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ENERGY AND ENVIRONMENTAL MANAGEMENT

# Transition Pathways for Decarbonisation and Self Sufficiency on the Isle of Eigg

## International Class 2024

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## INTERNATIONAL CLASS OF 2024

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## Executive Summary

The electricity system on the Isle of Eigg has attained an exemplary status being the fore-runner in off-grid renewable energy systems. With an annual renewable penetration up to 95%, the power system is an ideal for what self-sufficient energy systems can look like. However, other sectors of energy, including heating, cooking, and mobility, are dependent on conventional fossils, some of which are imported on the island.

A multi-disciplinary approach of qualitative and quantitative methods was used to develop transition pathways that were in line with Eigg's 2030 decarbonization goals. Data was gathered through community engagement activities, site-specific studies for the potential of renewable energy technologies, and through analysis of demand across all sectors. Workshops and surveys were also used to draw a representative image of the socioeconomic context of the Isle of Eigg community. Assumptions on population growth, tourism, and change in behavioural patterns were made to produce data that could be used for the transition pathways. A modelling framework was developed to compare transition pathways to net zero on Eigg.

Three long term scenarios were modelled. The Business-As-Usual (BAU) scenario sets the benchmarks for the other future scenarios. In the BAU scenario, everything remains as is until 2030. The community continues to be as reliant on conventional fuels. However, emissions increase due to increasing demand. In the sector coupling scenario, decarbonization is achieved through the electrification of heating, cooking, and mobility. In order to electrify these sectors, power system expansion will have to be made through tidal energy and increasing battery storage.

The third scenario was called Sector-Coupling with Energy Efficiency scenario, which built upon last scenario and utilised the anticipated gains of undertaking community-wide energy efficiency measures. This scenario indicated a similar outcome as last scenario, with the only difference being in the capacities of tidal and storage that were needed for expansion. The new capacities that were needed were smaller than last scenario, mainly because of shrunken demands due to energy efficiency gains. Also, while other sectors were fully electrified, heating sector could be electrified roughly 60%, which is higher than the electrification rate attained in last scenario. Realizing that both future scenarios suggest expansion with tidal energy, which is a technology that is relatively lesser commercial in comparison to solar PV and wind, an additional scenario was modelled that did not have tidal as an option. This was attempted to give the community insights into the alternative they would have if they decided other than tidal energy. This scenario indicated large expansions in solar PV, wind, and battery storage capacities, and these expansions were larger than the two scenarios modelled earlier. Even with these large investments, the heating sector could only be electrified half-way

through. This was an indication that while it is possible to have solar PV and wind expand to meet future demands, a diversity in technology is needed to keep the system size reasonably small for an off-grid community.

In all modelled scenario for the future, excluding the Business-As-Usual scenario, achievement of a net-zero cross-sectoral energy system is possible. The costs of this however vary by a lot, where the most economical transition could be undertaken through implementation of energy efficiency measures while the most expensive would be in the scenario where we do not have any tidal energy. Across the modelled scenarios, energy efficiency appears the most promising to achieve the least-cost carbon neutrality across all sectors. This study and its results are intended to serve as an analysis for future transition pathways that the community on Eigg can refer to; for their energy system expansion plans, for their decarbonisation plans, or to gain maximum benefit through their behavioural adjustments.

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# Abbreviations

| | |
|---|---|
| AC | Alternative Current |
| BAU | Business-As-Usual |
| BU | Business Units |
| B&B | Bed and Breakfast |
| CCS | Combined Charging Systems |
| CFD | Computational Fluid Dynamics |
| CIBSE | Chartered Institution of Building Services Engineers |
| CNI | Carbon Neutral Islands |
| DC | Direct Current |
| E | East |
| E2P | Energy to Power Ratio |
| EPC | Energy Performance Certificate |
| EV | Electric Vehicle |
| FEE | Fabric Energy Efficiency |
| FiT | Feed in Tariff |
| GHI | Global Horizontal Irradiance |
| HDD | Heating Degree Days |
| HH | Households |
| HP | Heat Pumps |
| ICE | Internal Combustion Engine |
| IEA | International Energy Agency |
| IEC | International Electrotechnical Commission |
| IRENA | International Renewable Energy Agency |
| kVA | kilovolts-amperes |
| kWh | kilo-Watt hours |
| kW | kilo-Watt |
| LABattery | Lead-Acid Battery |
| LiFePO4, LFP | Lithium Iron Phosphate Battery |
| MJ | Megajoules |
| N | North |
| NE | Northeast |
| NW | Northwest |
| PV | Photovoltaic |

| | |
|---|---|
| PVOUT | Photovoltaic Power Output |
| RdSAP | Reduced Data Standard Assessment Procedure |
| ROC | Renewable Obligation Certificates |
| SAP | Standard Assessment Procedure |
| SE | Southeast |
| S | South |
| SW | Southwest |
| USD | US Dollars |
| V2G | Vehicle to grid |
| W | West |

# 1. Introduction

Community engagement is the force that drives development and cohesion in many communities around the world. In Eigg, this is even more evident. Different from other places where community involvement is an abstract idea and has much interference from the government, Eigg took control of their destiny as residents purchased the island. This milestone not only revitalized hope in the community that suffered from a lack of basic infrastructure and depopulation, but also sparked a movement of local empowerment. Since then, Eigg residents have worked together to develop innovative projects that promote environmental, economic, and social sustainability. Despite the impressive achievements made by the Eigg community, the journey towards energy self-sufficiency has been one of the main challenges for them. Like many rural and remote communities, Eigg has faced significant obstacles in providing and managing electricity, and it is only through the collective involvement and determination of residents that these challenges have been overcome.

The Isle of Eigg is located in the West Coast of Scotland. As one of the four islands known as The Small Isles, Eigg is home to around 100 people. With more than 15 km separating it from the mainland, the island is around 9 km long and 5 km wide. Reachable only by ferry, Eigg gained fame when the isle managed to provide 24/7 electricity to its residents from virtually 100% renewables in February 2008 (Eigg 2023).

*Figure 1-1. Isle of Eigg location.*
Source: Google Maps

*Figure 1-2. Isle of Eigg.*
Source: OpenStreetMapScotland

Eigg is part of the Lochaber Geopark and is mostly made up of volcanic rocks (Lochaber Geopark). The weather is similar to the rest of the Isles from the Inner Hebrides; lots of rainfall in mountainous areas, year-round humidity, and strong winds coming from the Atlantic (southwest). East winds in winter tend to be drier and colder (Encyclopaedia Britannica 2024). The Isle's main economic activity is tourism. Other important activities are agriculture and public services.

## 1.1. Background

In 1997, the residents of Eigg bought the island from its previous owner. It was a collective effort that included donations from across the world, anonymous donors, and a grant. However, what is important here is the community spirit and mobilisation that gave way to the buyout. This became the core of the Isle's identity and is deeply embedded in the collective mind of its residents. This is not surprising. Land ownership has been an issue in Scotland for a long time. A 2019 report from the Scottish Land Commission states: "Land is vital for so many aspects of life in a rural community: housing development, community facilities, recreation, growing food and business expansion. If the supply of land is controlled by a single individual, then that individual has a huge degree of control over almost every aspect of life." (Glenn, et.al., 2019). A Reuters special investigation from 2022 mentions that "fewer than 500 people own more than half of Scotland's private land, and many of them are foreigners." (Marshall, 2022). Hence the importance of Eigg's success in buying the land and making it a community-owned property.

Before the buyout, living conditions on the island were less than ideal; there were almost no job opportunities, houses were in terrible conditions, and there was no infrastructure for public services. Each house used to have a small diesel generator to generate electricity. In the words of the residents, they were noisy, smelly, and they would "hate to see Eigg go back to that."

After the buyout, the Eigg Heritage Trust now manages the island. The goal of the trust is to "provide and create opportunity for economic development, housing and infrastructure, whilst conserving our natural and cultural heritage to ensure that development takes place in a sustainable way." (Eigg 2024a). It is formed by members residents of Eigg (through The Isle of Eigg Residents' Association), The Highland Council and the Scottish Wildlife Trust. The Residents' Association has 4 directors elected by the community, and the Highland Council and the Wildlife Trust appoint one director each. The board meets quarterly, and the island directors hold monthly meetings

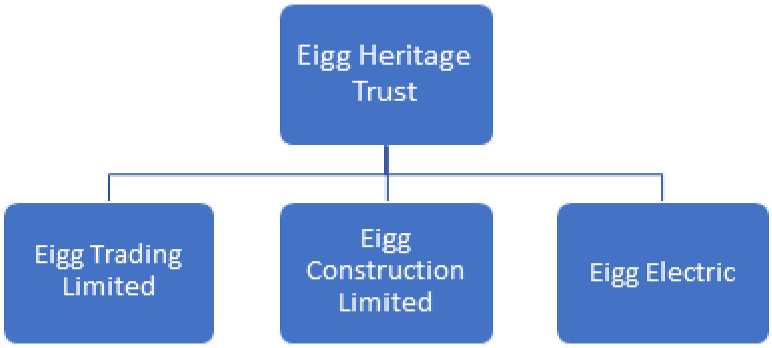


*Figure 1-3. Eigg Heritage Trust Organigram*

The illustration above represents the community organization throughout Eigg. All the agencies are formed by community members and play a vital role in providing a better organization within Eigg's administration.

Eigg's electricity is managed by Eigg Electric, one of the three subsidiaries of Eigg's Heritage Trust. It also has a Board of Directors that is composed of members of the community, who work on a voluntary basis. Eigg Electric employees' salary comes from the pre-paid electricity cards users purchase, and from a daily charge for capacity. Additionally, Eigg Electric receives payments from Renewable Obligation Certificates (ROC) and a Feed in Tariff (FiT) scheme.

The existing energy system on Eigg relies on a combination of wind, hydro, and solar power, with intermittent support from diesel generators and battery storage to meet the electricity demand of the island. The output from diesel generators and storage is mainly used to manage the variability of the renewable resources, which cover more than 90% of the annual demand.

## 1.2. Problem Definition

How can Eigg transition away from conventional fuels without risking satisfying its energy needs? Even though Eigg's electricity comes from renewable sources, it still uses conventional fuels to fulfil the rest of its energy needs for transportation, cooking, and heating. It also faces the challenges of an aging power system, where replacement of some equipment is imminent. The current capacity of the grid does not allow for sector coupling, with the grid unable to cover the electricity demand from the new sectors.

Achieving self-sufficiency while reducing the carbon footprint of the island presents its own set of challenges. Economic factors associated with the adoption of non-conventional alternatives and reducing the environmental impact across different facets of energy consumption, are things that must be considered when making decisions. In addition, having community buy-in is crucial if the new system is to be successful.

## 1.3. Scope and Objectives

The Isle of Eigg's desire to reach Net Zero Emissions posed an opportunity for us to model how that transition could look like. Therefore, the aim of the study is to identify the needs of renewable energy capacity enhancement on the grid, considering the future energy needs of the island across all energy sectors, including power, cooking, heating, and mobility, considering existing transmission limitations. To achieve this, the following objectives were established:

1. Assess the capability and current situation of five distinct energy technologies on the Isle of Eigg, including solar, wind, hydro, tidal, along with potential storage solutions each technology. Identify optimal sites for expanding existing capacities and provide critical technical and financial data.
2. Assess and project potential electricity demand at sector level for electricity, transport, heating, and cooking, whilst also considering the impacts of energy efficiency improvements on the demand for heating and electricity. Calculate new demand needed to achieve sector coupling.
3. Select modelling tool to assess and identify a set of pathways to reduce carbon emissions and achieve self-sufficiency in electricity generation to meet future demands across all energy sectors.
4. Understand the social, cultural, and economic context under which this transition scenarios could take place.

# 2. Methodology

Energy communities tend to be very heterogenous in terms of organisational models. For this reason, it is crucial to understand the socio-economic and political drivers that shaped the emergence and success of the Eigg energy community. Doing so would allow for a much-improved community energy system to be proposed. To perform this study, we adopted a mixed method approach combining both quantitative and qualitative research approaches. A survey was conducted to gather preliminary data on energy sources used, energy consumption habits, satisfaction levels with the current system, and openness to future changes to the energy system. According to Ribeiro et al (2011), quantitative methods such as these are useful in creating snapshots of public views, given sample size and statistical significance of a survey. However, their disadvantage lies in the fact the details behind respondents' answers remain obscure.

With this in mind, we conducted an interactive workshop session and a series of interviews to understand local attitudes towards the current energy system, identify areas of improvement and discuss the community's aspirations towards a net zero future. The purpose of combining structured interviews with an interactive workshop session was to capture a wide range of data – from individual experiences and expectations to collective attitudes and ideas for future energy solutions.

For the modelling framework, the methodology entailed the definition of scenarios that were identified to be important for the future transition pathways. This was accompanied by the selection of a modelling framework and its further development. Lastly, keeping in view the interests of the local community and the key attributes of a transition pathway, certain indicators were selected that formed the model results.

## 2.1. Interactive Workshop

The workshop component was meant to actively engage community members in shaping their energy future by gathering any worries and concerns they might have. The intention was to integrate these concerns in the scenarios to be modelled. This approach would ensure that the designed energy system would not only be technically feasible but would also align with community expectations and address their specific concerns. Due to the unique nature of the energy system, the workshop also aimed to evaluate what it meant to be energy poor on the Isle of Eigg.

Voluntary sampling, a non-probability sampling design, was used to facilitate the workshop. With the aid of Eigg Electric, an email was sent out to community members explaining the aim of the workshop, allowing community members to volunteer to participate based on their interest in the topic (Murairwa, 2015).

## 2.2. Interviews

Furthermore, insights gained during the workshop session were then used to create targeted interview questions. The interviews were intended to uncover perspectives that might not emerge in a group setting, thereby complimenting and validating the insights gathered from the survey and the workshop session.

In this project, we opted to use semi-structured interviews because of the usefulness of the method in gaining a deeper understanding of human experiences and behaviours. For this present research, the approach allowed us to capture the nuanced and context-specific aspects of the topic we researched. The interview questions were designed to be open-ended, focusing on the four identified themes: fuel poverty, dynamic tariffing, community engagement and social acceptance. For example, we set out to understand the community members' level of involvement in energy decisions and whether they felt limited in their energy use due to the 5 kW cap and if they would be open to a different electricity pricing regime. It is worth noting that, not every question was asked to every participant in an effort to foster a “dialogic space,” through which 1) participants would be better able to express their views and 2) members of the socioeconomic team would be able to unearth issues and perspectives that our preliminary research had not uncovered (Martin, 2020).

A total of 8 interviews were conducted, the names and identifiers of participants are anonymized to ensure their privacy. Purposive sampling, a non-probability sampling technique was used to select participants based on specific criteria and the researcher's judgment (Ames et al., 2019; Campbell et al., 2020). The aim was to deliberately select individuals who possess experiences relevant to the research objectives. Interviewees were recruited through participation in social activities, including the community lunch, singing events, and the interactive workshop. The main selection criteria for the interviewees were based on the following:

- All interviewees must be members of the local community and have lived on the island for at least two years.
- At least one of the interviewees should be directly involved in the running of Eigg Electric.
- The interviewees must be a mix of people who were born and raised on the island and those who moved to the island at a certain point.

*Table 2-1: Interviewee categories*

| Type of Interviewee | No. of interviewees | Description |
|---|---|---|
| Residential | 4 | In person interviews |
| Eigg Electric affiliate | 2 | In person interview and virtual call |
| Business Operator | 2 | In person interviews |

The workshop and interviews methods were used to build a comprehensive story of local attitudes about the current and future of the Eigg energy system.

## 2.3. Scenarios

An iterative process was undertaken to finalise the scenarios that were to be modelled for transition pathways towards decarbonisation. The process involved referrals to the commonly developed transition scenarios by renowned international energy agencies such as the International Energy Agency (IEA), while Scottish ambition for Carbon Neutral Islands (CNI). The pressing needs and expectations of the residents and stakeholders of Eigg were considered while developing the scenarios.

Four scenarios were developed with a target of achieving net-zero or near net-zero by 2030. Table 2-2 describes these scenarios and provides the timeframe of transition.

*Table 2-2: Definition of Scenarios*

| Scenario Title | Definition | Time frame |
|---|---|---|
| Current Scenario | Although titled as a scenario, it is a reproduction of the current state of the energy system. In this scenario, the performance of the system was simulated as it stands today so it could be used as a benchmark for other scenarios. As such, there is no cross-sectoral coupling, and the energy system fulfils its demands from the power sector. Note: *Cross-sectoral energy coupling refers to the shift of heating, cooking, and mobility sectors to technology that consumes power instead of conventional fuels.* | This scenario runs for one year across hourly timesteps. |
| Business-As-Usual (BAU) Scenario | The Business-As-Usual or BAU scenario is a future extension of the current scenario with the underlying assumption that no transformative measures have been undertaken and everything proceeds as it stands. This imminently means that no cross-sectoral energy coupling takes place even though the demands evolve in the longer run. This scenario forms the grounds to compare with other scenarios. | This scenario runs for 6 years from 2024 until 2030. 2024 serves as the starting year, and with 2-year long time-skips the modelled years are 2026, 2028, and 2030. Each of the modelled year runs across all hourly timesteps within the year. |
| Sector Coupling Scenario | This scenario is in direct contrast to the BAU scenario. The underlying assumption has changed, and transformative measures will be undertaken across the demand sectors. This imminently means that sectors like heating, cooking, and mobility will get electrified with the goal of achieving | This scenario runs for 6 years from 2024 until 2030. 2024 serves as the starting year, and with 2-year long time-skips the modelled years are 2026, 2028, and 2030. Each of the modelled year runs |

| | | |
|---|---|---|
| | decarbonisation to the highest extent. The targets are set at a 100% decarbonisation across all sectors, but the outcome shall be a result of the available capacity in the transmission network and therefore could be lesser than 100%. | across all hourly timesteps within the year. |
| Sector Coupling with Energy Efficiency Scenario | This scenario is an extension of the Sector Coupling scenario with the underlying assumption that significant measures to tap energy efficiency potential have been deployed across all sectors. This scenario is designed to deliver insights into the potential benefits that can be attained through energy efficiency. Preliminary assessment indicates energy efficiency gains between 15-30% through a reduction of energy consumption. Further insights on these gains will be analysed through the modelling of the scenario. | This scenario runs for 6 years from 2024 until 2030. 2024 serves as the starting year, and with 2-year long time-skips the modelled years are 2026, 2028, and 2030. Each of the modelled year runs across all hourly timesteps within the year. |

A more direct understanding of the scenarios can be derived from the schematics in figure 2-1 and 2-2, where figure 2-1 is the schematic representing current and BAU scenario, and figure 2-2 is the schematic representing sector coupling and sector coupling with energy efficiency scenarios.

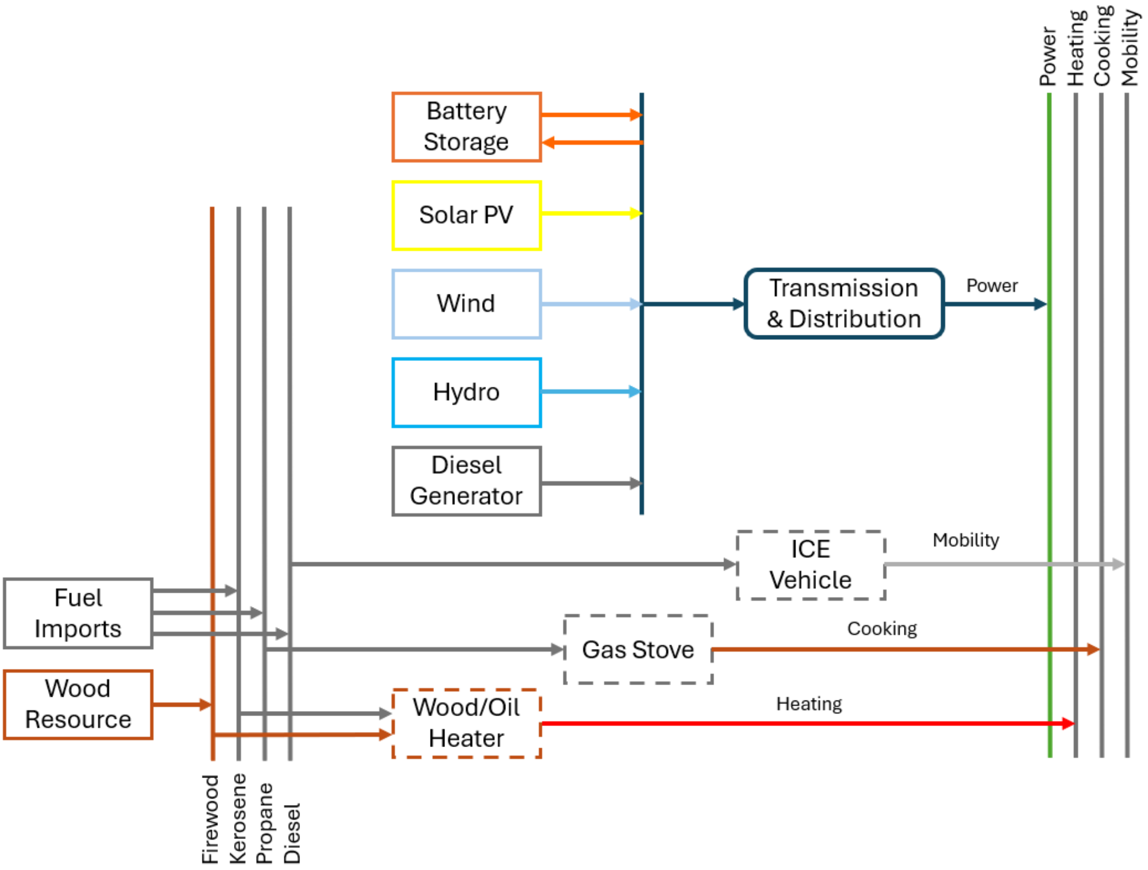


*Figure 2-1: Current and BAU Scenarios – Schematic*

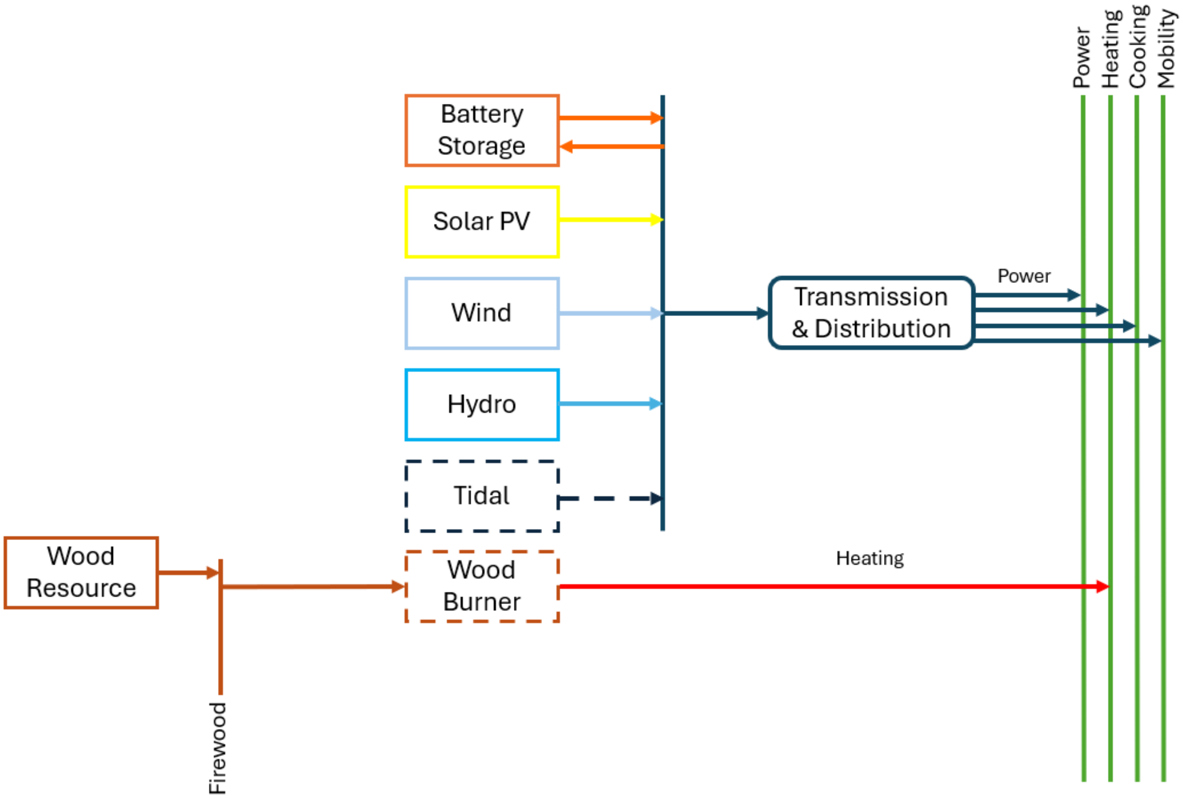


*Figure 2-2: Sector Coupling and Energy Efficiency Scenarios - Schematic*

## 2.4. Model Selection and Development

To analyse different scenarios, it was necessary to use a modelling tool. Options for scenarios development included commercial software like LEAP. However, we opted for an Open-Source Modelling Framework for the following reasons:

- We wanted to promote the use of open-source software as it brings innovation and contributes to the testing and development of scientific approaches. It also establishes that development of transition pathways shall not be restricted due to commercial ownership of the tools.
- Most of the commercial software are a black-box design, which take user inputs, process them, and provide outputs. The process behind the graphical user interface is hidden and hard to analyse. On the contrary, an open-source tool provides transparency and deeper understanding of the software's operation. This transparency gives developers insights of the working behind the graphic-interface and allows for an understanding of the results alongside the possibility of troubleshooting design problems.
- Open-source software is suitable for scenario development due to its flexibility and modularity. It provides the possibility of customising the framework and gives developers full liberty to change existing features to suit their specific requirements.

The model deployed for the study on the Isle of Eigg is the adaptation of the open-source energy modelling framework OSeMOSYS (Howell et al., 2011) and its extension GENeSYS-MOD (Löffler et al., 2017), are both licensed under Open-Source MIT License. OSeMOSYS is a tool that can be used to analyse decarbonisation scenarios at the global level, while keeping the focus on interdependencies between sectors like electricity, heating, mobility, and cooking. These models come with detailed documentation on the modelling of complex energy systems and the interplay between various components and can be accessed through the online GitHub repository. Details of the modelling framework OSeMOSYS and its extension GENeSYS-MOD are discussed in Chapter 3.

## 2.5. Scenario Indicators

To assess the future energy system across transition pathways, certain indicators were chosen for analysis. The chosen indicators were based on the common interest of the community and Eigg Electric. The following are the key indicators, aligning with the targets set by Eigg Electric for 2030, that will be analysed and visualised to further produce recommendations:

- **Carbon Emissions:** By keeping in view Eigg Electric's goal of having a net-zero energy system by 2030, this indicator holds significant importance. Annual carbon Emissions in tons of $CO_2$ at the end of 2030 will be analysed to see if the target has been achieved. By becoming carbon-neutral, the community contributes to greener future and helps the world in achieving global environmental goals.

- **Capacity Of Generation and Storage Technology**: As the overall demand for power increases with the electrification of other sectors like heating, cooking, and mobility, it is important to look at the overall increase in size of the energy system and its ability to meet the demand across all sectors, especially during peak times.
- **Investment Costs**: Increasing demand across all sectors necessitates the expansion of the energy system. This expansion will require investment in new renewable technologies and storage systems. It is important to note that these investment costs are only indicative of the investments needed for the expansion of the generation and storage technologies. Therefore, investment costs are an important indicator for each of the pathways, as they provide a means of comparison when looking at the economic feasibility of these expansions.

Moreover, we will also analyse other secondary indicators that will help us develop recommendations. These include the percentage of electrification and the renewable fraction across each sector, as these two factors are highly dependent on the available capacity of the existing transmission network. Additionally, the potential of surplus or excess generation is another important indicator. Surplus generation indicates the potential of the future systems to cater for new demand sectors or new opportunities for revenue generation. The relative timing of investment or the commissioning of the technology is also another factor as it informs about the need of the expansion across time. This may give the understanding of the financial planning of the project.

# 3. Modelling Framework Design

## 3.1. OSeMOSYS: GENeSYS-MOD

OSeMOSYS is an open-source energy system modelling framework for long-term integrated assessment and energy planning (Howells et al., 2011). It serves as an effective tool for designing energy systems across various scales, ranging from villages and regions to countries, continents, and even at a global level. This model is freely accessible and offers ease of updating and modification, catering to the specific requirements of energy system modelling analyses. To be able to model an energy system with OSeMOSYS, one must be familiar with the use of a spreadsheet tool (like Microsoft Excel) and should be able to follow the instructions in the online documentation of the model. No prior programming experience is necessary as the tutorials are very elaborate. Computation power can be a limitation for complex models however, and therefore will depend on the attributes of the model under study. In modelling practice, it is always recommended to start with simpler systems, followed by adding complexity to the model in steps so that the computation power can be assessed and controlled.

The model comprises of seven functional components, namely costs, storage, capacity, adequacy, energy balance, constraints, and emissions. Additionally, it adopts a four-level abstraction approach. The first level involves describing the model's sets, parameters, variables, constraints, and objectives. The second level focuses on their algebraic formulation. The third level entails the practical implementation in a programming language. Finally, the fourth level involves the application of the model in a study. For a user with no experience in algebraic formulation or programming, the second and third level remain inaccessible, and it is recommended that these levels are skipped. The model can still be operated at its full capacity while only accessing first and fourth levels, however, the customisation of the model design is then not possible as algebraic formulation and programming knowledge is a pre-requisite for that.

The primary objective of OSeMOSYS is to calculate the lowest net present cost (NPC) of an energy system that fulfils a specified demand for energy carriers, energy services, or their proxies. Achieving this objective involves adhering to a set of constraints and defined rules. For instance, constraints may include specifying minimum and maximum capacity limits for technologies within the energy system. These constraints and rules are integral components guiding the optimisation process toward minimising the net present cost while meeting the required energy demand.

Derived from the strategic framework of OSeMOSYS, a model-extension called GENeSYS-MOD was developed by Löffler et al. (2017). This model enables a disaggregated analysis of energy and emissions, where we could see the interactions between energy and emissions at granular level, employing a system of linear equations to explore least-cost solutions while adhering to externally defined constraints, primarily in terms of $CO_2$ emissions. GENeSYS-MOD conducts an in-depth analysis of decarbonisation scenarios at the global level, delineated into 10 pre-defined geographical regions. The primary emphasis is on understanding the interdependencies among electricity, transportation, and heating systems within these regions.

For Eigg, our objective is to model energy pathways for a decarbonisation plan extending until 2030, encompassing all energy sectors, including heating, cooking, and mobility. We have adopted and customised GENeSYS-MOD to align with the specific requirements on Eigg, aiming to derive a cost-effective solution with a predominant focus on reduction of $CO_2$ emissions and demand fulfilment while retaining self-sufficiency.

## 3.2. Input Collection

The optimisation of the energy system model involves choosing specific inputs to achieve a desired output which is optimal within the set of constraints. In our scenario, we optimise the energy system model for Eigg by prioritising low total costs for technologies; this includes capital and variable costs of the technologies. Input values were sourced from the analysis derived in Chapters 4 and 5. These include demand time-series data for cooking, heating, mobility, and power for the current year and for the future years. Also, technology specific details such as investment and variable costs, lifetime, minimum and maximum capacities, emission ratios, and capacity factors also formed a part of the model inputs.

These inputs can be categorised into six broader categories. These are accessible in the input folder of the Isle of Eigg model available on GitHub repository.

### 3.2.1. Demand

The total demand and hourly demand time series across each sector i.e. heat, mobility, cooking and power are provided as an input to the model.

### 3.2.2. Technologies

The input parameters used to evaluate the capacity requirements of technologies for power generation include potential technologies, their minimum and maximum capacities, residual (existing) capacities, lifetime, and capacity factors.

In the context of Eigg, the technologies subjected to optimisation for power generation include solar PV, hydropower, onshore wind turbines, tidal energy, and diesel generators. Additionally, gas stoves, internal combustion engine (ICE) vehicles, wood burners, oil heaters, electric stoves, electric vehicles, and electric heat pumps are considered as generic system components to aid the conversion of one form of energy to another.

An important consideration in the input parameters is the residual capacity of the existing technologies. This ensures that the model does not initiate investments in capacities starting from zero, recognising and accounting for the existing capacity and the remaining life of technologies in place.

### 3.2.3. Fuels

The necessary inputs for the operation of technologies as well as the outcomes produced by the technologies are specified as 'fuels. This results in a total of 7 fuels, including power, heat, mobility, and cooking, which are also the demand sectors, and diesel, propane, and firewood. The interconnection between fuels and technologies is established through input and output ratios, which typically indicate the amount of consumption of input fuel that produces one unit of output fuel after conversion by the relevant technology.

### 3.2.4. Storages

To optimise capacity for storages, various input parameters are considered. These include the type of storages, their efficiency, energy-to-power (E2P) ratio, lifetime, maximum storage capacity, and residual (existing) storage capacity.

### 3.2.5. Emission ratio and Emission limit

The emission ratio for each technology is specified, and annual emission limits are established for each year. This setup enables the model to make investment decisions in technologies based on the annual emission limits for the modelled years.

### 3.2.6. Investment and Variable costs

The investment and variable costs for each technology are specified, allowing the model to evaluate and consider cost-optimal solutions when determining capacities. Discount rate, referred to as Bank Rate in Scotland, is pre-defined at 3%, which is higher than the current rate of 1% (BOS, 2024) to account for the associated risks in investment in off-grid communities (Rahman et al., 2016).

Additional input parameters include the designation of dispatchable technologies, specifying that the diesel generator is dispatchable in our case while the renewables are not. Moreover, in addressing power demand, the model considers both technologies that can and cannot be connected to the grid, focusing on the capacity of only grid-tagged technologies while considering grid capacity constraints. For example, all power producing technologies are tagged as grid-tagged technologies, but conversion technologies like wood burners or oil heaters, gas stoves, or ICE vehicles are not as they do not depend on the power from or to the grid and therefore the transmission constraint does not apply to them.

For long-term planning scenarios, various parameters are defined for each modelling year. These include the maximum capacity of technology and storage that depend on the theoretical and geographical potentials, annual emission limits that attempt to be close to 0 to achieve decarbonisation goals, capacity factors that have been assumed to stay the same across these years and demands that have been adjusted with the predicted growths in population or technology adoption rates. This comprehensive set of parameters allows the model to account for and optimise the planning of various aspects over the specified modelling years.

## 3.3. Model Design Attributes

Formulation of the model is based on multiple attributes. These attributes are distinct in their function and each attribute plays a key role in the optimisation process. Tables 3-1, 3-2, and 3-3 show the sets, variables, and constraints of the model, respectively.

### 3.3.1. Sets

Sets are the dimensions across which the model iterates while finding the optimal solution.

*Table 3-1: Definition of Model Sets*

| Name | Description |
|---|---|
| *Technology* | Everything that processes energy in any form is considered a technology |
| *Fuel* | The consumable of a technology is defined as a fuel |
| *Storage* | The component that can store fuel and deliver when needed |
| *Hours* | The set of hours across each year |
| *Year* | The set of years for the modelled period |

### 3.3.2. Variables

All variables in the model are unknown functions that the model attempts to find. These variables are all ranged domains that can assume any value within that domain. The model iterates over all the possible combinations of each value of all the variables to find the values that bring the least possible value of the Objective function. Some of these variables later directly or indirectly also form output solutions while the model pursues the optimal solution.

Table 3-2: Definition of Model Variables

| Name | Description |
|---|---|
| *TotalCost* | Total cost of the system comprising of capital and variable costs |
| *FuelProductionByTechnology* | Output produced from the generators and conversion technologies |
| *NewCapacity* | Capacities of generators introduced at each year |
| *TotalCapacity* | Final capacity of the generators at the end of each year |
| *FuelUseByTechnology* | Input used by the Generators and conversion technologies |
| *AnnualTechnologyEmissions* | Total amount of emissions per Technology at the end of each year |
| *Surplus* | Energy that is overproduced or potential for excess production |
| *NewStorageEnergyCapacity* | Capacities of storages introduced at each year |
| *TotalStorageCapacity* | Final capacity of the storages at the end of each year |
| *StorageCharge* | Amount of energy being charged in the storage at each hour |
| *StorageDisCharge* | Amount of energy being discharged from the storage at each hour |
| *StorageLevel* | The state of storage at each hour |
| *TotalStorageCost* | Total cost of storage comprising of capital and variable costs |
| *SalvageValue* | End of life value of the generation technology |
| *CapacityUnits* | Number of units of the minimum available technology size |
| *TotalCapitalCost* | Amount of capital cost of the generators at the end of each year |
| *TotalVariableCost* | Amount of variable cost of the generators at the end of each year |

### 3.3.3. Objective Function

The objective function is another important attribute of the model. It was set to minimise the net present cost of an energy system that meets the given demands. In our modelling framework, this is done by summing up the total discounted costs associated with each technology and storage across each year. By optimising the objective function, we will get the least cost combination of technologies and storages until 2030, while keeping in view the constraints of the systems programmed in the model. An effect of incorporation of discounting in the model is the delayed investments, therefore the model tends to delay any investments to gain the maximum benefit from the discounting while minimising the objective function. Below is the general algebraic representation of the objective function for our model:

$$\min z = \sum_{t} TotalCost_t$$

### 3.3.4. Constraints

The model constraints function as the governing functions that limit the ranges of the solution domain for the optimisation, making finding of a solution possible. Table 3-3 shows the list of constraints used in the model.

Table 3-3: Definition of Model Constraints

| Name | Description |
|---|---|
| *demand_adequacy* | Energy balance equation that balances supply and demand |
| *productioncost* | Governs the cost of production |
| *totalcapitalcostfunction* | Governs the capital costs of investments |
| *totalvariablecostfunction* | Governs the variables costs of production |
| *Productionfunction* | Governs the production from technologies |
| *usefunction* | Governs the use of fuel for technologies |
| *maxcapacityconstraint* | Governs the maximum capacity limits for technologies |
| *totalcapacityaccounting* | Governs the addition of new capacity into existing |
| *gridcapacity* | Governs the sum of production to be within grid limits |
| *capacityunitfunction* | Governs the identification of number of units to be installed |
| *technologyemissionfunction* | Governs the total emissions from each technology |
| *annualemissionlimitconstraint* | Governs the sum of total emissions against annual limits |
| *storagechargefunction* | Governs the magnitude of energy charged to the storage |
| *storagedischargefunction* | Governs the magnitude of energy discharge to the storage |
| *storagelevelfunction* | Governs the logging of storage level for all instances |
| *storagelevelstartfunction* | Governs the starting level for storage |
| *maxstoragelevelfunction* | Governs the storage level against the max storage levels |
| *storagecostfunction* | Governs the costs of investment and operation of storages |
| *storageannualbalancefunction* | Governs that energy charged and discharged is balanced |
| *totalstoragecapacityaccounting* | Governs the addition of new capacity into existing |
| *storagemaxcapacityconstraint* | Governs the capacity against the max capacity |
| *salvagevalue_endoflife* | Governs the use of salvage value if life runs out within years |
| *salvagevalue_duringlife* | Governs the use of salvage value if life extends beyond years |

The model used for the analysis of the energy system on the Isle of Eigg required the reformulation at all four levels of abstraction. The modularity of the modelling framework eased the process of customisation, and ultimately several modifications and additions could be made to the model. These additions and modifications in the GENeSYS modelling framework can be found in Annex A. Alongside new additions or modifications, some simplifications and generalisations were also made in the model; these are also available in Annex B. This information can furthermore be accessed in the public repository on GitHub.

# 4. Insights into Key Demand Sectors

The demand was calculated at sector level for electricity, transport, heating, and cooking, whilst also considering the impacts of energy efficiency improvements on the demand for heating and electricity. Assumptions were made for projecting future demand based on the community's growth projections and they are as shown in the table below. 2024 is considered as the point of departure. Projections were made until 2040 to guarantee coverage of future demand. However, the model only considered projections until 2030.

*Table 4-1: Demand forecasting assumptions*

| | Added Households | Total households | Added Population | Total population |
|---|---|---|---|---|
| 2024 | - | 64 | - | 110 |
| 2026 | 2 | 66 | 4 | 114 |
| 2028 | 3 | 69 | 6 | 120 |
| 2030 | 3 | 72 | 6 | 126 |

It is important to note that most of the emissions and energy consumption from the transport sector come from the ferry that comes from Mallaig. However, this was not considered given that this falls under the Scope 3 of the GHG Protocol, and this project will only consider Scope 1 emissions. There is also no petrol station on the island, and no single importer of fuel in the island, so there are no official numbers on the amount of fuel purchased, consumed, or imported into Eigg. Therefore, a series of assumptions were made to calculate the emissions and fuel consumption from transport.

## 4.1. Electricity

Currently, about 95% of electricity generation comes from renewable energy sources, and only 5% from diesel (Eigg Electric, 2024). Fossil fuels are still used for heating, cooking, and transportation. The project not only aims to understand how the island can meet its electricity generation and demand, but also how the heating, cooking, and transportation sectors can be electrified, including the analysis of energy efficiency measures for buildings and appliances. Heating, cooking, and transportation sectors represent an almost negligible electricity consumption due to grid capacity and infrastructure limitations and use preferences by population. Eigg Electric has set an electrical consumption cap of 5 kW for homes and 10 kW for businesses, and its maximum value (lower than the cap) can vary from one household or business to another.

A BAU scenario was analysed. This required a data set for each type of demand. They are used as input data in the model together with renewable energy generation datasets, including constraints. The electricity generation dataset is provided at hourly resolution for 2023 (base year). This year is as deemed representative for the analysis of projected demand (2026, 2028 and 2030). By the time of the visit no electricity meters had been installed at the transformers, so it was not possible to directly obtain the total electricity consumption at distribution level; therefore, the challenge here was to estimate it using the data available considering a time series from Sunny Portal as starting point.

The baseline time series was extracted from this platform, which is an interactive dashboard that allows monitoring, system configuration, visualization, and logging of system data for the Eigg Electric generators, with the exception of the small hydropower plants, the wind turbines, and the diesel generators. The devices for measuring the energy generated and consumed are necessary to properly track the energy balance of a particular system. This platform also allows downloading a csv file of the energy balance in daily, weekly, monthly, and yearly format for the period 2008-2023 (Sunny Portal, 2023).

As the generation data from the portal included the electricity used in the dump loads and the grid losses, the demand profile had to be adjusted by subtracting an average of 8kW from the production figures, considering that the load-following hydropower generation led to overproduction when close to the load. Then, this information was compared to the electricity income to verify the calculated demand.

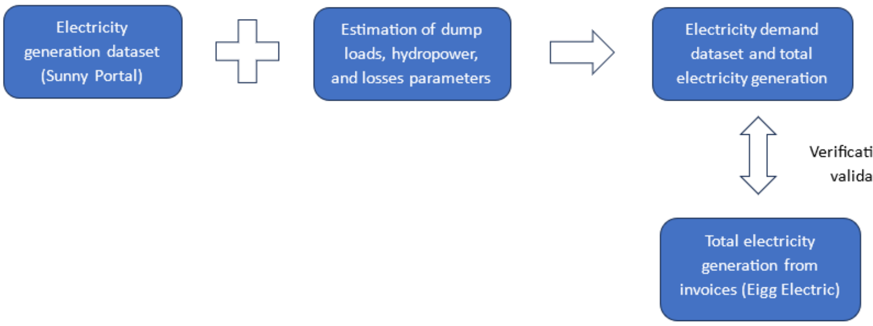


*Figure 4-1: Methodology for estimation of electricity demand (2021)*

### 4.1.1. Calculation of electricity demand and results

Eigg Electric provided monthly reports of its electricity generation that allowed for an approximation of electricity demand. The number of electricity cards sold annually plus the amount businesses were invoiced for their electricity consumption, in the 2022-2023 fiscal year, was also used in the calculation of electricity demand. It was assumed that there was not a significant change between years 2021 and 2023. The invoiced amount of electricity was divided with the electric tariff and resulted in the approximate annual electricity demand. The following table was then constructed:

*Table 4-2: Electricity consumption in a year for households and businesses (2023)*

| Item | Consumption in a year (MWh) | Share | Number of buildings | Average consumption per building (MWh) |
|---|---|---|---|---|
| Households | 164 | 65% | 64 | 2.5 |
| Business | 89 | 35% | 26 | 3.4 |
| **TOTAL** | **253** | **100%** | **90** | **5.9** |

In order to obtain the estimated demand, it was necessary to check the year that provided the most consistent information in Sunny Portal. The yearly data timeseries of 2021, 2022 and 2023 were observed and it was perceived that year 2021 had the least gaps and provided the most consistent data. However, it is important to mention that there was not significant variation between the electricity demand of the years 2021 and 2023. Consequently, the latter year was selected. Years prior to 2020 were not taken into account because gaps in the data were even greater. The data was then cleaned up and adapted to the requirements of the modelling team. As mentioned, there was some missing information in the data acquired from Sunny Portal. Some cells had no values and the reasons for this could be portal downtime, power plant failure, sensor failure, maintenance, and so on. Since the model needs values at an hourly resolution, an average of the previous hours was applied when a blank cell was found. Moreover, a minimum threshold of 10 kW was also applied to the curve. Next, hydropower generation was also evaluated as it follows the electric load. When there was insufficient generation from this source, diesel generators were used.

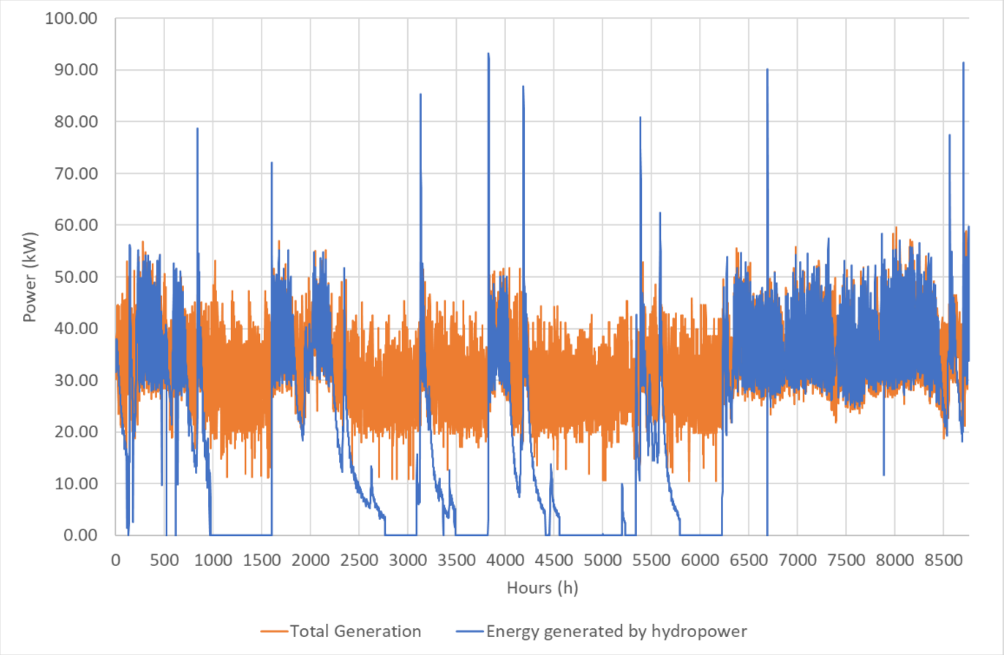


*Figure 4-2: Total and hydropower generation (2023)*

In the graph there are some regions where, indeed, generation from the hydroelectric power plant at Laig (in blue) follows total generation (in orange) and in others it reaches zero. It is necessary to mention that the other small hydropower plants are not separately visible in Sunny Portal. The latter occurs mainly due to the lack of rainfall, which is more frequent in summer. Dump loads are installed in places such as churches, community halls, tea rooms and other places on the island, and are mainly used for heating. They are only turned on when there is excess electricity generation from renewable energy sources.

Then, to calculate the demand, a threshold of 15 kW for the hydropower plant was set. The assumption used to obtain this parameter was as follows: whenever the generation of the hydroelectric power plant was less than 15 kW, no energy was used in the dump loads. Otherwise, the excess energy was used to power them up. Therefore, the dump load was subtracted from the hydropower generation, resulting in the demand. As a result, the total estimated annual demand was 254 MWh, and the total electricity used to power the dump loads up was 40 MWh in same period. The estimated annual demand is as shown in the graph in figure 4-3.

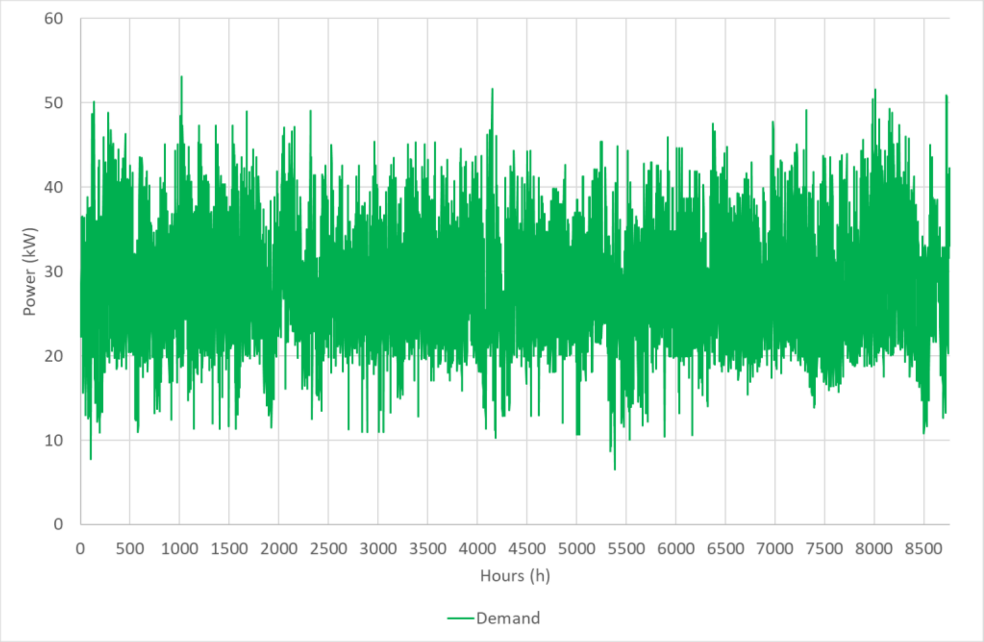


*Figure 4-3: Electricity demand (2023)*

The total consumption projections shown in the Table 4-3 represent the total electricity consumption of households and businesses without losses. Moreover, it can be seen that this number is similar to the one that was estimated using the timeseries from the dashboard (254 MWh).

To calculate the demand including system loss, it was assumed that losses were 7% of the demand. In total, the sum of all the demand and losses is 272 MWh.

The projected electricity demand for the years 2026, 2028 and 2030 in the BAU scenario was calculated using the population growth rate of 4%, 10% and 15%, respectively, compared to the year 2011. In addition, the consumption of a 10-kW antenna was included in the forecasted demand.

*Table 4-3: Projected Electricity consumption*

| Projected demand in 2026 (MWh) | Projected demand in 2028 (MWh) | Projected demand in 2030 (MWh) |
|---|---|---|
| 352 | 366 | 380 |

### 4.1.2. Analysis

Figure 4-3 shows very little seasonality in the annual distribution of electricity demands, which could be explained by an absence of electric heating and electric hot water boilers. Additionally, this can also be explained by the electricity caps of 5 kW and 10 kW for homes and businesses, respectively. It would be expected that electricity consumption would be higher in summer, since many tourists come to the island; however, it may be that owners of holiday houses inform visitors of the electricity consumption limits, so the tourists are more aware of it. Figure 4-3 shows that the maximum value of electricity demand is 53 kW, and the average value is 29 kW for the year 2023.

## 4.2. Heating

Heating represents the biggest energy demand on the island and is also one of the key sectors to be decarbonized. The fuels currently being used include wood, kerosene and coal with the greatest consumption coming from wood. Some houses rely on just one fuel source, others use a mix two or all three. Some households also have solar thermal for hot water production. According to the local wood supplier data, households in Eigg consumed about 189m$^3$ of firewood in 2023. The businesses are predominantly heated with wood, with an approximated consumption of 23 tonnes per year for the businesses at the Pier alone. Some of the remaining businesses use kerosene while other businesses have no heating at all. Moving to lower emission heating fuels will mean moving to electricity, or wood which fortunately is available on the island, and this may result in potential cost savings as well as the reduction of energy poverty. The pricing data was sourced from Eigg electric personnel and a comparison on the basis of calorific values for the different heating fuels is a shown in table 4-4 below (engineeringtoolbox, 2014). Due to the limitations of the grid, electrification of heating will only be considered for the residential sector including holiday homes.

Table 4-4: Heating Fuels costs comparison

| | Unit | Cost/unit | Energy content | Cost/kWh |
|---|---|---|---|---|
| Electricity | kWh | £0.27 | COP=3.5 | £0.077 |
| Wood | kg | £0.25 | 4.50kWh/kg | £0.056 |
| Kerosene | litres | £0.86 | 10.35kWh/l | £0.083 |
| Coal | kg | £0.66 | 8.39kWh/kg | £0.079 |

The approaches to calculating heat demand and generating load profiles are as explained below. The total demand was calculated separately for space heating and for domestic hot water.

### 4.2.1. Space heating

The heat required in a building not only relies on heat provided by a heating system, but also internal gains as well as solar gains. Heat demand is impacted by heat losses which are dependent on temperature difference as well as the design, orientation, and construction of a building. The heat loss is a combination of sensible heat loss through conduction, infiltration, and ventilation loads (Burdick, 2011). These losses are also referred to as air infiltration losses and fabric losses both of which were considered in the calculation of heat demand.

The island has a residential building stock of 64 which was divided into categories based on energy efficiency levels guided by the EPC certificates. This will be discussed further in the energy efficiency section of the report. Over 50% of the existing building stock has poor insulation according to EPC ratings, which would significantly increase the heat demand. Five categories were identified, and an additional sixth category was added for holiday homes to account for lower occupancy, which is presumed to be 70% of the year based on the information provided as well as on literature (CIBSE, 2008). The categories are as shown in the table below and an increase in population at each time step will be considered as an addition in housing in the "super" category.

Table 4-5: Housing Categories

| Category | Quantity |
|---|---|
| Old houses | 10 |
| Bungalows | 23 |
| Renovated homes | 13 |
| New builds | 6 |
| Super | 2 |
| Holiday homes | 10 |
| **Total** | 64 |

A bottom-up approach for calculating heat demand was used which considers estimated energy consumption of a representative set of individual houses based on the categories as identified above and applied to the rest of the houses that fall within the same category across the island (Ahern & Norton, 2020). The heating degree days (HDD) method was then used for analysing energy consumption in buildings (Bizee, 2024). HDDs are essentially a measure of how much (in degrees), and for how long (in days), the outside air temperature was below a certain base level; and applying the HDD method can help estimate the energy demand and, consequently, carbon emissions from space heating for buildings. The limitation with this method is the definition of the base temperature, which refers to the energy balance between the building and the heating system, and the rough assumptions made for the annual internal heat gains. The base temperature for the UK is 15.5 °C (CIBSE, 2006).

The formula used to calculate heat demand according to the HDD method is as shown below.

$$Space\ Heat\ demand\ (kWh)\ =\ Overall\ heat\ loss\ coefficient\ *HDD*24(h/day)$$

*Equation 4-1: Space heating demand equation*

The overall heat loss coefficient is a summation of both fabric losses as well as air infiltration losses, both of which can be calculated as shown in the equations below. U-values were assumed for the elements of each building taking in consideration the insulation levels of the building and the associated area (A) was identified by looking at houses of a similar size on the Tabula webtool, where national residential building typologies from European countries can be found (Tabula, 2024). The ventilation losses were calculated based on the air change method with the air exchange rate (ACH) for the houses being determined on the basis of the building design, while the volume (V) was calculated based on the given household data (Bhatia, 2020). The factor 0.33 is the product of the specific heat and density of air under typical conditions which is the energy required to raise one cubic metre of air by one Kelvin (BRE, 2023).

$$Fabric\ heat\ loss\ coefficient\ =\ \Sigma U*A\ (W/K)$$

*Equation 4-2: Fabric losses*

$$Air\ infiltration\ loss\ coefficient\ =\ 0.33\ *ACH*\ V\ (W/K)$$

*Equation 4-3: Air infiltration losses*

The heating degree days (HDD) were sourced for the year 2023 on the Bizee website through selecting the closest weather station to the island with high accuracy data the summary of which is as shown in the table below. As with electricity demand, 2023 was identified as the representative year and it is also important to note based on observations from the year 2021 that temperatures on the island do not fluctuate much from year to year. The total degrees days for the year are 1996 (Bizee, 2024).

*Table 4-6: Heating degree days source*

| | |
|---|---|
| Description: | Celsius-based heating degree days with a base temperature of 15.5 C |
| Source: | www.degreedays.net |
| Accuracy: | Estimates were made to account for missing data (0.9% estimated) |
| Station: | Islay (6.26W, 55.68N) |
| Station ID: | EGPI |

### 4.2.2. Domestic hot water

The calculations for domestic hot water were made based on the CIBSE guidelines. This approach gives the energy required to increase the temperature of the water to the defined set-point whilst also taking into account heat losses. For the sake of simplicity, the heat loss was considered homogeneous throughout the year which of course may not be the case practically but may suffice for a desktop approach for the heat losses and helps the evaluation of the hot water needs of the island (Syse, et al., 2016).

Due to the different average inlet temperatures from month to month, the domestic hot water requirements were calculated from month to using the equation below. The inputs for the equation are as describes in the two tables below the equation. The inlet temperatures were sourced from the manual which describes the Government's Standard Assessment Procedure (SAP) for assessing the energy performance of dwellings (UK Government, 2019).

$$Ereq/month = [((C * (Ts - Ti) * n) / 3600) + (qi / 12)] * Vc * pop$$

*Equation 4-4: Monthly domestic water requirements*

*Table 4-7: Domestic hot water demand inputs*

| Description | Symbol | Value | Unit | Source |
|---|---|---|---|---|
| Population | pop | 110 | people | Eigg decarbonisation feasibility study |
| Consumption/person/day | Vc | 50 | litres | Energy Savings Trust survey report |
| Water inlet temp | Ti | Weather dependent | °C | UK SAP Guidelines |

|  |  |  |  |  |
|---|---|---|---|---|
| Water set point temp | Tset | 60 | °C | UK Health and Safety Executive |
| Water tank losses/year | Qi | 4.36 | kWh/l | University of Strathclyde |
| Water specific heat capacity | C | 4.18 | kj/kg/k |  |

*Table 4-8: Average monthly water inlet temperatures*

| Jan | Feb | March | April | May | June | July | Aug | Sept | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 9.5 | 10.4 | 11.5 | 12.9 | 15.3 | 18.4 | 19.6 | 18.5 | 17.2 | 14.9 | 12.1 | 8.9 |

### 4.2.3. Total Heat Demand

The overall heat demand is as shown below for the different time steps with an increment in demand reflected in the "super" category based on the assumption that all new houses to be built will be at this level of energy efficiency as has already been mentioned in the space heating section.

*Table 4-9: Total heat demand BAU*

|  | Heat demand 2026 (GWh) | Heat demand 2028 (GWh) | Heat demand 2030 (GWh) |
|---|---|---|---|
| Old | 0.246 | 0.246 | 0.246 |
| Bungalow | 0.369 | 0.369 | 0.369 |
| Standard | 0.170 | 0.170 | 0.170 |
| New build | 0.072 | 0.072 | 0.072 |
| Super | 0.129 | 0.170 | 0.211 |
| Holiday homes | 0.111 | 0.111 | 0.111 |
| Total | **1.096** | **1.137** | **1.178** |

Using the above formulas and data, an annual load profile was generated for each of the time steps as an input for modelling. The daily degree days data was broken down to an hourly average and with an adjustment for peak heating in the mornings and evening. The domestic hot water totals were averaged for each day then distributed evenly over a 6-hour time period in a day. The hourly load profile for 2030 is as shown below.

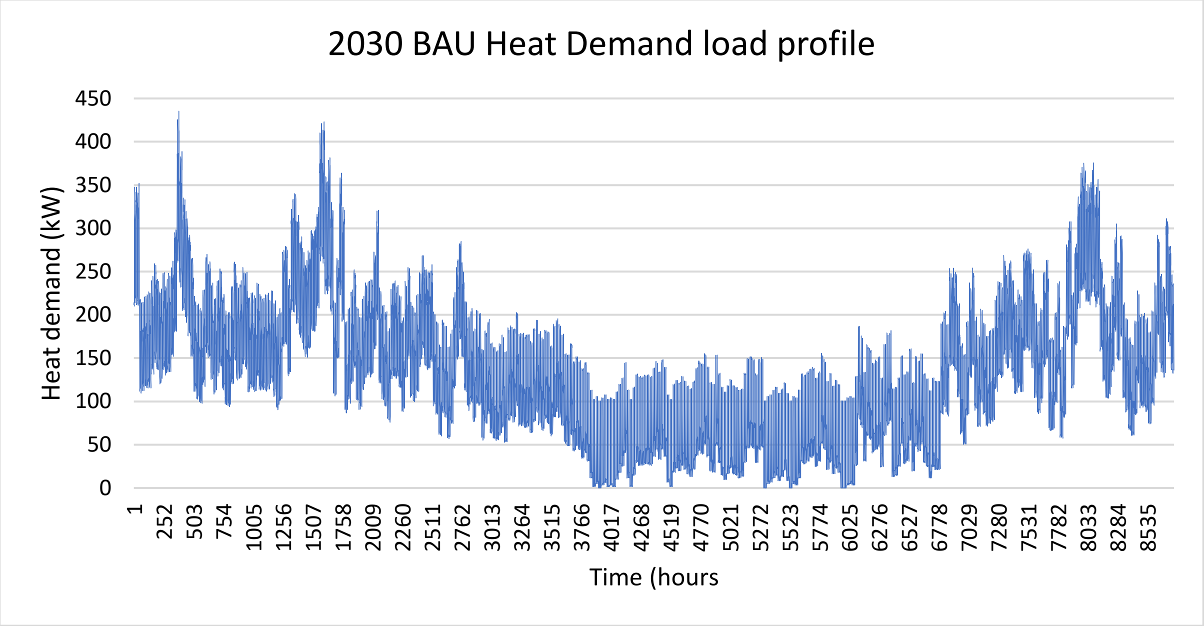


*Figure 4-4: 2030 BAU heat demand load profile*

### 4.2.4. Technology recommendations

Suggestions in the documentation on the methodology for mapping from the Heat Roadmap Europe project (www.heatroadmap.eu) are that individual heat pumps can be a solution for low-carbon residential heating in rural circumstances with air-source HPs being the most deployable type at a residential level as they are comparable in size to other domestic appliances (Persson, et al., 2017). Reduced performance due to temperature drops below zero is a concern with air source heat pumps, Eigg however has stable temperatures rarely below 0 degrees and not below 10 degrees.

Air-to-water heat pumps are quite prevalent in the UK and may achieve very good seasonal coefficient of performance values, which are a measure of the efficiency of the heat pumps. However, taking into consideration the lower installation costs as well as the ease of installation, an air to air, air source configuration is best to consider for the Island. In the model, a heat pump with a conservative estimate of a seasonal coefficient of performance value of 3.5 was considered as guided by some average given ranges for the UK (Burns & Strachan, 2021).

Even though storage heaters are currently being explored due to their low cost, they may not be the best solution not only due to their lower efficiency but there may potentially be an increase in airborne dust when using fans to circulate heat (Judson, et al., 2015). Also, surveys done in Scotland identified better overall performance with air source heat pumps resulting in warmer homes as compared to storage heaters. The Scottish government is offering support for not only building improvements but also for the procurement of heat pumps through the Boiler Upgrade scheme, with rural households eligible to receive up to £9000. This may be considered for further exploration for the island, for supporting the transition process (Gov.scot, 2024).

## 4.3. Cooking

For Eigg to fulfil its carbon neutrality goals, one key step is converting conventional fuel stoves into electric cookers. For this to be done, it is essential to ensure that Eigg Electric can meet the additional electricity demand from the cooking sector. The purpose of this section is to estimate the current cooking demand and use it to estimate future electricity demand to provide inputs for the energy model.

To gather detailed information on fuel types, cooking habits, and the community's willingness to adopt renewable energy-powered cooking appliances, a questionnaire was distributed online and responses from households and businesses were used. In total, 5 questions were used to capture the cooking habits of the island, see below.

*Q1: Which fuel do you mostly use for cooking?*

*Q2: How much of this fuel do you consume on an annual basis?*

*Q3: At what time of day do you usually cook?*

*Q4: Approximately, how much time do you typically spend cooking your meal?*

*Q5: How likely are you willing to shift your cooking habits from conventional fuels to renewable by using electric appliances?*

Among the answers, the survey indicated that most residents on Eigg use gas for cooking, therefore the number of gas cylinders will be counted for this study. After preliminary data analysis, 27 responses were considered representative for further analysis.

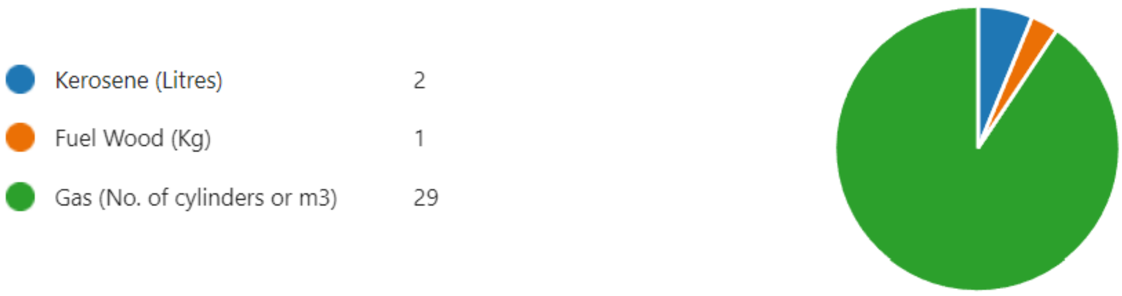


*Figure 4-5: Type of fuel mostly used for cooking*

Also, the residents were asked about their willingness to use electric cooking appliances and shift from conventional to renewable cooking methods. The responses indicate a high likelihood of implementing new cooking habits as shown in the figure below. These positive responses confirm that a shift to electric cooking may have high acceptance in the community.

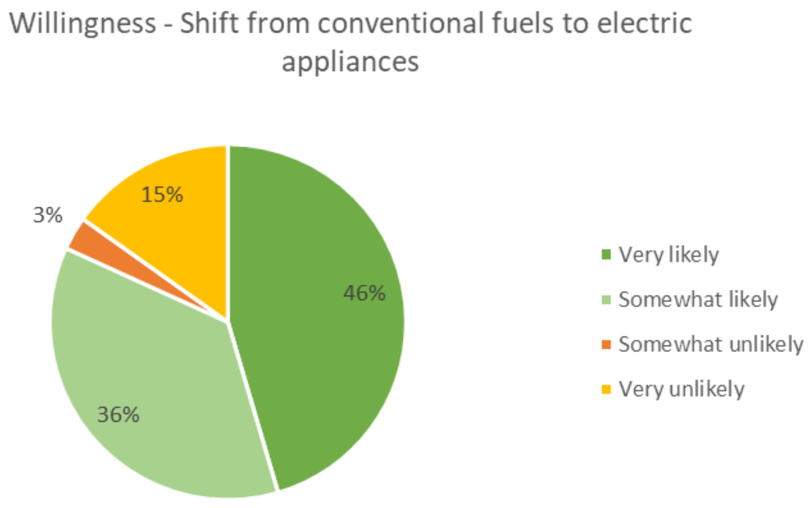


*Figure 4-6: Community likeliness to accept new cooking habits.*

From the survey questions, it was possible to determine the type and amount of fuel used in cooking as well as the amount of time spent cooking. It was determined that there was an average propane consumption of 100 kg per year per household and 900 kg for the most consumption-relevant business units, the Galmisdale Bay Café and Bar. It is important to note that there are other business units on the island, such as B&Bs and accommodation houses, however, from the survey, their fuel consumption does not differ significantly from that of a household. For this reason, for the cooking sector, the business unit refers to “food establishments.” Due to the differences in seasonal behaviour between domestic consumers and businesses, the load profiles were developed separately differently and summed up at the end.

Fieldwork was used to verify cylinder size from the supplier. The island is mainly supplied with 47 kg propane cylinders. Because gas cookers have lower efficiencies than electric cookers, the following formula and conversion rates were adopted to transform propane gas consumption into electricity demand:

$$Energy\ in\ kWh = \frac{Heat\ Value}{3{,}6} * \frac{\eta\ gas}{\eta\ electric}$$

*Equation 4-5: Formula conversion kg of propane to kWh of electricity*

Parameters used:

Propane heat value: 46,4 MJ/kg. (Linstrom, 2021)

Gas stove efficiency: 50%

Electric stove efficiency: 80%

Conversion factor 3.6 MJ / kWh

Applying above in the formula, the value to generate the same amount of heat from 1 kg of propane is 8,05 kWh of electricity.

$$\frac{46{,}4\ MJ}{kg} * \frac{1\ kWh}{3{,}6\ MJ} * \frac{0{,}5}{0{,}8}$$

$$1kg\ Propane = \ 8{,}05\ kWh\ electricity$$

### 4.3.1. Cooking Demand in Households

For households, the cooking hours distribution was assumed according to the survey answers. **¡Error! No se encuentra el origen de la referencia.**4-10 shows how the daily electricity consumption could be distributed between breakfast, lunch, and dinner hours. Subsequently, the proportion for each meal was distributed according to the percentage within the hours as shown on table below.

*Table 4-10: Demand distribution per meal - HH*

| Meal | Cooking Hours |
|---|---|
| Breakfast | 26% |
| Lunch | 26% |
| Dinner | 48% |

*Table 4-11: Demand distribution per hour - HH*

| | | |
|---|---|---|
| Breakfast | 05:00-08:00 | 08:00-11:00 |
| | 14% | 86% |
| Lunch | 11:00-14:00 | 14:00-17:00 |
| | 94% | 6% |
| Dinner | 17:00-19:00 | 19:00-22:00 |
| | 83% | 17% |

The logic can be read as that 26% of daily cooking demand is destined for breakfast. Of that 26%, 14% will be distributed between 05:00 and 8:00, and 86% between 08:00 and 11:00. A similar logic can be applied for the other meals. The time between 23:00 and 05:00 was considered to be without cooking demand. Then a daily curve demand for households was then created and will repeat throughout the year. Figure 4-7 shows the demand in kg of propane for the surveyed number of 27 houses (2024) versus the future demand for 72 households projected to 2030.

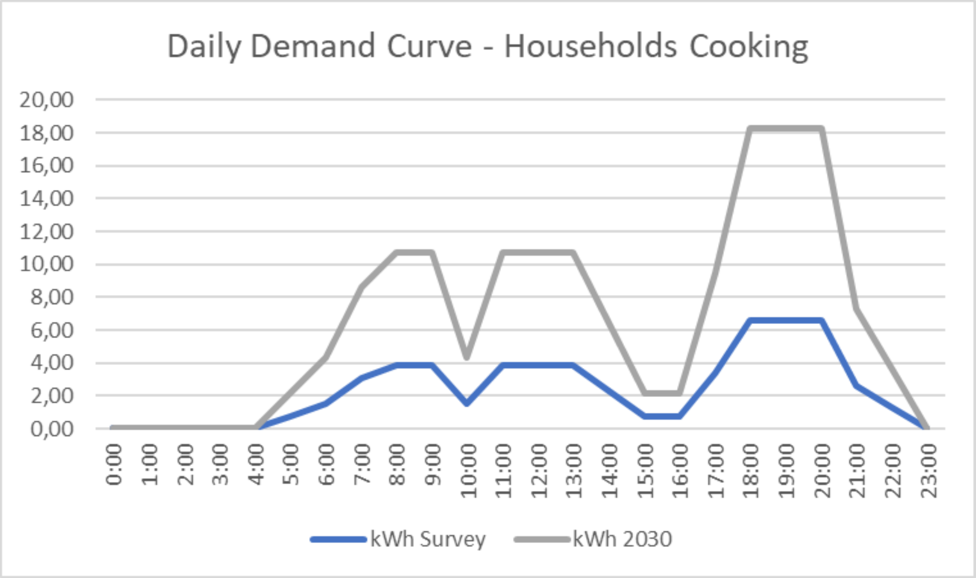


*Figure 4-7: Cooking Daily Curve Households*

### 4.3.2. Cooking Demand in Businesses

For business units, a more complex variation was defined, considering seasonality between months, weeks, and days, and using information such as ferry frequency, and opening hours of the business establishment. The first categorization of monthly seasonality is based on the ferry frequency. According to the CalMac timetable, the ferry operates 3 times per week between October and March, and at daily occurrence from April to September (CalMac, 2023). This information was used to define the low-season months. The remaining months were divided into two categories: shoulder-season and high season. Based on the climate and holidays calendar, April, May, and September are the middle season, while June, July and August are high season. Those times were also confirmed by business owners during the field study. In short:

- Low season: October, November, December, January, February, and March
- Middle season: April, May, and September
- High season: June, July, and August

During summer, the activity on the island is at least 3 times more intense, taking into consideration ferry frequency, tourism intensity and working hours. Table 4-12 provides a detailed overview of seasonality for a business unit in 2030. It was considered a growth on the business unit sector of 1.5 and a total of 1350 kg of propane per year.

*Table 4-12: Business Unit Demand per season*

| | LOW | MED | HIGH |
|---|---|---|---|
| Months | 6 | 3 | 3 |
| Open Days | 103 | 78 | 92 |
| Propane (kg) | 167 | 417 | 769 |
| Average Daily (kg) | 1.59 | 5.35 | 8.36 |

Analysing the table above, we can see that despite the low season being twice as long, considering the working days, the average working days through each of the seasons are around the same. Considering the working hours, the cafe opens daily and for longer periods in high season months, resulting in a considerably higher demand.

Next step is to distribute the proportional demand accordingly to a daily profile. For low seasons months, there are two profiles, when the business is open and closed. During winter, the business opens 4 days a week and the kitchen is open for around 2 hours. For shoulder and high season months, the opening days increase gradually, until they are open for 6 hours per day. 3 profiles were adopted, which follow the same logic. Fridays and Saturdays high, Sundays and Thursday's medium and Monday to Wednesday low. The table below compiles the logic into parameters.

*Table 4-13: Daily Variation BU*

| | LOW | | MEDIUM | | HIGH | |
|---|---|---|---|---|---|---|
| | % | Daily (kg) | % | Daily (kg) | % | Daily (kg) |
| Sunday | 0% | 0 | 0% | 0 | 15% | 8.78 |
| Monday | 25% | 2.8 | 15% | 5.61 | 12% | 7.02 |
| Tuesday | 0% | 0 | 15% | 5.61 | 12% | 7.02 |
| Wednesday | 25% | 2.8 | 15% | 5.61 | 12% | 7.02 |
| Thursday | 0% | 0 | 18.3% | 6.86 | 15% | 8.78 |
| Friday | 25% | 2.8 | 18.3% | 6.86 | 17% | 9.95 |
| Saturday | 25% | 2.8 | 18.3% | 6.86 | 17% | 9.95 |

This logic is applied to differentiate a Saturday in January, from one in April and one in July, for example.

The final analysis for the curve is done by following the steps described:

I. Check month season: Low / Medium / High
II. Check weekday: Sun / Mon / Tue / Wed / Thu / Fri / Sat

III. Allocate the shared amount within working hours of the day.

Different profiles will be drawn according to month and weekday. For better visualization, **¡Error! No se encuentra el origen de la referencia.**-8 illustrates how a Saturday demand behaves in different months.

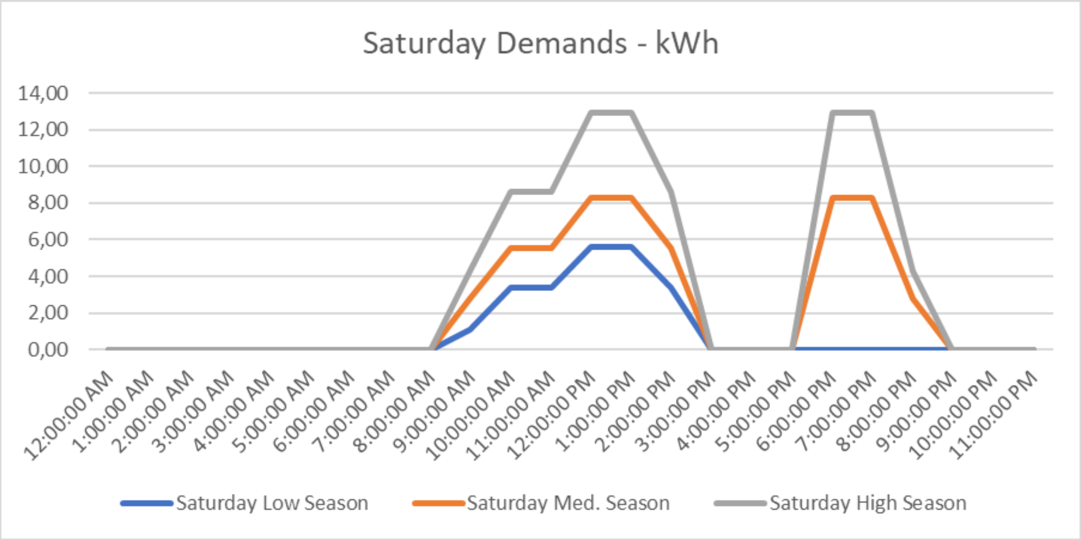


*Figure 4-8: Saturday Cooking Demand for Business Unit*

### 4.3.3. Cooking Demand for Scenarios

After creating the daily profiles for both household and business units, where business units have different profiles according to the season and day of the week, the data was combined and extrapolated for a whole year.

Figure 4-9 illustrates the designed scenarios for cooking demand. The BAU scenario stands for the current situation, with no relevant use of electric stoves. Aligned with Eigg Electric's plan to carbon zero, the premise is that all 100% of households will transition to electric cooking by 2030. This shift is assumed to be conducted in two steps before full electrification is achieved in 2030. The first phase is projected to change 40% of households to electric stoves, considering a total of 66 households in 2026. At this point, old and inefficient stoves should be prioritized. In 2028, it is considered that 70% of households will transition to electric cooking, considering a total 69 households (HH). In the last phase, households on Eigg and also the business units will be fully reliant on electric cooking appliances, and projection of 72 HH and an expansion by 1.5 business units (BU) was also considered.

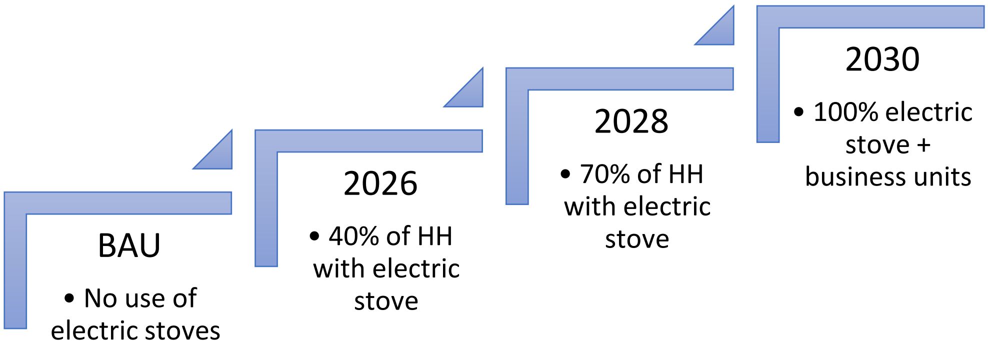


*Figure 4-9: Cooking Demand Scenarios*

The hourly load profile for the carbon zero scenario is as shown in figure 4.10.

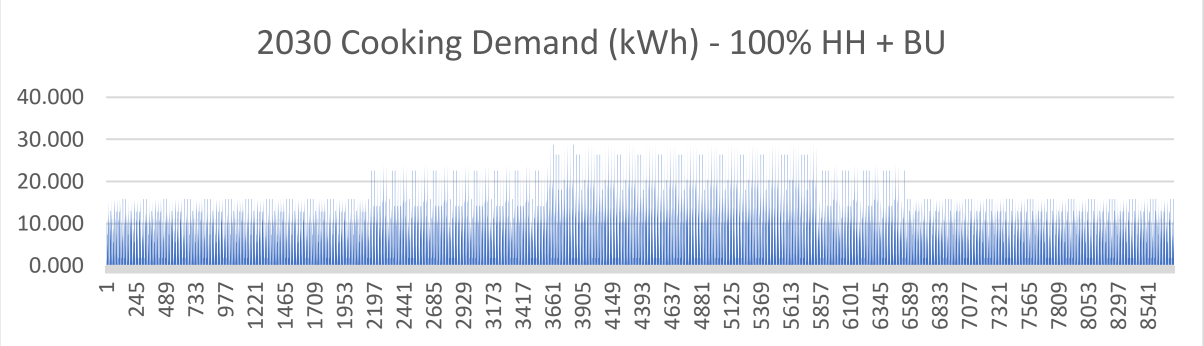


*Figure 4-10: Cooking Load Curve 2030*

## 4.4. Transport

The roads on Eigg are easily travelled by foot or car. Most (if not all) of the residents possess at least one car to move around the island, to go shopping when the ferry arrives, or to go to the pier to pick up packages. Bikes are also available on the island but are not widely used. The last study conducted on Eigg regarding transport was done in 2014. Since there is no official data and the island is small, national data cannot be scaled down to fit the consumption of the Isle. Furthermore, there is neither public road transport nor railways. However, there is one minibus taxi that can be hired for travel around the island, and at least one lorry and some tractors mainly used to transport fuels across the Island. However, given the limited data and short time to conduct field research, private transport (mainly cars) will be the focus of the transport sector. To comply with Eigg's vision of being a Net Zero island, we take a look into the full adoption of electric vehicles.

Although cars are the main mobility source in the Isle of Eigg, tourists are not allowed to bring or drive cars on the island, unless they are registered as disabled persons. Therefore, it is only the residents who can drive and own cars, tractors, and electric buggies. Visitors can rent bikes and electric bikes.

According to the Scottish government transport statistics, there is one car for every 2 persons over the age of 17 in the Highlands (Scottish Transport, 2023). This would mean there are around 55 cars on the island. From observations made on the ground, it appears as if there are more cars than that. However, it was not possible to know whether some of the visible cars were in fact fit for driving. Therefore, the 55 figure was kept and used for the calculations.

There are around 9 hybrid and electric cars on the island. However, their electricity consumption was considered as part of the power demand given the lack of time to conduct an origin-destination survey.

The island is around 10 km long from one end to the other. The main road connects one extreme of the island to the other (North to South). After a series of inquiries with the locals, an average daily round trip of 4 km was assumed for each car. This means that each car covers around 56 km per week. No seasonality factor was considered given the ban on tourist cars. The only vehicle that was considered to double its trips during summer was the Isle's only private Taxi Service. A mix of sedan cars, pickups and SUVs was considered to calculate the fuel required. The models were selected from both interviews with the locals and from observations made on the ground. There is one petrol car in the Isle, and the rest are powered by diesel.

For the fuel efficiency of the cars, the city driving factors from the technical sheets of each model were considered, given that the residents do not drive long distances and cold starts are frequent.

For the EV Scenario, it is assumed that all cars will be electric by 2030. The rate of adoption is an assumption.

The table below shows the number of cars for the Business-as-Usual Scenario and the EV Scenario.

*Table 4-14: Number of cars*

| | # of cars | EV Scenario |
|---|---|---|
| Baseline | 55 | 55 |
| Increase 2026 | 62 | 46 |
| Increase 2028 | 65 | 35 |
| Increase 2030 | 68 | 0 |

A seasonality factor was considered for the taxi-van that operates on the island, given that in summer, it can do up to 30 drives per day for three months in Summer (June, July, August). As we can see, consumption of diesel plummets under the EV Scenario, assuming a fast rate of adoption of electric vehicles. The annual fuel consumption is the following:

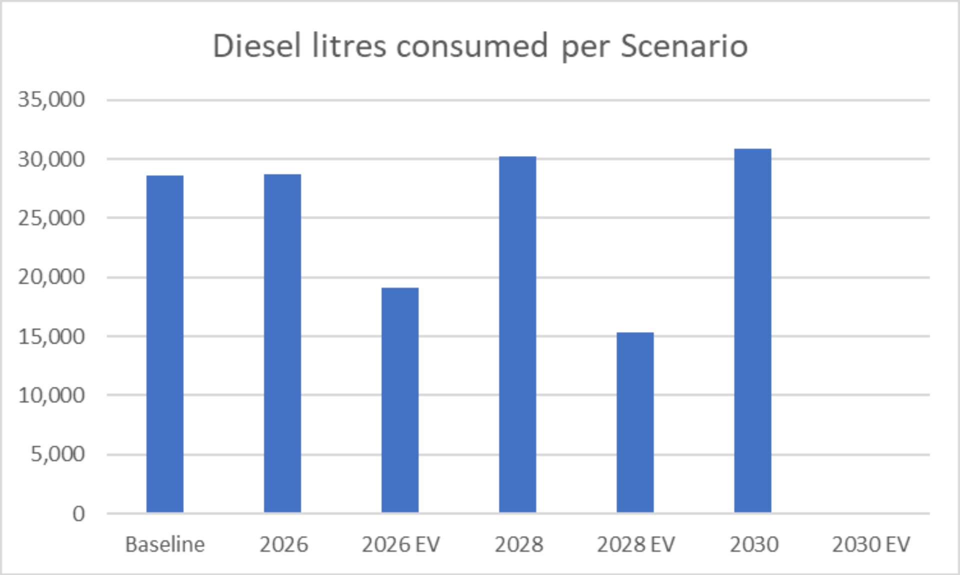


*Figure 4-11: Diesel Consumption*
Source: Authors

An Origin-Destiny Survey could help shed light on the driving habits and fuel consumption of private cars on the island, allowing for better planning of where to install EVs, the number of stations, and potential charging times. It is also possible that the uptake of EVs will be slower than the rate proposed in this study. However, if Eigg is to become a Net Zero Island, it needs to start thinking of ways to phase out diesel cars.

### 4.4.1. Electric Vehicles

Electric vehicles are set to dominate the global car market, comprising two-thirds of all vehicle sales by the year 2030. This surge in popularity follows a distinct trajectory known as the "S-curve," a pattern already evident in leading EV markets such as northern Europe and China. According to projections from the University of Exeter in 2023, this trend suggests that EV sales will experience a staggering sixfold increase by 2030, capturing a substantial market share ranging from 62% to 86% of total sales. (Alex Morrison, 2023)

#### *4.4.1.1. Overview of the existing system*

While electric vehicles typically come with a higher initial cost compared to traditional cars, they may lead to significantly lower operating expenses over their lifetime, primarily due to reduced fuel and maintenance costs. Additionally, the reduced maintenance requirements of EVs not only decrease ongoing expenses for owners but also lessen the dependence on local garages, which can have implications for the overall economy, especially on islands where resources may be limited. (Autovista24, 2023)

Despite the domination of traditional fossil fuel-based cars with internal combustion engines on the island, there is a shift towards electric vehicles where currently, there are reports of nine fully electric, hybrid, or buggy cars in operation (where the percentage of EVs compared to the population is 8% and it’s expected to increase to reach 51% by 2030).

The list of the electric vehicles currently available on the island is as follows:

*Table 4-15: EVs on the island*

| Vehicle Model Type | EVs | Battery Capacity (kWh) |
|---|---|---|
| **Buggy** | Renault Twizy | 7 |
| | John Deere Gator TE | 12 |
| | Ezgo Electric Golf buggy | 3.3 |
| | Cushman Hauler 800 | 12 |
| | Sector Lithium-Ion | 16.5 |
| | Polaris Ranger | 14.9 |
| **Hybrid** | Mitsubishi Outlander | 20 |
| **Fully electric** | Nissan Leaf | 40 |
| | Citroen Ev'ie | 30 |

Over the next 5 years, we expect the population to grow, leading to a rise in the number of electric vehicles (EVs) on the island. This increase in EVs will be driven by two main factors: the declining cost of these vehicles and the expansion of electrical infrastructure. As the cost of EVs becomes more affordable where It's been estimated that the price of an EV could match that of conventional motors as soon as 2025 or 2027, with EVs predicted to be even cheaper than petrol cars as the 2030 approaches (The Energyst, 2023). In addition to that the island's capacity for electrical sources grows, more people are likely to adopt electric vehicles as their mode of transportation.

The following table will monitor the growth of electric vehicles alongside the population increase.

*Table 4-16: Percentage of EVs compared to the population.*

| Year | Population | N° of EVs | % of EVs / population | Storage capacity in EVs (kWh) |
|---|---|---|---|---|
| **2023** | 110 | 9 | 8% | 133 |
| **2026** | 114 | 16 | 14% | 420 |
| **2028** | 120 | 29 | 24% | 715 |
| **2030** | 126 | 63 | 51% | 1487 |

#### 4.4.1.2. Upgrading the transport system

##### The Prospect of a common EV Minibus or VAN

In response to the growing need for efficient and sustainable transportation options on the island, the idea of obtaining a shared electric van emerges as a good solution and that by introducing a common mode of transportation.

One promising option for this initiative is the LDV EV80 (Leyland DAF Vans an all-electric version of the LDV V80 van). This electric van offers a combination of environmental friendliness, and good battery range.

By opting for the LDV EV80 as a common electric van, its spacious interior can be adjusted to accommodate the diverse transportation needs of island either residents or tourists. Furthermore, the LDV EV80's robust battery range ensures that it can manage the demands of daily operations without frequent recharging, enhancing its efficiency and convenience. With a lithium-ion battery pack, the LDV EV80 can achieves an electric range of up to 120 miles or 200 km on a single charge, making it well-suited for both short trips and excursions across the island.

In terms of charging, the LDV EV80 supports both standard AC charging and DC rapid charging options, offering flexibility and convenience to users. With DC rapid charging, the van can be recharged from flat to full in just 90 minutes, minimizing downtime and maximizing operational efficiency, granted that charger capacity is available. Prices for the LDV EV80 start at around £54,000.

*Table 4-17: EV Van characteristics*

| Vehicle Type | Battery Capacity (kWh) | Chargin time (h) | Electric range (km) |
|---|---|---|---|
| **LDV EV80** | 56 | 1.5 | 200 |

Source: (Auto Express, 2020)

Incorporating the LDV EV80 into the transportation infrastructure aligns with the commitment to sustainability and net zero emission goal.

*Figure 4-12: Charging option for the LDV EV8*

### *Charging features on the island*

A recent survey conducted on the Island of Eigg aimed to understand residence habits in their homes and outside. The survey targeted 32 households across various regions of the island, focusing on the presence of residents at different times of the day.

The survey as shown in the table below collected data on the presence of residents at home during four distinct time periods.

*Table 4-18: Availability at home*

| **Time slots** | **Morning (06:00-12:00)** | **Afternoon (12:00-16:00)** | **Evening (16:00-21:00)** | **Night (21:00-06:00)** |
|---|---|---|---|---|
| **% of availability at home** | 70% | 27% | 73% | 93% |

Based on a storage capacity of 133 kWh in 2023 derived from nine electric vehicles, in addition to the findings of a survey of home occupancy, the below charging trend chart has been created. This chart considers the collective charging capacity across the entire island in 2023. it aims to provide an insightful view of the charging patterns.

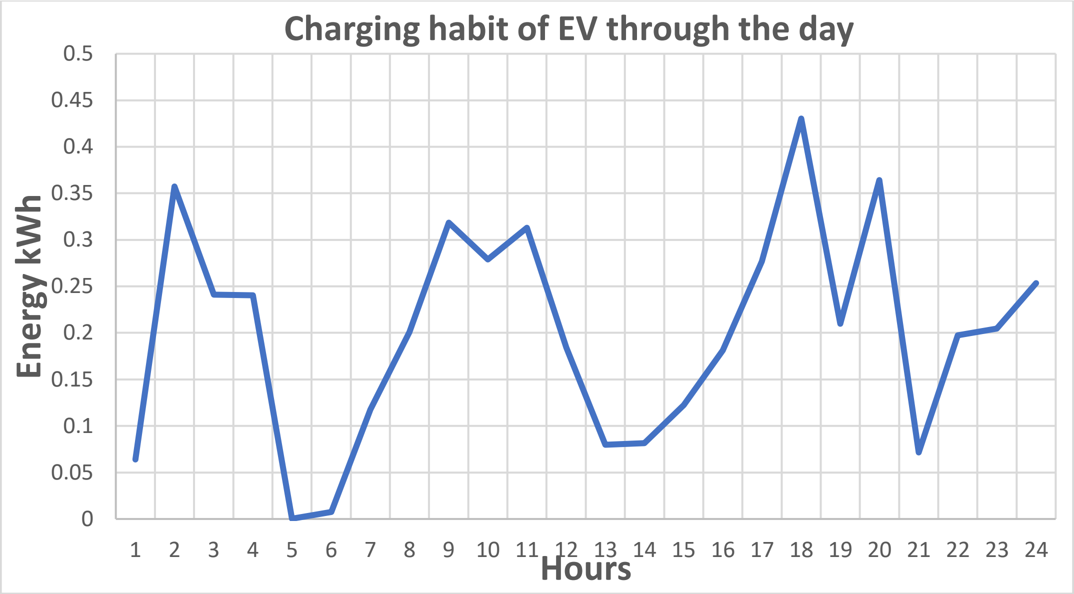


*Figure 4-13 Current charging of EV through the day*

These availability patterns have implications for EV charging habits on the island. Residents who are typically available at home during the morning and night periods may prefer to charge their electric cars during these times. This aligns with the concept of smart charging, where EV owners take advantage of off-peak hours to charge their vehicles, reducing strain on the grid and potentially benefiting from lower electricity rates.

Furthermore, the lower availability during the afternoon period suggests that fewer residents may be present to charge their EVs during this time.

### *The Prospect of Vehicle to Grid (V2G)*

EV' owners on the island of Eigg currently, rely totally on domestic charging systems to recharge their vehicles since there are no public charging points on the island.

As part of the ongoing efforts to integrate sustainable technologies into the transportation infrastructure, Vehicle-to-Grid (V2G) technology may be developed on the island. This allows electric vehicles (EVs) to not only draw power from the grid for charging but also to discharge power back to the grid when needed, effectively turning EVs into mobile energy storage units.

At its core, V2G technology enables bidirectional energy flow between EVs and the grid, unlocking a range of potential benefits for both vehicle owners and grid operators. By leveraging the energy stored in EV batteries during periods of high demand, V2G systems can help stabilize the grid, alleviate strain on power generation facilities, and reduce the need for costly infrastructure upgrades.

Based on an average capacity of 23kWh and according to the table in the previous section where the number of electric vehicles has been defined according to the growth in population at the island, a progressive increase in storage capacity within electric vehicles (EVs) over the coming decades is expected, where starting in 2023 with 133 kWh, the capacity is expected to nearly triple by 2026, reaching 420 kWh. By 2028, it is forecasted to reach 715 kWh and exceed 1,487 kWh by 2030. The table below illustrates this trend.

The integration of electric vehicles (EVs) into the grid through Vehicle-to-Grid (V2G) technology offers a promising avenue for enhancing energy flexibility and sustainability. However, the extent to which an EV can inject its stored energy back into the grid is subject to various factors. One critical factor is the manufacturer's safety measures to protect the battery, which may impose limits on discharge rates to prevent potential risks such as overheating or damage. (Ana Simarro-García, 2023)

A common estimation suggests that V2G systems allow for the injection of 50-70% of a vehicle's total energy capacity into the grid (Virta Global, 2023). The energy that can inject back into the grid can exceed 800 KWh in 2030.

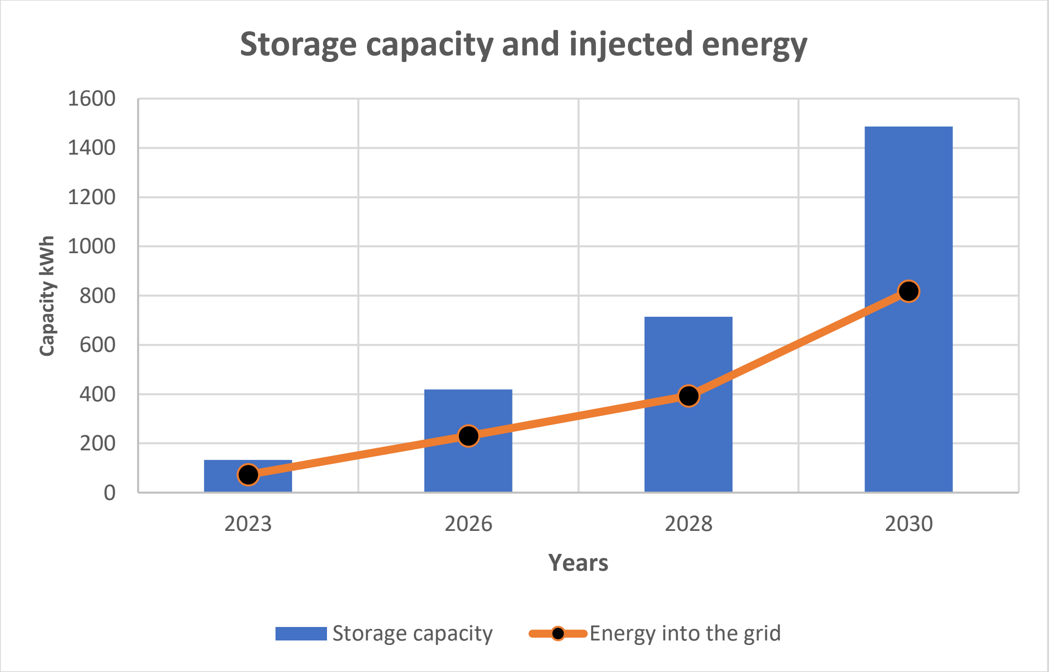


*Figure 4-14: Storage capacity and the energy that can be reinjected into the grid*

### *Connectors for the Vehicle-to-Grid (V2G) Integration*

One of the key components of V2G technology is the charging infrastructure, which includes various types of charging plugs and connectors that facilitate communication and power transfer between EVs and the grid (Lee Goldberg, 2023). These include:

- Type 1 (SAE J1772): Commonly used in North America and Japan, Type 1 connectors feature a single-phase AC charging capability and are suitable for residential and light commercial applications.
- Type 2 (IEC 62196): Widely adopted in Europe, Type 2 connectors support both single-phase and three-phase AC charging, making them versatile and well-suited for a range of charging scenarios.
- CHAdeMO: CHAdeMO connectors enable DC fast charging and are commonly used in electric vehicles with high-capacity batteries, offering rapid charging speeds and convenience for drivers on the go.
- Combined Charging System (CCS): Developed as a universal charging standard, CCS connectors integrate both AC and DC charging capabilities into a single plug, providing flexibility and interoperability across different EV models and charging infrastructure.

Of the charger types mentioned, the Combined Charging System (CCS) emerges as the most suitable for Vehicle-to-Grid (V2G) applications due to its unique capabilities. Unlike other connectors, CCS integrates both AC and DC charging functionalities into a single plug. This integration empowers CCS to facilitate bidirectional power flow, enabling not only the drawing of energy from the grid to charge the vehicle but also the discharge of energy back into the grid for V2G purposes. In contrast, while CHAdeMO connectors offer DC fast charging capabilities, they typically lack support for bidirectional power flow, which makes them unsuitable for V2G applications. The same case applies with Type 1 and Type 2 connectors where are primarily designed for one-way charging from the grid to the vehicle and do not have features essential for V2G functionality. By providing charging possibility of AC and DC, CCS ensures the necessary flexibility required for V2G applications across diverse electric vehicle models and charging infrastructure, making it the optimal choice.

### *Bidirectional DC Charging Solution for the Island of Eigg*

EnerCharge's 40kW V2G Bidirectional DC Charger, is a solution for electric vehicle (EV) charging and grid interaction. With its advanced bidirectional charging capabilities, this charger enables vehicles not only to draw power from the grid but also to discharge energy back into it.

Figure 4-15 DCW40 Wallbox Bidirectional DC Charger

Designed to meet the evolving needs of electric mobility and smart grid solutions, EnerCharge's charger offers high power output and seamless bidirectional communication, unlocking new opportunities for grid stability and renewable energy integration. (EnerCharge, 2024)

The EnerCharge's 40kW V2G Bidirectional DC Charger price is: $15,610 (Solarics GmbH, 2024)

In summary, the potential of electric vehicles (EVs) in shaping the island's mobility is clear. And the path is open towards increased EV adoption, driven by factors such as declining costs and expanding infrastructure. Despite initial cost barriers, the long-term economic and environmental benefits of EVs make them an attractive choice, especially for a community with limited resources. The proposed solutions, such as shared electric vans and Vehicle-to-Grid (V2G) technology, demonstrate a strategic approach towards sustainability and grid resilience. In addition to that by the usage of innovative solutions like the Nuvve Bidirectional DC Charger, the island stands to not only reduce carbon emissions but also enhance energy flexibility and efficiency.

## 4.5. Energy Efficiency in Buildings

Energy efficiency has been designated as a national priority in Scotland. According to the Eigg Electric 2030 Feasibility Study, energy efficiency is also a part of strategic priority by improving building performance for the Isle of Eigg (Eigg Electric, 2023). Based on the survey we conducted in 2024 (see the Annex D, question 13 to 16), at least eight houses still have no wall insulation, eight houses have no roof insulation, 18 houses have no floor insulation, and three houses have single glazed windows. Considering these numbers, the improvement of building insulation fabric is suggested to reduce energy demand, resulting in homes that are warmer and easier to heat. Improving the building fabric insulation can also affect long-term energy bills. However, building retrofit can be challenging considering the economic, social, and technical situation on the Isle of Eigg.

### 4.5.1. Energy Efficiency in Building Scenario

As previously mentioned, there are 64 residential buildings on the island, with 37 houses being EPC registered with the Energy Saving Trust. Energy Performance Certificate (EPC) are required for houses, especially for rentals, new builds, and those that are up for sale in Scotland. The EPC provides information on how energy efficient a building is and how to improve energy efficiency (Scotland Government, 2020). The certificate also describes energy efficiency indicators, such as energy performance of Fabric Energy efficiency (FEE), primary energy per unit floor area, energy cost rating, environmental impact base on $CO_2$ emission and dwelling $CO_2$ emission rate (The Building Research Establishment, 2021).

EPC has seven levels to define the energy efficiency rating of buildings, A to G based on the points generated from Standard Assessment Procedure (SAP) for new buildings and RdSAP for existing buildings.

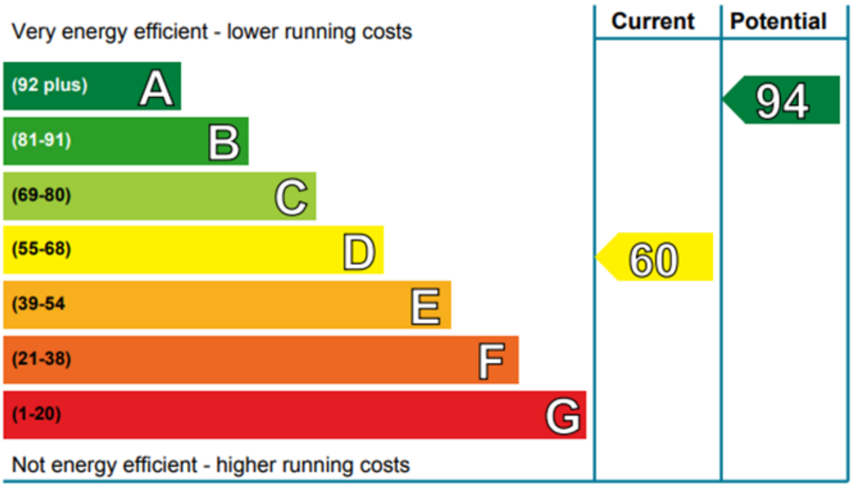


*Figure 4-16: Example of EPC rating level*
Source: Energy Saving Trust, 2024

Interviews with The Isle of Eigg Heritage Trust's Warm Homes Manager were conducted to fill the data gap of 27 houses without an EPC. Assumptions were used to categorize houses. Similar EPC rates were assumed for homes that have similarities in building fabric. It is important to note that this was done despite these houses being of different sizes and having similar floor areas, resulting in less accurate heating calculations.

*Table 4-19: Categories of Houses on the Isle of Eigg*

| Categories | EPC Level | No. of House |
|---|---|---|
| Old | E, F, G | 10 |
| Bungalow | E, F, G | 23 |
| Renovated | D | 13 |
| New Build | C | 6 |
| Super | B | 2 |
| Holiday Homes | C, D, E, F, G | 10 |
| | Total (Houses) | 64 |

The “Renovated” house, with EPC band “D,” is considered the average rating of EPCs in Scotland. Because the rate at which a building loses heat is relative to its size, detached houses with an EPC below D are classified as 'Old', while detached bungalows with an EPC below D are classified as 'Bungalow'. The “Super” category is for houses that are highly efficient and have lower thermal transmittance of fabric insulation than other categories. The Super category has EPC band B. Additionally, there are 10 Holiday Homes with seasonal occupancy, which influences heating demand, thus we assigned them to different categories.

Based on these six categories, 51 houses (Old, Bungalow, Renovated, and 5 Holiday Homes) on the Isle of Eigg are still below EPC Band C. Therefore, to reduce energy demand, basic or traditional building retrofit is necessary. This requires the alteration of the existing building fabric to increase its energy efficiency (Alabid, 2022).

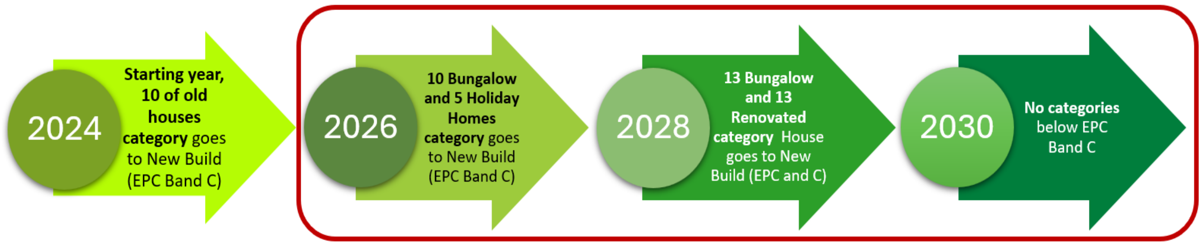


*Figure 4-17: Scenario of Energy Efficiency in Building*

In 2019, the Scottish Government announced the Energy Efficiency Scotland Route Map, for all homes in fuel poverty (those households which spend 10% of their income on fuel costs (Scottish Government, 2019). It is assumed that energy efficiency in buildings will be achieved in three stages by 2030, bringing all homes on Eigg to EPC band C.

In the first stage, homes categorized as “Old” will be the first to be retrofitted, starting 2024. In 2026, the Bungalow and Holiday Homes categories will be retrofitted, and in the final stage (until 2030) all the renovated houses will be renovated to new build status which is EPC band C.

On top of that, as mentioned in the previous section, there will be additional houses built by 2030. It is projected that in 2026 there will be two passive houses in the super category, three more passive houses in 2028, and three more passive houses in 2030.

EPC Band C is equivalent to a space heating demand of about 71- 120 kWh/m$^2$/year (Scottish Government, 2023). Furthermore, each category of houses on the Isle of Eigg has different characteristics of fabric material. The EPC ratings also define building fabric for each category, which can be used to determine the u-value. Bungalow and Old category's fabric characteristics are as listed in table 4-20.

*Table 4-20: Comparison of Building Materials in the Bungalow and Old Category and New Building Category*

| Insulation | Bungalow and Old | U-value (W/m$^2$K) | New Building | U-value (W/m$^2$K) |
|---|---|---|---|---|
| Wall | Granite or Whinstone (no insulation) | 2.1 | Wood Fiber Internal insulation | 0.4 |
| Roof | Pitched 150mm | 0.35 | Pitched 280mm | 0.16 |
| Floor | Solid (no insulation) | 0.59 | Solid (insulation) | 0.23 |
| Window | Single Glazing | 4.8 | Double Glazing | 2.2 |
| Door | Wood | 3 | PVC | 2.2 |

Source: (Tabula, 2024 and Historic Scotland, 2013)

The table shows that the house types "Bungalow" and "Old" have poor insulation, indicated by the higher u-values, which result in higher heat demands. As a result, recommendations are made to insulate walls, roof, and floor, and to replace windows and doors, which will reduce heat loss by almost 45% in old and bungalow categories.

Historical or traditional houses in Scotland typically have breathable construction that can absorb and release moisture. Selecting an appropriate water vapor permeable material to avoid a vapor barrier is important when deciding to improve insulation. Wood fibre internal insulation for wall insulation is suggested since it is cheaper to refurbish and can be safely applied directly to granite walls without a vapor barrier. Furthermore, roof loft insulation is proposed for at least 270mm of insulation installed (Historic Scotland, 2013). Double glazing installation and improvements to panelled doors may also be practical for the old and bungalow categories.

For the renovated category, the suggestion is to install thicker roof insulation, this is a feasible option that can reduce heat loss of a house by about 10%. Some of buildings insulation are qualified in

Renovated category in standard of band C of EPC such as wall, floor, window, and door already insulated.

*Table 4-21: Comparison of Building Materials in the Renovated Category and New Building Category*

| Insulation | Renovated category | U-value ($W/m^2K$) | New Building category | U-value ($W/m^2K$) |
|---|---|---|---|---|
| Wall | Granite or Whinstone (Insulated) | 0.26 | Granite or Whinstone (Insulated) | 0.26 |
| Roof | Pitched (loft Insulation) | 0.2 | Pitched 280mm loft insulation | 0.16 |
| Floor | Solid (insulated) | 0.23 | Solid (insulated) | 0.23 |
| Window | Double glazing | 2.2 | Double glazing | 2.2 |
| Door | PVC | 2.2 | PVC | 2.2 |

Source: (Tabula, 2024 and Historic Scotland, 2013)

### 4.5.2. Energy Savings in Buildings

By applying energy efficiency throughout the following years until 2030, the energy demand for heating can be reduced. After completing the first stage of the energy efficiency measures to retrofit all homes in the old house category, around 118,000 kWh can be saved within 2 years after 2024, corresponding to energy savings of 11 %. In the next 4 years after the starting year, the retrofit of 10 Bungalow category buildings and 5 Housing homes can reduce 208,000 kWh, equivalent to 11% of savings by 2026. The last stage is in 2030, which will reduce 315,000 kWh with a percentage of savings achieved of 14% compared to BAU.

*Table 4-22: Total Energy Heating Demand before and after Energy Efficiency*

| | BAU 2026 | EE 2026 | BAU 2028 | EE 2028 | BAU 2030 | EE 2030 |
|---|---|---|---|---|---|---|
| Total Energy for Heating (MWh) | 1,096 | 978 | 1,137 | 929 | 1,178 | 0.863 |
| Total Energy Saving Potential (%) | | 11 | | 22 | | 36 |

Upgrading of the building fabric of Old, Bungalow, and Renovated categories results in an improvement of thermal performance. Energy efficiency in buildings would be an option for improving housing comfort and reducing the electrical system upgrades to electrify heating. Retrofitting houses to their specific EPC categories by 2030 may be feasible, although there will be an additional cost that should be considered. (Palmer, 2017) collected data from interviewing households in the UK to find the cost of retrofitting houses based on the types of houses and the fabric material of the building. For example, improving internal wall insulation in a small, detached house (< 117m$^2$) will cost around £6,600 to £8,000, and changing into double glazing will cost around £5,000 to £7,000 for a small, detached house. However, it cannot be denied that cost can be an issue when developing a recommendation for retrofitting the houses on the island.

## 4.6. Energy Efficiency in Appliances

Energy efficiency measures in electrical appliances have been progressively improving access to energy services and reducing average domestic electricity consumption in Scotland. It was estimated that average domestic electricity consumption (kWh per household) has been reduced by 27% in 2021 (Fig 4-18) compared to 2005 (Hub, 2021). The survey conducted by our team on the of Isle of Eigg showed that the most used appliances in the houses are refrigerators, washing machines, dishwashers, microwave ovens, and water heating systems. As per the discussions with residents, some of these appliances are old and on the verge of their end of life. Some of the residents find it difficult to replace them with energy efficient appliances due to high cost of A level energy efficient appliances, compatibility with grid frequency fluctuations, and transportation from the mainland to the island.

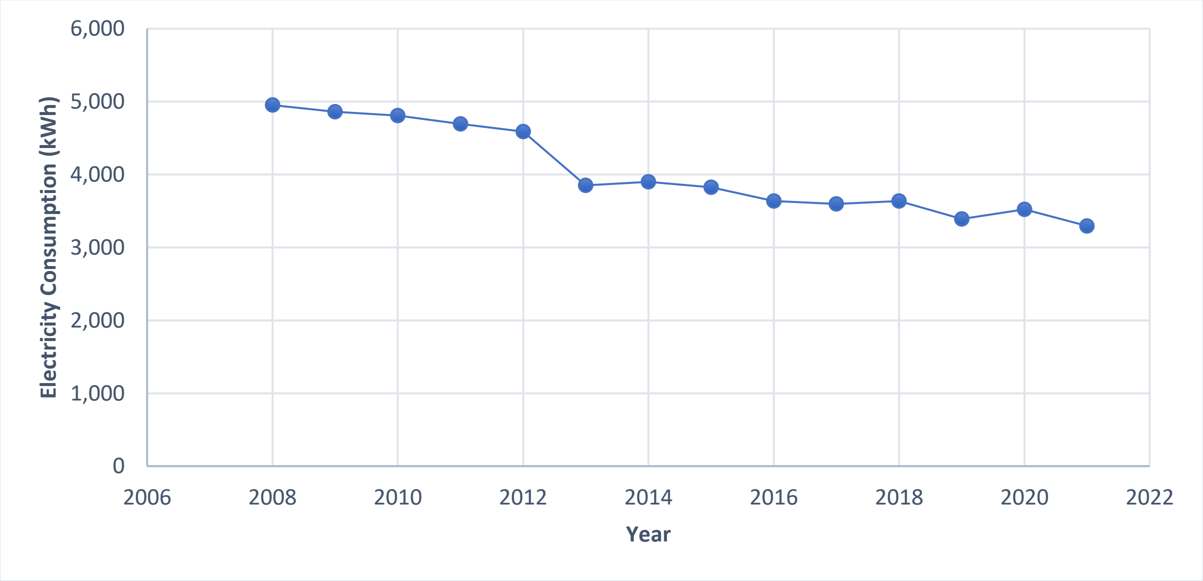


*Figure 4-18: Average domestic electricity consumption in Scotland (kWh per household)*

Moreover, it is also important to mention that some of the people live in small dwellings such as caravans and share major appliances with other residents of the island. Aside from this, our survey showed the behavioural pattern of people living in household and working hours. Most people stay home almost 75% during morning (06:00 to 12:00) and most people (almost 72%) are at work during afternoon (12:00 to 16:00) and come home by night (18:00 to 21:00). This shows that most of the peak consumption of electrical appliances happens during early morning (07:00 to 10:00) and nighttime (17:00 to 20:00).

### 4.6.1. Calculation of energy efficiency potential in Appliances

Energy efficiency measures in electrical appliances can be a significant step towards reducing the energy bills of households and businesses. As stated earlier, old appliances nearing the end of their lifetime may need to be replaced by new A grade appliances (UK, 2020) as they might be consuming more electricity than more energy efficient appliances. Also, replacing old electrical appliances with new energy efficient appliances would require a higher initial capital investment for households and businesses. However, replacement of these appliances will conserve energy, resulting in cost savings during operation of these appliances throughout their lifetime period. Moreover, efficiency of most of the electrical appliances varies from one grade value to another as per the energy efficiency scale given by UK Energy Label.

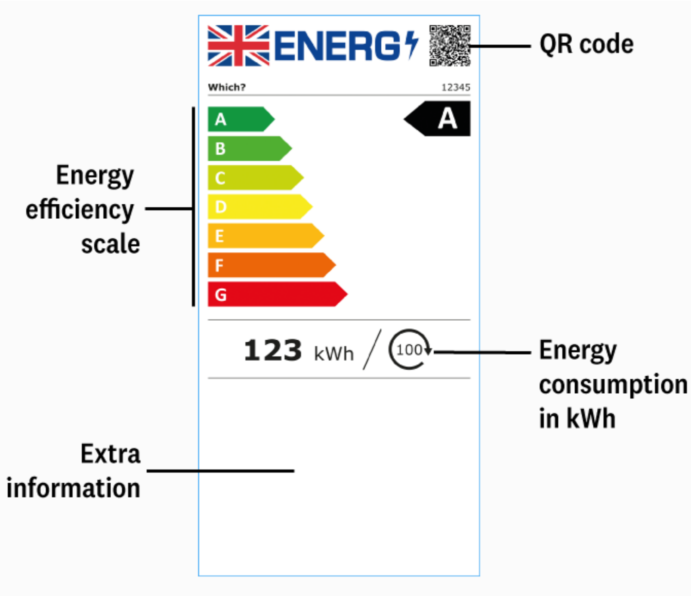


*Figure 4-19: Energy Efficiency Logo, UK*

As such, we have come up with a top to bottom approach where we have modelled one house with all the energy efficient appliances, with most of the appliances having A grade energy efficiency (Kaplan, 2018) and the current electrical appliances are considered to be C rated as some of the appliances become less energy efficient (as per the one-on-one discussions with some individuals). This gives us an estimation of the amount of energy saved by each appliance, including a percentage of the energy share of these appliances) (Trust, Energy Saving Trust, 2022).

Although the total energy consumption of an average household in Isle of Eigg comes out to approximately 2.5 MWh per year. Yet the total energy consumption of a household can be reduced by using energy efficient appliances. In the table below we estimated total yearly energy consumption for an energy efficient household which comes out be around 1.9 MWh per year in an ideal scenario.

*Table 4-23: Total yearly consumption (in kWh) by a household*

| House (A rated App | No. Applia | Usage Der | Total Power Run | Monthly Energy Cosnumption | Yearly Energy Consumption (kWh) |
|---|---|---|---|---|---|
| Lighting | 5 | 40 | 50 | 60000 | 720 |
| Washing Machine | 1 | 3 cycle | 1064.21 | 8005.48 | 96.06576 |
| Dishwasher | 1 | 3 cycle | 871.97 | 5231.82 | 62.78184 |
| Refrigerator | 1 | All Time | 782.83 | 26,400 | 316.8 |
| Oven | 1 | 3 cycle | 1052.45 | 16,364 | 196 |
| TV | 1 | 14 | 100 | 8413 | 100.956 |
| Computer | 1 | 14 | 65 | 14946 | 179.352 |
| Kattle | 1 | 2 | 104.84 | 6864.2 | 82.3704 |
| Other Appliances (Ha | 2 | 2 | 8000 | 12000 | 144 |
|  |  |  |  | **Total Energy Consumption** | 1898.69 |

In the next step, based on the data from the Sunny Island Portal we have estimated that a total consumption of energy (after removing the grid losses and other factors) comes out to be around 254 MWh (this was calculated based on the summation of energy in kWh for one-year 2021 as base year) and it change respectively with the increase in population and business as per the Eigg electric plan 2030. As per the percentage distribution of energy share among households and businesses on the island, 65% and 35%, the total energy consumption comes out to be 164 MWh and 89 MWh respectively (these estimations are taken from the table 4-2). Moreover, we have estimated the number of appliances in each household for 2026, 2028, and 2030 based on the assumption that ownership of major energy consuming appliances such as washing machines, refrigerators, and dishwashers and estimated their share in monthly energy bills (Trust, Energy Saving Trust, 2024). Finally, the electricity demand pattern using probability distribution curve was designed to estimate the distribution of electricity demand throughout a year. This results in providing energy saving on the based on total appliances used by the people of island of Eigg in case they shift towards energy efficient appliances by 2030.

### 4.6.2. Analysis of Energy Efficient Appliances

Based on the electricity demand pattern, a probability distribution curve was designed to estimate the distribution of electrical load throughout a year. In next step, taking this probability distribution in consideration and load factor of each year 2026, 2028, and 2030, new electricity demand pattern has been generated for 8760 hours of the year for all three years, respectively.

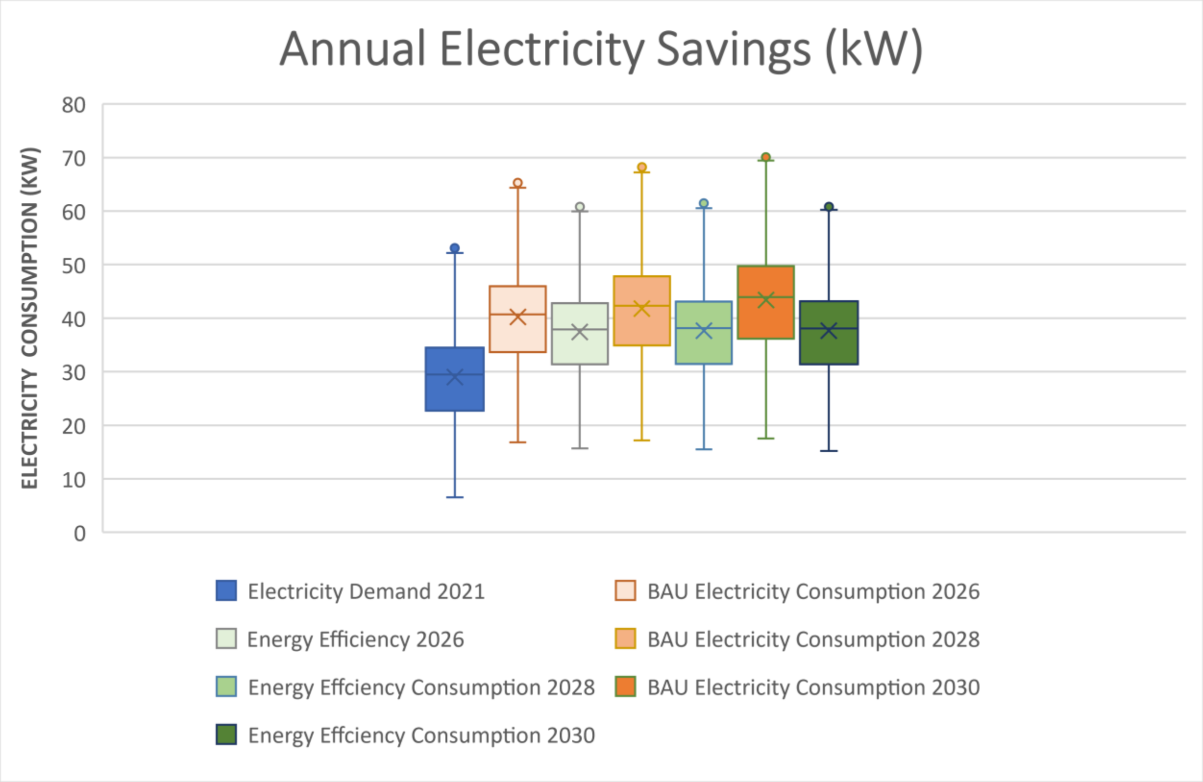


*Figure 4-20: Electricity Consumption after Energy Efficiency Measures*

Finally, the total energy consumption of the years 2026, 2028, and 2030 using energy efficient electrical appliances showed that energy efficiency helps in reduction in total energy consumption and peak demand for the island of Eigg.

*Table 4-24: Annual Energy Saving by the Island of Eigg*

| Year | 2026 | 2028 | 2030 |
|---|---|---|---|
| Annual Energy Savings | 40,880 | 42,793 | 44,459 |
| Percentage Savings (%) | 11% | 13% | 14% |
| Annual Energy Consumption (MWh) | 352 | 366 | 380 |
| Reduction in Peak load | 7% | 11% | 14% |

In conclusion, addressing energy efficiency in electrical appliances for the community on the island of Eigg requires a comprehensive approach. Although our results show significant savings in overall energy consumption of the island throughout the year using a top to bottom approach. But a detailed approach would also require studying the electrical appliances on household level and their usage pattern. By evaluating energy consumption comparing the efficiency of old and new appliances, and considering long-term costs, households on Eigg can make informed decisions about the necessity of upgrades.

Additionally, exploring financial options, raising community awareness, and collaborating with local authorities and organizations can help overcoming challenges such as high upfront cost and transportation limitations of the major electrical appliances. Using proactive measures and constant monitoring, the community on the Isle of Eigg can develop towards greater energy efficiency while saving costs of expanding the power system and ultimately reducing  energy poverty.

# 5. Renewable Energy Technologies for the Isle of Eigg

This chapter conducts a comprehensive evaluation of five distinct energy technologies on the Isle of Eigg, including solar, wind, hydro, tidal, along with potential storage solutions. Through in-depth analysis, the objective is to assess the current utilisation and the perspective for future use of each technology. We will also identify suitable sites for expanding existing capacities and provide critical technical and financial data. This information will serve as crucial input for the various scenarios and assist in the strategic planning of future energy pathways for the Isle of Eigg.

## 5.1. Solar Energy

Solar energy is one of the key renewable energy sources that can significantly contribute to meeting energy needs. The average levelized cost of solar PV electricity generation has decreased by 90% between 2010 and 2022 due to technology advancement and production improvements (IEA 2023). As a result, solar PV is now one of the most cost-effective electricity generation technologies in many regions. In this section we will evaluate the solar PV potential in Isle of Eigg and evaluate the possible strategies to effectively use the solar energy within this area.

### 5.1.1. Current Solar System

Presently on the Isle of Eigg, there is a solar PV power plant located at the Glebe and close to Glebe powerhouse with a total capacity of around 181 kW. The first series of PV modules was installed in 2008 with subsequent arrays installed in 2011, 2013, and 2023. Figure 5-1 shows the location of solar PV plant on the Isle of Eigg along with an image of the plant, and Table 5-1 demonstrates the characteristics of the PV modules and inverters.

*Figure 5-1 The location of solar PV plant on Eigg*
Source: Authors, Google Earth.

*Table 5-1. Solar PV plant system characteristics*

| Year of Installation | Modules | Inverters | Capacity (kW) |
|---|---|---|---|
| 2008 | BP Solar BP3165S 165Wp | SMA Sunny Boy SB-3000 | 9.9 |
| 2011 | BP Solar BP4180 180Wp | SMA SMC-7000HV | 22.6 |
| 2013 | REC Solar REC 250 PE 250Wp | SMA SMC-7000HV | 22.5 |
| 2023 | REC Solar REC 440AA 72 XV 440Wp | SMA STP 20000TL-30 | 126.72 |

### 5.1.2. Future Solar Potential on the Isle of Eigg

Figure 5-2 displays the maps of Global Horizontal Irradiation (GHI) and Photovoltaic Power Potential (PVOUT) in the Isle of Eigg. Global Horizontal Irradiance (GHI) is the total amount of solar radiation received per unit area by a surface horizontal to the ground including both direct sunlight and diffuse sunlight scattered by the atmosphere and clouds while PVOUT estimates the electricity generation from a solar photovoltaic system, considering solar radiation levels, system specifications, and other relevant factors specific to the region (Yang et al., 2015). Both PVOUT and GHI are higher in southern parts of the Island. The average values for GHI and PVOUT are 855.1 kWh/m2 per year and 903.6 kWh/kWp per year, respectively (Solargis 2024).

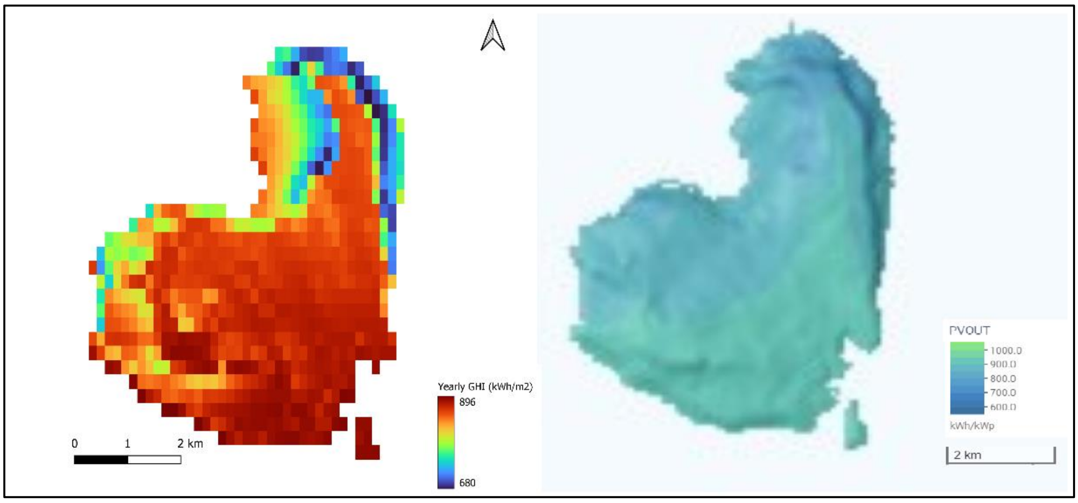


*Figure 5-2: Solar photovoltaic power potential (PVOUT) and Global Horizontal Irradiation (GHI)*
Source: (solargis, n.d.)

One crucial factor to consider when assessing solar potential is the average yearly temperature and its fluctuations. Figure 5-3 illustrates the average hourly temperature and precipitation in Isle of Eigg throughout the year, revealing an average temperature range of 2°C to 15°C. Since the average temperature is not too high throughout the year, the PV panels can work properly and are not negatively impacted by high temperatures. Precipitation peaks in winter, potentially reducing solar panel output due to cloud coverage, while the summer months experience lower precipitation, suggesting higher solar irradiance and improved solar panel performance.

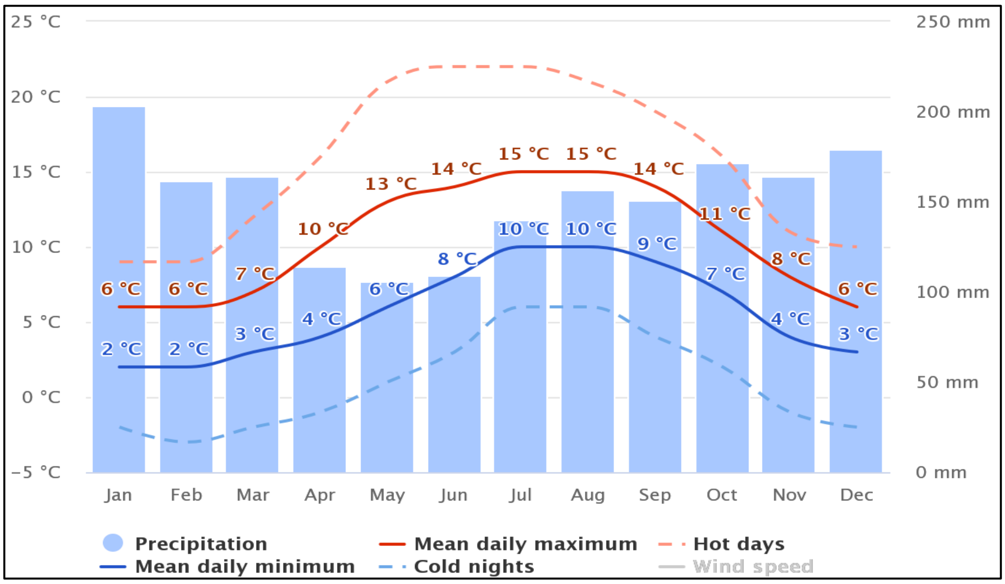


*Figure 5-3. Average hourly temperature and precipitation*
Source: (Meteoblue, 2024)

Figure 5-4 shows the monthly solar PV electricity production for a 1kW capacity plant with tilt angle of 30 degree on the Isle of Eigg. The data are derived from ‘renewables.ninja’ website (Pfenninger & Staffell, 2016) for the year 2021. The highest electricity output from solar panels occurs in the summer, with peaks from April to July. Winter months, from November to February, have the lowest solar electricity production, which aligns with the higher precipitation reducing efficiency during these months. Overall, the solar panels perform best in the summer and worst in the winter. This data with hourly resolution will be considered as an input for modelling section of this report.

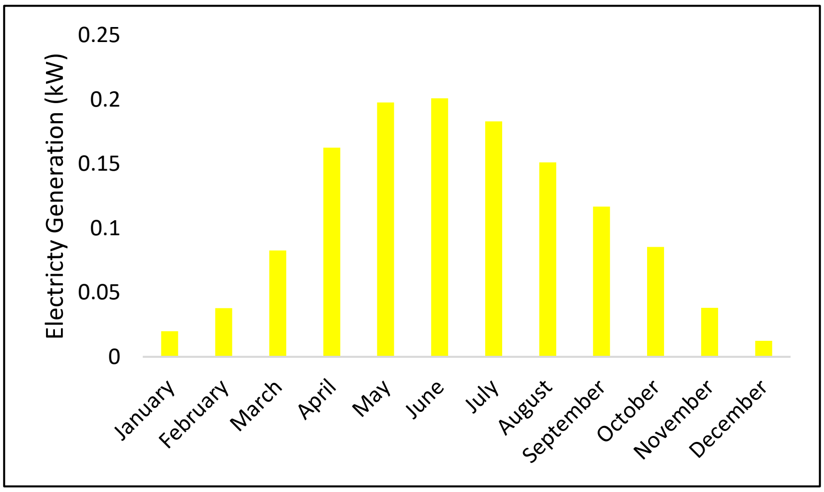


*Figure 5-2:Monthly solar PV electricity production for a 1kW capacity plant*
Source: renewables.ninja

### 5.1.3. Site Assessment

Several factors including economic, geographic, technical, social, and environmental aspects should be considered while conducting a detailed site assessment for solar PV power plant. For the case of Isle of Eigg, we have utilized 'QGIS' software and field research to review and analyse the suitability of potential locations. For this purpose, we have considered GHI (solargis, 2024), terrain slope (Pope, 2017), terrain aspect (Pope, 2017), and land cover (Space Intelligence and NatureScot, 2021) layers which have been depicted in Figures 5-2, 5-5, 5-6, and 5-7, respectively.

*Table 5-2: Criteria for PV site suitability*

| Factor | Unit | Criteria |
|---|---|---|
| GHI | kWh/m$^2$/year | Greater than 860 |
| Terrain Slope | ° | Less than 5 |
| Terrain Aspect | ° | South or South-East or South-West facing |
| Land Cover | - | Different types of grasslands |

Source: Almasad et. al, 2023 & Nebey et. Al, 2020

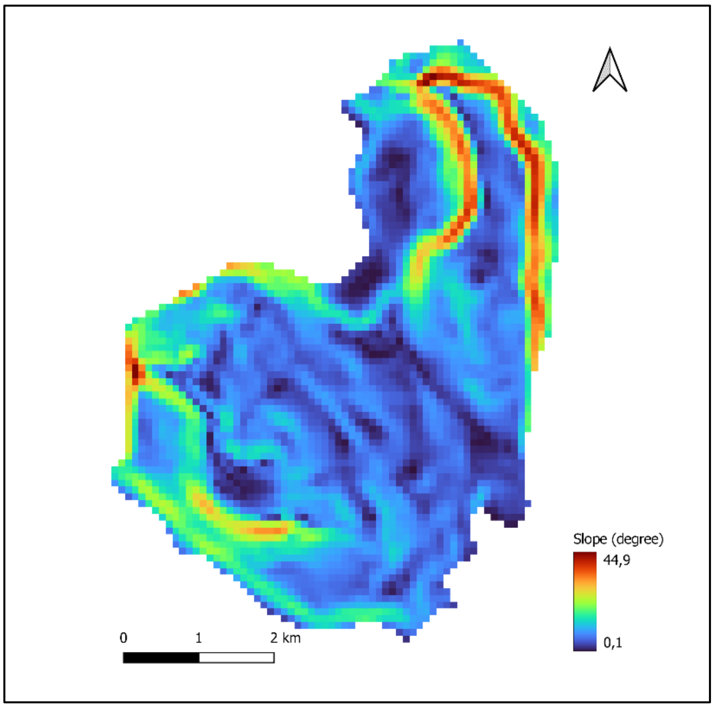


*Figure 5-5: Terrain slope in Isle of Eigg.*

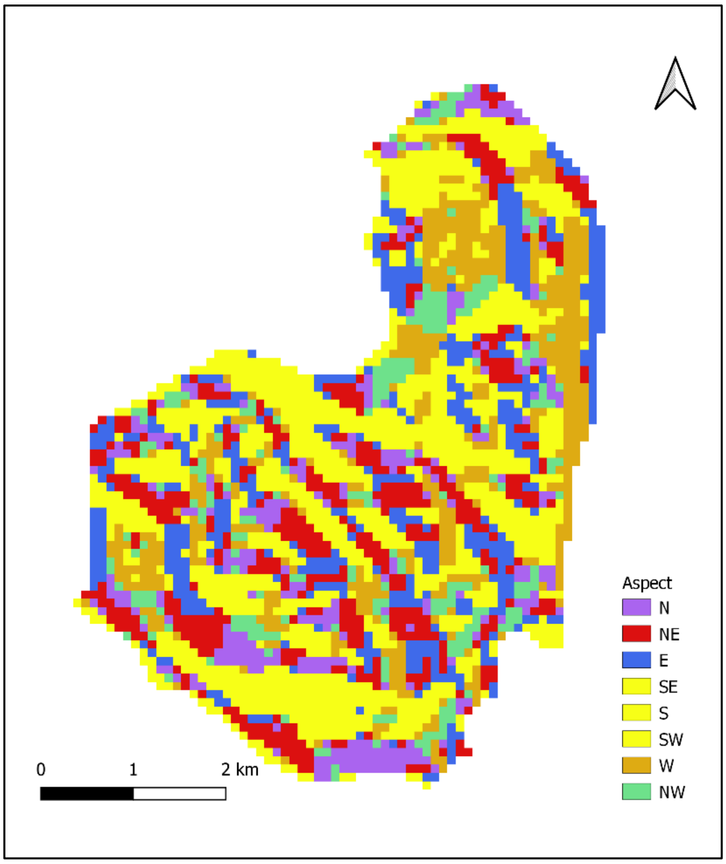


Figure 5-6: Terrain aspect in Isle of Eigg.

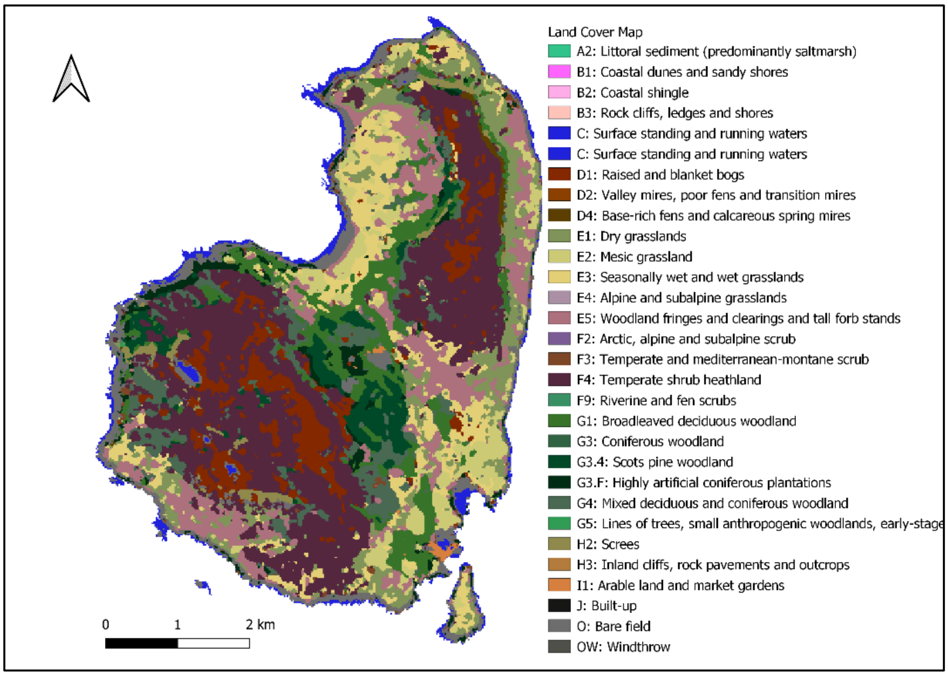


Figure 5-7: Land Cover map of Isle of Eigg

Each of these layers have been processed and refined in QGIS software for better visualization and further calculation to obtain solar suitability map. Table 5-2 shows the criteria for each of these parameters that will be considered to generate suitability map. The final suitability map has been generated in QGIS using raster calculator and considering all criteria (Figure 5-8).

*Figure 5-8: Solar PV suitability map in the Isle of Eigg*

As can be seen, we have added cable and transformer layers to the suitability map and displayed them on the OpenStreetMap for enhanced visualization. The suitable areas are depicted in yellow. Additionally, due to technical and economic considerations, areas close to the powerhouse are considered as the best options for installing new solar PV plants, as illustrated with the zoom tool in the Figure 5-8.

### 5.1.4. Financial Parameters

Table 5-4 shows the most important financial parameters of a solar PV plant on the Isle of Eigg to conduct further examination of pathway scenarios. The investment cost value is derived from discussion with Eigg Electric based on the values of recent real project in 2023 as described in Table 5-1. Based on the reports the fixed operation and maintenance costs for solar plants in the UK is 6000 £/MW/year (Department for Business, Energy & Industrial Strategy, 2023). According to this value and considering the yearly PV electricity generation on the Isle of Eigg, the variable costs being calculated.

*Table 5-3. Financial parameters for solar PV plant on the Isle of Eigg*

| Parameter | Value | Unit |
|---|---|---|
| Investment Cost | 510 | $/KW |
| Lifetime of New Capacity | 25 | Years |
| Variable Cost | 0.008 | $/kWh |

### 5.1.5. Solar Rooftop Systems Potential

Solar rooftop systems are one of the suitable options for households to generate electricity for either own use or grid export, and can assist them to be more self-sufficient, especially in remote areas. Currently, residents of the Isle of Eigg are not encouraged to install grid-connected roof-top solar panels; however, ongoing discussions indicate that plans and financing for the development of rooftop solar systems in this region might be applicable soon. Therefore, conducting a simulation for such a system can play a useful role in the decision-making.

Presently, there are around 64 households on Eigg which are not similar in terms of house area, roofing material, and orientation. As previously discussed, the orientation of solar panels plays a crucial role in absorbing maximum solar radiation. Based on the reviewing aerial photographs on Eigg (Bing Maps, n.d.), roughly 33% of homes face south, 52% face east or west, and the rest are in between. As it is not feasible to simulate all possible configurations for houses, we will first simulate a 3.15kW solar rooftop system on a south facing house with a tilt angle of 50° as modules will be installed parallel to a sample roof with the slope of 50°. The technical specification of the selected system is presented in Table 5-5, and a schematic of system along with electricity flow diagram has been shown in Figure 5-12. The average annual electricity demand for a single household is 2579 kWh per year based on the data and assumptions which are provided in the demand section of this report.

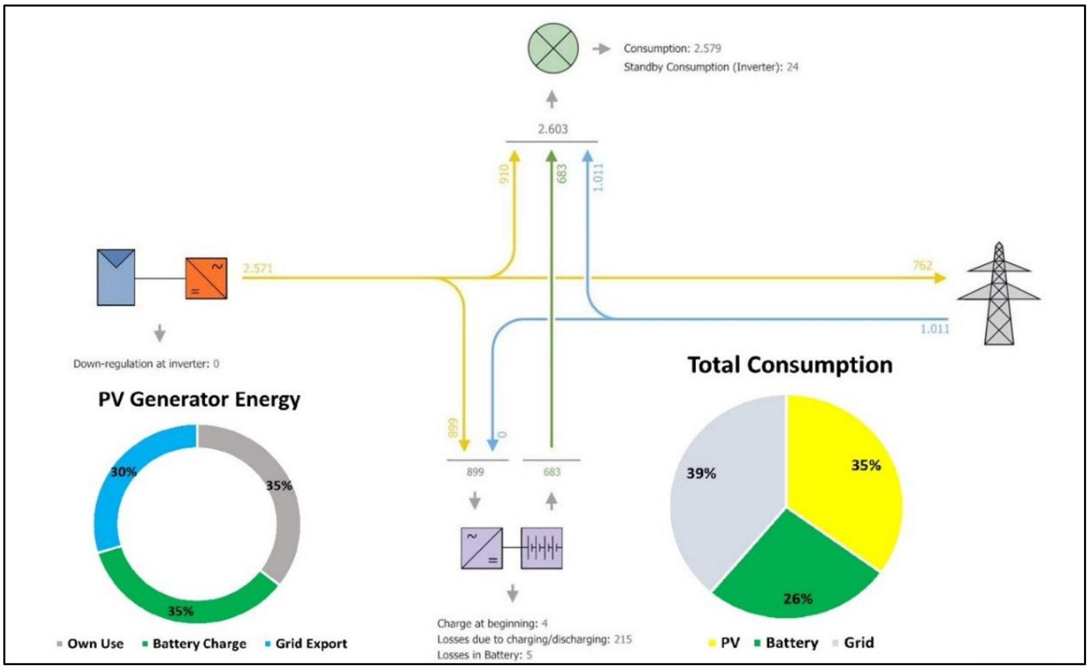


*Figure 5-9. Annual electricity flow diagram of the sample solar rooftop system on Eigg*
All values are in kWh. Source: PVSOL simulation result

*Table 5-4. Technical specification of the selected system*

| Item | Specification |
|---|---|
| PV Modules | 7 x Sample PV Module (450 W) |
| Inverter | 1 x Sample Inverter (3 kW) |
| Configuration | MPP 1: 1 x 7 |
| Battery | 1 x 4.4 kWh Sample Battery |
| PV Generator Surface | 15.2 m² |
| Battery Voltage | 48 V |

As depicted in Figure 5-9 around 61 % of total annual consumption can be supplied by solar PV as the battery is also completely charged by solar panels and does not receive any electricity from grid. Also, approximately 30% of PV generation could be exported to the grid. However, the PV performance is subjected to weather conditions and changes significantly throughout the year. Figure 5-10 demonstrates the PV system performance and its contribution to meet demand by considering battery storage and interactions with the grid. The annual specific yield of such a system is 808.40 kWh/kWp.

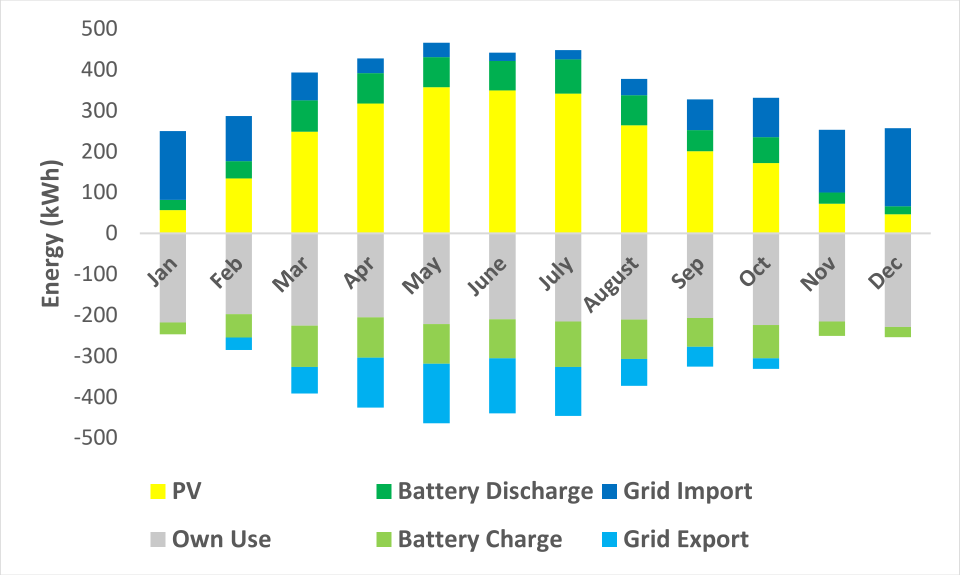


*Figure 5-10. Monthly performance of the sample solar rooftop system on Eigg*
Source: PVSOL simulation result

The chart shows a fluctuating pattern of energy production throughout the year. In months like April, May, June, and July, solar production is high, resulting in a significant amount of solar energy being consumed in household and some share of grid exporting as indicated by the light blue sections at the bottom of the columns. In contrast, during the months of November, December, January, and February, solar energy production is lower, and consumption from the grid is higher as indicated by the dark blue sections. It is important to note that some of the energy produced by the solar panels is stored in batteries as depicted by the light green sections, which can then be used to cover consumption needs as shown in dark green sections. As shown in the chart, the battery system is more active during summer.

As previously discussed, the annual yield of PV system is highly dependent on modules orientation. To compare performance of PV systems in different house orientations, we altered panel facing towards different directions and compared the general annual results in Figure 5-11.

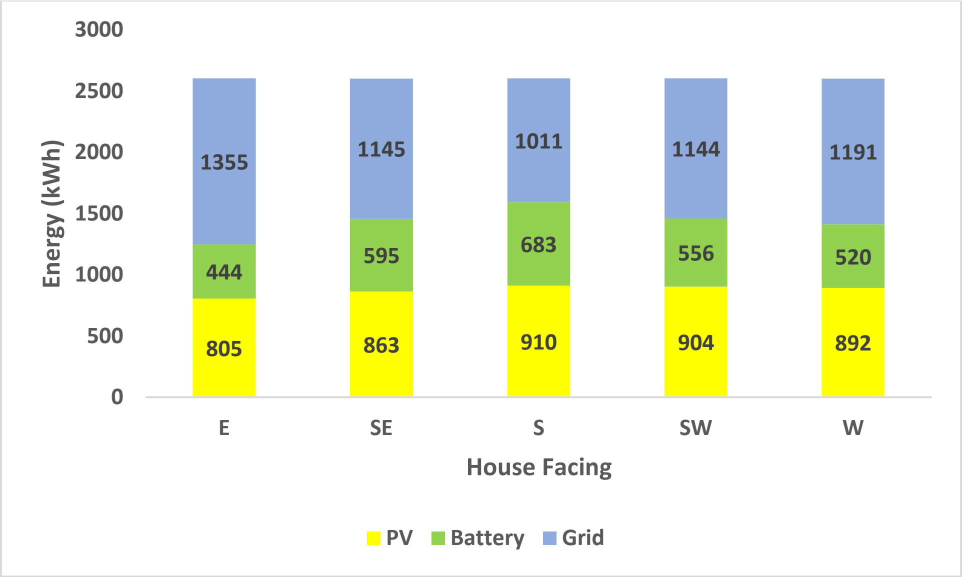


*Figure 5-11. Comparison between different house direction in terms of source of energy consumption.*

As can be observed, maximum PV generation is achieved with south-facing panels. There is minimal difference between panels facing south, southeast, or southwest. For east and west-facing panels, it is advisable to install modules on both sides of the rooftop to maximize energy absorption year-round. In this case, an inverter with 2 MPPTs is required. The analysis suggests that installing rooftop solar systems could offer advantages and challenges. On one hand, such installations could significantly enhance self-sufficiency for households on Eigg, especially during the summer. However, in winter, when energy demand also increases, the potential for solar to supply household energy needs decreases markedly. Additionally, the possibility of exporting electricity to the grid, typically during summer, may lessen with decreasing the demand of whole Island which means the grid might not require as much supply from rooftop solar systems. Another challenge is the varying directions of houses, which lead to different electricity generation levels for each household. Therefore, these factors should all be considered when considering the installation of such systems.

## 5.2. Wind Energy

This part is dedicated to exploring the existing wind generation on the island and evaluating the potential for expansion through the installation of new wind turbines. The current generation profile will be generated utilising specifications from the existing turbines and weather data. Additionally, the geographical data and wind resources will be analysed to assess the viability of installing new turbines. This assessment will include the identification of a suitable location for new turbines considering the technical aspects of connecting them to the current power system.

It is essential to note that Eigg Electric has already chosen a specific type of wind turbine for their power system. Considering this predetermined turbine a generation profile was calculated. The profile aims to serve as the basis for optimization in the energy model, allowing us to determine the required number of wind turbines in alignment with the power system demand.

### 5.2.1. Explore the Generation by Existing Wind Turbines on the Island

Since 2008, the Eigg power system has been using four identical wind turbines for electricity generation, each with a capacity of 6kW , a hub height of 15m, and a rotor diameter of 5.5m (Eigg Electric 2008). Due to the unavailability of annual hourly generation data from the wind turbines through the sunny portal system, WindPro software was employed to simulate the existing wind turbines' generation. To facilitate this simulation, wind data encompassing wind speed, turbulence, temperature, and pressure for the designated turbine area in 2021 was imported. Additionally, landscape data, incorporating roughness area and elevation, was imported, and subsequently modified for the site. The figure below illustrates the electricity generation from the four wind turbines in 2021.

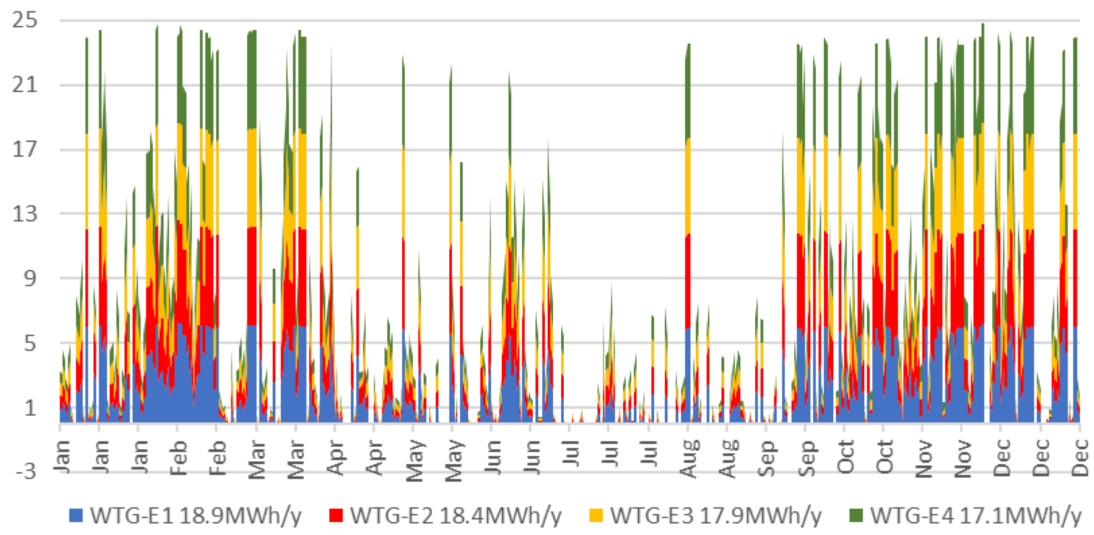


*Figure 5-3 electricity generation from existing four wind turbines for 2021*
Source: WindPro data

The figure reveals a high fluctuation in generation, higher generation in winter and spring, and lower in summer and autumn. The profile also shows 5% annually higher generation from WTG-E1 (west WT) compared to the WTG-E4 (east WT), see the table below. Site visits from the control room of wind turbines have been conducted, and the hourly differences between the turbines were higher than the annual output. Part of the difference in generation could be explained by the influence of the wake effect or the complexity of the terrain on the wind resource. Since the turbines are located in one row, perpendicular to the prevailing wind direction, as well as adequately distanced at 6 times rotor diameter, the reason might be due to the existence of a small hill in the north area of WTG-E1.

Since a detailed analysis of the wind turbine performance in such a complex terrain necessitates a sophisticated numerical analysis like Computational Fluid Dynamics (CFD), which is beyond the scope of this project, a simplified approach was adopted. Using the linear flow model of the WindPro software, the existing hill was removed to demonstrate the effect of the hill on the wind turbines' performance. The results of this comparison are presented in the table below.

*Table 5-5. Comparison of existing Wind Turbines generation in different terrain*

|  | Total | WTG-1 | WTG-2 | WTG-3 | WTG-4 |
|---|---|---|---|---|---|
| Terrain type | MWh/year | MWh/year | MWh/year | MWh/year | MWh/year |
| With Hill | 72.6 | 19.0 | 18.5 | 17.2 | 17.9 |
| No Hill | 71.5 | 19.0 | 18.3 | 16.8 | 17.5 |

As evident from the data, the presence of the hill in front of WTG-1 has a positive impact on the performance of the three turbines, while it does not affect WTG-1, which is situated in front of the hill. Higher accuracy of these findings requires a Computational Fluid Dynamics (CFD) analysis. An in-depth analysis could not only validate the observed outcomes but also provide insights into the reasons behind this discrepancy, necessitating a comprehensive assessment. Many individual studies conducted to explore the effect of complex terrain on wind turbines performance, for instance; Ann Hyvärinen and Antonio Segalini mentioned in their article that “the introduced hills have a positive impact on the wind-turbine performance and that wake-interaction effects are significantly reduced during turbulent inflow conditions” (Hyvärinen and Segalini 2017).

Furthermore, regarding the technical aspects of the existing wind turbines, each turbine is connected to a 6kW inverter, and collectively connected to a 75kVA transformer. Additionally, given the wind turbines' nearly 14 years of operation, the remaining life is assumed to be no more than six years, after which parts of the turbines will have to be replaced.

### 5.2.2. Potential for the Expansion of Wind Energy

#### *5.2.2.1. Geographical wind data analysis*

To analyse the wind energy potential across the Isle of Eigg, an assessment of the wind power density maps is essential. A wind power density map gives a reasonably accurate indication of the available wind resource (GWA 2024). This data illustrates the distribution of wind energy potential across the island, with a selected hub height of 50m, which is near the predetermined hub height of the wind turbine at 38m. Additionally, high-resolution terrain data from Great Britain’s Geospatial Data platform, offering an elevation layer with 10m equidistance for each line, is utilized to gain a clear understanding of the Isle's topography (Ordnance Survey 2024). Figure below displays the wind energy distribution and elevation characteristics for Eigg Island.

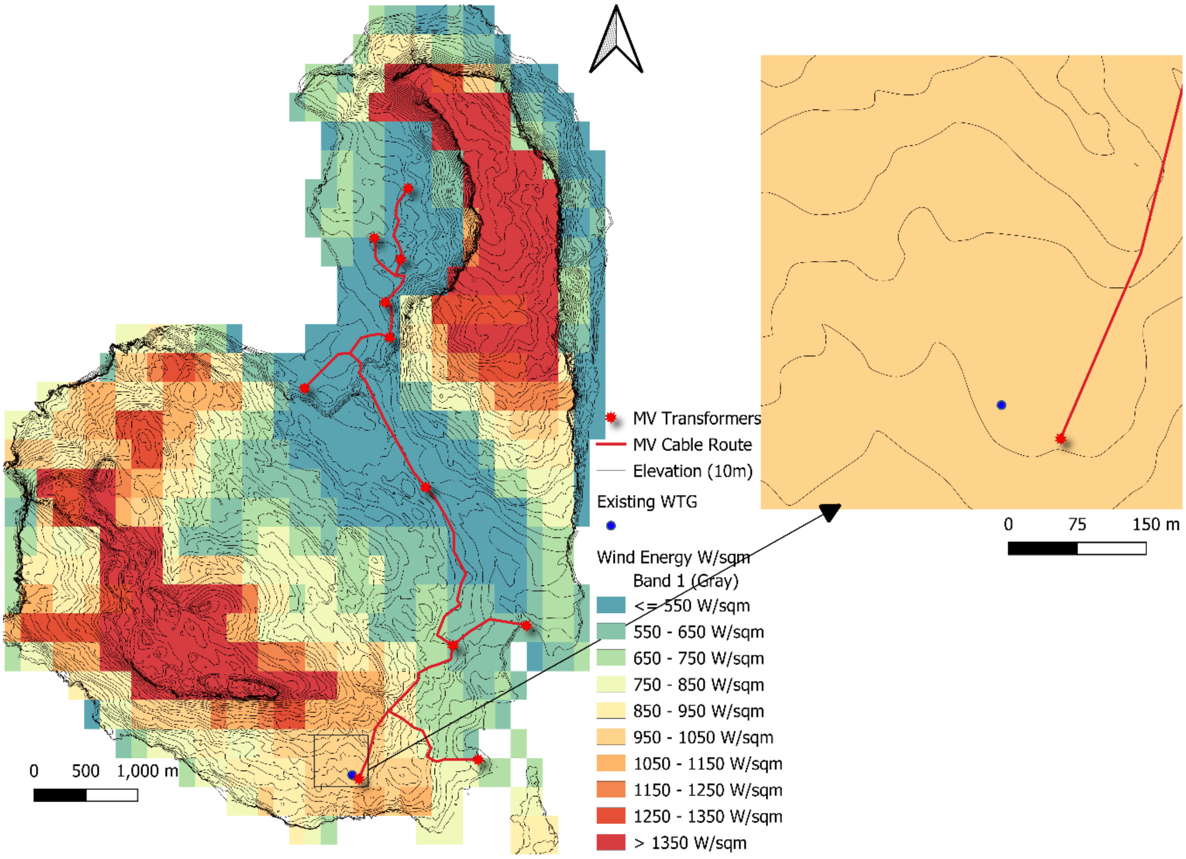


*Figure 5-4. wind energy distribution and elevation characteristics of the Isle of Eigg*
Data Sources: GWA; Ordnance Survey; Eigg Electric

The map highlights the higher potential of wind energy in the north, west, and south regions, characterized by mountainous terrain and higher altitudes, consequently featuring a greater wind energy potential. In the north and west, the high wind potential is situated at the mountain's peak, posing challenges for installation, maintenance, and operation due to unavailability of access roads. Moreover, these areas are far from the current power infrastructure.

In the south region, where the existing wind turbines are located, there is already a demonstrated wind energy potential of around 1000 W/m$^2$ and a mean wind speed of approximately 8.5 m/s. The area is already near the power system infrastructure. Additionally, since the area is occupied by wind turbines, it will be more acceptable to the island's community.

As observed, the roughness type of the area is open terrain covered with grass. This characteristic defines the roughness class of the area as 3 with a length of 0.03m (Linacre & Geerts 2023). Since the nearest building is located 430m away from the selected turbine location, WindPro was employed for shadow and noise analysis. The conducted analysis revealed that the house is not affected by either the shadow or the noise generated by the turbines.

#### 5.2.2.2. Wind Time series data analysis:

The next step involves the utilization of WindPro software to generate time series of wind resource data and model the energy output. For this purpose, mesoscale data from the EMD-WRF dataset, specifically generated for the southern part of the isle, was selected. The mesoscale model data offer a numerical weather prediction model that simulates atmospheric conditions on a mesoscale, typically covering a regional or local area, providing information on wind speed, wind direction, temperature, and turbulence intensity. The authoritative data for this project spans over the past 24 years, with the data from 2021 being utilized to align the time series with demand and other technologies. The data presents a spatial resolution of 3x3 km with an hourly temporal resolution (EMD 2023).

Analysing the past 24 years' wind speed data reveals an average wind speed of 8.6 m/s at a hub height of 38m, along with an average turbulence intensity of 9%. According to the International Electrotechnical Commission (IEC) 61400 standard, wind speeds of 8.5 m/s and turbulence intensity below 16% classify the area as IEC class II/b (IEC 2008). This classification is crucial for wind turbine selection. It seems that the characteristics of the NPS Northern Power wind turbine selected by Eigg Electric, as shown in the table below, meet the requirements of the wind class of the selected area.

*Table 5-6. Selected Wind Turbine Characteristics*

| Description | Rated Power | Rotor Diameter | Hub Hight | WT Class | Cut-in/out/rated /extreme | Noise level |
|---|---|---|---|---|---|---|
| | kW | m | m | IEC 61400-1 | m/s | dBa |
| NPS 100C-21 | 100 | 21 | 38 | II/A | 3/25/12-15/59.5 | 50 |

To strategically position the wind turbines, it is essential to analyse the wind rose diagram. Figure 3 shows an hourly rose diagram illustrating the frequency and energy distribution of wind in various directions.

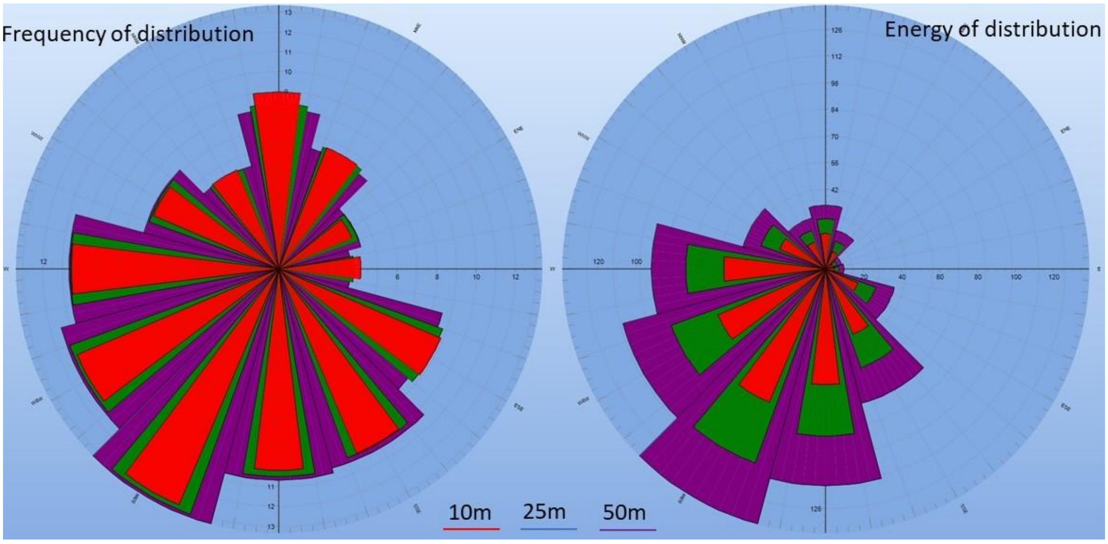


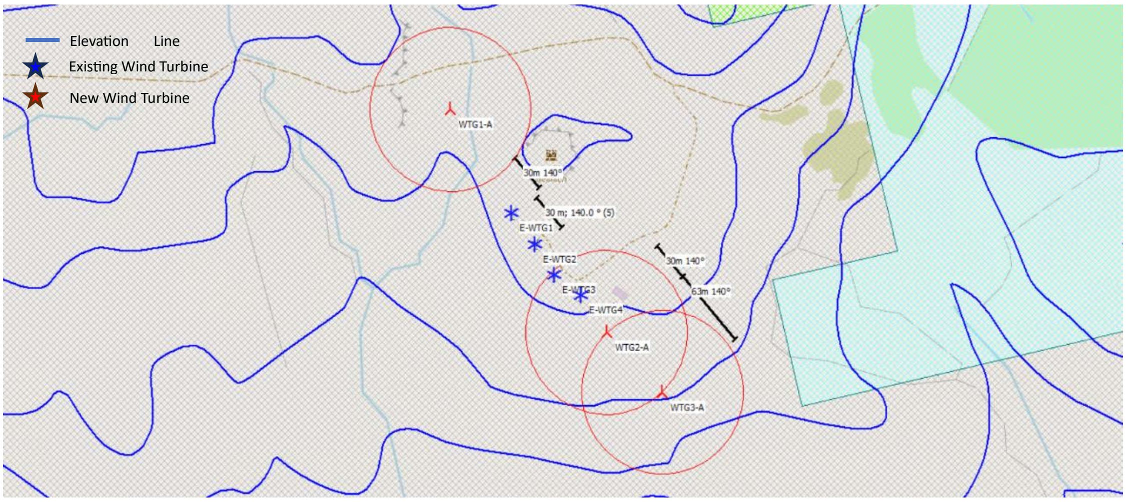
*Figure 5-5. wind energy distribution and elevation characteristics of the Isle of Eigg*
Source: WindPro

The rose distribution diagram reveals that the highest wind energy mostly comes from the range of south to west by higher potential from southwest. Although the blade face automatically aligns with the wind direction, understanding the wind direction is crucial for arranging the wind turbines at the correct angle and considering required distances between wind turbines in a row as a group. This helps to minimize the wake effect and optimizes energy production. The distance between wind turbines may vary depending on the wind direction. If the wind is perpendicular to the row of turbines, the distance could be reduced to three to five times the rotor diameter. However, if turbines are installed downstream, this distance may increase to ten times (Daphne Schwanz 2012).

In further step the new wind turbines arranged in a group of three wind turbines to generate per unit generation profile. The number of turbines is subject to the on-going decision process of Eigg Electric and subject to the conducted Feasibility Study for Phase 2 of Eigg's Decarbonization by 2030 report (Russet Engineering 2023). The final number of wind turbine will be modified considering the optimization result. Different arrangements have been examined to find out the most suitable location by having higher annual generation for the wind turbines. Below the most suitable location for three wind turbines according to the landscape and wind data resources.

In the selected area for wind turbines, the focus is on choosing a location with more open space, minimal terrain impact, and minimal interference with the performance of existing wind turbines. With the necessary location and the wind resource data, the average generation profiles for each month over the past 22 years has been generated and illustrated in the figure below.

*Figure 5-6. Arrangement of the wind turbines (including the altitude and roughness data map)*



Source: WindPro

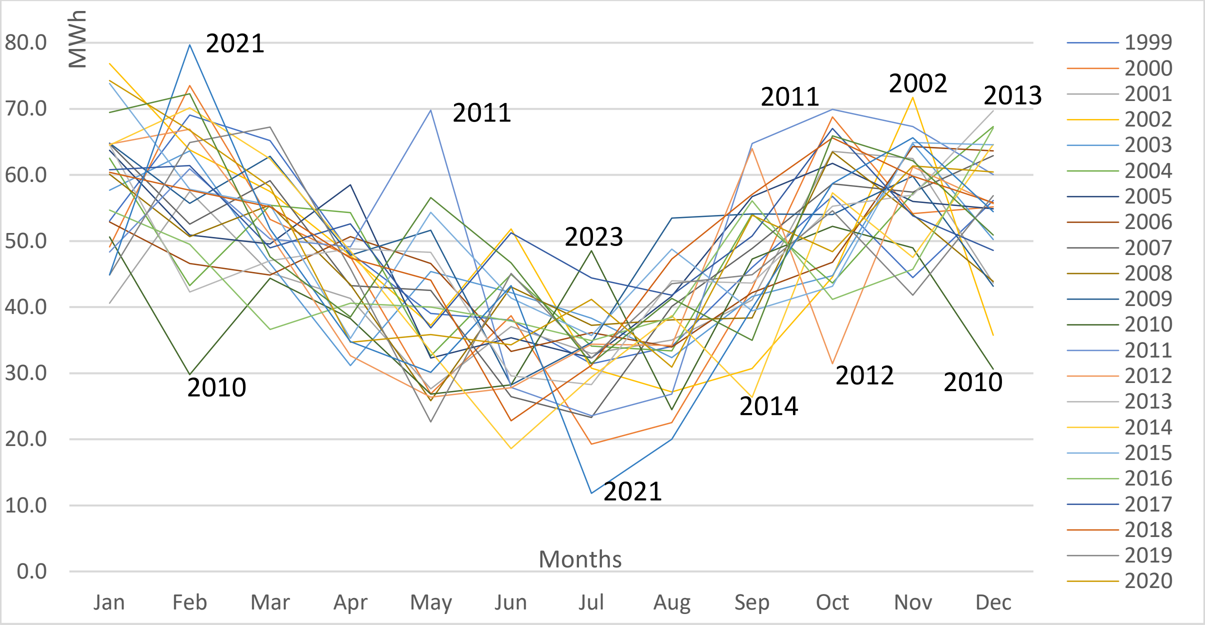


*Figure 5-7. Monthly hourly average wind energy generation from 1999-2022 for Isle of Eigg*
Source: WindPro data

The graph depicts a consistent pattern of wind energy generation over the years, with higher output during winter and spring and lower output in summer. There are also variations in total annual generation, with the lowest recorded in 2010 and the highest in 2022 which has been shown in below graph.

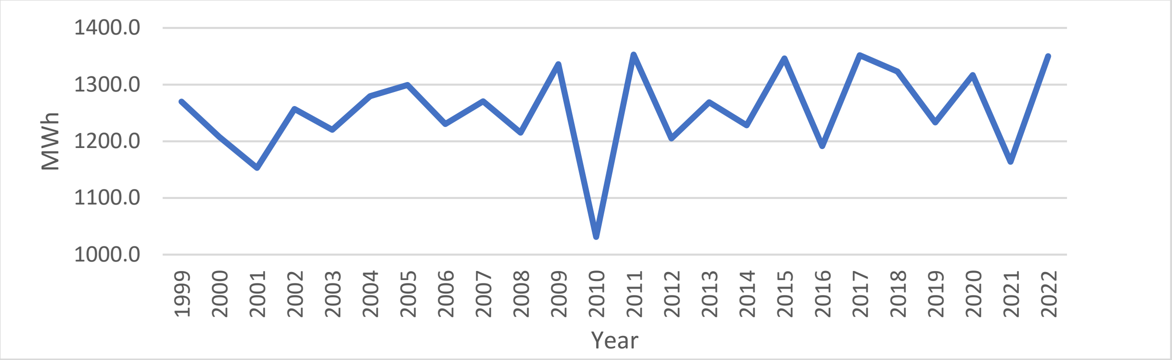


*Figure 5-8. Annual wind energy generation from 1999 to 2022*
Data source: WindPro

To ensure consistency with other renewable energy sources and demand, the data from the year 2021 has been chosen for further optimization. The annual generation for the selected data is 1.164 GWh, which is 8% lower than the total annual average generation for past 22 years, which is 1.2 GWh. This decision is based on its representation of the average generation across all available data and its alignment with the variation profile of solar generation since It is crucial to consider the relationship between wind and solar energy when selecting the year to maintain practicality and coherence in the data. The below figure shows the monthly generation of single selected wind turbine for 2021.

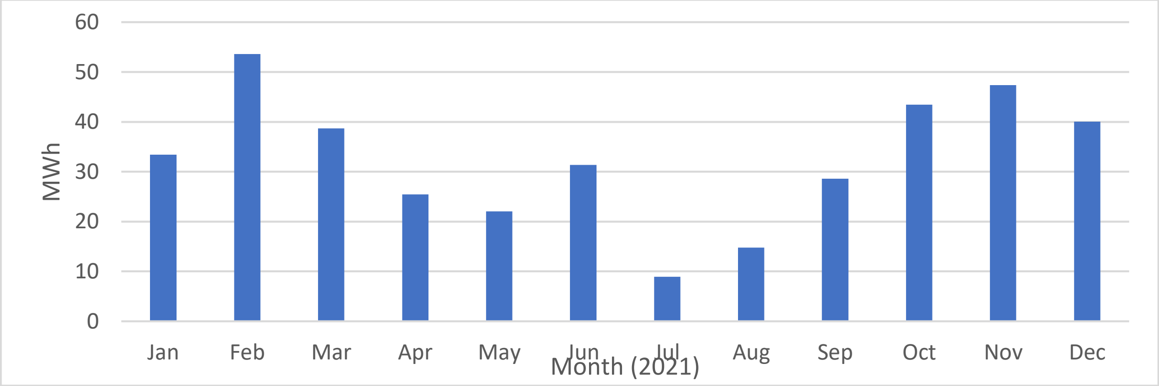


*Figure 5-9. Monthly wind energy generation for 2021*

It appears that the generation during April, May, July, and August in 2021 is less compared to the other months. This lack of generation could be covered by production from solar energy, which is higher for this year during these months. The annual generation from the selected wind turbine for the year 2021 is 387 MWh, and the capacity factor calculated is 42%.

### *5.2.3. Financial Analysis*

To analyse the financial aspects of the wind turbine, the investment cost, including the turbine and its installation, is required. According to the IRENA Renewable Power Generation Cost in 2022 (IRENA, 2022), the average cost of an onshore wind turbine with a capacity range of capacity of 2MW to 4.8

MW in class II is between 840 to 1175 USD/kW. The average total installed cost for the United Kingdom is 1274 USD/kW. Additionally, a 10% extra cost has been assumed due to the selected wind turbine having a lower capacity, resulting in a higher cost compared to larger wind turbines. This leads to a total cost of 2693 USD/kW.

Additionally, as per the Electricity Generation Cost 2023 report from the Department for Energy Security & Net Zero, the variable operation cost of the wind turbine is stated as zero (Department for Energy Security and Net Zero). However, to account for fixed annual costs, including maintenance and operation costs, these have been converted to variable costs, with a fixed cost of $32.3 per kW per year. This has been done using the formula below:

$$
\begin{aligned}
Variable\ cost\ \left[\frac{\$}{kWh}\right] \\
&= fixed\ cost\ \left[\frac{\$}{kW * year}\right] \\
&* Wind\ turbine\ capacity[kW]/\ Annual\ generation\ [kWh/year]
\end{aligned}
$$

*Equation 5-1. Variable cost calculation formula*

Considering this information and the wind turbine specifications, the table below illustrates the cost analysis of the selected wind turbine (IRENA 2022; Department for Energy Security and Net Zero).

*Table 5-7. Cost analysis of selected wind turbine*

| Total Investment Cost | Wind Turbine Lifetime | Annual Generation (2021) | Fixed O&M cost | Variable Cost |
|---|---|---|---|---|
| USD/kW | Year | kWh/Year | USD/kW/year | USD/kWh |
| 2693.9 | 20 | 390000 | 32.258 | 0.008 |

## 5.3. Tidal Energy

Tidal energy has been identified as a renewable resource that follows a distinct pattern and therefore is easier to predict, unlike solar and wind energy. In comparison to wind energy, tidal flow has a higher density and can produce more power with the same rotor size. Tidal energy is the energy generated by the to-and-fro motion of the tides. These flows are caused by the centrifugal and gravitational forces acting on the Earth, Moon, and Sun, which cause periodic motions of water known as tides (Shetty and Priyam 2022).

Technologies commonly employed for ocean or tidal energy include tidal ranges, tidal currents or streams, and waves. Firstly, a tidal barrage, is a dam built in a bay with a tidal range typically in excess of 5 m (Etemadi et al. 2011). Secondly, tidal current and tidal stream technologies use kinetic energy to generate usable energy. Tidal stream technologies also come in a variety of designs, including hydrofoil-shaped, enclosed turbines, and horizontal or vertical axis cross-flow turbines. Lastly, wave technology uses a wave energy converter (WEC) machine to capture and convert electricity (IRENA 2021b).

### 5.3.1. Tidal Energy Potential

Scotland is at the forefront of tidal energy potential, with 10% of Europe's tide resources located here (Lizzie Stevens 2021). The opportunity to develop tidal energy in the UK is high. In 2020, the UK planned six tidal stream projects between 2021 to 2026. The map below shows Scotland's average tidal energy power potential.

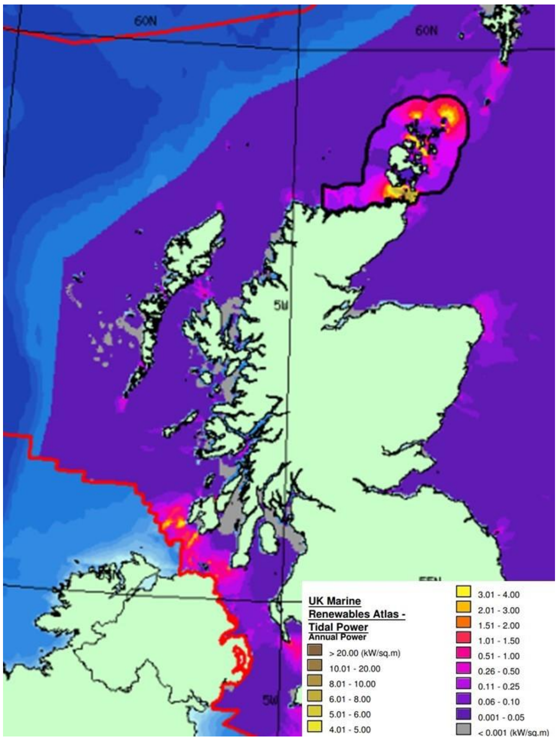


*Figure 5-11 Average Tidal Energy Power Maps*
Source: UK Renewable Atlas, 2024

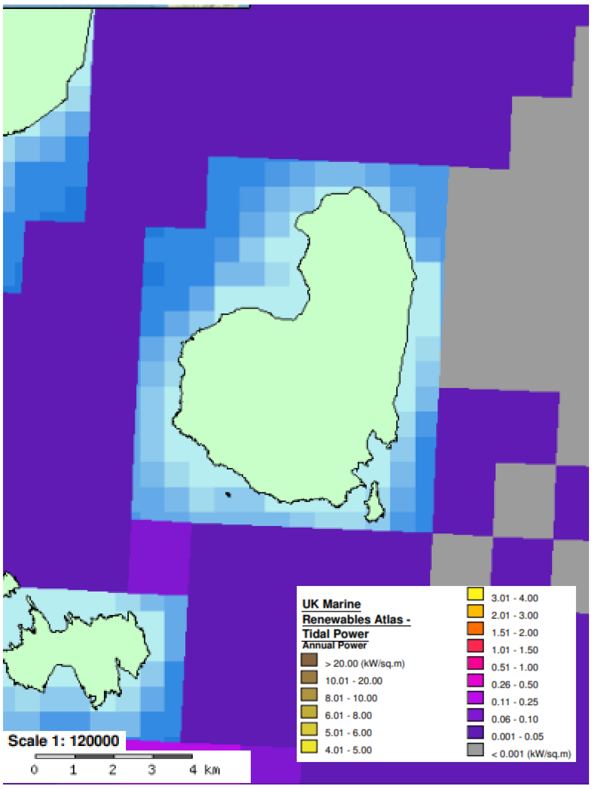


*Figure 5-10. Average Tidal Energy Power Maps on The Isle of Eigg*
Source: UK Renewable Atlas, 2024

The figure above shows the average tidal power potential on the Isle of Eigg with the highest tidal power on the island is 0.11 to 0.25 kW/m$^2$. Due to high environmental impact, we are excluding the tidal barrage technology and will focus on tidal stream only. Tidal barrage remains the most widely used technology in the UK, but tidal stream and wave technology is starting to take the lead (IRENA 2021a).

Considering spring (half-daily of the largest range) and neap (half-daily of the smallest range) peak flow for determining the potential location of tidal energy, especially for tidal streams, the highest mean spring peak flow accounted of 0.84 m/s on the southwest of Eigg. In the same location, the highest mean neap flow showed 0.36 m/s and the average water depth is 10 m (UK Renewable Atlas 2024).

### 5.3.2. Estimation of Tidal Potential

According to a study conducted by the University of Strathclyde, there are some specific locations on the island that could be analysed. The tidal types featured in this study are streams and barrages (Mundie, et.al., 2016). Tidal energy has received more attention in recent years because there are many places in the world with high potential. Barrages often involve the construction of a dam and, consequently, an alteration of the ecosystem. Therefore, only the latter type will be evaluated in this report. The stream turbine is quite like a wind turbine and one advantage of extracting energy from tidal is that since water has a higher density than air, the energy that can be generated from the tide is also higher per unit of rotor area.

To calculate the potential, some parameters are needed. There are approximately two tidal periods per day (12.40 hours each) and there are about twelve lunar phases during the year. In addition, the amplitude and speed of the tidal current are also needed. To estimate the power generation (P) the following formula will be used.

$$P = 0.5 * Cp * \rho * A * v\^{}3$$

*Equation 5-2 Power generation formula for tidal energy potential*

From the formula, current speed v has a significant effect on power generation P as it is expressed to the power of 3.

For a current turbine, typical values of the Power Coefficient (Cp) are between 0.2 and 0.35, for this specific calculation the lowest value will be considered (Ocean Energy Council 2018) The density of seawater (ρ) is 1027 kg/m3 and the area (A) corresponds to the dimensions of the selected turbine passage area. In the study conducted by the University of Strathclyde, after comparing different types of steam turbines, the "Oryon Watermill" was considered to be one of the most suitable. It has a nominal power of 50 kW, a vertical shaft, a diameter of 6 m and a height of 3 m. With these values, to facilitate the estimations, a cross-sectional area of 18 m2 is considered. The current velocity (v) is estimated considering the tidal period, the wave amplitude, and the specific time of day. As mentioned before, once the calculations for the first 28 days have been made, the results will be repeated until a full year's data set has been completed in an hourly resolution.

Here it is assumed that there are no significant differences when there is spring and neap tide, which occur twice each month.

Using the calculated values of current velocity from the study of the University of Strathclyde, the maximum value of this parameter is 1.2 m/s (Mundie, A., Haughey, S., Marshall J., Berbass, S 2016). However, the minimum value for a current to be considered as having adequate potential is 2.5 m/s. From this speed, turbines become economically feasible (Great Western Power Barrage 2024). The maximum stream speed needs to be twice as much to reach the minimum recommended, and it would also suppose an increase of around 9 times the amount of power generated.

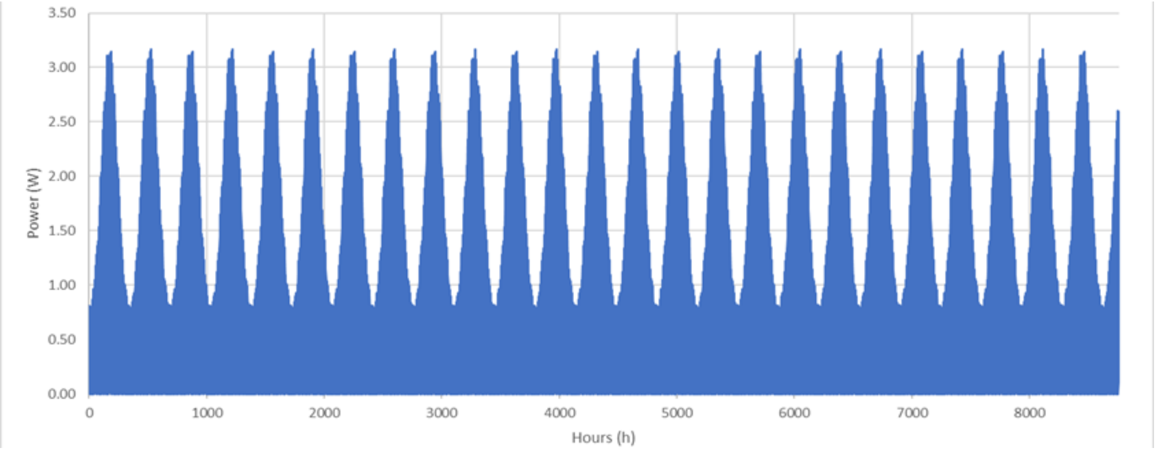


*Figure 5-12. Tidal potential for a single stream turbine*

The graph shows that the peak tidal power is 3.17 kW, which represents only 6% of the rated capacity. Even if there is a pattern and predictability of generation, its adequacy will be determined in the economic evaluation.

### 5.3.3. Financial Parameters

It is important to mention that the industrial development of tidal energy has been relatively slow compared to other renewable energy technologies. Therefore, the estimation of investment, operation, and maintenance costs of the ocean technologies is highly uncertain (IEA 2010). The current investment cost of tidal energy is about 3600 $/kW with a lifetime of 25 years (Energy Data Expert 2023). The table below shows the financial parameters of tidal energy.

*Table 5-8. Financial Parameters of Tidal Energy on the Isle of Eigg*

| Parameters | Value | Unit |
|---|---|---|
| Stream Turbine “Oryon Watermill” | 50 | kW |
| Investment cost | 3600 | $/kW |
| Lifetime of new capacity | 25 | Years |
| Variable cost | 0.0645 | $/kWh |

One of the reasons why tidal power has not been deployed at many potential sites is that, unlike solar or wind, tidal turbines are not manufactured on an industrial scale and there is not much research conducted about this topic. This means that costs remain high and are not expected to decrease significantly in the coming years. In addition, maintenance costs are higher than those of a wind turbine due to rust or debris (Ross Jennings 2015). Certain specific conditions must also be considered for the realization of tidal projects. Particularly, in the case of the Isle of Eigg, the potential generation is constrained by the slow current speed, consequently, decreasing the energy generation.

## 5.4. Hydropower System

Hydropower is an important source of renewable energy and a reliable generation technology. As of 2022, it held the title of the most widely deployed renewable energy source globally, as reported by the International Renewable Energy Agency (IRENA 2022). Beyond its renewable status, hydropower offers a dual advantage: it provides electricity at a comparatively low cost while concurrently providing a valuable source of flexibility to energy grids.

Hydropower plants generate energy by the usage of the flow of water, by utilizing turbines to convert the kinetic energy of flowing water and the potential energy from differences in height into electricity.

### 5.4.1. Overview of the current hydropower system

On the island, the hydroelectric infrastructure uses three generators, contributing to an average of 66% of the region's energy production during the period from 2009 to 2023. Among these, the largest hydro generator, stationed in Laig, has a capacity of 100 kW. In addition, the Kildonan hydro and Pier hydro generators each possess a capacity of 6 kW (Eigg Electric line drawing), These hydro generators play a vital role in meeting the daily electricity needs of the island's residents and businesses.

From 2009 to 2023, hydropower consistently played a significant role in energy production within the region, during this period the data indicates varying levels of hydropower generation each year, with percentages ranging from 50% to 86%. With a yearly generation ranging from 137,962 kWh in 2023 and 494,911 kWh in 2016. (Eigg Electric Generation 2007-2024)

Despite these fluctuations, hydropower remains an important source of energy, contributing to the energy mix of the island.

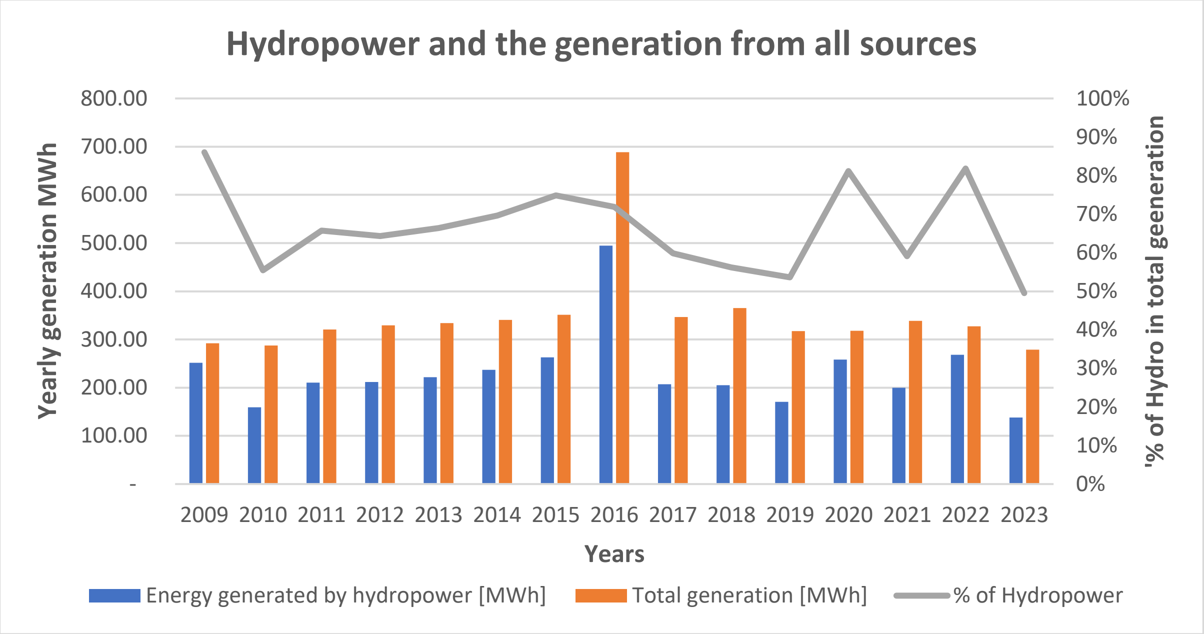


*Figure 5-13 Hydropower generation and the energy generation from the other sources*

*Table 5-9. Characteristic of the current Micro hydro plant*

| Capacity | Lifetime | Investment Cost |
|---|---|---|
| kW | Year | USD/kW |
| 100 | 60 | 5629.46 |

The hydropower generation system on the island has a projected lifetime of 60 years, this system offers long-term sustainability and resilience in energy production. The investment costs for this hydro system amount to $5,629.46 per kW (IRENA 2022, 2022).

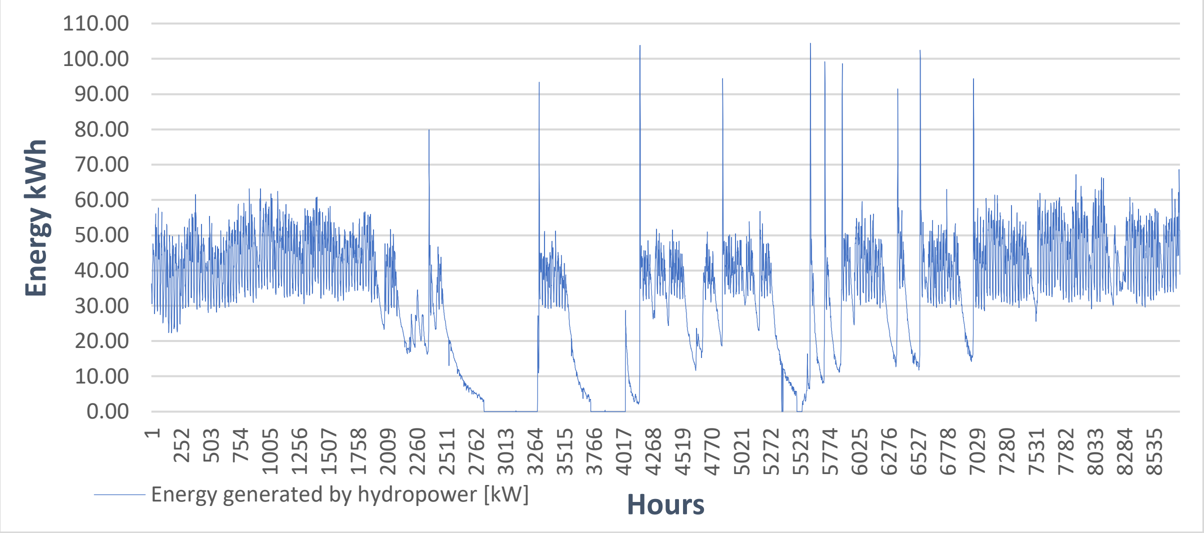


*Figure 5-14. Yearly energy generation from Hydro in 2020*

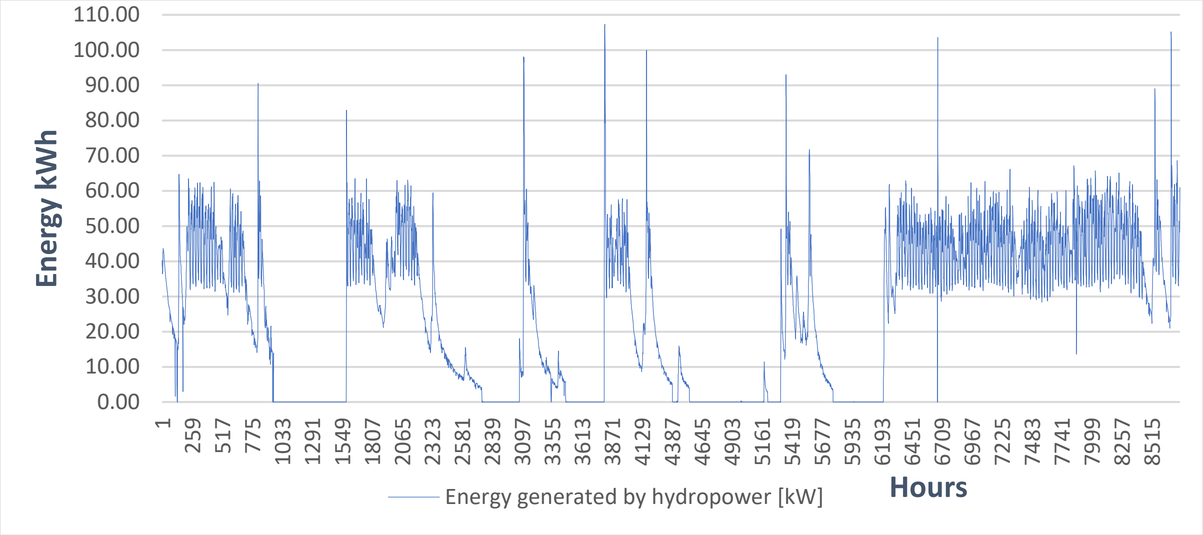


*Figure 5-15. Yearly energy generation from Hydro in 2021*

Analysing the data from 2020 and 2021, a noticeable seasonal effect is shown, with hydropower generation exhibiting more stability during the autumn and winter periods, in opposite to the spring and summer seasons where an increased fluctuations can be noticed, with the possibility of no energy output from hydro during extended periods.

### 5.4.2. Hydropower System Upgrade

Loch Beinn Tighe, a lake spanning 8 hectares and 15 hectares in total with the surrounding areas, can be connected to the 100-kW hydro generator located in Laig. By connecting this lake, the annual energy production may be expanded by roughly 10% by the increase in water flow.

Water flow on the island is closely tied to precipitation levels. The chart below illustrates the hourly precipitation fluctuations throughout the year 2021, with the highest recorded value being 5mm in a single hour (Renewable.ninja 2024).

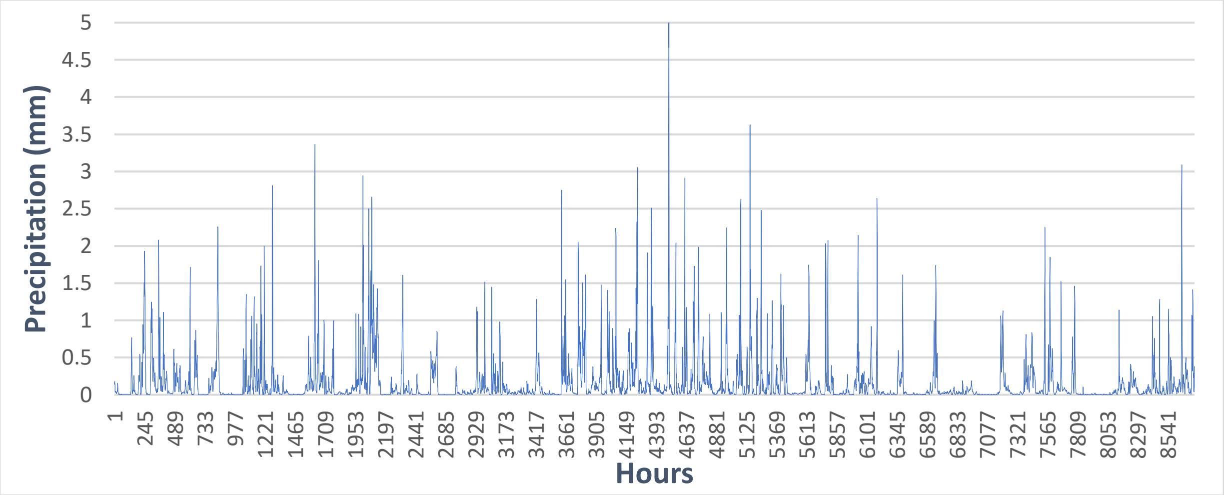


*Figure 5-16. Yearly Precipitation in 2021*

Taking into consideration the previous chart, the annual volume of water in 2021 has been calculated using the following formula:

$$Water\ runoff\ in\ Loch\ beinn\ tighe\ (m3) = \frac{Precipitation\ (mm\ /\ hour)}{1000} * The\ total\ surface\ (m^2)$$

*Equation 5-3. formula for Annual volume of water*

Considering a total additional catchment area of 0.184 km² which represents the surface of the lake in addition to the surrounding surfaces, the total additional water runoff in 2021 was 266,211 $m^3$.

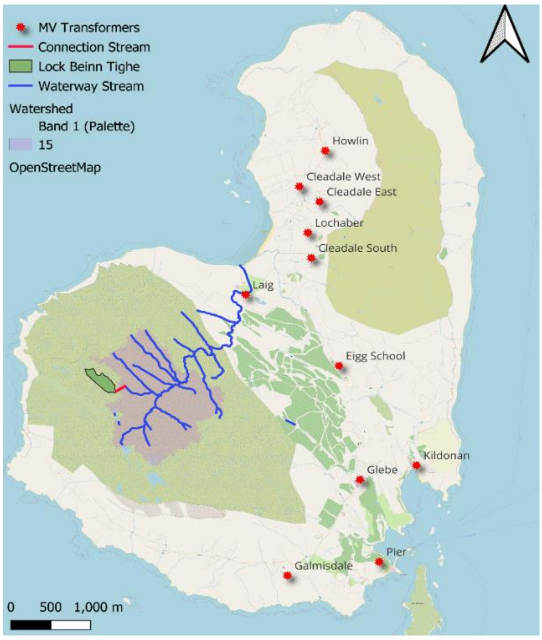


*Figure 5-17. connecting the lake Beinn Tighe with the hydro generator*

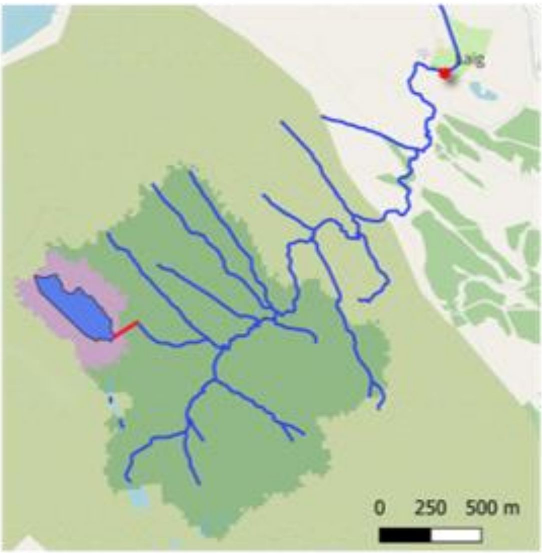


*Figure 5-30 The additional catchment area highlighted on the map*

As shown in the figures above, the lake of Loch Beinn Tighe can be connected with the hydro generator in Laig through a channel for a distance of 400 to 500m that connects the lake to the stream Abhainn Gleann; By connecting the lake with the hydro generator at Laig, an increase in energy generation by 10% is expected according to the increase in water runoff and the flow that goes through Laig hydro system. Translated to, the numbers generated for the year 2021, yearly energy generation of 311 MWh/year may be achieved. The chart below shows the forecast of the hourly power generation.

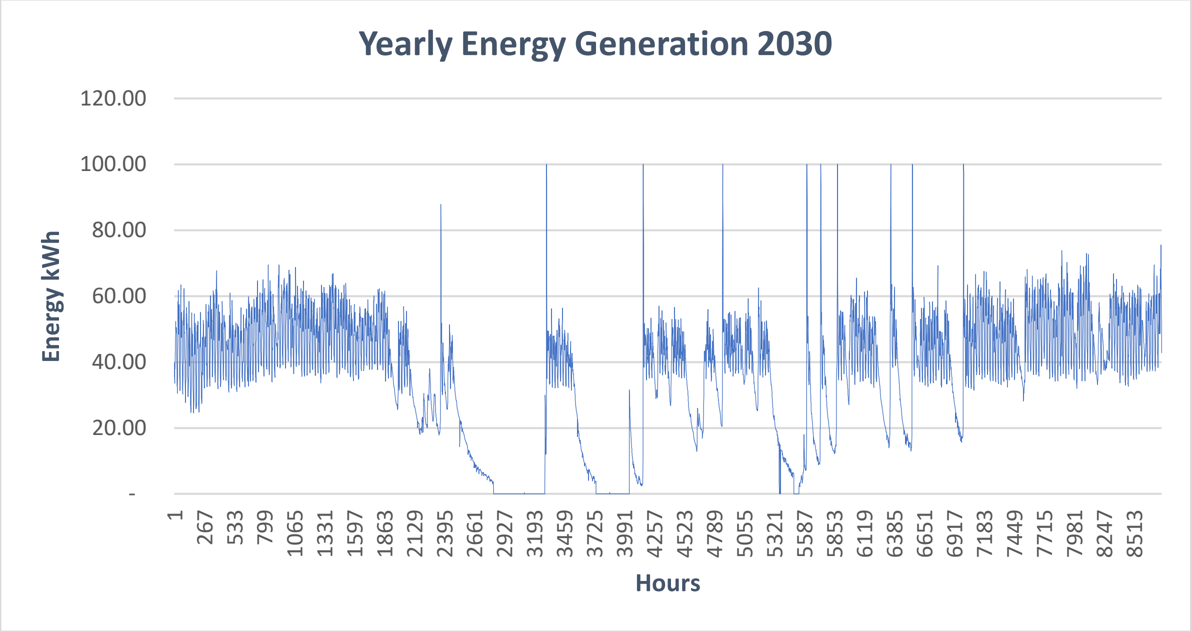


*Figure 5-18. Yearly energy generation from Hydro in 2030*

## 5.5. Energy Storage System

In renewable energy and sustainable power systems, the utilization of battery storage systems plays an important role. These systems not only provide a means for storing excess energy generated but also offer crucial support in stabilizing grids, managing peak demand, and enhancing energy reliability.

### 5.5.1. Overview of the existing storage system

The existing energy storage system has a total capacity of 1.3 MWh where the installed batteries are all lead-acid type in addition to taking into consideration the new batteries that will be added where Eigg Electric is adding further batteries and inverters to the existing energy storage system.

This system is comprised of 12 clusters and a total number of batteries of 288 ROLLS 25P SERIES 5000 4v battery. The maximum possible Sunny Island power rating that would be achieved with 36 Sunny Island 8.0H inverters with 6kW rated output power for each is 216kW (Voltaico 2024).

The depth of discharge  of the system is maintained at 40%, ensuring that the batteries are utilized within the optimal range of 100% to 60%. This strategic utilization policy helped in prolonging the operational lifespan of the system, with certain batteries boasting an impressive lifetime of up to 17 years.

In addition to strategic discharge management, predetermined maintenance for the batteries is conducted regularly. This regimen involves the watering of the batteries with distilled or de-ionized water. Deionized water in particular serves a crucial role in mitigating corrosion within the battery cells. By eliminating mineral ions, deionized water prevents the conduction of electricity, thereby safeguarding against any potential drop to battery performance. It is important to highlight the multifaceted benefits of regular maintenance practices. Not just by extending battery lifespan but also routine maintenance causes optimal performance, mitigates the risk of malfunction, and enhances overall system reliability. Moreover, by employing de-ionized water, the maintenance protocol not only addresses immediate concerns related to corrosion but also contributes to the long-term sustainability of the system.

*Table 5-10. Current Battery system specification*

| Storage Capacity | Storage Lifetime | Storage Charge Efficiency | Investments Costs | SOC Max. and Min |
|---|---|---|---|---|
| kWh | Year | % | $/kWh | % |
| 1291.4 | 15 | 66 | 341.86 | 100 - 60 |

Source: Rolls Battery User Manual, 2020 (VOLTAICO, 2024)

### 5.5.2. Storage System Upgrade

Although Lithium-ion batteries offer a wide range of advantages from the capacity, efficiency and charge and discharge cycles compared to lead-acid batteries. However, a new type of batteries can also be more efficient and cost competitive than traditional Lithium-ion batteries.

Lithium iron phosphate (LiFePO4) batteries have more advantages than traditional lithium-ion batteries. Where Lithium iron phosphate (LiFePO4) batteries marked an advancement in battery technology, (Elfa UK, 2023). One of their features is their safety profile. Due to their stable chemical structure, LiFePO4 batteries are less prone to failures such as thermal runaway, which can lead to overheating and even fire in lithium-ion batteries. This safety feature makes LiFePO4 batteries an attractive choice for applications where reliability and risk mitigation are necessary, such as grid-scale energy storage systems or electric vehicle powertrains.

LiFePO4 batteries also have a much higher lifespan. Unlike lithium-ion batteries, which can experience capacity degradation over time and with repeated charge-discharge cycles, LiFePO4 batteries have remarkable durability, maintaining their capacity through thousands of cycles. This longevity not only ensures consistent performance over the battery's lifespan but also translates to significant cost savings in terms of reduced maintenance and replacement costs, particularly in applications requiring frequent use. Another key advantage of LiFePO4 batteries is their ability to maintain their performance and reliability. This resilience ensures uninterrupted operation and makes LiFePO4 batteries an excellent choice for off-grid or remote applications where extreme conditions are in place (Murden 15-Mar-22).

Furthermore, LiFePO4 batteries have a quick response time. This rapid energy discharge capability makes them well-suited for applications such as uninterruptible power supplies or emergency backup systems. Whether providing backup power during grid outages or supporting critical operations in industrial settings, LiFePO4 batteries offer reliable and continuous energy delivery. An additional point is the environmental benefits of LiFePO4 batteries, where unlike traditional lithium-ion batteries, which often contain environmentally harmful materials such as cobalt and nickel, LiFePO4 batteries are completely recyclable (Dave Murden, 2023). This not only reduces their environmental footprint but also simplifies the recycling process, contributing to a more circular and sustainable battery ecosystem (Anker 2023).

In our case a study has been conducted to study the possibility of using LiFePO4 batteries to cover the needs for a system. The chosen batteries are of the type of Roamer 460SMART3 LiFePO4 battery with characteristics 12V 460AH.

This system offers a lifetime of 10 years with depth of discharge of 80%. The investment cost of the system is estimated to be 290$/kWh (Roamer 2024).

*Table 5-11. LiFePO4 batteries specification*

| Storage Lifetime | Storage Charge Efficiency | Investments Costs | SOC Max. and Min |
|---|---|---|---|
| Year | % | USD/kWh | % |
| 10 | 90 | 290 | 100 - 20 |

### 5.5.3. Hydrogen as an alternative backup of energy

Green hydrogen, despite its high initial investment cost compared to other storage technologies such as batteries, is gaining traction as a promising energy storage solution. This fuel is produced through electrolysis, using renewable sources like wind or solar power. And then a fuel cell can be used to convert hydrogen into electricity whenever is needed.

Its advantage lies in its ability to store excess renewable energy generated during periods of low demand for use during peak demand times. (Siemens-Energy 2023).

When replacing electricity generation from e.g. a diesel generator with hydrogen, this offers a clean and renewable alternative, reducing greenhouse gas emissions and mitigating climate change. Moreover, its storage capabilities help stabilize the grid and enhance energy resilience, particularly in regions with intermittent renewable energy sources.

In our system a Hydrogen generation system of HOGEN NEL H Series has been chosen according to the size of the electricity system of the island. At full load, the system may generate 12.94kg of Hydrogen per day where one kg of Hydrogen is the equivalent of 34 kWh, the energy content of this amount is

440kWh, which can be used in Hydrogen power generators or transferred into electricity using fuel cells (Nel Hydrogen 2018).

The power required for the system is 55 kVA with a lifetime of more than 50,000 hours (NEL H Series Spec Sheet, 2024). The total investment cost in the system is set to be 1250$/kW, in addition to that a storage system will be used to store 50l of pressurized hydrogen (50Mpa/500 bar).

*Table 5-12. Hydrogen storage system specification*

| Storage Capacity | Storage Lifetime | System Efficiency | Investments Costs |
|---|---|---|---|
| kg/24 h | Year | % | USD/kWh |
| 12.94 | 7 | 40 | 1250 |

# 6. Results and Analysis

## 6.1. Insights from the Survey and Community Workshop

The initial survey carried out started with a question to gauge the community level of satisfaction with the current energy system. All 33 of the respondents were either somewhat satisfied or very satisfied with the current energy system, as show in the diagram below:

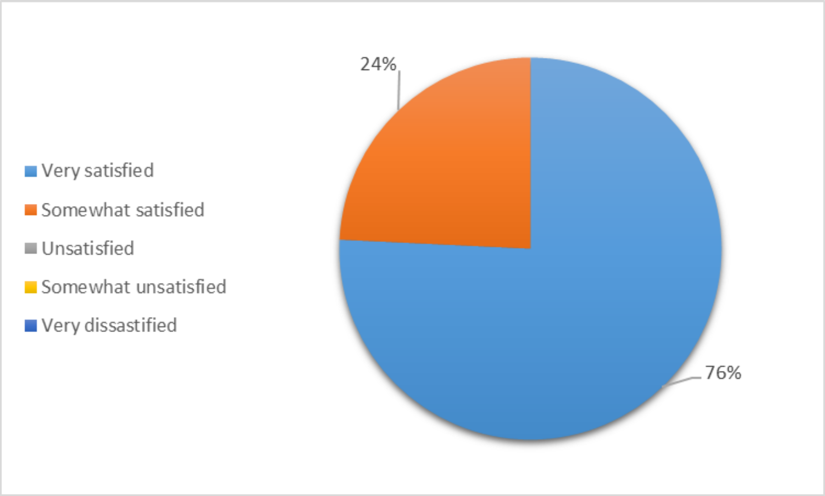


*Figure 6-1: Community level of satisfaction with energy provision with energy provision based on 33 respondents*

A few reasons were given for this high level of satisfaction during the workshop session:

1. Before the current system was installed, each household relied on individual diesel generators and in a small number of cases micro hydro or wind turbines. As people were overly dependent on diesel generators, respondents described this system as dirty, noisy, and unreliable. As such, the transition to a centralized system operated by Eigg Electric came as a relief, offering a cleaner, quieter, and more reliable energy solution.
2. Residents expressed a general satisfaction with the current system, noting that the imposed energy cap did not feel restrictive. Despite some limitations in appliance usage, for example, absence of electric showers in some households, the residents have adapted to live comfortably within the cap. Because of this, it may be necessary to reframe what it means to be energy poor within the context of the Isle of Eigg.
3. Another reason for satisfaction with the current system is that it is fair as everyone living on the island gets charged the same for electricity and is subjected to the same cap.

Even though community members were satisfied with the energy system as it is, some concerns were raised about its future capacity, particularly in the context of a growing population. Moreover, the idea of transitioning to a fully electric system was met with some apprehensions. For one, there was a fear of prolonged system outages that would require external support. System management of a complex power system is already a challenge due to a limited island population and difficulty accessing support. Currently, local staff on Eigg have been trained to provide frontline support and maintenance to ensure a reliable power supply. Financial constraints were also a significant concern.

A fully electric system is capital intensive. Even though funding is readily available for the initial infrastructure investment, it is difficult to attain maintenance funding. There were challenges in staffing and training for specialized maintenance, as they needed to outsource from the mainland. Its hard-to-find people that understand the Eigg system. Despite the concerns raised, community members were open to change, as long as the basic principles of what makes the current system so successful were kept in place.

These insights were used to inform the modelled scenarios so that the suggested transition pathways would align with community needs and expectations.

## 6.2. Modelling Results

### 6.2.1. Current Energy System

This scenario is to confirm and replicate the current energy system, its operation, its potential, and its impact. It will give a clearer image of how the current energy system on the Isle of Eigg performs in terms of the supply and demand balance. By visualising the current energy system, insights on how the system has been delivering throughout the year will be achieved and the amount of carbon emissions being emitted annually across all the sectors could be seen. This short-term scenario has also created the foundation for the other three long-term future-based scenarios.

The power system on the Isle of Eigg is a combination of solar PV, onshore wind turbines, hydro turbines, lead-acid battery storage, and standby diesel generators. Figure 6-2 shows the capacities of each of the generation and storage technologies.

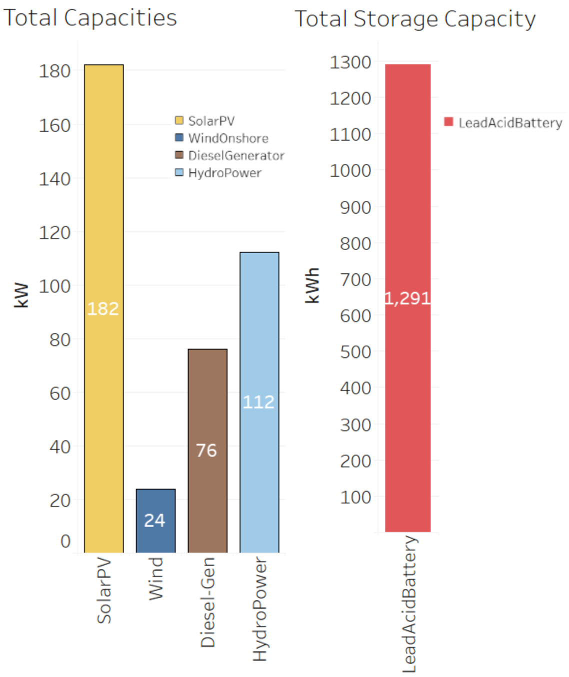


*Figure 6-2: Current Scenario - Generation and Storage Capacities*

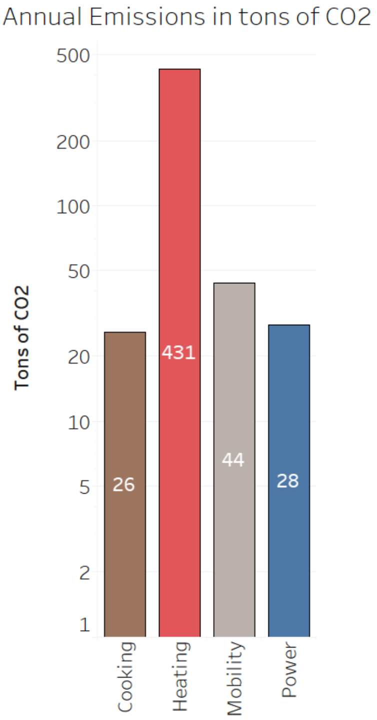


*Figure 6-3: Current Scenario – $CO_2$ Emissions across Sectors*

The current energy system only serves power demand. Most of the heating, cooking, and mobility is served through alternate fuels as the sectors are decoupled. The usage of conventional fossils leads to carbon emissions into the atmosphere. It is important that we estimate these emissions while we consider decarbonisation pathways to set benchmarks for the future scenarios. Figure 6-3 shows the sum of emissions annually across each sector. It is to be noted here that the emissions from the heating sector are the highest due to usage of kerosene alongside firewood. Depending upon how the forest resource is managed, firewood can be considered carbon neutral. This consideration will remove the emissions by about 60% from Eigg's heating sector. In our analysis, the emissions from the heating sector account for the emissions from the burning of the firewood.

Renewable energy generation is complemented by a lead-acid battery storage of 1,291 kWh capacity. On top of it, to maintain system availability and reliability, a standby diesel generator of 76 kW is also available with another of 64 kW serving as its back-up. While the system balances demand and supply at every instant, an hourly energy balance can be established for modelling purposes. However, *an hourly energy balance is devoid of the intermittent variations due to the real-time variations of the renewable resource, and therefore the hourly energy balance is only a representation of the actual balance at best and not a true imitation.* Figures 6-4 and 6-5 show the hourly generation profiles of two successive winter days and two successive summer days in the simulated year that shows the interplay of all generation and storage discharging on the top half of the graph. The demand, battery charging, and the surplus energy or potential of excess generation can be seen in the bottom half of the graph. The x-axis shows the number of hours.

In the winter-days profile, we see a period when hydro power is not at its full potential, the sun does not shine, and the wind also does not blow, but the demand is there to be served. In such a scenario when the system cannot meet the demand from its renewables, it is supported by its battery storage and the diesel generator. We see here very significant battery activity and very frequent successive operational hours of diesel generators. Shortly after, hydro generation recovers and the system is restored to renewable generation, even showing potential of excess generation during the later hours of the selected winter days (Figure 6-4).

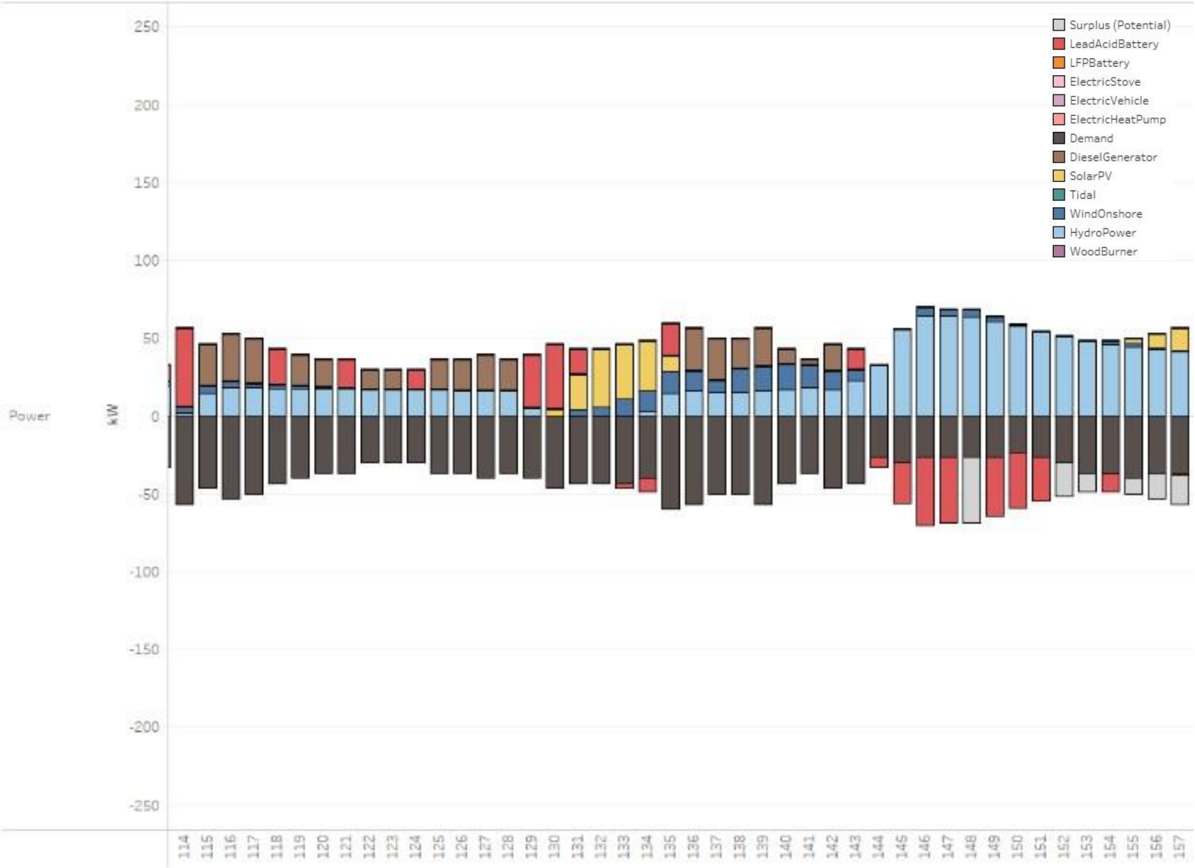


*Figure 6-4: Current Scenario - Winter-days Generation and Consumption Profile*

A total contrast can be seen in the summer-days profile for current scenario. We see that all three renewable technologies produce at their maximum potential. The demand is however little in comparison and therefore not all the potential of the currently installed renewable capacity could be utilised and therefore is reflected here as a surplus or potential to produce surplus. The current system has the potential to produce 144 MWh more than its current generation. *This is, though, an estimation* *based on the capacity factors of the technologies from the selected reference year and could vary depending on the representativeness of the reference year chosen.*

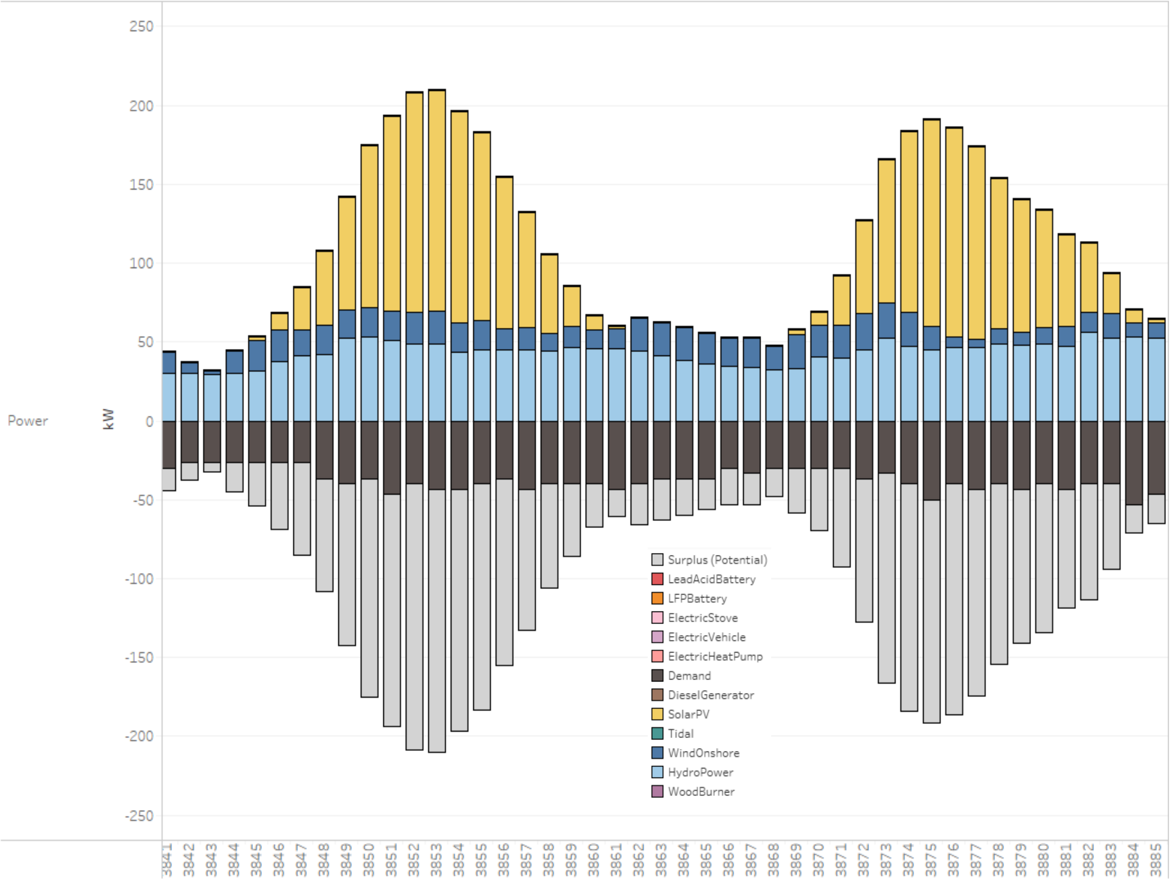


*Figure 6-5: Summer-days - Generation and Consumption Profile*

Modelling and simulating the current configuration provided us with insights about the periods where the current system falls short of sufficiency through renewables, but it also showed us the tremendous potential for many periods across a year, where the potential was unutilised due to absence of a bigger load. This attempt of simulating the current generation and storage activity may be challenged to offer little utility, as the hourly profiles we have simulated rarely match with the sub-hourly changes that happen stochastically. However, this has helped us to get an estimation of carbon emissions and surplus energy while providing the foundation for the long-term scenarios modelling as the model for future transition pathways was built upon the model-state that produced this current simulation.

### 6.2.2. Business-As-Usual Scenario

The current scenario was reconfigured to optimise the Business-As-Usual (BAU) scenario, and therefore an iterative dimension for modelling years was added to the model that extended the model until 2030. *This scenario however is not optimised with the intention of proposing a solution to the community but to use it as a benchmark for the long-term scenarios, and to already produce a foresight* *of where the community and its energy system would be if no transformative measures are taken.* The underlying assumption of this scenario is that the energy system will keep the current state of the decoupled sectors until 2030. This means that with the increase in demand, the capacities of technologies and storage might increase due to increasing power demand but the sectors that are not electrified will still be powered by conventional fossils. This scenario will give us the opportunity to estimate the amount of carbon emissions, if the energy system does not move towards the decarbonisation across all sectors, and the expansion still needed in the capacity to cater growing power demand.

For this scenario, the model returned no new investments in expansion of generation capacities. The model suggested an investment in only 20 kWh of Lithium-Iron-Phosphate (LFP) Battery as can be seen in Figure 6-6. This is an indication that the current system is sufficiently sized to cater the demands of the future if no cross-sectoral coupling happens. This little investment in LFP battery could be to cover up for a brief event where renewables are not available, and the existing storage capacity is close to depletion. This investment can also be neglected as it is too small to bring a big impact in the system and also in event where this was required, the diesel generator could run for longer and provide support.

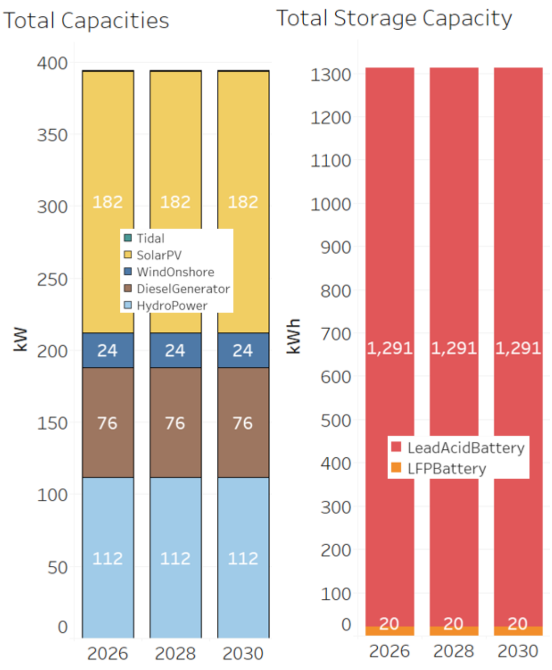


*Figure 6-6: BAU Scenario - Generation and Storage Capacities*

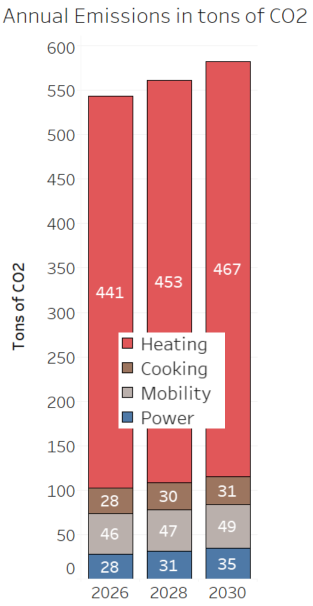


*Figure 6-7: BAU Scenario – $CO_2$ Emissions across Sectors*

Until 2030, the demand for energy across all sectors will have slightly increased. This has direct implications for the emissions from the energy system as no sector is getting electrified in the BAU scenario. Figure 6-7 shows the emissions across the modelling years for the BAU scenario. The emissions keep a similar share as seen in the current scenario, with the only change being the slight increase across all that is there because of slight increase in demands for energy from all four sectors.

Figure 6-8 and 6-9 show the generation and storage profiles for the same two winter-days and summer-days, for the year 2030. In the winter-days, we see that the generator now runs more than it ran in the current scenario, to serve the increasing demand in absence of solar, wind, and hydro. We see more frequent exchange of energy between the batteries with the new LFP battery capacity playing its part to keep the system balanced.

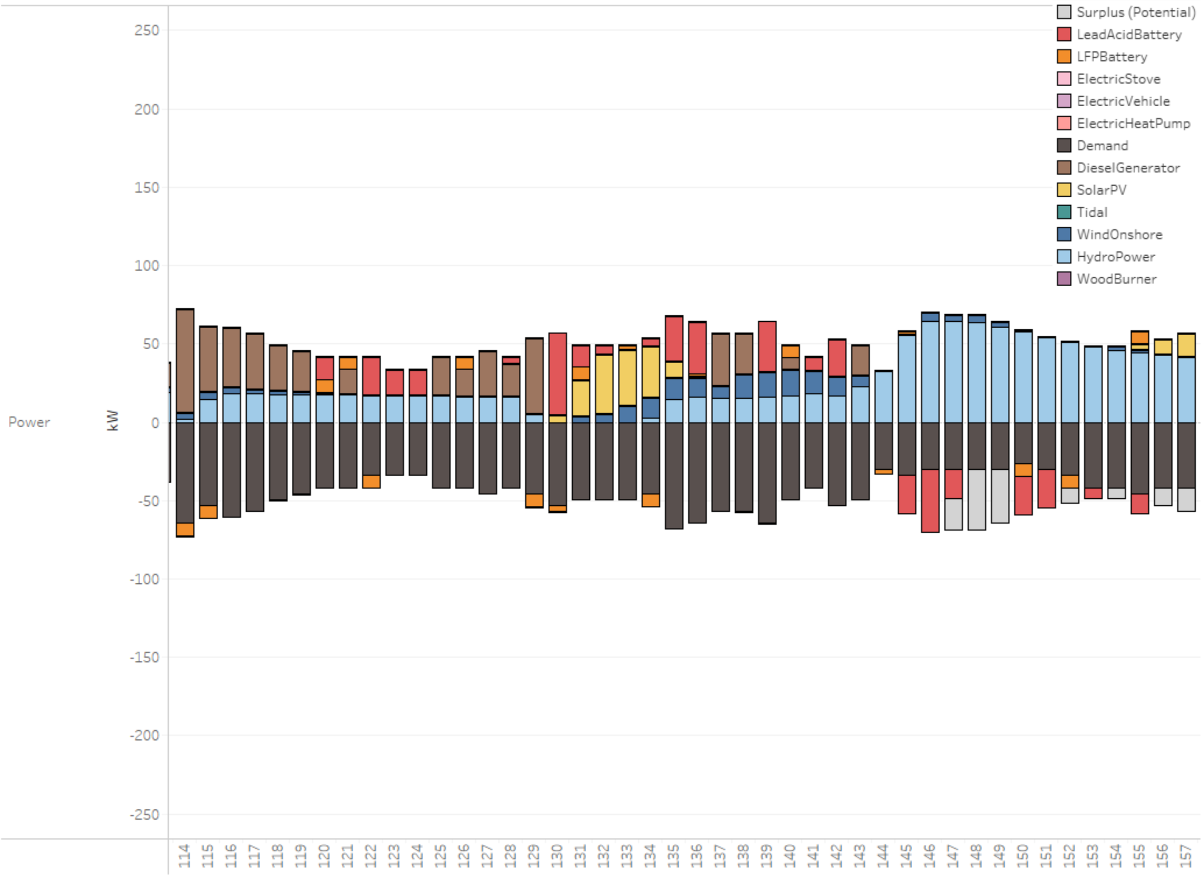


*Figure 6-8: BAU Scenario – Winter-days Generation and Consumption Profile - 2030*

On the other hand, during the same summer-days, the behaviour is not any different than what was seen during the current scenario, as against the high renewable availability, the demand is relatively lower, indicating a significantly high potential of surplus generation (Figure 6-9). The surplus or potential of excess generation in BAU scenario for the year 2030 amounts to 122 MWh, which is 22 MWh lower than the potential discussed in current scenario, mainly due to the increased demand and the energy that was additionally stored by the LFP battery through the year.

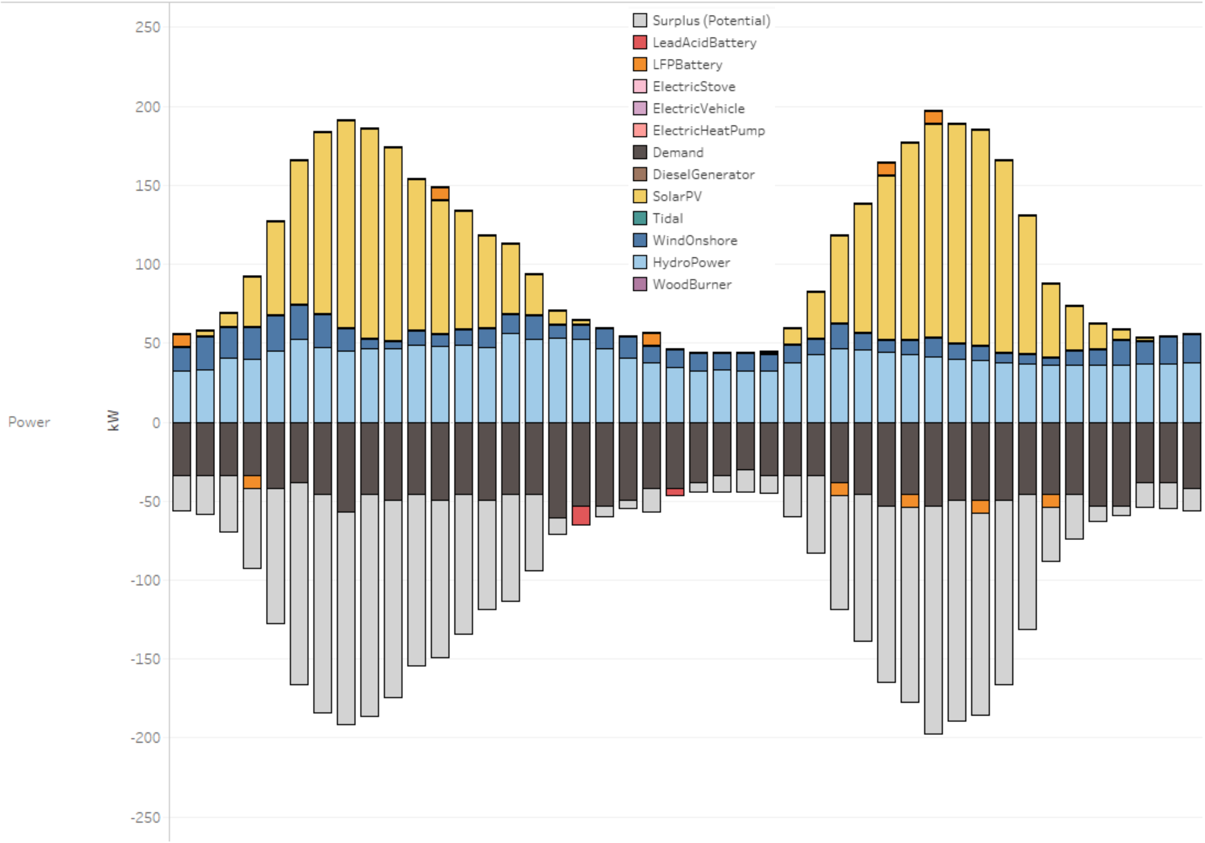


*Figure 6-9: BAU Scenario – Summer-days Generation and Consumption Profile – 2030*

### 6.2.3. Sector Coupling Scenario

The model was reconfigured to optimise the Sector Coupling scenario. This scenario follows the 2030 decarbonisation plans and goes with the underlying assumption that by 2030 all the sectors will be able to electrify to the highest extent, ideally 100%.

When heating, cooking, and mobility sectors are coupled with the power sector, the overall increase in the demand for power is significant, between 2-3 times depending upon the extent of electrification across the new sectors. Unlike the earlier two scenarios, it was inevitable for the system this time to expand its generation capacity and/or storage capacity to meet the increased demand. The model suggested expansion of generation capacity through 300 kW of tidal energy. This raises a question about the selection of tidal energy over wind or solar, as it is costlier than wind or solar in terms of capital cost per kW. This is an important indication that there are some instances where the demand is high but the potential of solar, wind, and hydro is poor, it would be more feasible economically to have tidal installed over additional capacities of solar and wind as it would have ultimately costed more due to their poor generation potentials during such instances. The expansion in generation capacity is also accompanied by the expansion of storage capacity where 153 kWh of LFP battery and an additional 530 kWh of Lead-Acid battery storage was suggested. Figure 6-10 shows the total capacities of generation technology and storages after expansion.

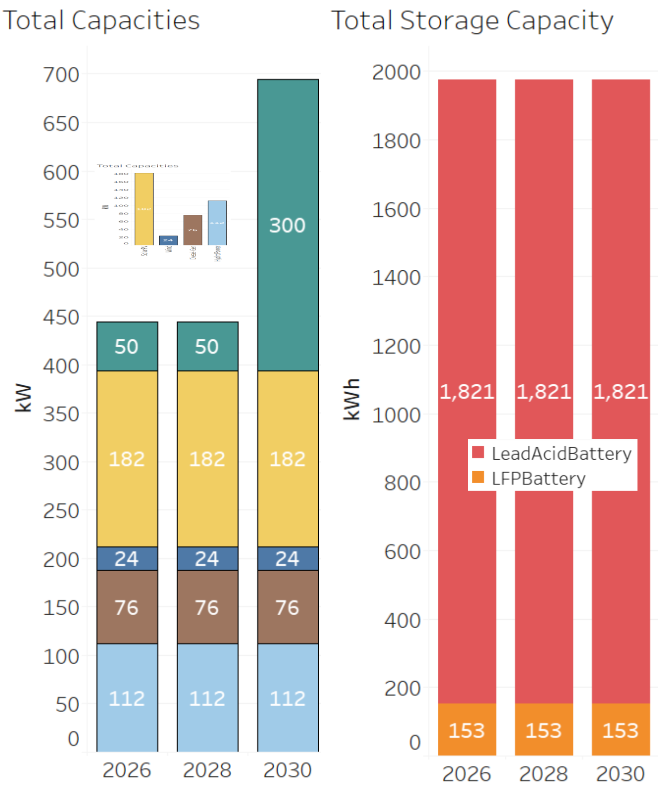


*Figure 6-10: Sector Coupling Scenario - Generation and Storage Capacities*

Figure 6-11 shows the emissions in tons of $CO_2$ across the modelling period for each modelling year for the sector coupling scenario. It can be seen overall that there is a constant decline in the total emissions across the sectors due to sector coupling. The emissions are reduced to a minimum by 2030, where the last remaining bit is due to heat demand that cannot be electrified due to limited transmission capacity. Only 48% of the total heat demand could be served through electric power and therefore, the other 52% will have to be served through conventional means. *These last emissions, however, can be removed as well if the unelectrified heat demand is served through wood fuel, which is considered carbon neutral if it comes from a properly managed forest. Therefore, in an ideal scenario, given that heating practices are strictly shifted to firewood burning, Eigg can be fully decarbonised across all sectors by 2030.*

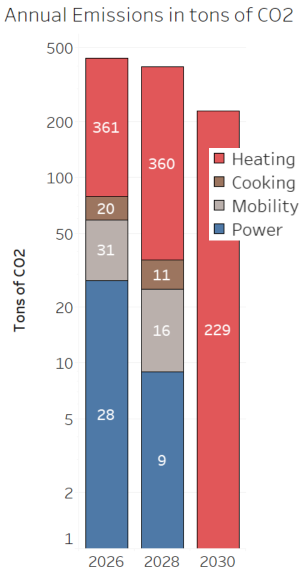


*Figure 6-11: Sector Coupling Scenario - $CO_2$ Emissions across Sectors*

With the new proposed system sizes and the new demand sectors, we look at the same two winter-days and summer-days in the year 2030 to compare. Only this time we also look at the heat demand profile to see the proportion of heat covered through an electric heat pump or through a conventional method like a wood burner. Figure 6-12 shows the two successive winter-days. We already see that the axes have expanded because the magnitude of the total demand has changed due to coupling of other sectors. The top half of the figure represents energy balance for power and the bottom half represents energy balance for heat. We now see that the periods where earlier there was no solar, wind, and hydro, and where the generator and the battery had to play their part, it is covered sufficiently through tidal energy which at some instances was also high enough to serve the heat demand through electric heat pumps. Since these days are also coincidental with the low-tide periods, we see some battery activity as well.

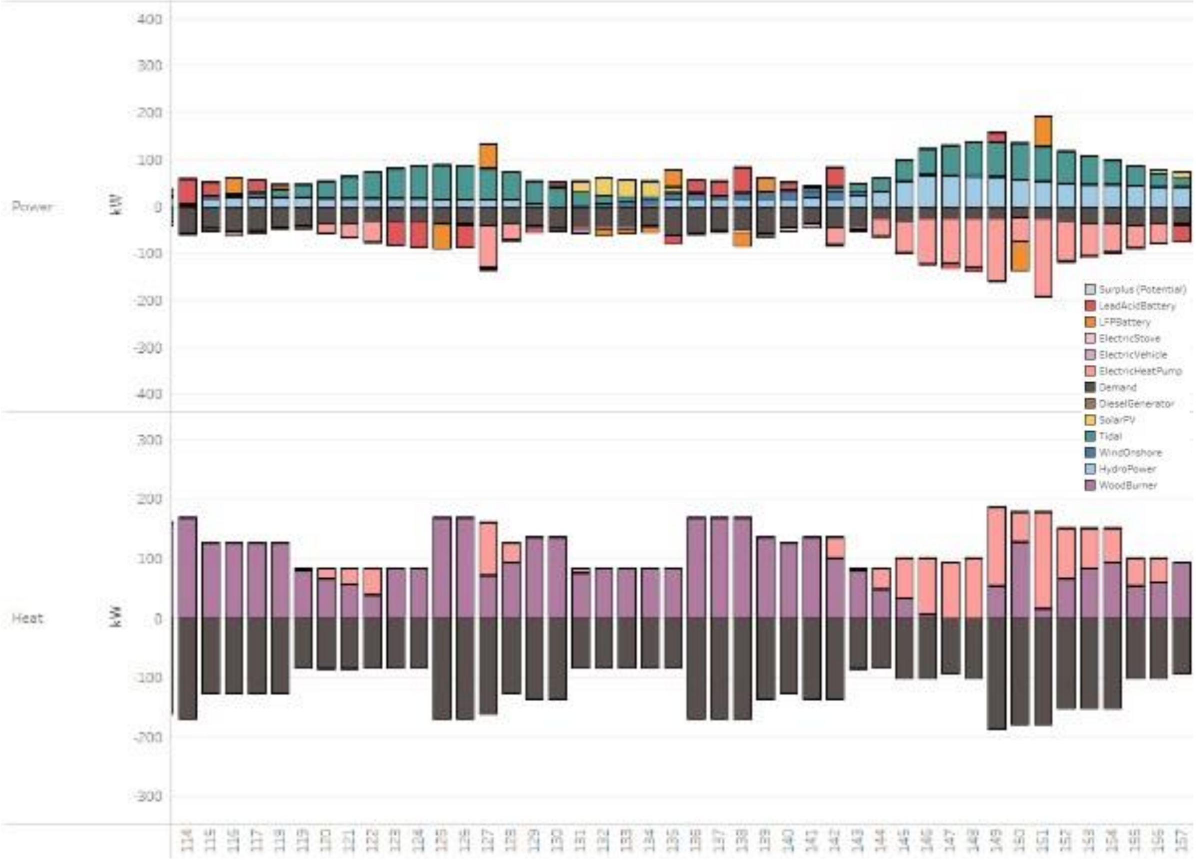


*Figure 6-12: Sector Coupling Scenario - Winter-days Generation and Consumption Profile – 2030*

In a similar manner, we also look at the same two summer days where we earlier had no large demand, and the renewables were producing surplus (Figure 6-13). These two days are also coincidental with high-tide periods and therefore the surplus generated appears much larger than before, even while the system served all the little heat demand that there is. No significant battery activity is seen, also for the same reason. This surplus energy for the year 2030 amounts to 113 MWh, which is 9 MWh lesser than BAU scenario. While surplus is expected to increase due to increasing capacities, the consumption has also increased due to the coupling of the other three sectors with power and therefore the net effect is a reduction in the surplus for Sector Coupling scenario, in comparison to the BAU scenario.

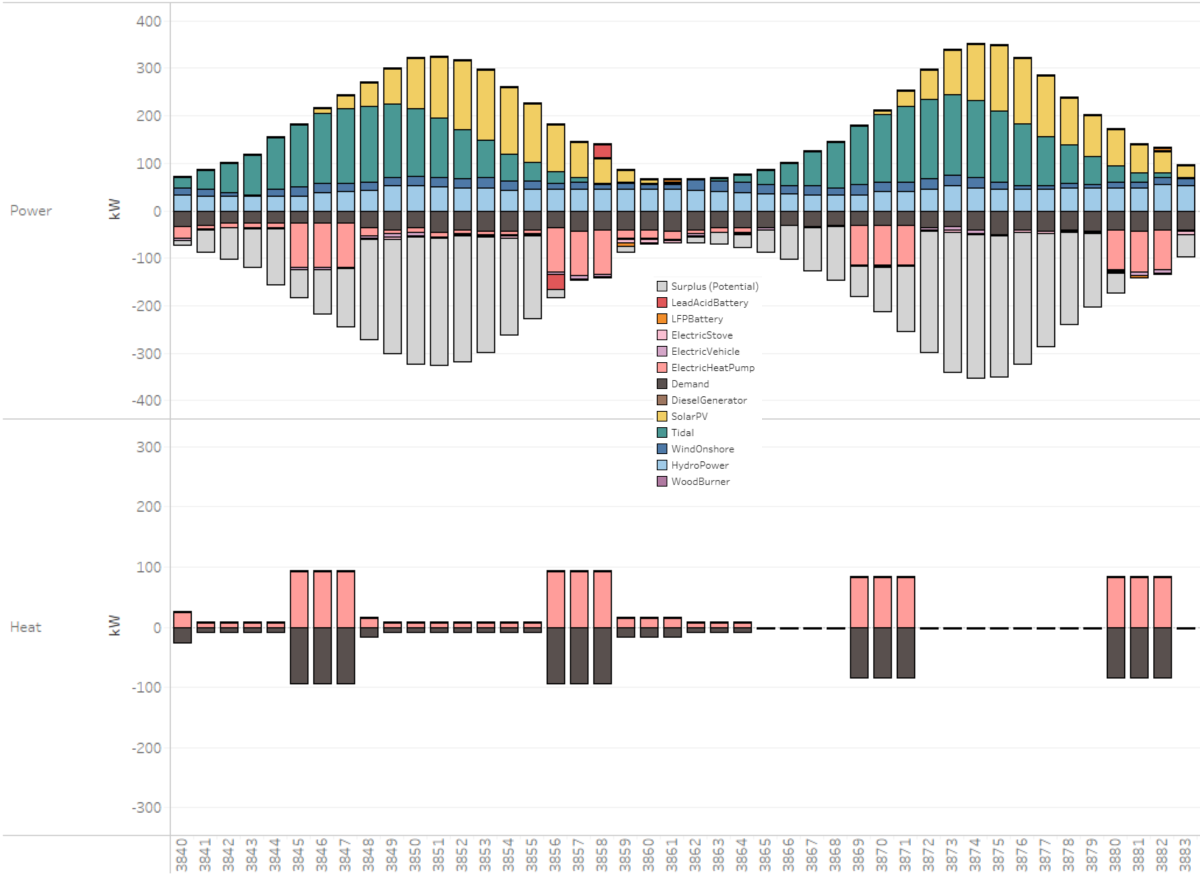


*Figure 6-13: Sector Coupling - Summer-days Generation and Consumption Profile – 2030*

### 6.2.4. Sector Coupling with Energy Efficiency

The implementation of energy efficiency measures plays a significant role in reducing the overall energy consumption. Consequently, a system with lower capacity is required, contrary to the scenario where energy efficiency was not considered in the design. To analyse how significant is the impact of energy-efficient measures on the overall system design, the model was executed using demand profiles that explicitly incorporated energy efficiency measures, particularly in the heating and power sectors. For energy efficiency analysis, the mobility and cooking sectors are excluded from consideration. This exclusion assumes that these sectors will undergo a complete transition to new technologies, and it is expected that the newly acquired technologies will already account for energy saving measures.

Modelling of this scenario also suggests expansion of both generation and storage technologies. Figure 6-14 illustrates the suggested generation and storage capacities for the sector coupling with energy efficiency scenario. A 10kW addition in solar PV capacity is needed alongside a major expansion through 250 kW tidal. Additionally, the storage expands by 312 kWh of Lead-Acid battery and 156 kWh of LFP battery. It is important to highlight that while the model recommends an increase in capacity, the addition in capacity and storage in this scenario is around 15% lower as compared to the sector coupling scenario where energy-efficient measures are not considered.

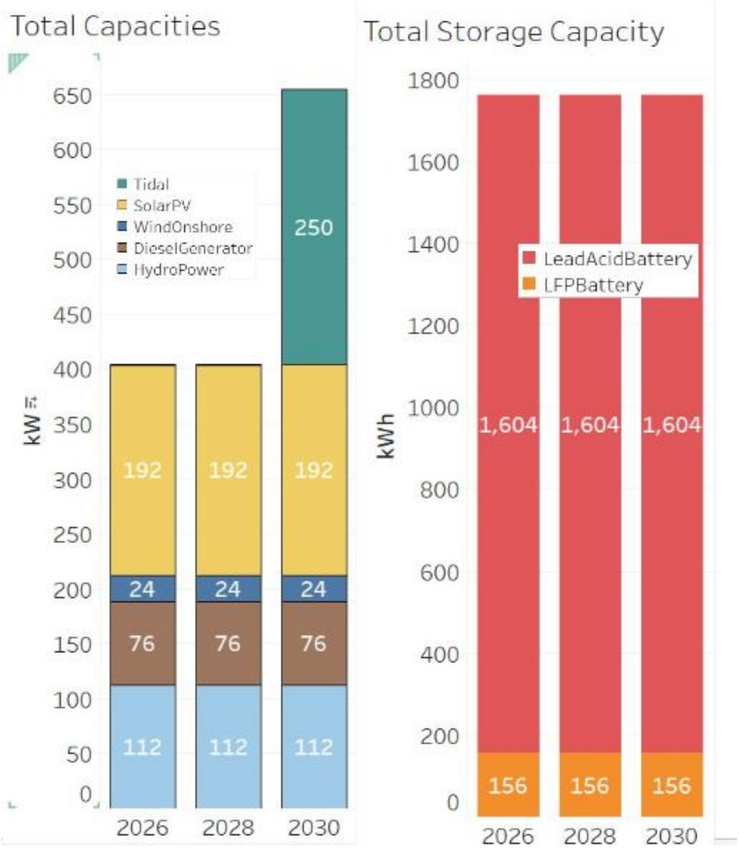


*Figure 6-14: Energy Efficiency Scenario - Generation and Storage Capacities*

As technology transitions to renewable alternatives through the modelling period, a noticeable reduction in carbon dioxide emissions is observed due to the electrification of carbon intensives sectors of heating, cooking, and mobility. Figure 6-15 indicates that the emissions were reduced significantly by more than 60% from 439 tons of $CO_2$ in 2026 to 180 tons of $CO_2$ in 2030. The reduction in emissions for each modelling year is considerably higher as compared to the scenario when energy efficiency measures are not considered, mainly due to the reducing demands. Therefore, it indicates that the journey towards achieving carbon neutrality can be expedited by giving due consideration to energy efficiency. The remaining bit of emissions are associated with the unelectrified heat demand. In this scenario, 58% of the heat demand could be served through electric power, leaving behind about 40% to be served through conventional methods. If all is served through firewood, the remaining demand can as well be displaced to zero.

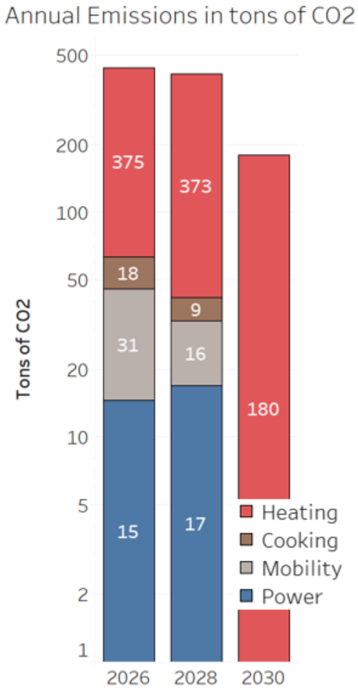


*Figure 6-15: Energy Efficiency Scenario - $CO_2$ Emissions across Sectors*

We yet again analysed the generation profile across the same two successive winter and summer days. Top of Form Figure 6-16 shows a behaviour of winter-days that is identical to the one seen in the sector coupling scenario. In the absence of solar, wind, and hydro, it is tidal that serves not just the power demand, but also the heat demand to the highest possible extent. The remaining heat demand is served by wood burner. During the later periods, when hydro power recovers, the overall supply is sufficiently large to cover most of the heat demand as well as all of the power demand.

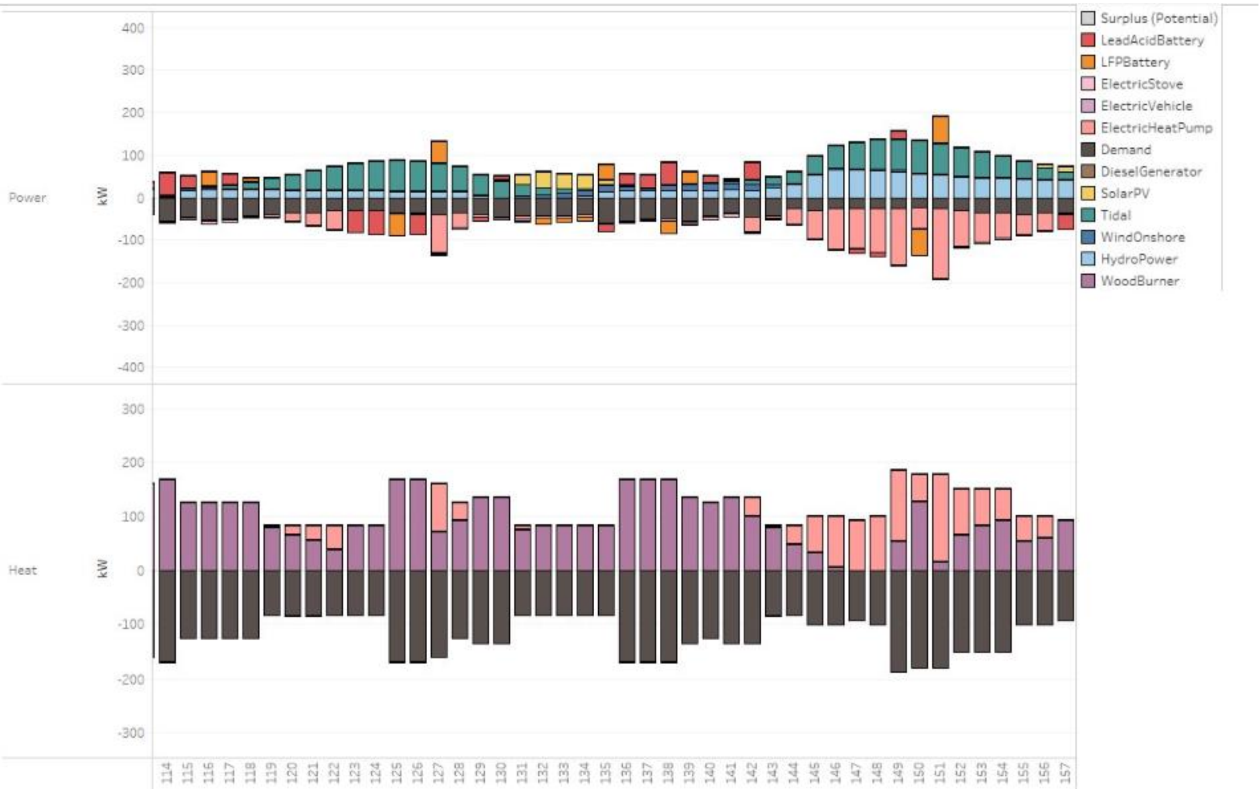


*Figure 6-16: Energy Efficiency - Winter-days Generation and Consumption Profile - 2030*

When observing the same summer-days, it can be seen in Figure 6-17 that all four generation technologies are active and producing enough power to supply the power and heat demand, with minimal activity observed in battery. Additionally, it is prominent here that in summer seasons the generation is exceeding the demand by a significant margin. This surplus is mainly generated during periods of reduced heating demand in summer, coupled with an abundance of available solar and tidal energy, amounting to 133MWh in 2030.

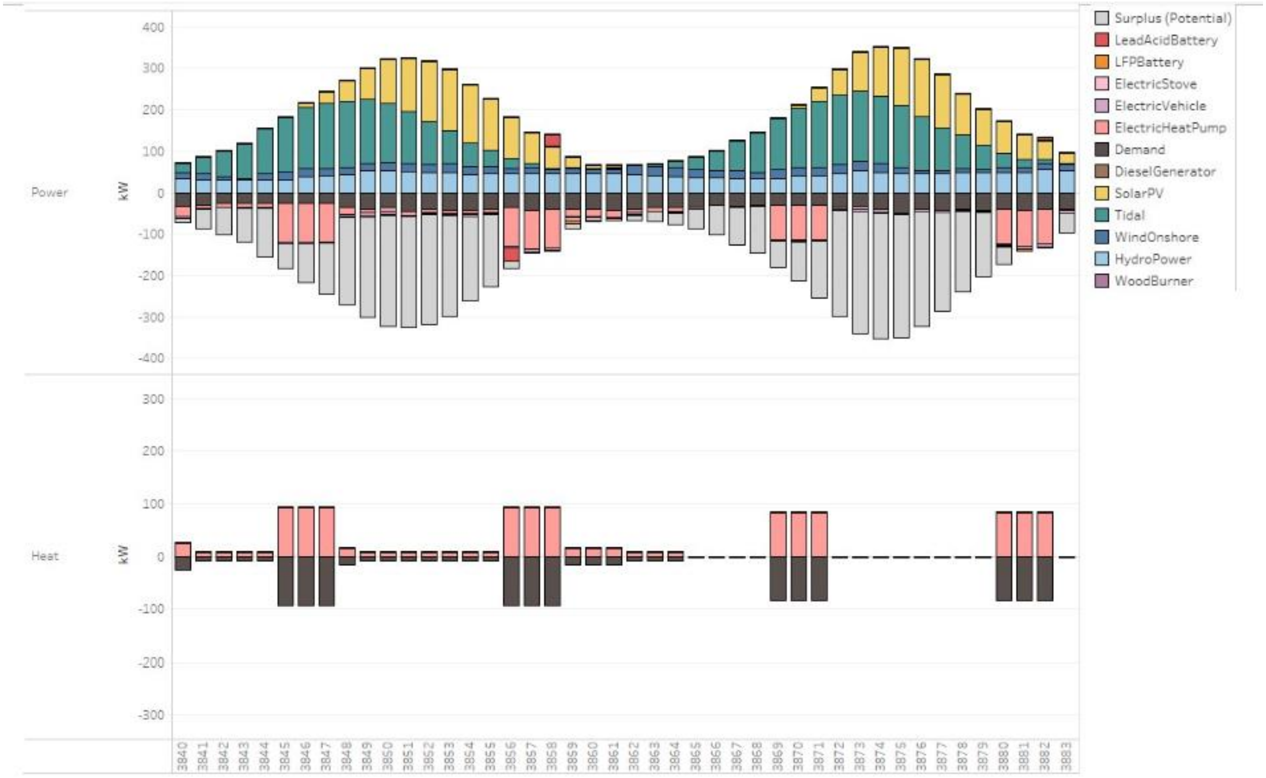


*Figure 6-17: Energy Efficiency - Summer-days Generation and Consumption Profile - 2030*

### 6.2.5. Alternative Scenario – Without Tidal Energy

Assessing the results of the sector coupling and sector coupling with energy efficiency scenario, a new alternative scenario was conceived that enforced no presence of tidal in the potential technologies for the future energy system. Identifying that both the scenarios suggested investment in or expansion of the energy system through tidal energy, and the fact that tidal energy at a small scale is still a technology that is not commercially competitive, it was decided to model a scenario where tidal was never an option to see the impact of it on the model's decision-making. This scenario is also intended to serve as another choice to refer to for the local community at Eigg.

In absence of tidal energy, the model found it difficult locating the least-cost optimal solution as it the processing took 1.5 times longer than the other two long-term scenarios that suggested tidal energy. Nevertheless, the optimal solution suggests capacity expansion much larger than what was suggested in the last two scenarios. The model suggests additional 330 kW of solar PV, 100 kW of Wind energy. The model also suggests expansion of battery storage by around 3550 kWh which is around three times of the current battery storage capacity. This is understandable as the model always picked tidal as the events that were the most critical and enforced expansion had little to no solar, wind, or hydro potential, all coincidentally. Now with tidal not being an option, the model is forced to choose from solar and wind. With no good solar and wind potential in the most critical events, the only solution is expansion of battery storage such that it stores the excess generated by the expanded solar and wind until the critical moments appear. Figure 6-18 shows the system capacities for the no-tidal scenario.

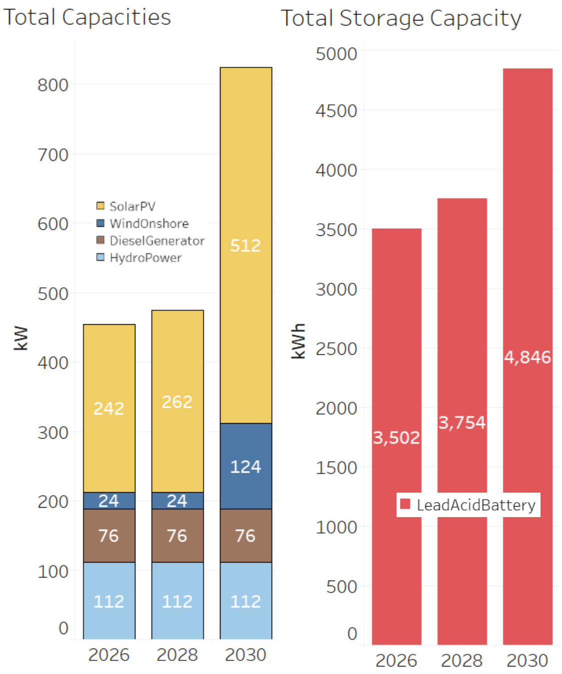


*Figure 6-18: No-Tidal Scenario - Generation and Storage Capacity*

Figures 6-19 and 6-20 show the winter-days and summer-days generation profiles. From winter-days profile it is evident that the expansion of solar PV and wind energy capacities are still not productive enough as we see very frequent and constant battery activity. Also, even with such large capacity, the system is only meeting a fraction of the heat demand through power and most of it is being covered through conventional means.

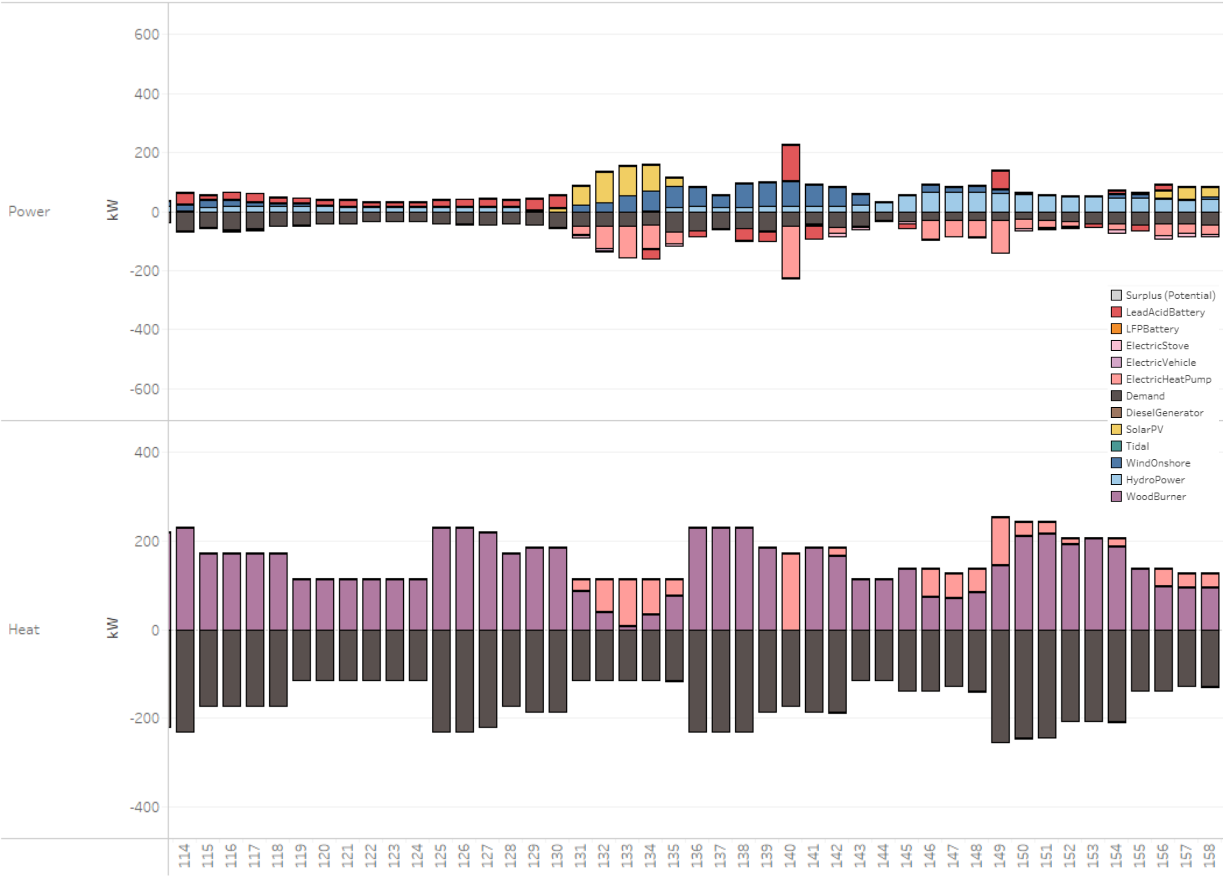


*Figure 6-19: No-Tidal Scenario - Winter-days Generation and Consumption Profile – 2030*

The summer-days profile follows a pattern similar to the ones seen earlier across the other scenarios, where the demand is not high enough as compared to the generation potential and therefore the potential to produce a surplus is high. Battery activity is also very limited during this time which is an indication that batteries do not need to act during these periods, and they remain with a high storage level. The surplus is in fact a total of 107 MWh for the year 2030, and this surplus is close to or even less than the surplus seen in other scenarios.

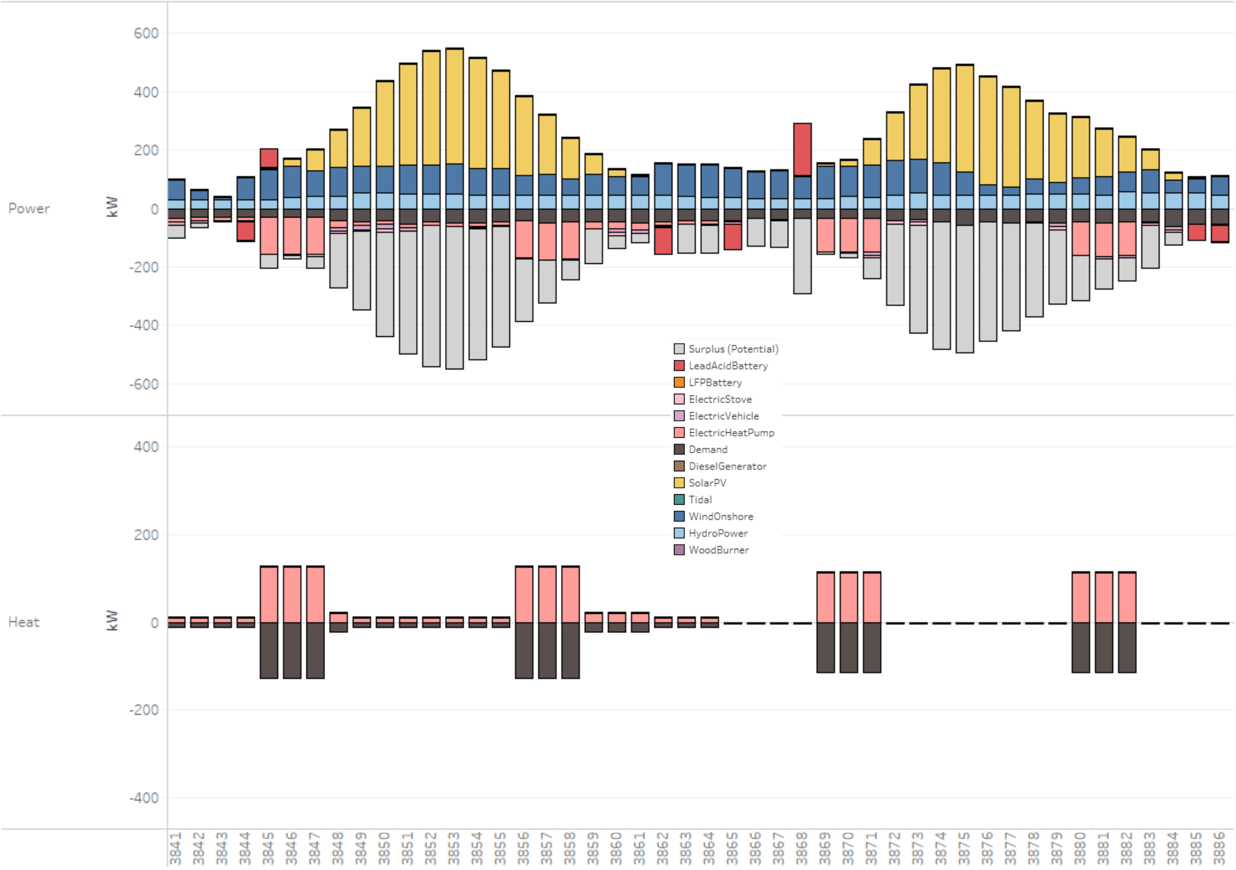


*Figure 6-20: No-Tidal Scenario - Summer-days Generation and Consumption Profile – 2030*

## 6.3. Comparison of scenarios using Indicators

### 6.3.1. Emissions

Figure 6-21 shows the emissions across each modelling year for each of three long-term scenarios alongside the alternative scenario that we modelled. For BAU, emissions follow along the increasing trend as the demand grows over the years. This is however not replicated by the other three scenarios as all three scenarios see a decline due to coupling of the sectors and subsequent electrification of the demands. In these scenarios, the emissions still do not reach zero because the heating sector cannot be fully electrified with the existing transmission capacity. For the sector coupling scenario and no-tidal scenario, the emissions are a bit higher than sector coupling scenario with energy efficiency, mainly because the overall demands were lower in latter that allowed more of the heat demand to be electrified. Nevertheless, these emissions can be substituted through use of firewood for remaining heat demand as we consider firewood to be carbon neutral. This will eventually make the three scenarios zero emissions pathways.

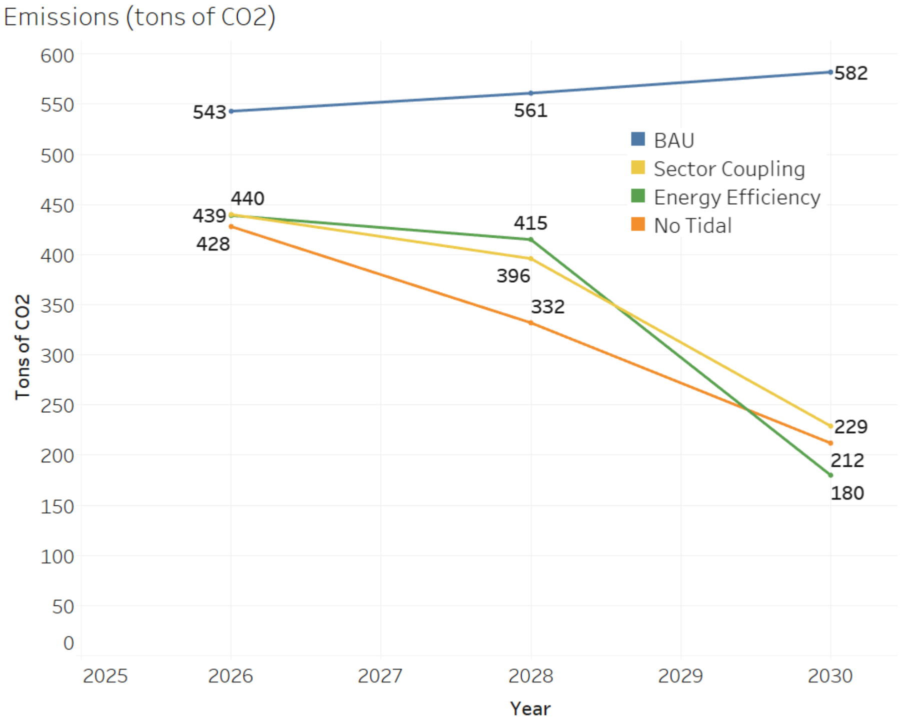


*Figure 6-21: CO$_2$ Emissions across Scenarios*

### 6.3.2. Annual Capital Costs

Figure 6-22 gives the schedule of the investments for the three scenarios alongside the alternate scenario. It is to be noted here that the schedules are only an indication of when the technology has to be ready and not necessarily when the investment has to be made. This should be used only as an indication and planning for the investment should be done in advance. In the figure, we see that the BAU scenario only needs an investment of 6,000 US$ as there are no major expansions in the system. However, the situation for the other three scenarios is different due to major reinvestments. First instalment of the investment is highest in no-tidal scenario, followed by Sector Coupling scenario and then Energy Efficiency scenario. The next instalment of the investment is only applicable to the no-tidal scenario, whereas for the other three scenarios no investments need to be made until the last model year. In the last model year, the last instalment of the investment is the most decisive in the total costs. The highest investment is seen by the sector coupling and energy efficiency scenario as both see expansion of the same technology and by the same capacity. The next largest is no-tidal, followed by BAU. While no-tidal sees lower investment than the other two scenarios in the last modelling year, the Net Present Cost (NPC) of the total investments across all modelling periods is the largest in no-tidal scenario (around 1.3 million US$) than Sector Coupling (1.25 million US$) and Energy Efficiency (1 million US$).

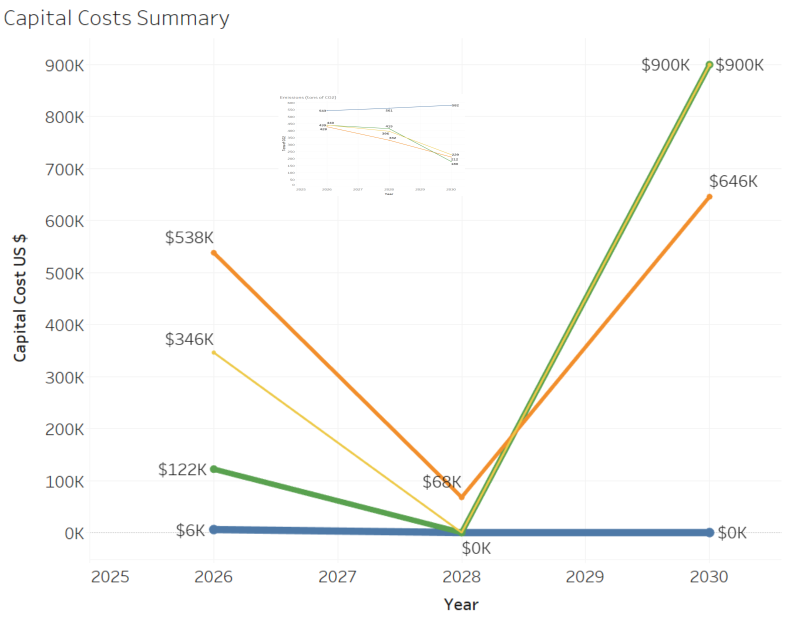
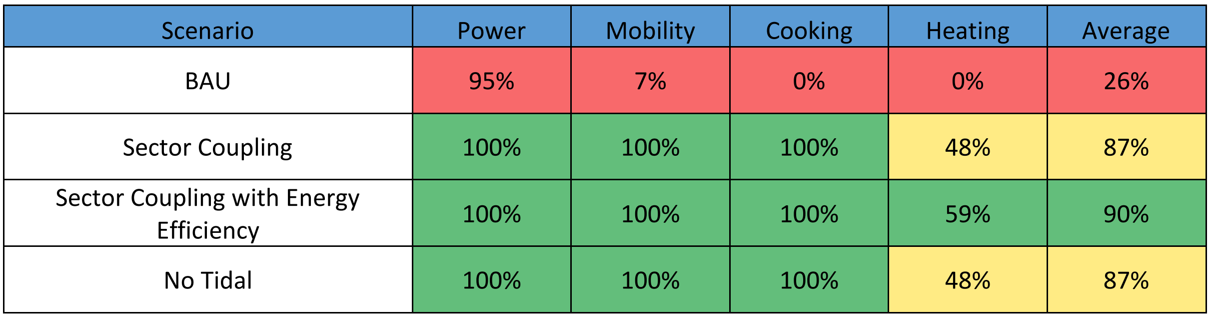


*Figure 6-22: Capital Costs (US $) Comparison across Scenarios*

### 6.3.3. Sectoral Renewable Fraction

Here we look at how the four scenarios compare in terms of their renewable (electricity) fraction across all sectors. The current energy system at Eigg has a high renewable electricity fraction (>90%), but this applies only to its power system as the other sectors are not powered through renewable energy systems. We also refer to renewable fraction as renewable electricity fraction because this makes a distinction with renewable fuels that are not powered by electricity, like firewood. Looking at the renewable (electricity) fraction could be an indication of the extent to which cross-sectoral coupling can be achieved while moving towards decarbonisation. Figure 6-23 shows a comparison where green marks the highest renewable (electricity) fraction across the scenarios for each sector and red marks the lowest renewable (electricity) fraction across the scenarios for each sector, with yellow indicating a moderate fraction across the scenarios for each sector. The figure also indicates the average renewable (electricity) fraction for each scenario, indicating the progress that can be made while making a choice between one scenario or the other. Note that for sector coupling, energy efficiency, and no-tidal scenarios, renewable (electricity) fraction can directly correspond to the electrification rate across a sector as these scenarios do not see any power generation from the diesel generator. BAU sees the lowest average fraction as three of the four sectors remain unelectrified. Sector coupling and no-tidal scenarios share the same average fraction as coincidentally both could only power 48% of the heat demand. The best average could be achieved through energy efficiency scenario, where 59% of the heat demand could be powered, taking the average electrification rate across the sectors, and also the renewable electricity fraction to 90%.



| Scenario | Power | Mobility | Cooking | Heating | Average |
|---|---|---|---|---|---|
| BAU | 95% | 7% | 0% | 0% | 26% |
| Sector Coupling | 100% | 100% | 100% | 48% | 87% |
| Sector Coupling with Energy Efficiency | 100% | 100% | 100% | 59% | 90% |
| No Tidal | 100% | 100% | 100% | 48% | 87% |

*Figure 6-23: Comparison of Renewable Fraction across Sectors and Scenarios, 2030*

### 6.3.4. Surplus or Potential for Excess Generation

The last metric we analyse is the surplus generation or the potential for excess generation in each scenario. Figure 6-24 shows the surplus generation in MWh during the last model year, 2030, in each of the four scenarios, alongside the current scenario. There is little to separate these scenarios in terms of surplus generation, as all present the potential of producing surplus between 100-130 MWh annually. This is almost half of the total energy demand from the power sector in current scenario. This presents a possibility of using this surplus for innovative technologies like hydrogen or ammonia generation, bitcoin mining, or other economic activities that could increase the utility of the technologies installed while also bringing in more revenue on the island. The figure also shows that the current and BAU scenarios have larger proportion of surplus, indicating the system to be having sufficient capacity, while the other three future scenarios to have much lesser surplus as a % of total generation, indicating that the suggested capacities are much better optimised as surplus is less than 15% of the total generation.

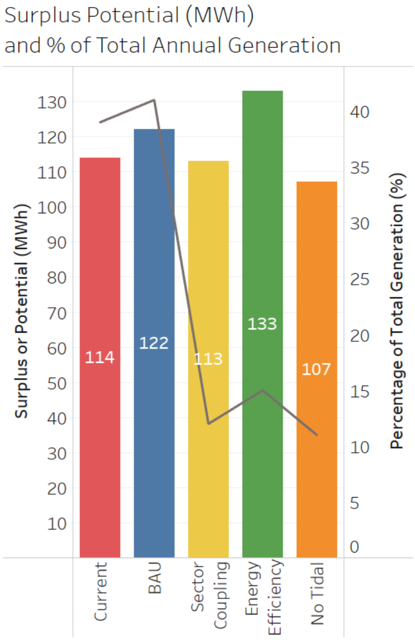


*Figure 6-24: Comparison of Surplus or Potential of Excess Generation*

## 6.4. Discussion and Socioeconomic Insights into the Modelled Scenarios

### 6.4.1. Current Energy System

Energy communities play two roles. As decentralized, renewable energy based projects, they are key in promoting sustainable energy production and consumption practices. As community driven-initiatives, they represent a shift where a traditionally passive consumer becomes a co-owner of renewable energy resources, taking an active role in the production and management of energy. Furthermore, the primary purpose of energy communities like Eigg is to generate social and environmental benefits rather than financial profits (Caramizaru, & Uihlein, 2020).

We set out to understand the social, cultural, economic and to some extent political factors within which community energy on the Isle of Eigg operates. From the workshop and interviews, a few reasons emerge as to why community energy has been so successful on Eigg:

1. It is evident that community members have an intimate understanding of how they use energy so as not to exceed the 5 kW cap. There also exists a shared sense of responsibility where residents understand the role they play in the energy system.
2. The desire to be self-sufficient and promote a sense of community is particularly prevalent among residents. Their motivations go beyond simple electricity production as community members are more likely to take an active role in communal energy management.
3. Decision-making is placed into the hands of the community, creating a more socially fair model of ownership and responsibility.

In terms of the political context, higher-income countries with a strong tradition of social enterprises and community ownership have a higher concentration of community energy initiatives (Caramizaru & Uihlein, 2020). Funding programs have been key to the establishment and expansion of community energy on the Isle. In 2008, the project cost for developing a renewable based off-grid electricity system on Eigg was €1.94 million. Funding the investment was a significant challenge and was secured through a number of sources including grants and donations (Chmiel, & Bhattacharyya, 2015).

Because of these reasons, any transitions in the current energy system must take place within the socioeconomic context of the local community to deliver value to all residents.

### 6.4.2. Business-As-Usual Scenario

In the business-as-usual scenario, no sector coupling takes place, and the energy system runs as it does today. The heating, cooking and transport sectors continue to run on fossil fuels resulting in increasing carbon emissions every year. Even though community members are satisfied with their current energy system and a BAU scenario would be a continuation of the same, this scenario would not be acceptable to the community in the long run as it is not in line with the community’s decarbonization goals by 2030.

### 6.4.3. Sector Coupling Scenario

The Sector Coupling Scenario follows the existing 2030 decarbonization plans. Under this scenario, the island needs to transition from fossil fuel use to low carbon energy, which would necessitate the electrification of heating, cooking, and transport on the island.

For the Isle of Eigg, this would represent a significant increase in electrical demand, which would have to be managed carefully and cost-effectively. Furthermore, it is important to deliver these changes in a manner that gains the acceptance and support of the local community.

The community workshop and interviews revealed a complex set of concerns about the electrification of heating and cooking. Given the dissatisfaction with the initial system where each household provided their own electricity through generators, electrification could be seen as additional improvement that would further improve living standards on the island. For those particularly concerned with environmental sustainability, electrification of heating might be viewed as a necessary evolution. As such, they would likely support electrification that aligns with broader renewable energy adoptions.

With that said, electrification of the heating and cooking sectors brings also brings out some concerns. Islanders place a high value on self-sufficiency, a theme that is consistently highlighted in interviews. There is a desire to maintain a degree of autonomy from mainland assistance and expertise. Eigg Electric made every effort in the design of the current system to ensure that it would be able to maintain and operate the system independently (Rae & Bradley, 2013). This proactive, firsthand approach to the island’s energy system also extends to its residents who would like a system they can fix and maintain themselves that also incorporates backup solutions.

When implementing the electrified future scenario, it is important to take into account the following:

- In interviews, most residents seemed to favour electricity reliability and availability over how green it was. In the author’s opinion, it is more important to residents to have a reliable electricity supply that is easily managed rather than a system that is perfectly optimized for reduction of carbon emissions.
- Diesel generators, which allow for a readily available and long-lasting form of energy, are an important component of the current energy system and the BAU scenario as well. The community's resistance to a fully electric system due to the potential for system failures indicates that any electrification plan must prioritize resilience and community self-sufficiency.

The presence of diesel generation in the BAU scenario would alleviate community concerns about having a backup system in place. Still, the continued investment in multiple renewable energy sources helps to balance seasonal fluctuations in output from each source, which in turn helps to reduce diesel fuel usage over the year.

- The opposition to electric heating, despite struggles with keeping their homes warm, requires a hybrid heating solution in order to respect the community's preferences. A combination of electric and wood heating can offer flexibility, allowing residents from the convenience of electric heating while also having the option to use wood, which may be more accessible and culturally preferred. A hybrid approach can also provide a backup. It is worth noting that concerns about heating are further addressed further in the energy efficiency scenario that takes into account retrofitting of homes for better insulation.

The acceptance of this scenario is underpinned by the community's positive experiences with the current energy system. In 2008, the island of Eigg became the first community to launch an off-grid system based on renewables. Being self-sufficient is a source of pride for residents on the island, making it important to retain these principles even as the energy system undergoes changes.

While on the subject of self-sufficiency, it is also important to discuss another idea that is equally relevant to the Isle of Eigg: sufficiency, the state of having enough. Dawby and Fawcett (2018) define energy sufficiency as "a state in which humanity would only consume energy services equitably and in quantities compatible with sustainability and ecological limits." Sufficiency, in this context, goes beyond the mere idea of supplying adequate energy. It encapsulates the idea of meeting needs without excess, promoting energy conservation alongside the shift to renewables. It is a principal hat challenges conventional growth-oriented models of energy use and supply. An interesting perspective that was expressed in the workshop was "perhaps the mainland has it wrong" in its approach towards energy use.

The case of Eigg serves as a compelling example of how the principles of sufficiency are being applied and can continue to be applied in practice. Sufficiency involves significant reduction of an energy-intensive behaviour and advocates for a model where less energy is used in a more efficient manner (Zell-Ziegler et. al., 2021). For the Isle of Eigg, the 5 kW cap already proves to be sufficient, as none of the interview or workshop respondents expressed dissatisfaction with this limit. Furthermore, with an average annual household consumption of about 2560 kWh per year, the Isle of Eigg does not fall behind the Scottish average household electricity demand of 3635 kWh per year (Martin, 2020). It can be argued that not only are the residents of Eigg satisfied with the electricity supply on the Island, but the supply is also adequate to meet their needs.

### 6.4.4. Sector Coupling with Energy Efficiency

Building on the Sector Coupling Scenario, it is assumed that electricity becomes the primary source of energy in the island. Transport, cooking and heating sectors get electrified by 2030 and wood, diesel, kerosene, and gas get only used as back-ups. Self-sufficiency is very important for the residents in Eigg. Two interviewees mentioned that even if they had the option to switch to electric heating, they would still like to keep another source of heat as back up. The fact that the island is so isolated makes it difficult for emergency services and technical operators to reach Eigg. Therefore, residents prefer appliances and technologies that make them independent. "*We like things that we can repair ourselves*" was mentioned by one interviewee.

For this scenario to work, support from the community is vital. The change in habits, the adjustments to new appliances and technologies, and its adoption, are all key in the success of this scenario. The survey results show that residents on Eigg are very open to adjusting to changes. On it, more than 70% of the respondents answered they would be likely to shift to electric appliances for cooking, and 70% would also adjust their cooking schedule to align with the availability of renewable energy.

The easy adoption of the 5 kW cap, and the willingness to shift times and fuels show that the Energy Efficiency Scenario could be one of the most successful scenarios for the island. It is the one that addresses most of the concerns mentioned by the interviewees, and that could fit the behaviours, preferences, and current knowledge of the residents. Two interviewees also mentioned they would rather have their house insulated before considering purchasing an electric heat pump.

Social acceptance of energy projects in general, is closely linked to how fair the community members perceive the proposed solutions. Two concepts are identified in literature: distributive justice and procedural justice. A third uncommon one is also mentioned in a few studies; recognition justice, which is particularly important in multicultural communities. Recognition justice refers to the concept of having a fair representation in a group, "recognising that some groups are at a disadvantage within formal participation processes. Within the field of energy, recognition justice draws attention to the dominance of certain demographics within energy decision-making processes, and the need to recognise and integrate the perspectives of less powerful stakeholders." (Roddis et al. 2018). In the case of Eigg, and given its demographics, one could argue that the recognition justice is addressed. Given the community-owned nature of the island, each resident can participate in the monthly meetings, where decisions are made as a group. Part-time residents can also participate in those meetings but cannot vote on decisions. They are also included in the mailing list to stay informed about what is going on in the island. Therefore, the focus of this section will be on distributive and procedural justice.

Distributive justice refers to how the costs and benefits of a project are distributed across stakeholders (Mundaca et al. 2018). Eigg easily addresses this both with the 5 kW cap, and the fixed tariff price for the residents, and the higher tariff for holiday houses. Both solutions (the tariff and the cap) was something that most interviewees mentioned as positive and something that they liked about the system. That it is fair. Even when asked about the limitations that a cap like that could bring to a household, the general response was that it is not a problem at all. "*We have enough for our needs. I do not even think about the 5 KW cap. I have been able to work within this capacity over the years, so I am okay.*" With the energy efficiency scenario, keeping that cap would not be a problem, since residents are used to monitoring their energy consumption and lowering it whenever is necessary. However, this begs the question of what would happen if a household needed more energy. Most households on Eigg have 1 or 2 people living per house. Families may have two children. But for families with many children, or a family member with special needs, this cap could be seen as anything but fair.

Still, the fixed tariff, the transparency on the costs from Eigg Electric, and clearly establishing the reasons for raising the tariff are good for an energy community project. It keeps the community informed and on even ground. According to Li, Hakvoort and Lukszo, community energy systems are innovative precisely because of how they involve local community members. "They play an important role in the energy system by actively involving in the planning, development, and administration of the energy system as well as the allocation of its costs and benefit." (Li, et. al., 2021). This perceived allocation of cost and benefits is closely linked to how the people in Eigg make decisions when it comes to the electricity system. These costs and benefits are not always monetary, and not always individual. As mentioned before, a common worry among the interviewees was the future capacity of Eigg as a whole (enough to satisfy the growing demand as a community), but not for personal consumption. This sense of shared responsibility was mentioned by all interviewees, and some even made a point on wishing to receive more information to adapt their behaviours. Two interviewees said they know when they should lower their electricity consumption, but they would also like to know when it is okay to use more because the renewable generation is high. The stoplight system was mentioned as being useful. However, currently it feels like only the red light works, limiting the amount of information residents have to make decisions.

Another reason that supports the hypothesis of the energy efficiency scenario's easy implementation is the deep understanding residents have of how the island's grid works. This was observed both from the conducted interviews and a paper published in 2020, where it was concluded that "residents draw on heat-based and weather-based forms of sensory feedback, which help them to understand domestic energy consumption, and renewable generation, respectively" and that this "enables them to understand domestic energy consumption and renewable generation in a meaningful way; such understandings are a key first step in householders' ability to engage in energy shedding and shifting practices" (Martin 2020). This was mentioned by some interviewees that seem to know which appliances consume the most energy: "*I am always under 1 kW, but if I received the email alert, I would not use the toaster for example. And my number one priority would be to buy efficient appliances if I needed new ones. Always look for the highest grade*."

When implementing this scenario, it is important to highlight that no regulator is involved in Eigg's energy system. "The community itself needs to agree on the cost allocation method themselves. It, therefore, requires that the selected […] method be socially acceptable to local stakeholders." (Li, et. al., 2021). Therefore, consensus needs to be reached to ensure its success. Said consensus must also be conducted in a way that is perceived as fair by all parties involved.

Procedural justice refers to this agreement process. While distributed justice means to ensure a fair result, procedural justice is concerned with how fair the process to reach this result is. (Roddis et al. 2018). Mundaca mentions that "the perceived fairness of procedures seemed to increase the perceived legitimacy of outcomes" (Mundaca et al. 2018). This seems to be true for Eigg as well. The Big Green Challenge is an example of how when the whole community engages in the planning process, the buy-in is greater.

The Big Green Challenge was a competition sponsored by Nesta, the UK's innovation agency. With a £1 million prize, it aimed to "stimulate and support radical new community-led responses to climate change in the UK." (ChallengeWorks). The Isle of Eigg was one of four winners. The competition looked at four criteria to decide on the winners: CO2 reductions; innovation of the initiatives; longevity and scalability of the proposed projects, and level of community engagement. Eigg managed to reduce their emissions by 32% in one year (Webster, 2010).

An interviewee mentioned that "*For the Big Green Challenge we formed working groups, a lot of community involvement. It was a big success, got lots of people involved and interested, particularly because it was about improving the living conditions in the island. There were lots of community meetings, where priorities were collectively decided. Practical things.*" Therefore, the same process should be followed to brainstorm ideas for energy efficiency strategies in the island, or ideas for educating tourists that visit the island in summer.

This was also something mentioned by two interviewees; they know when they should lower their electricity consumption, but they would also like to know when it is okay to use more because the renewable generation is high. The stoplight system was mentioned as being useful. However, currently it feels like only the red light works, limiting the amount of information residents have to make decisions.

Finally, it is important to show the benefits that could be reaped from implementing energy efficiency measures, particularly those that are not related to consumption reduction but to increasing thermal comfort, the reduction of local emissions from replacing thermal generation (like conventional cars), and better natural lightning.

### 6.4.5. Demand Shifting

While a demand shifting scenario was not modelled, a qualitative analysis was conducted to determine how applicable it would be to the Isle of Eigg.

In electricity grids, supply and demand must be balanced at all times, as is evident on the Isle of Eigg. User behaviour and energy consumption patterns have a tangible impact on off-grid systems (Rae & Bradley, 2013). In an energy system like Eigg a single user of electricity represents a much greater fraction of the total demand, which means individual behaviour has a much greater effect on the energy balance of the system. On Eigg, to ensure that the electricity supply is constant and sustainable, household consumption is capped at 5 kW and 10 kW for businesses. While islanders do not feel restricted by this cap, there are plans in place to increase the cap to 10 kW for households to allow for electrification of heating. The island also utilizes a traffic light system, set up at the pier, to communicate when renewable energy is low: the red light signals to community members to limit energy usage while green indicates that they can use electricity as normal (Chmiel, & Bhattacharyya, 2015). Despite having to decrease their energy consumption well below the average standard, this system works well for the residents of Eigg as there is a general consensus on the island that everyone does their part not to burden the grid.

As such, it can be argued that the elements that enable successful application of dynamic tariffs are present on Eigg. Demand shifting involves incentivizing consumers to adapt their energy use patterns to better align with the available supply of renewable energy resources, a system already in use on the Isle of Eigg. Implementation of a dynamic tariff customized to the island may create a win-win situation for both Eigg Electric and the residents of Eigg. As the producer of electricity, Eigg Electric can long-term average costs  while consumers can save on electricity bills.

But the Isle of Eigg continues to be an interesting case study. Responses to the idea of implementing a dynamic tariff were mixed among both workshop and interview participants. On one hand, some expressed interest in dynamic tariffing, valuing the visibility it would provide into their energy system as well as their household consumption. On the other hand, having a tariff that changed even twice a year would be undesirable for the islanders. They expressed a desire for stability, predictability, and transparency. Even though respondents also had some reservations about the efficacy of current traffic light system in guiding energy use, the idea of integrating smart meters was also met with some concerns about privacy and information security.

There are multiple ways in which an electricity tariff can be designed with regard to how costs are allocated to users and how users react to tariff signals. Traditionally, tariffs are designed in a static way, focusing on the recovery of costs. Currently, the Isle of Eigg operates on a fixed rate electricity tariff. The tariff is designed to provide sufficient funds for system operation, staffing, maintenance, and replacement of components (Chmiel, & Bhattacharyya, 2015). On Eigg, a dynamic tariff would be designed in such a way that it would be cheaper to use electricity during the times when there is less demand on the grid.

However, there are a number of reasons why a peak shifting scenario would prove difficult to apply in the Eigg energy community.

1. While community members are open to the cost saving aspects of dynamic tariffing, the current tariff scheme in place on Eigg is viewed to be fair and reasonably-priced. As such, the designed dynamic tariff scheme would have to create cost savings sufficient enough to over adoption barriers.

2. The limited use of energy monitors. While all households on Eigg are provided with an OWL brand energy monitor, the extent to which they are used in understanding individual household consumption is still unclear. Also, the hesitation among some to move to a smart metering system would hinder the effectiveness of a dynamic tariff (Ma et. al., 2018). Furthermore, changing the entire metering infrastructure already in place could result in significant costs.

3. Any changes to the pricing model must be carefully aligned with the community's desire for stability and transparency, the introduction of a dynamic tariff scheme on the isle would therefore require full community buy-in so as to preserve the principles of fairness that characterize the current system.

### 6.5. Energy Poverty in the Context of the Isle of Eigg

Generally, fuel poverty also called energy poverty is associated with households that spend a high proportion of their household income to keep their homes warm (Bolton et al., 2024). Fuel poverty is a critical consideration for this current study. Given that our study found that 21% of the islanders are fuel-poor and 12% are extremely fuel-poor, we believe addressing the issue of fuel-poverty is paramount in achieving sustainable and equitable energy transitions. Our findings indicate that a significant percentage of the respondents fall within the fuel-poor and extremely fuel-poor bracket (a total of 33%), this underscores the need to design de-carbonization strategies that will not only reduce carbon emissions but also prioritize affordability, accessibility, and resilience. Failure to adequately address fuel poverty could exacerbate social inequalities and hinder the effectiveness of transition efforts.

In Scotland, the Fuel Poverty Act (Act 2019) defines a household to be fuel-poor if:

- after housing costs have been deducted, more than 10% (20% for extreme fuel poverty) of their net income is required to pay for their reasonable fuel needs; and
- after further adjustments are made to deduct childcare costs and any benefits received for a disability or care need, their remaining income is insufficient to maintain an acceptable standard of living, defined as being at least 90% of the UK Minimum Income Standard (MIS) (Bolton et al., 2024).

Due to the different methodologies used in measuring fuel poverty in nations of the UK, the poverty rates cannot be directly compared. Latest estimates show that England has the lowest fuel poverty rate of 13%, followed by Wales at 14%, Northern Ireland at 24%, and Scotland being the highest at 25% (The Scottish Parliament, 2024). Scotland targets to have not more than 5% of its citizens in fuel poverty and not more than 1% in extreme fuel poverty by 2040 (The Scottish Parliament, 2024).

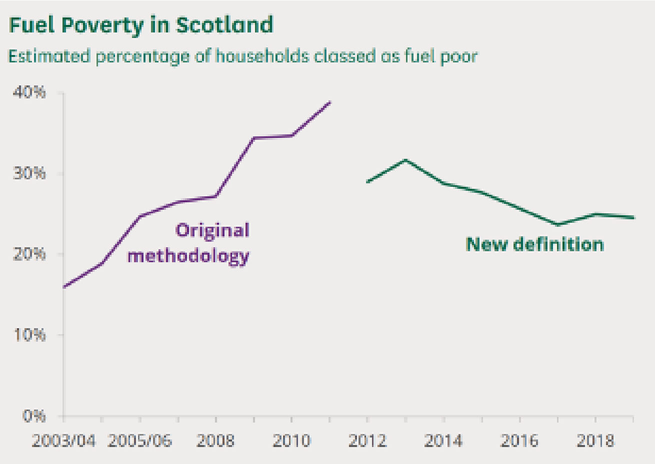


*Figure 6-25: Fuel poverty in Scotland*
Source: UK House of Commons, 2023

Figure 6-25 indicates that from 2003 to 2011, fuel poverty was measured and defined differently, the original methodology was used to measure fuel poverty from 2003 to 2011. In the original methodology, a household is considered to be fuel-poor if: before housing costs have been deducted, more than 10% (more than 20% for extreme fuel poverty) of their net income is required to pay for their reasonable fuel needs.

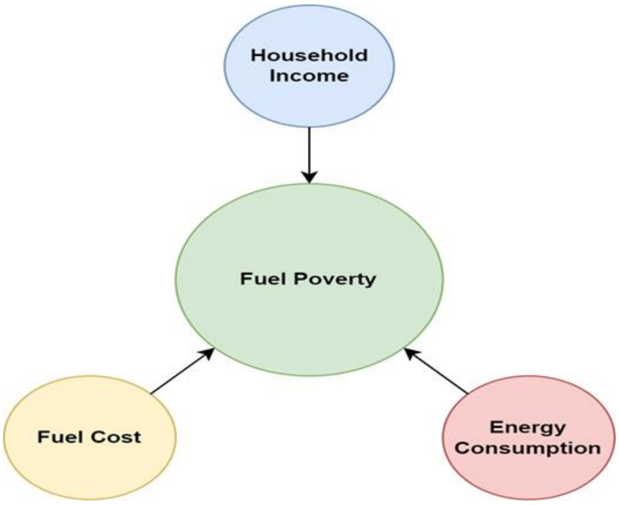


*Figure 6-26: Key factors affecting fuel poverty*

The three factors that affect fuel poverty are household income, fuel cost, and energy consumption (Belaid, 2019; Charlier and Legendre, 2021; Longhurst and Hargreaves, 2019). When households have limited financial resources, they may struggle to afford adequate heating and energy services. Likewise, if a home is poorly insulated with high energy-consuming appliances this can adversely affect the energy efficiency of the house and lead to fuel poverty. Higher fuel prices make it more difficult for low-income households to afford heating and electricity, leading to fuel poverty. Fuel poverty also deepens the vulnerability of people and adversely impacts health, education, and overall quality of life.

### 6.5.1. Measures of Fuel Poverty on the Isle of Eigg

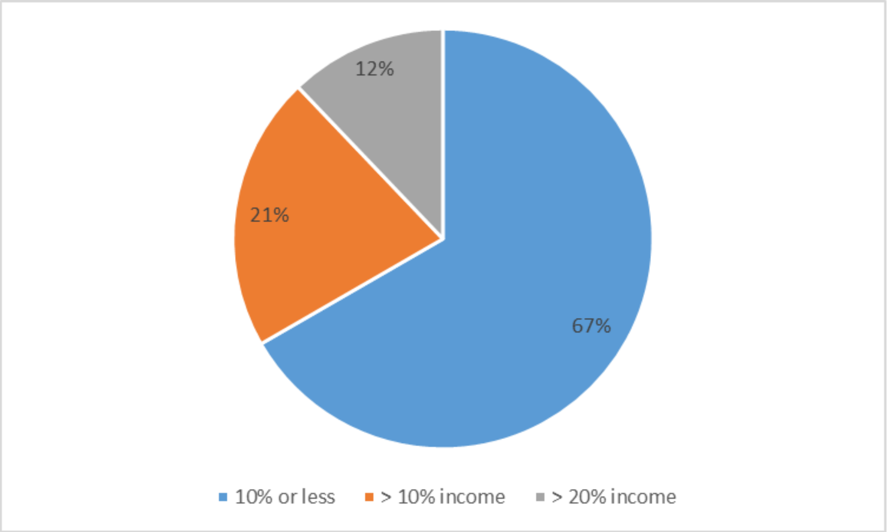


*Figure 6-27: Annual fuel poverty on the Isle of Eigg*
Source: International Class Survey, 2024

Figure 6-27 shows the percentage of annual income respondents on the Isle of Eigg spend on electricity, heating, and cooking. Out of thirty-three participants who took part in this quantitative survey, 22 representing 67% of the respondents were not fuel poor. However, 7 participants representing 21% of the respondents fell in the fuel poverty bracket. These individuals indicated that they spend more than 10% of their monthly household income on energy needs. The Isle of Eigg has some residents who are extremely fuel-poor. According to this survey, 4 persons on the Isle of Eigg are in the extreme fuel poverty category. This figure represents 12% of the total number of residents that took part in the survey. This implies that these individuals spend more than 20% of their monthly income on energy bills. Results from the survey show that majority of the islanders are not experiencing fuel poverty. Even though majority of the people are not experiencing fuel poverty, quite a significant percentage of the islanders are in the energy poverty and extreme poverty bracket (33%). This is why there is the need to design de-carbonization strategies that will prioritize affordability for the islanders.

#### 6.5.1.1. Expenditure on energy bills

A key theme that emerged during the data analysis was expenditure on energy bills by households and businesses. Regarding expenditure on energy bills, all the households interviewed indicated that they spend less than 10% of their household income on energy bills. One of the interviewees said: *“averagely I spend less than 10% of my income on energy bills monthly”.* Another householder responded: “*I can tell you that I spend less than 10% of my monthly income on energy bills”.*

#### 6.5.1.2. Keeping homes warm in the winter

All but one interviewee struggled to keep the home warm during winter, responding: *“I’ve never had challenges heating my home in the winter.”* However, most of the interviewees indicated that due to no insulation, it is always a challenge to heat the home in the winter months. This is what a participant said: *“yes, I do, there is no insulation in the house I live in.”*

#### 6.5.1.3. Effect of inadequate heating on the health of residents

Regarding the consequences of inadequate heating on the health or well-being of residents, all the interviewees indicated that they have not become unwell due to lack of access to adequate heating, at least none that readily comes to mind. When one of the interviewees was asked about the impact of inadequate heating on health or well-being, the response was: *“none that I can remember, so I will say no.”* Other interviewees believed that even though they have not been unwell due to inadequate heating, they appreciated that lack of access to adequate heating can have detrimental consequences on the well-being and health of people. This is what one of them said: *“I have not become unwell, but sometimes life can be more stressful if there is no adequate heating.”*

#### 6.5.1.4. Sacrificing other essentials for energy

The interviewees were unanimous in their responses when they were asked if they had sacrificed other essentials like food, and medical expenses to cover their energy costs in the past year. All the interviewees said they did not have to sacrifice food or medical expenses to cover energy bills. It was evident that the interviewees did not have affordability issues regarding energy. This was confirmed by one of the participants who stated that: *"no, I've never experienced that, remember I spend less than 10% of my income on energy bills".*

### 6.5.2. Interpretation of the Findings on Fuel Poverty

The findings of this current study show that majority of the people living on the Isle of Eigg are not fuel-poor. All the householders that were qualitatively interviewed indicated that they were not experiencing fuel poverty. However, our results show that businesses on the island spend more than 10% of their monthly profit on energy bills. A comparison between the qualitative results of this study and the quantitative results produced by the International Class 2024 survey shows some similarities. Both results indicated that majority of the respondents were not fuel-poor.

When it comes to heating, several studies have established that inadequate heating in the home can have detrimental impacts on the health of occupants (Awaworyi Churchill and Smyth, 2021; Boemi and Papadopoulos, 2019). Inadequate house heating can lead to a range of detrimental health conditions. These include respiratory problems such as asthma and bronchitis due to exposure to colds. Additionally, cold homes can exacerbate cardiovascular issues, increase susceptibility to infections, and worsen mental health conditions such as depression and anxiety.

Ballesteros-Arjona et al., (2022) found that inadequate heating as a consequence of fuel poverty exposes individuals to health risks such as poor mental health and respiratory health. In this study, we found that the health of residents on the Isle of Eigg have not been negatively impacted. However, this is not to say that residents on the island do not struggle to keep their houses warm. Majority of the houses are not well-insulated, which is why when given the option, respondents would choose to invest in building insulation rather than electric heating. A significant observation that was made during our interactions with the participants was that residents of Eigg are frugal with energy consumption. This is probably one of the major reasons why they have seemingly sufficient energy even with the 5kW cap placed on consumption.

Indeed, fuel poverty often forces individuals to make difficult choices, sometimes sacrificing essentials like food and medical expenses to cover energy bills. People in the fuel poverty bracket are sometimes faced with tough choices, risking their well-being to keep the lights on and heating their homes. Some people due to fuel poverty divert funds set aside for essentials like groceries and medical emergency purposes to cater for their energy needs (Longhurst and Hargreaves, 2019). Our findings revealed that residents on the Isle of Eigg do not have to sacrifice money meant for essentials such as food and medical expenses to pay for their energy needs. The reason could that majority of the residents were not having affordability challenges. When people are able to comfortably afford their energy needs, the issue of sacrificing other essentials for energy needs does not come up. Our finding is consistent with what Brown et al., (2020) found in their study.

In conclusion, our findings revealed that majority of the households were not energy poor, as per the Scottish definition for fuel poverty, indicating a favourable situation. Our results also confirmed that residents have adapted to live comfortably within the restrictions placed on energy access, suggesting that the energy provided on the island is enough for the current population. We also found that the islanders are frugal with energy usage, a key reason for the islands' energy management successes. It is not surprising that Eigg has consistently remained a step ahead of the other small islands in Scotland when it comes to sustainable energy promotion. Further studies may be needed to explore the specific factors contributing to the successful management of the energy needs of the island. Understanding these factors could offer valuable insights for other island communities that wish to emulate Isle of Eigg’s sustainable energy success story.

# 7. The Role of the Eigg Community in the Energy Transition

A commitment to self-sufficiency and environmental preservation are a source of pride for the Eigg community. This sense of pride also shapes their behaviour toward energy consumption. The community is aware of the system's constraints, and they have adapted to live comfortably within it. They are open to change when necessary. Eigg's energy system is sustained and strengthened by the active participation and commitment of the local community. They recognize the importance of energy education and awareness of sustainable practices. This collective awareness is essential to promote a culture of energy sustainability on the island.

Eigg residents play an active role in energy conservation by adopting daily practices that reduce unnecessary consumption. Community engagement in energy conservation and being responsible with the energy cap is critical to ensuring the effectiveness and stability of the island's energy system.

When it comes to decisions and planning, the community actively participates in the island's decision-making process and energy planning. Even though there are pre-requisites, determined by the grants and programs that Eigg participates in, when it comes to an open decision, residents' opinions and concerns are considered in discussions about energy policies, infrastructure investments, and future project development. This inclusive participation strengthens the sense of ownership and shared responsibility towards the island's energy system.

Overall, the community is satisfied with the service and the current scenario. But there are concerns about the future capacity, due to the advance of demand in the upcoming years. Besides the population's natural growth, the biggest impact would be the changes necessary to meet Eigg's goal of becoming carbon neutral by 2030.

## 7.1. The Community Role in the Eigg Carbon Neutral Target

To meet the target the population will need to shift from fuel-consuming habits to electric solutions. At this point, the following question arises, *"Are we going to have enough energy for electric heating or cooking?."* This is a valid thought behind the concern that the current scenario is temporary and that changes will be necessary in the near future. And as with any change it takes time to digest, understand and adapt.

The process of change in communities is distributed by several distinct phases, which include significant adaptations. As developed by Kurt Lewin, a pioneer in social psychology best known for his field theory and work in group dynamics, Lewin's change model involves three steps. Often change begins with a phase of discomfort and disequilibrium, where the need for change is recognized but not yet fully understood or accepted by the community. It is common to encounter resistance to change, due to fear of the unknown, concerns about loss of control, or simply the desire to maintain the familiar status quo. To overcome this stage successfully the community will need to take advantage during meetings and social events to intensively work on social awareness. Open talks, debates, and information spread through different ways can be game changers.

Later on, the goal is to see the needed changes incorporated in Eigg, where new practices become part of the cultural and social fabric. During this period of transition, it is critical to cultivate a culture of openness and continuous learning, where mistakes are visible as opportunities for growth and innovation.

## 7.2. Eigg Electric and Community Involvement

Eigg Electric is a community-owned company, meaning it is controlled and managed by the island's members. Despite being conceived by residents, the business model creates a “supply vs client” relationship ensuring that community interests are prioritized and transparency is promoted.

Eigg Electric serves as the operational and organizational body that facilitates energy management and distribution on the island. But goes beyond simply providing electrical services, Eigg Electric promotes local empowerment by empowering residents to actively participate in the management and operation of the electrical system. Residents have the opportunity to acquire technical skills, gain business management experience, and exert influence over decisions that affect their daily lives. This speaks for Eigg Electric's social responsibility, as job creation in rural areas is typically an issue hard to assist. Today Eigg’s Electric team counts on 6 part-time workers and 5 volunteers on the director board.

In addition to implementing renewable energy sources, the Eigg community also faces technical and logistical challenges in managing and integrating these systems. Ongoing maintenance and monitoring of the wind turbines and solar panels requires specialized skills and constant commitment from residents. Most of the Eigg workforce had no experience with energy before, however, through training and cooperation programs, the inhabitants of Eigg have acquired the skills necessary to operate and maintain these systems efficiently and reliably. They are building a polyvalent team, to sum up their skills.

Eigg Electric has an open channel to the community and due to its environment is easy to access one of the members. However, there are also official communications. Every month a status report including the latest updates of the energy system, such as improvements or announcements is sent out via e-mail to the whole community.

The community works efficiently with grants and Eigg Electric collaborates with other organizations, institutions, and governments to promote sustainable development and innovation in energy. These partnerships are extremely important to allow the island to access additional resources, expertise, and financing to support its energy and community goals.

In sum, Eigg Electric is a partnership with the community itself, but as with any relationship have matters to solve every once in a while. Those topics are open for debate during resident meetings and some decisions are made by voting, during those moments it is possible to clarify doubts and endorse the discussion. This dynamic holds a relevant part for Eigg Electric as a facilitator in the transition to a carbon-neutral island, and as mentioned before, they are still working on community awareness about the strategy throughout those channels.

# 8. Conclusion and Recommendations

A model was developed from an Open-Source modelling framework to model the future transition scenarios for the Isle of Eigg. These scenarios were current scenario, a Business-As-Usual (BAU) scenario that extended the current scenario until 2030, a sector coupling scenario that electrified the sectors, a sector coupling with energy efficiency scenario that incorporated the utility of energy efficiency, and a scenario that was conceived to provide another perception and was called No-Tidal scenario where investment in tidal energy was never a choice. Below are some of the key takeaways from the scenarios modelled.

- Current system size is sufficient to serve the power demand of the future if no sectors get coupled.
- If all sectors get coupled, the most economical solution is through the expansion of the installed capacity through investment in tidal energy of at least 250 kW.
- If all sectors get coupled, current battery storage will have to be expanded by at least 500 kWh.
- The highest renewable fraction or cross-sectoral electrification rate can be attained through sector coupling with energy efficiency scenario, taking the overall renewable fraction to 90% across all four sectors.
- If tidal cannot be pursued as an option, new investments in solar PV and wind expansion can also meet the future demand. But the investment costs in this case could be more than 30% higher.
- All scenarios sufficiently bring the emissions down to less than 50%. Remaining emissions are only from heating sector and constrained by the limited power transmission capacity but can be displaced totally using only carbon-neutral firewood for heating. Therefore, decarbonisation is achievable through all three long-term scenarios involving.

It is also important to address concerns. Each of these topics covers an opportunity which then can be developed into a plan.

### 1) Knowledge Handover and Records

A lot of the knowledge comes from firsthand experience and not from an established procedure. Concentration of data can create bottlenecks or loss of information. A first step could be to run a process mapping and registration of the procedures conducted regularly. The creation of a task force can be an opportunity to promote training and professional development for the community, besides the creation of an archive that preserves the knowledge for the future.

### 2) Report Layout and Topics

As mentioned before, the monthly report allows the residents to stay informed. It is a way to maintain transparent and open communication between stakeholders. The monthly report could be improved by establishing a standard layout with topics that the community is interested in the most. For example, key financial aspects, risks, and highlights. Such that the community would know what to expect each month and where to look for specific information. This could also help to catch the attention of the audience. See a proposed model in the appendix A.

### 3) Use of Different Media and Channel

There are different ways to communicate a message, and people also receive information differently depending on the channel. The use of different media to diffuse the information could bring effective spread. So far there has been face-to-face communication during meetings and written correspondence. This is good for fast and efficient communication. However, for bigger projects, videos and media can be an ally to mobilise the community. Thus, a video talking about the carbon neutral plan, could motivate the inhabitants to know more about what they need to do to reach it, how could the living conditions on the island be improved or create empathy about the topic and prepare for when the changes come.

### 4) Educational Programs

Workshops and campaigns can be a way to get the community involved in a desired goal and give extra value to it. Different from courses and training, those moments should be fun and count on moderation tools to keep the public interested. A day where the island stops and dedicates time to a certain topic, engagement approaches such as the use of the same t-shirt, colours, signs, and slogans, create a visual identity and impact. It can also be a section to refresh good practices about the importance of energy conservation and efficient use of resources. This collective awareness is essential to promote a culture of energy sustainability, as well as reinforce the community bonds.

5) Continue to Engage on Eigg Energy System and support Eigg Electric

The community already participates in decision-making processes and public consultations related to energy and island development. Maintaining this engagement is essential to ensure that community interests and concerns are represented and considered. This could be volunteering or providing constructive feedback. The residents and Eigg Electric must support and collaborate with each other to provide clean, reliable, and affordable energy to the community.

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# Annex

## A. Modifications and Additions to GENeSYS-MOD

OSeMOSYS and its extension GENeSYS-MOD provide detailed documentation on the modelling of the energy system and the interplay between various components. Open-Source access of the modelling framework laid the foundation of the model that was used for the energy system at Eigg. The modularity of the framework allows changes that are suited to each unique application. In this context, to fit the energy system installed on Eigg and to attain the desired outputs, several modifications and additions were made to the GENeSYS-MOD framework. Ultimately, the working framework exclusive to the application at Eigg has around 12 parameters, 14 variables, and 11 constraint functions that were components of GENeSYS-MOD and 5 parameters, 6 variables, and 5 constraint functions that were either modified or newly added as a necessary requirement to suit the model for the application at Eigg. The model derived from GENeSYS-MOD is referred to here as the 'adapted model' or just the 'model,' a reference to the original parent modelling framework will always be explicitly made as 'GENeSYS-MOD.' These modifications and additions are enlisted below.

- For long term energy modelling, GENeSYS-MOD aggregates the demand and supply profiles to reduce the timesteps worked upon. Such aggregation methods are a common practice in long-term energy modelling where micro-level interactions of components is not a requirement. In our application, aggregation of the timesteps and reducing them from 8760 hours to aggregated timesteps led to a variation of +/- 40% in the results, and therefore no compromise was made on the number of timesteps involved. This was an unavoidable decision as aggregation would have led to inconsistencies in the calculation of battery activity, variable costs, and estimation of surplus potential, on top of the usual loss of representation of extreme events that occur in between aggregated hours and are consequently lost due to aggregation (Kotzur et al., 2018). A major trade-off of this change has been the long optimisation run-times, that varied from 20 min to 7 hours across different phases of framework development.
- GENeSYS-MOD is a capacity expansion modelling framework that builds new generators to meet a new demand. The modelling framework did not contain the provision of modelling of existing capacities. In our application, the energy system at Eigg already had sufficient capacities of renewable and non-renewable energy generators and storage, all well in their lifetimes, and therefore these had to be modelled. A new parameter-variable pair was modelled that fulfilled this limitation. The adapted model builds upon the existing capacities only while it optimises and finds the new capacities to install.

- GENeSYS-MOD expands capacity with no consideration of the minimum feasible technology size and produces results as real numbers that are the most optimum to meet the demand. It will not be unusual for an optimisation in GENeSYS-MOD to suggest a hydro powerplant of 1.85kW while the minimum feasible technology size is 5kW available in the market (hypothetically drafted situation created as an example- these can vary). Due to the size of the community, magnitude of the demand, and location of the island with its associated logistical constraints, it was essential that the minimum feasible sizes of the generators were specified so that the model could only pick from a selection of these. With this addition in the model, the model was also configured to only operate between integer ranges while selecting the number of units. Reconfiguring the selection to integer from real numbers led to added complexity as the problem turned into a Mixed-Integer Linear Programming (MILP) optimisation problem, but also a reduction in processing time could be seen as the model now only iterated between integers over infinite combinations of real numbers.
- GENeSYS-MOD gives default values to certain parameters that ought to be very large as long integers (for example: maximum hydro capacity = 999999 kW). While this operates without a problem in most cases, such large values become a problem when a parameter also has a very small value (for example: variable costs per kWh of solar = 0.0008), as this leads to 'Out of Memory' run-time errors. Academic license of the solver used (Gurobi) recommends the matrix range to be lesser than 1E08 (Parzen et al., 2022). This was reprogrammed to be an infinite function which instead of assuming a large number to begin with starts small and only grows as large as needed to produce optimal solution. Through such downscaling across some parameters, run-time was significantly reduced from 7 hours to below 1 hour. Gurobi is a commercial solver and provides accelerated processing of MILP models. While Gurobi can be freely accessed through an academic license, other open-source solvers also exist that perform functions. These are GLPK, CBC, and IPOPT. The relative performance of these solvers deviates hugely depending on the complexity of the model.
- The energy system at Eigg has a physical constraint in its transmission network. GENeSYS-MOD offers no provision of modelling a physical transmission or distribution grid congestion. OSeMOSYS offers a module for load flow analysis of the network but that could not be modelled in our application due to complexity and detachment of the scope. To still have the transmission constraint represented, the model was adapted such that it gathered all power flows at each hour and limited it against the capacity at the transformer level in the transmission network. This addition allowed the model to see the maximum electrification

rates that can be achieved with the same power transmission network against all sectors in the future scenarios.

- GENeSYS-MOD has no direct provision of attaining the total capital costs or variable costs across different dimensions of years, technology, and hours. In order to attain these values, dual suffixes or shadow variables are to be used, making the processing and post-processing tedious. Two new constraints solely calculating and storing the total capital costs per technology per year and variable cost per hour of energy production per fuel per year, respectively, were created that provided direct insights into these figures. A trade-off of this has been the extension of optimisation run-time.

While these modifications and additions made the model more suited to the application at Eigg, the model kept some simplifications and generalisations, a few of them carried over from GENeSYS-MOD.

## B. Simplifications and Generalisations of the Model

Neither GENeSYS-MOD nor the adapted model are devoid of simplifications and generalisations. These are sometimes essential to aid the discovery of the optimal solution, to reduce the complexity of the problem thereby reducing the run-time, and to aid modularity of the modelling framework (Subramanian et al., 2018). Enlisted below are some of such simplifications or generalisations that were either in GENeSYS-MOD and got carried over in the adapted model or were created newly in the adapted model.

- The hourly resolution although gives an accurate reflection of the interplay of the supply and demand as compared to the aggregated schedules, it fails to capture the sub-hourly intermittence induced by Variable Renewable Energy (VRE) and therefore the reliability of the model output on micro-transactions remains low (de Boer and can Vuuren, 2017).
- The time-skip of 2-years between modelling years marks all activities as dormant during the years between the modelling years. This has implications especially in terms of the scheduling of the investment as capacities only expand during the modelling years and it gives no information separately on when the investments should be made (Prina et al., 2020). In a similar context, the model fails to capture any intra-modelling period variations that would otherwise be seen in real life (for example, change of prices, discount rates, seasons, and associated resource availability) (Prina et al., 2020).
- Modelling of the diesel generator in a Linear Programming (LP) problem or in a MILP problem is always generalised as a component that operates with linear profiles (Kusakana and Vermaak, 2014). This is in total contrast to the actual reality as the power curve or fuel consumption rates per unit of power produced and the emissions rates vary with the load on

the generator and therefore cannot be linear. However, generalisation of diesel generators as a linear component is a common modelling practice as most transition pathways are for decarbonisation and diesel generators play an insignificant role in most (Ameen et al., 2015). This is a generalisation that has been carried over in the adapted model from GENeSYS-MOD.

- Modelling of battery SOC or battery level in a capacity expansion model is a non-linear function as the battery charge or discharge at any hour is a variable for the model alongside its capacity (Ameen et al., 2015). The model cannot take the existing capacities and expand on top of them while taking in account the depths of discharge (DOD). To achieve the battery level or SOC indications, a way around was determined where the existing battery DOD was re-referenced such that minimum DOD indicated 0 kWh of storage and maximum DOD indicated the difference maximum storage capacity and minimum DOD.
- To incentivise investments in the later years of the modelling period, a common modelling practice is to encode a salvage value such that during optimisation the model can see the benefit of deferring the investment until later (Howells et al., 2011). This is a helpful tool, as without this provision the model will tend to invest right away and this could lead to excessive new capacities or unutilised capacities in case regulations evolve in the years to come against the installed technology or if the demands reduce further for some reason (for example: due to energy efficiency) (Howells et al., 2011). Usually, a non-linear curve for depreciation of renewable energy assets is needed for a true representation of the depreciation rates. For simplification, a straight-line depreciation is modelled that serves the purpose of incentivising investments during the later parts of the model (Howells et al., 2011). This approach is commonly used in applications where salvage values are not explicitly required.

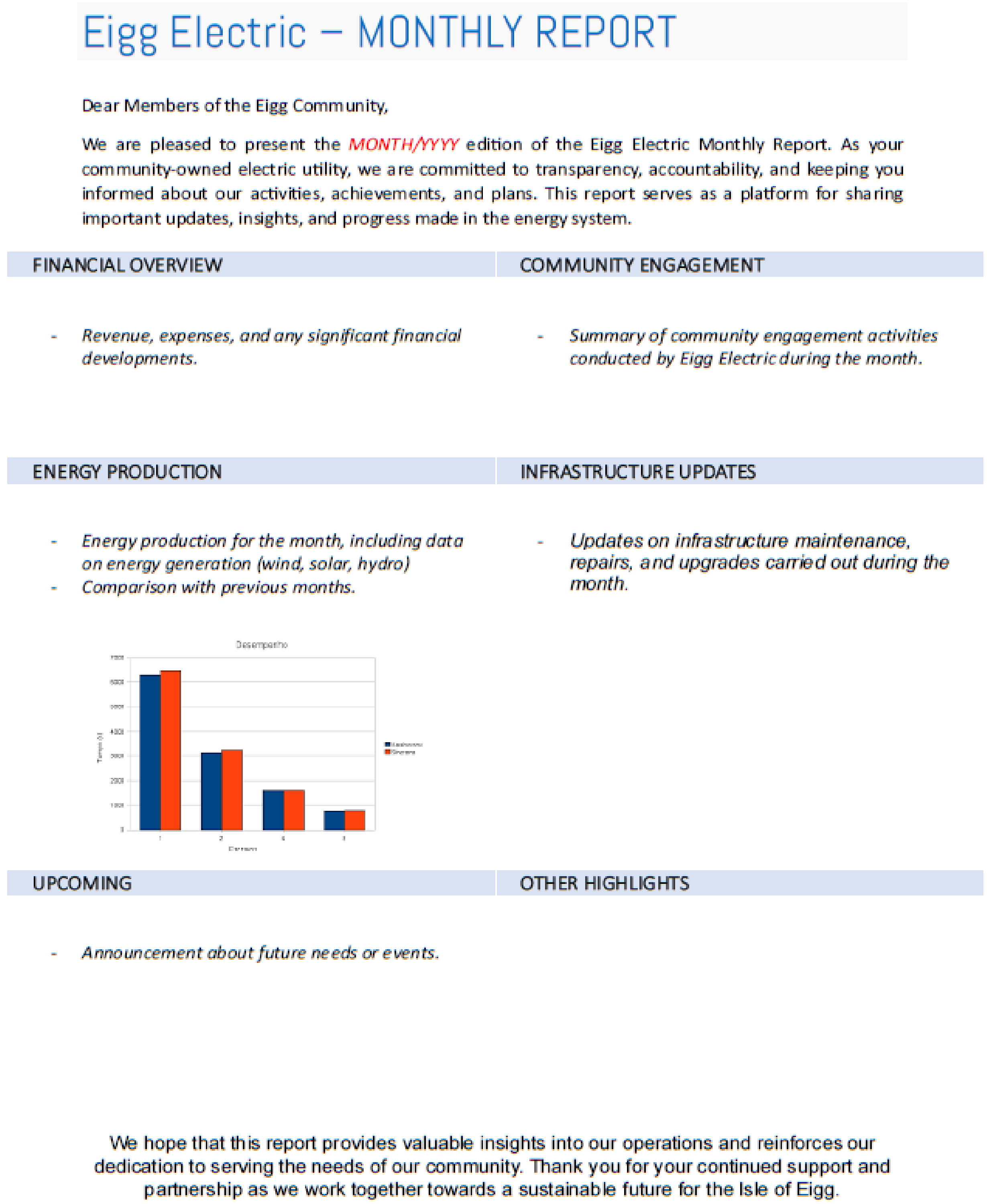
With the defined modifications and additions, and simplifications and generalisations, the model simulates the 4 scenarios and produces optimal results. The model is publicly available on GitHub and can be accessed and run following the instructions on the GitHub repository. The 4 scenarios have each a folder of their own with defined and pre-set inputs and configured output sheets. Below in table 4-4 are the model attributes for the future scenarios. Next section looks at the results and analysis of the 4 scenarios as optimised by the model.

*Table 0-1: Model Attributes*

| Model Attributes | Value |
|---|---|
| Number of Constraints | 5,203,719 |
| Number of Variables | 5,019,768 |
| Number of Binary Variables | 0 |
| Number of Integers Variables | 33 |

| | |
|---|---|
| Number of Continuous Variables | 5,019,735 |
| Number of Non-Zeros | 15,825,921 |

## C. Eigg Electric Monthly Report Layout Suggestion



# Eigg Electric – MONTHLY REPORT

Dear Members of the Eigg Community,

We are pleased to present the *MONTH/YYYY* edition of the Eigg Electric Monthly Report. As your community-owned electric utility, we are committed to transparency, accountability, and keeping you informed about our activities, achievements, and plans. This report serves as a platform for sharing important updates, insights, and progress made in the energy system.

**FINANCIAL OVERVIEW**

- *Revenue, expenses, and any significant financial developments.*

**COMMUNITY ENGAGEMENT**

- *Summary of community engagement activities conducted by Eigg Electric during the month.*

**ENERGY PRODUCTION**

- *Energy production for the month, including data on energy generation (wind, solar, hydro)*
- *Comparison with previous months.*

**INFRASTRUCTURE UPDATES**

- *Updates on infrastructure maintenance, repairs, and upgrades carried out during the month.*

**UPCOMING**

- *Announcement about future needs or events.*

**OTHER HIGHLIGHTS**

We hope that this report provides valuable insights into our operations and reinforces our dedication to serving the needs of our community. Thank you for your continued support and partnership as we work together towards a sustainable future for the Isle of Eigg.

## D. Isle of Eigg Renewable Energy Transition Survey

The survey form aims to gather information from the community in Isle of Eigg, Scotland to develop a renewable energy plan. This plan targets the transition from traditional fuel-based cooking and heating methods to renewable alternatives and includes energy-efficient measures to ensure an efficient and reliable energy system.

There are a total of 19 questions, and it is expected to take maximum 10 minutes to complete the survey. The survey is anonymous and will be solely utilized to refine our findings and conduct research activities for the design of a renewable energy system for the Scottish community.

1.Are you participating in this survey as a household or business consumer? Single choice.

- ○ Household
- ○ Business
- ○ Other

2.How many people are living in your household? Single choice.

- ○ 1-2
- ○ 3-4
- ○ 4-5
- ○ N/A
- ○ Other

3.What type of business do you own? Mention N/A if household. Single line text.

*Enter your answer*

4.How much are you satisfied with the energy supply on the island? Single choice.

- ○ Very satisfied
- ○ Somewhat satisfied
- ○ Unsatisfied
- ○ Very dissatisfied
- ○ Somewhat dissatisfied

5.What approximate percentage of your annual income goes towards your yearly energy expenditure, covering electricity, heating, and cooking costs? Single choice.

- ○ 5%
- ○ 10%
- ○ 15%
- ○ 20%
- ○ 25%

- 30%
- More than 30%

6.During which times of the day are you typically at home or away? Likert

7.Which fuel do you mostly use for cooking? Single choice.

- Kerosene (Litres)
- Fuel Wood (Kg)
- Gas (No. of cylinders or m3)

8.How much do you consume this fuel on annual basis? Mention your answer in relevant unit. Single line text.

*Enter your answer*

9.At what time of day do you usually cook? Likert.

- Breakfast – 05:00-0:800, 08:00-11:00, 11:00-14:00, 14:00-17:00, 17:00-19:00, 19:00-22:00
- Lunch – 05:00-0:800, 08:00-11:00, 11:00-14:00, 14:00-17:00, 17:00-19:00, 19:00-22:00
- Dinner – 05:00-0:800, 08:00-11:00, 11:00-14:00, 14:00-17:00, 17:00-19:00, 19:00-22:00

10.Approximately, how much time do you typically spend cooking your meal? Likert.

- Breakfast – 1h, 2h, 3h, 4h
- Lunch – 1h, 2h, 3h, 4h
- Dinner – 1h, 2h, 3h, 4h

11.Which are the most important electrical appliances which you use in your daily routine? You can select more than one option. Multiple choice.

- Refrigerator
- Washing machine
- Dishwasher
- Cloth dryer
- Microwave
- Water heating system
- Other

12.How old is your building? Single choice.

- old - 1980
- 1981 - 1990
- 1991 - 2003
- 2004 - 2009
- 2010 - 2016

  - 2016 - 2023

13.What type of insulation is used for Walls? Single choice.

  - No insulation
  - Timber Frame
  - Granite or whinstone
  - Solid Brick
  - Cavity Wall
  - Sandstone or limestone
  - Other

14.What type of insulation is used for Roof? Single choice.

  - No Insulation
  - Pitched, loft insulation
  - Roof Room, ceiling insulated
  - Flat, Insulated
  - Other

15.What type of insulation is used for Floor? Single choice.

  - No Insulation
  - Solid, Insulated
  - Suspended, limited insulated
  - Other

16.What type of insulation is used for Windows? Single choice.

  - Single Glazed
  - Double Glazed
  - Other

17.How likely are you willing to shift your cooking habits from conventional fuels to renewable by using electric appliances? Likert.

18.How likely would you adjust your cooking schedule to align with the availability of renewable energy? Likert.

19.What time would you prefer to cook if you consider changing your cooking routine? Likert.