. This total of 14.7km is significantly lower than the total length of undersea cables that would be required if each island were to be connected to Mallaig on the Scottish mainland, as shown in Figure 33.

Figure 33: Plot of Island-to-Mainland Grid Connections [Digimaps, 2017]

Measuring from Digimaps 33.5km from Muck to Mallaig, 21km from Eigg to Mallaig, 28km from Rum to Mallaig, and 45km from Canna to Mallaig, a total of 127.5km of undersea cabling would be required for this scenario (as shown in Figure 33). This costly investment would help to eradicate the use and reliance of diesel generators on the islands, however as the population is relatively small it is difficult to justify such a significant engineering project.

6.3.1 Cost Analysis of Transmission Lines

When grid connections are considered, the capital costs significantly increase. Tables 9 and 10 show the price guidelines for HVAC and HVDC transmission connections respectively [Sarkar, 2012].

Table 9: Cost of Equipment for a HVAC Transmission Line [Sakar, 2012]

Component	**Specification**	**Cost (in £Millions)**
Transformer (132/400kV)	240MVA, 132/400kV)	2
Switchgear (132kV)	132kV	0.75
Switchgear (400kV)	400kV	2.6
Shunt Reactor	200MVAr, 400kV	1.5
Cable	500MVA	2.5 per km

Table 10: Cost of Equipment for a HVDC Transmission Line [Sakar, 2012]

Component	**Specification**	**Cost (in £Millions)**
Voltage Source Converter	2000MW, 400kV	130
Cable	2000MW, 400kV	0.62 per km

A cost comparison was made between HVAC and HVDC transmission lines to investigate which would suit the Small Isles. The results are shown below in Table 11 and 12.

Table 11: Cost Breakdown of HVAC Subsea Transmission Lines for Small Isles

Component	**Cost (£ Millions)**
Transformer x 4	8
Switchgear x 4	3
Shunt reactor x 4	10.4
Cable x 14.7km	36.75
TOTAL	**58.15**

Table 12: Cost Breakdown of HVDC Subsea Transmission Lines for Small Isles

Component	**Cost (£ Millions)**
VSC x 4	520
Cable	9.11
TOTAL	**529.1**

It was assumed that that equipment such the transformers, switchgears, shunt reactors, VSCs would be required on each of the Small Isles, thus these were multiplied by four. The length of cable required – see Figure 32 – was calculated using Digimaps. As expected, the HVAC option is cheaper than HVDC as the distance of cabling is relatively small. As the length of cabling increases, reaching the "critical distance" from the mainland, HVDC transmission lines become the better economic option (as shown in Figure 12). As the distance between the Small Isles is significantly less than this critical distance, HVAC is the more viable option.

It is worth noting that these calculations only give an estimation of the potential transmission costs. In reality, there are many variables involved in grid connection projects that would affect the total cost of installing a network. Additionally, the data (as outlined in Tables 9 and 10) used for these calculations is over five years old, thus shouldn't be relied on completely – instead, these calculations should be used only for an estimation. In the context of this project, a value of £58million was used (see Table 11) as an estimation of the grid connection costs.

6.4 Summary of Results

Table 13 concludes the optimal results for each of the Small Isles. The number of each renewable source has been totalled to highlight (see bottom row of Table 13) how much generation/storage equipment would be required, if the islands were to operate independent of one another with 100% renewable penetration.

Table 13: Summary of HOMER Results for Each Island with Capital Costs

Island	Hydro (kW)	Battery (1kWh LA)	PV (kW)	Wind (G3)	Initial Capital Cost (£)
Muck	-	188	15	5	19,500
Canna	-	17	4.03	-	17,300
Eigg	112	18	-	-	99,400
Rum	112	-	-	-	92,760
Total	**224**	**233**	**19.0**	**5**	**228,960**

Table 14 summarises the optimal combination of technologies for the scenario where the islands are interconnected.

Table 14: Summary of HOMER Results for Combined Scenario with Capital Costs

Combined	Hydro (kW)	Battery (1kWh LA)	PV (kW)	Gen/Storage Costs (£)	Grid Costs (£)	Total Capital Cost (£)
Cheapest Option	112	145	21.7	207,000	58,150,000	**58,357,000**

It can be seen in Table 14 that wind generation has been negated, as HOMER has suggested that there are cheaper alternatives. Regardless of this, the hydro and battery capacities are significantly lower: hydro capacity requirements decrease from 224kW to 112kW, and battery decreases from 233 kWh to 145kWh. The capacity of PV remains similar (19kW without grid connections, 21.7kW with connections).

7 DISCUSSION

This section explores the financial, environmental and social aspects that would need to be considered.

7.1 Economic Analysis

The installation of more renewable generation capacity and undersea cables would be a significant one-off investment, which in turn would reduce the continuous spending on diesel fuel. This has financial benefits as, after the initial payment, the communities' monthly and annual outgoings will decrease and it will be possible for the communities to invest more frequently in their community. It should be considered however that money would need to be set aside to maintain and replace the new technologies, as required.

One of the biggest investments for the project is the undersea cables, which have significant capital costs. Due to the complexity and unique nature of this case study, where the distances are less than 50km, it is difficult to gauge how much the undersea cables would cost; an estimation of between £2million and £5million was assumed [ESRU, 2017]. Referral to Sarkar [Sarkar, 2012] validated this estimation of cost, and a value of £2.5million per kilometre of cabling was assumed. If all of the Small Isles were to be connected, as illustrated in Figure 32, the total capital cost would exceed £58million (see Table 13). This includes the value of all generation technology required to ensure 100% renewable penetration, thus does not account for the renewable sources currently installed amongst the Small Isles. As the technologies do not match exactly, it was presumed that the islands would install these new sources in addition to what they already have deployed. This assumption also removes the need to be completely reliant on the current technologies; if the HOMER outputs were considered and deployed amongst the Small Isles – collectively installing 224kV of hydropower, 19kV of PV, 15kV of wind power and 233 kWh of battery storage (see Table 12) – this would allow 100% renewable penetration in ideal circumstances. While HOMER accounts for the stochasticity of energy demands and intermittent nature of weather and renewable outputs, having addition generation supplies would furthermore aid in ensuring that the islands always have a secure energy supply.

The budgets of the communities are not clear, and generally the renewable projects that have already been conducted amongst the Small Isles have received generous funding from external sources. As it is unreasonable to assume that additional grants would be available to fund this type of project, it cannot be said that this is financially feasible for the Small Isles.

The economic barriers present do not alter the potential of the project. Without financial constraints, inter-island connections would be possible. Having undersea cables connecting the islands would remove the reliance on diesel, as the quality of the electricity from renewable resources would be enhanced. Additionally, according to residents of the Isle of Canna, the cost of electricity could be reduced as a result of inter-island connections; considering that the average income of the islanders is significantly lower than that of mainland residents, this is an important consideration.

If the islands were not connected, and more storage was incorporated to allow renewable energy to be captured and used at a later time, there would be less capital costs required. Compared to £58million (with the grid connections), the value of £229,000 is significantly lower considering that both options eradicate the reliance of diesel. While this is more financially feasible, and is what is already been practiced within the Small Isles, the amount of physical space required to accommodate this amount of storage is large. Residents of the Isle of Canna expressed concern regarding this matter, despite it being the more financially feasible option.

7.2 Environmental Impacts

The Small Isles' current approach to maintaining a steady electricity supply – namely, using battery storage - has significant environmental impacts, and as such is less than ideal. However, the new system proposed in this paper, of using undersea cables to connect the islands, also has significant impacts, which should be considered.

There would be direct impacts on the marine life, due to the exploitation of the seabed. Careful planning would need to be conducted in order to mitigate impacts as much as possible. The subsea cabling, as plotted in red in Figure 32, are optimal (meaning that the length is minimised); there are perhaps longer routes, requiring more cable and incurring extra costs that would potentially present less harm to marine life. Residents also expressed concerns regarding the bathymetry of the seabed: for example, between the Isle of Canna and the Isle of Rum there is a dip that would make it difficult to deploy cables. This must be taken into consideration when planning the grid connections, in combination with the effects on the surrounding wildlife.

Archaeological sites must be assessed carefully, as archaeology and heritage are important factors amongst the Small Isles. The Isle of Canna is an excellent example in that the island has sites dating up to 1,300 years. Additionally, the island is owned by the National Trust for Scotland (NTS), which is an independent charity that sets out to conserve, manage and promote Scotland's cultural and natural heritage. In this particular case, any project linking to the Isle of Canna would require consultation with this association, to ensure that the culture and nature of the island would not be compromised in any way. This is also relevant to the other Small Isles – in addition to any other island or site where a project is being sought out – where the nature and culture are at risk of being exploited, to any extent. This applies to the deployment of cables, in addition to any new renewable generation projects that would need to be carried out.

These projects can also induce visual impacts. In the case of grid connections, the location of connection points on the islands would need to be selected carefully, to ensure that the scenic landscape is not exploited. This also applies to new generation projects. In the case of the Small Isles, it is common that residents are impartial to renewable generation being visible from their homes. This is primarily due to residents placing high importance on improving their environment through the practice of renewable generation, as it symbolises the lack of fossil fuel energy generation. This gives an incentive to increase renewable generation on the islands, where communities can reap the benefits. However, the opinion of residents' should never be assumed, and therefore consultation and careful consideration of these potential impacts should always be considered.

On the other hand, there are positive environmental impacts that come with the installation of the scheme proposed in this paper. For example, the implementation of this system would aid in reducing the carbon dioxide emissions from the diesel generators, as the reliance on diesel would be significantly reduced. Additionally, the noise pollution would be removed with the absence of the diesel generator. This would enhance the quality of life of islanders and marine life. There would also be less risk of diesel oil spills, which is potentially harmful for local marine life.

7.3 Social Impacts

7.3.1 Fuel Poverty

With incomes significantly lower than that of the mainland, and more expensive electricity costs due to the remoteness of the Scottish Isles, fuel poverty is a significant problem within the Small Isles. After consultation with residents, concerns were expressed about the installation of more renewables:

"Wind and PV [on Canna] will be more expensive than diesel [per unit of electricity], and significantly more than what is paid on the mainland. We could be paying up to 25 pence per unit." – [Donald MacKenzie, 2017]

This is an example of one of the negative impacts of renewable integration. While the positive impacts are usually more acknowledged, negative impacts like these should also be considered. According to feedback from residents, communities can usually "arrange a deal" on electricity prices, however the tariffs remain to be high. Islanders of Canna expressed doubts about the installation of wind and photovoltaic technologies from a financial perspective and from a logistical perspective. The Isle of Canna is a very fragile community – as are the communities of Eigg, Rum and Muck – with a small population. Islanders showed concerns that there may not be enough people on the island to contribute to the operation and maintenance of the proposed renewable technology plans. On Canna, workers are currently paid to commute from the mainland and work on projects on the island such as fieldwork and maintenance of buildings. This highlights the island's extremely small population, as there are not enough residents to undergo this local work. The proposal of renewables on the island has therefore not been fully accepted by locals, due to concerns of this nature.

On the other hand, having the renewables on the island would reduce the reliance on the diesel generator. Furthermore, if grid connections were installed and the Small Isles achieved 100% renewable penetration, the need for the diesel generator would be completely removed. This would eradicate the need to check the generator daily – which is one islander's job – allowing more time to be invested in renewable maintenance and operations. When asking the manager of the diesel generator on the Isle of Canna about the potential of inter-island connections, Donald MacKenzie, doubts of how financial barriers would be faced were expressed, while appreciation of how the network would benefit the community of Canna and the other Small Isles:

"It would be better in that I wouldn't have to check the generator daily – which is what I currently do, in addition to other jobs around the island. An undersea cable would have its obstacles in installation – and of course financial and political barriers – however, if it were to get set up it would require much less maintenance than the diesel generator. When it's there, it's there." – [Donald MacKenzie, 2017]

Each island varies in population, and therefore certain new projects would be better for some communities where there is a need for more jobs. This in turn encourages people to stay on the island, particularly younger people, as they have more opportunities and incentives to stay.

7.3.2 Community Impacts

One of the biggest social impacts that interconnections would provide is a new sense of community between the islands. While each island currently has a strong sense of community independently, the presence of a local inter-island grid would generate a new type of community, as the islands would grow to be reliant on one another to some extent. As each of the islands has such a fragile community, this would potentially provide benefits such as more financial security and security of energy supply. As the connections would require the Small Isles to cooperate more amongst each other, it would therefore strengthen the status of the islands. This would be good in lessening the fragile status of the communities. The Isle of Eigg is currently recognised overseas for its innovation; there is potential that a project like this would allow the entirety of the Small Isles to gain a similar recognition, enhancing tourism and foreign investment.

8 CONCLUSIONS

Despite the prosperous benefits that inter-island connections could bring to the Small Isles – the main advantage being that residents would have access to a secure supply of renewable energy – there are many barriers to deployment that make the project unfeasible. Due to the circumstances, as detailed below, it is not recommended that a local microgrid should be implemented.

8.1 Barriers to Deployment

From an economic aspect, the implementation of inter-island connections is not financially feasible: for fragile communities such as those found amongst the Small Isles, spending over £58,000,000 on infrastructure is not possible without major external funding. As mentioned previously, due to the significantly small populations of the Small Isles, the communities of Muck, Eigg, Rum and Canna are very fragile. Because of this, any changes – whether small or big – will have direct, indirect and cumulative impacts on the residents and community. In this case, the concept of a project that involves such a high magnitude of investment and effort to deploy would not be easy to integrate into the communities without external help.

The Small Isles have a relatively low population, totalling at value of around 158 residents, which means that the electricity demand is low (relative to main cities on the mainland). Generally, there needs to be a significant demand in order to justify the installation of transmission lines – particularly subsea connections – due to the high capital costs and complications.

There are also environmental considerations linked to inter-island connections. The implementation of new infrastructure would impose risks for local wildlife and marine life. There are also landscape and visual impacts – both direct and indirect – that would need to be taken into consideration. While the main barrier to deployment is the cost of the infrastructure, these are also aspects that should be considered.

8.2 Incentives for Deployment

On the other hand, it remains that there are numerous potential benefits of inter-island connections. The islands currently rely heavily on diesel generators for electricity, which requires daily attention to ensure safe operation is conducted; removal of these generators would also remove this maintenance, as grid connections do not require the same amount of upkeep. Eliminating this task would therefore allow more time to be spent on renewable projects amongst the islands, and in maintaining and operating new generation/storage facilities. Moreover, eliminating the diesel generator would immediately eliminate associated noise pollution, thus enhancing the residents' quality of life to an extent.

With 100% renewable penetration – which would be encouraged with inter-island microgrid connections – carbon dioxide emissions would also reduce. This is a major incentive for deployment, as the UK government strives to reduce the country's carbon footprint. The grid connections would help to ensure that the Small Isles always are able to access a clean, secure energy supply. This aligns with the targets of the government, in providing decarbonised energy.

Another incentive for deployment is that a project of this nature could encourage the communities of Muck, Eigg, Rum and Canna to cooperate more and work together as one. This would form a new identity for the Small Isles, and a new sense of community – in turn, this would strengthen the islands and furthermore provide energy security. This would also potentially decrease residents' electricity prices, and therefore reducing fuel poverty.

9 RECOMMENDATIONS AND FURTHER WORK

Presently, the financial barriers presented by such a huge project unfortunately outbalance the benefits of having a local grid. Despite the numerous incentives for deployment, the proposal for inter-island connections is not recommended for the Small Isles within the current economic context.

As an alternative, the Small Isles could consider increasing their battery storage capacity – and renewable generation – in order to achieve 100% renewable penetration. It has been discussed in this dissertation that battery storage could also be a method of eradicating the reliance on diesel generators amongst the Small Isles.

As this project has involved various assumptions in the modelling stage, it is recommended that a more detailed analysis be carried out in order to achieve more accurate and robust results. For example, data collection should be conducted for each of the Small Isles to ensure that the modelling inputs/outputs are truly representative of the islands (including weather data). Moreover, further research could be conducted into the Small Isles considering the heating and transport loads. Factoring in these additional demands – should transport and heating become electrified in the future – would potentially increase the renewable generation required.

An outcome of this dissertation, in addition to the key results for the Small Isles, is a methodology for assessing how clusters of islands – which are not connected to the mainland grid – can reduce their reliance on fossil fuels and diesel generators. This methodology could be taken and used in other groups of islands as further work, within or outside of the UK (See Appendix D), to investigate how renewable penetration can be increased where the mainstream grid network is not accessible.

10 REFERENCES

Angus, S. (2014). The implications of climate change for coastal habitats in the Uists, Outer Hebrides. *Ocean & Coastal Management*, 94, pp.38-43.

Bahramara, S., Moghaddam, M. and Haghifam, M. (2016). Optimal planning of hybrid renewable energy systems using HOMER: A review. *Renewable and Sustainable Energy Reviews*, 62, pp.609-620.

Banerji, A. (2013). MICROGRID: A Review.

BBC News. (2017). *What is the National Grid and why does it cost to connect to it? - BBC News*. [online] Available at: http://www.bbc.co.uk/news/uk-scotland-scotland-politics-29509021 [Accessed 22 Jun. 2017].

Groot, J. and Bailey, I. (2016). What drives attitudes towards marine renewable energy development in island communities in the UK?. *International Journal of Marine Energy*, 13, pp.80-95.

Echevarria, J. (2017). *Energy Live News – Energy Made Easy – Could microgrids be a part of UK's energy system?*. [online] Energylivenews.com. Available at: http://www.energylivenews.com/2016/02/19/could-microgrids-be-a-part-of-uks-energy-system/ [Accessed 22 Jun. 2017].

Energy.gov. (2017). *How Microgrids Work*. [online] Available at: http://energy.gov/articles/how-microgrids-work [Accessed 22 Jun. 2017].

Esru.strath.ac.uk. (2017). *Electricity*. [online] Available at: http://www.esru.strath.ac.uk/EandE/Web_sites/98-9/offshore/elec.htm [Accessed 21 Jul. 2017].

Fadlullah, Z. and Kato, N. (2015). *Evolution of smart grids*.

Foley, A. and Olabi, A. (2017). Renewable energy technology developments, trends and policy implications that can underpin the drive for global climate change. *Renewable and Sustainable Energy Reviews*, 68, pp.1112-1114.

Gils, H. and Simon, S. (2017). Carbon neutral archipelago – 100% renewable energy supply for the Canary Islands. *Applied Energy*, 188, pp.342-355.

Google.com. (2017). *Google Maps*. [online] Available at: http://google.com/maps [Accessed 23 Jun. 2017].

Gov.scot. (2017). *Renewable Energy*. [online] Available at: http://www.gov.scot/Topics/Business-Industry/Energy/Energy-sources/19185 [Accessed 22 Jun. 2017].

Gov.scot. (2017). *Energy in Scotland: Get the facts*. [online] Available at: http://www.gov.scot/Topics/Business-Industry/Energy/Facts [Accessed 22 Jun. 2017].

Gurkan, G. and Langestraat, R. (n.d.). Modeling and Analysis of Renewable Energy Obligations and Technology Bandings in the UK Electricity Market. *SSRN Electronic Journal*.

HeraldScotland. (2017). *The Highland Line: a shocking surcharge on the fuel poor in our remote areas*. [online] Available at: http://www.heraldscotland.com/news/13185120.The_Highland_Line__a_shocking_surcharge_on_the_fuel_poor_in_our_remote_areas/ [Accessed 22 Jun. 2017].

Kennedy, N., Miao, C., Wu, Q., Wang, Y., Ji, J. and Roskilly, T. (2017). Optimal Hybrid Power System Using Renewables and Hydrogen for an Isolated Island in the UK. *Energy Procedia*, 105, pp.1388-1393.

Kumar, Y., Ringenberg, J., Depuru, S., Devabhaktuni, V., Lee, J., Nikolaidis, E., Andersen, B. and Afjeh, A. (2016). Wind energy: Trends and enabling technologies. *Renewable and Sustainable Energy Reviews*, 53, pp.209-224.

Kumar, P., Pukale, R., Kumabhar, N. and Patil, U. (2016). Optimal Design Configuration Using HOMER. *Procedia Technology*, 24, pp.499-504.

Lockwood, M. (2016). The UK's Levy Control Framework for renewable electricity support: Effects and significance. *Energy Policy*, 97, pp.193-201.

Morales, D., Besanger, Y., Sami, S. and Alvarez Bel, C. (2017). Assessment of the impact of intelligent DSM methods in the Galapagos Islands toward a Smart Grid. *Electric Power Systems Research*, 146, pp.308-320.

Münnich Vass, M. (2017). Renewable energies cannot compete with forest carbon sequestration to cost-efficiently meet the EU carbon target for 2050. *Renewable Energy*, 107, pp.164-180.

National River Flow Archive. (2017). *Search for gauging stations*. [online] Available at: http://nrfa.ceh.ac.uk/data/search [Accessed 6 Jul. 2017].

Newbery, D. (2017). Tales of two islands – Lessons for EU energy policy from electricity market reforms in Britain and Ireland. *Energy Policy*, 105, pp.597-607.

Networks.Online. (2017). *Grasp the UK microgrid opportunity*. [online] Available at: https://networks.online/gphsn/industry-insight/1000043/grasp-uk-microgrid-opportunity [Accessed 22 Jun. 2017].

New.abb.com (2017). *Investment Cost (image) Available at:* http://new.abb.com/images/default-source/p-s-hvdc/illustrations/investment-cost_large.jpg?sfvrsn=1 [Accessed 31 Jul. 2017].

Nicolini, M. and Tavoni, M. (2017). Are renewable energy subsidies effective? Evidence from Europe. *Renewable and Sustainable Energy Reviews*, 74, pp.412-423.

Nikolic, D., Tereapii, T., Lee, W. and Blanksby, C. (2016). Cook Islands: 100% Renewable Energy in Different Guises. *Energy Procedia*, 103, pp.207-212.

Pepper, R. (2016.). A Review of Storage and Load-Shifting in Energy System Modelling Tools, University of Strathclyde

Prasad, R. and Raturi, A. (2017). Grid electricity for Fiji islands: Future supply options and assessment of demand trends. *Energy*, 119, pp.860-871.

Sakar (2012), Power Transmission Options for Offshore Windfarms in Scotland, https://www.strath.ac.uk/esru/degrees/renewablenrg/reseindividualtheses/.,University of Strathclyde, ESRU, [Accessed 31 Jul. 2017].

Scottish Government (2011). *UK Renewable Energy Roadmap*. Department of Energy and Climate Change, http://www.gov.scot/Publications/2011/08/04110353/0 [Accessed 22 Jun. 2017].

Scottish Island Federation (2017). *Small Isles Energy Audit*. Scotland: James Ardagh.

Scottish Power (2017). *Longannet Power Station To Close In March 2016 - ScottishPower*. [online] Available at: http://www.scottishpower.com/news/pages/longannet_power_station_to_close_in_march_2016.aspx [Accessed 22 Jun. 2017].

Scotlandinfo.eu. (2017). *Scotland Info*. [online] Available at: http://www.scotlandinfo.eu/images/small-isles/isle-of-eigg.jpg [Accessed 23 Jun. 2017].

Sharifzadeh, M., Lubiano-Walochik, H. and Shah, N. (2017). Integrated renewable electricity generation considering uncertainties: The UK roadmap to 50% power generation from wind and solar energies. *Renewable and Sustainable Energy Reviews*, 72, pp.385-398.

Sse.com. (2017). *Harnessing remote island wind*. [online] Available at: http://sse.com/newsandviews/allarticles/2017/01/harnessing-remote-island-wind/ [Accessed 22 Jun. 2017].

The Guardian. (2017). *Will the micro-grid put major power companies out of business?*. [online] Available at: https://www.theguardian.com/sustainable-business/micro-grid-power-companies-business [Accessed 22 Jun. 2017].

The Isle of Eigg. (2017). *About Eigg - The Isle of Eigg*. [online] Available at: http://www.isleofeigg.org/ [Accessed 23 Jun. 2017].

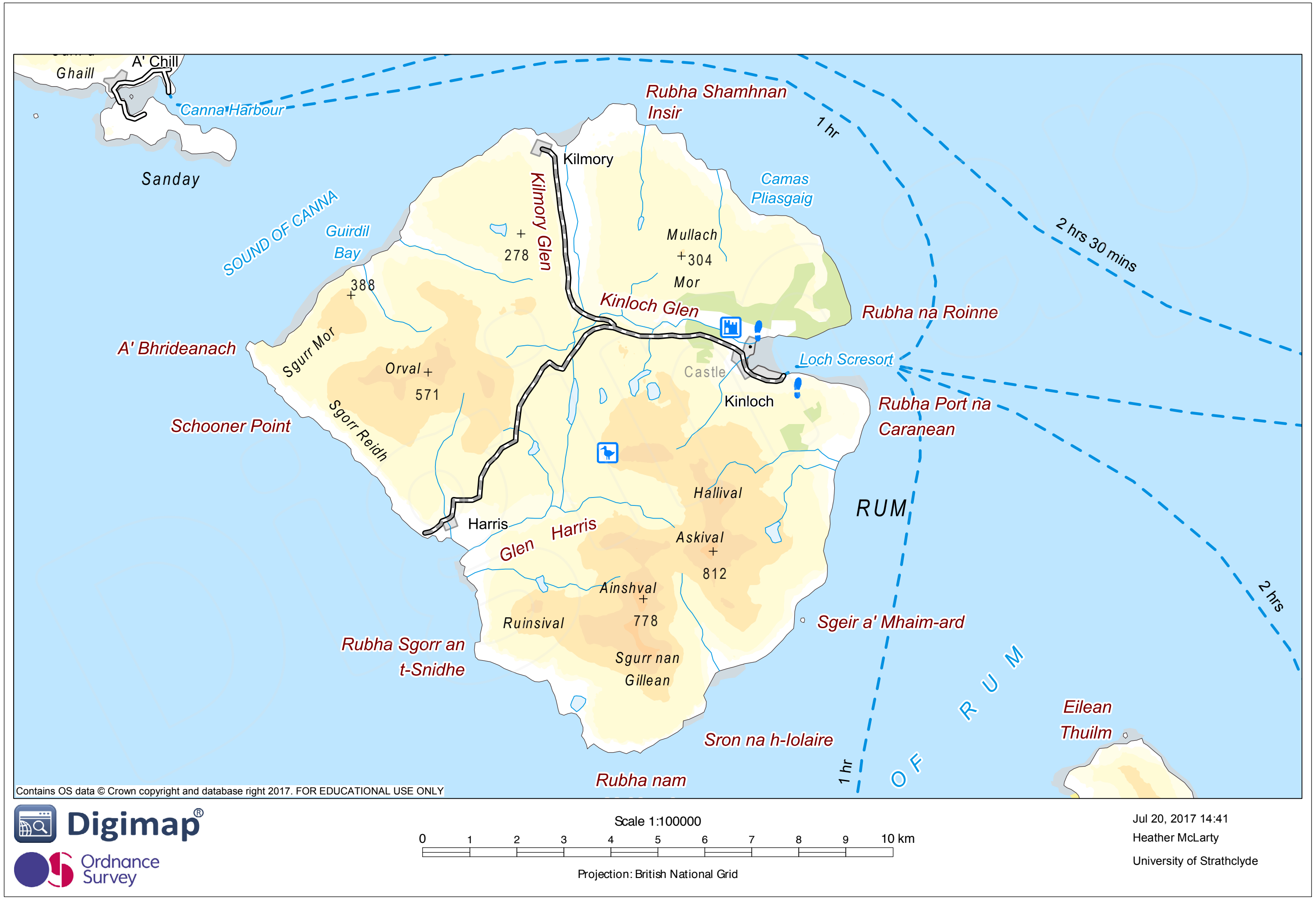
The Isle of Eigg. (2017). *Eigg Electric - The Isle of Eigg*. [online] Available at: http://www.isleofeigg.org/eigg-electric/ [Accessed 23 Jun. 2017].

Windandsun.co.uk. (2017). *Isle of Muck | Wind & Sun*. [online] Available at: http://www.windandsun.co.uk/case-studies/islands-mini-grids/isle-of-muck.aspx#.WU0tERPyvPA [Accessed 31 Jul. 2017].

Windandsun.co.uk. (2017). *Isle Of Rum | Wind & Sun*. [online] Available at: http://www.windandsun.co.uk/case-studies/islands-mini-grids/isle-of-rum.aspx#.WU0rzxPyvPA [Accessed 31 Jul. 2017].

Windandsun.co.uk. (2017). *Isle of Muck | Wind & Sun*. [online] Available at: http://www.windandsun.co.uk/case-studies/islands-mini-grids/isle-of-muck.aspx#.WUuV2hPyvPA [Accessed 22 Jun. 2017].

11.1 Appendix A – Map of Isle of Rum



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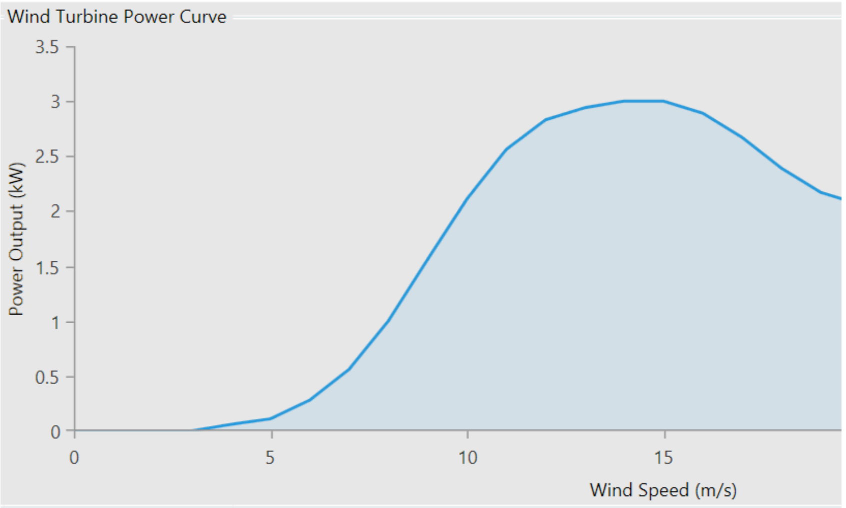
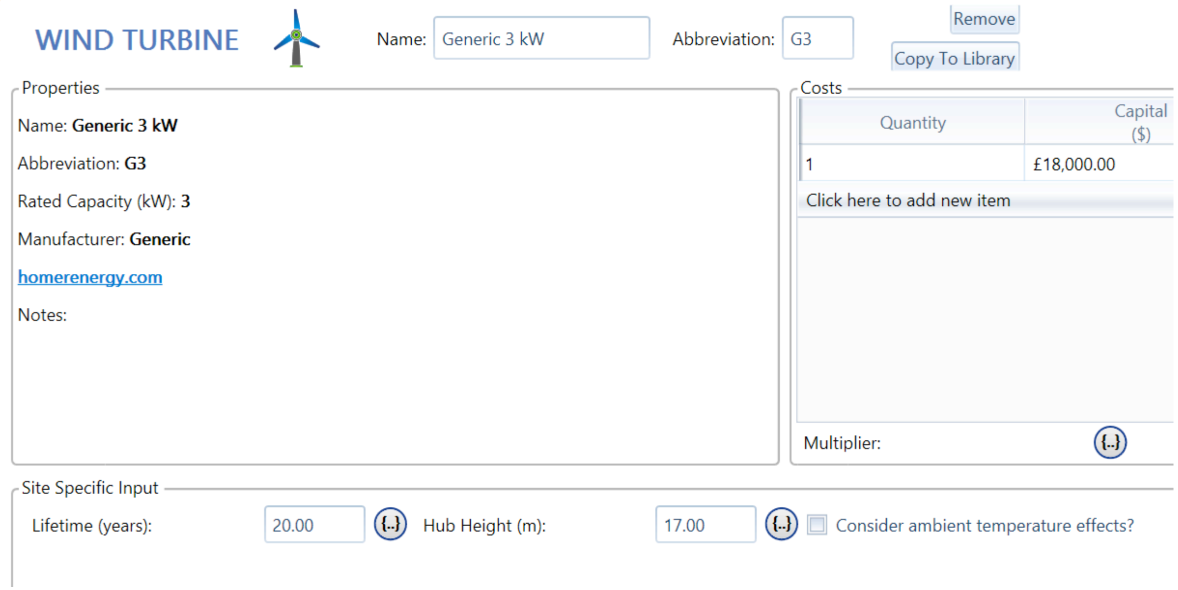
Jul 20, 2017 14:41
Heather McLarty
University of Strathclyde

11.2 Appendix B – Generic Wind Turbine Specification





Name: Generic 3 kW

Abbreviation: G3

Properties

Name: **Generic 3 kW**

Abbreviation: **G3**

Rated Capacity (kW): **3**

Manufacturer: **Generic**

homerenergy.com

Notes:

Costs

Quantity	Capital ($)
1	£18,000.00
Click here to add new item	

Multiplier:

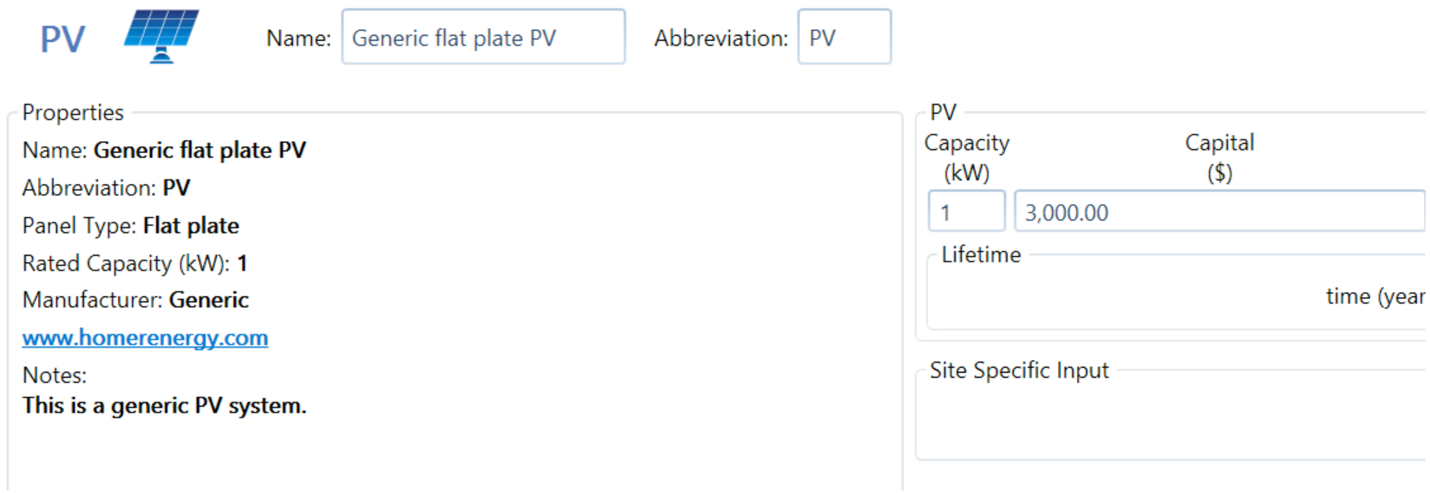
Site Specific Input

Lifetime (years): 20.00

Hub Height (m): 17.00

☐ Consider ambient temperature effects?

11.3 Appendix C – Generic PV Specification



Name: Generic flat plate PV

Abbreviation: PV

Properties

Name: **Generic flat plate PV**

Abbreviation: **PV**

Panel Type: **Flat plate**

Rated Capacity (kW): **1**

Manufacturer: **Generic**

www.homerenergy.com

Notes:

This is a generic PV system.

PV

Capacity (kW)	Capital ($)
1	3,000.00

Lifetime

time (year

Site Specific Input

11.4 Appendix D – Assessment of Groups of Islands