Sustainability Evaluation of Scottish Islanded Mini-grids

Towards asset management strategies for remote off-grid energy infrastructure

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Executive Summary

The delivery of reliable electrical services in remote locations around the world face sustainability challenges in techno-economic and social aspects of planning, design and operation for private, community-based organisations as well as local and national governments. This study aims to increase the positive social and economic impact of renewable energy mini-grids through addressing their sustainability challenges by evaluating seven existing islanded mini-grids in Scotland. The purpose of the study is to inform mini-grid asset management strategies and frameworks, identify opportunities to reduce the management burden on local communities, propose a pathway towards long term financial viability for the mini-girds, and capture operational lessons learned for sharing with other mini-grid organisations internationally.

A sustainability indicator framework has been developed and used to analyse operational challenges and successes in technical, economic, environmental, social and organisational themes, through a consolidated series of interviews with islanded electrical network managers, technology installers, government agencies and mini-grid consumers. Results distil over 20 years of remote, islanded electrical power system operational experience and provide recommendations for the future design and management of these types of energy systems, both in Scotland and in other regions of the world.

It has been found that the mini-grids considered in this study generally provide a reliable electricity supply to remote communities allowing enhanced social impact in a low carbon manner. However, several technical challenges exist, operational frameworks are often conducted in an ad-hoc manner with room for improved cost efficiency, and there is economic uncertainty regarding their future sustainability.

Additional support is required in the provision of technical expertise, management support and long-term business planning. The operation and management of these networks can be a time burden for volunteer directors and in many cases for the volunteer or underpaid operations team. In the absence of professional support and additional resource capacity the electrical service, maintenance of the assets and donor investment money for these networks is put at risk.

Income generation is currently insufficient to provision for end-of-life asset replacement costs, and therefore regular injections of government/donor funding will continue to be required if there is no change in the current model. These energy systems require new consumers and flexible, productive uses of energy to generate additional income from spare renewable energy capacity that will allow for surplus resources to be provisioned for end-of-life asset replacement. Detailed techno-economic analysis is required to determine the specific scale and design of each islanded network to ensure long-term financial viability.

Recommendations have been offered to improve the long-term sustainability of these energy systems in the themes of optimum scale, collaboration and asset management planning. Ultimately the long-term sustainability of electrically islanded mini-grids requires an integrated economic development plan to create communities that have sufficient scale to be independent and resilient. A portfolio management approach is proposed to pool resources and operational costs, reducing the burden on mini-grid managers and achieving economies of scale, while increasing economic sustainability.

The results of the study should be used by policy makers to inform future strategies for off-grid energy networks that enhance economic growth and social impact in a sustainable manner. Mini-grid owners may wish to build upon suggestions in this report and learn from other operators. A commercial opportunity exists to develop efficient management strategies for mini-grids in Scotland, which could be replicable to other mini-grid deployments around the world.

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1. Introduction

Providing reliable, affordable, safe and secure electrical services sustainably in remote locations around the world, as highlighted by the Sustainable Development Goal 7 (1) presents a techno-economic and social challenge for private and community-based organisations as well as local and national governments. These locations may be characterised by low population density and energy demand, where logistical constraints increase the cost of infrastructure installation and maintenance, and the availability of local operational staff can be limited. In such areas, local distribution grids with generation sources operating independently from the main, or mini-grids, can offer a solution to these challenges.

However, globally mini-grids face several sustainability challenges (12), and although barriers to sustainable operation are being overcome through increased deployment, the focus for stakeholders has been largely technological to date. Business models have also been explored extensively (13), as well as different financing mechanisms and potential for national and international interventions. Technological performance monitoring frameworks for mini-grids exist (14), but rarely involve a comprehensive methodology that considers the full range of potential impacts and sustainability challenges; only by assessing a holistic set of indicators can the full success and sustainability of a mini-grid scheme be determined.

In Scotland, there are seven "off-grid" or islanded electrical power networks that are owned and operated by community-based energy companies or government agencies (2). Recent transitions from private land ownership to community buyouts have brought with it the responsibility to maintain the energy infrastructure for the benefit and future growth of the community. To date regular capital injections from local and central government have been required to keep the systems operating, and it is unclear whether these community-based energy companies can become independently financially viable. Targeted research can be used to understand what changes might be necessary in both the technical design and operations of these energy systems to move them closer towards long term economic viability. Furthermore, lessons can be learned from these remote, islanded electrical networks, which may be applied to the development and operation of future mini-grids internationally.

Developed countries have the resources to build and operate remote energy networks so that basic, common living standards can be offered to all citizens. However, in the Scottish context, the communities are pioneering a cooperative energy ownership structure that is both technically and managerially challenging for volunteer company directors as well as costly per capita for national government. This research has therefore a dual purpose: to identify opportunities to reduce the management burden on local communities and identify a pathway towards long term financial viability for Scottish islanded mini-grids; and to capture operational lessons learned for sharing with other organisations that are active in the development and operations of mini-grids internationally.

The work of the study investigates the sustainability of these islanded mini-grids in Scotland, through indicators themed in technical, economic, social, organisational, and environmental sustainability. The framework is intended to provide a holistic evaluation in order to provide targeted recommendations to increase the sustainability of the mini-grids, increase their technical efficiency, social impact, and economic profitability, while reducing the requirement for on-going government funding.

In the remainder of this report section 2 provides a brief introduction to mini-grid definitions and global trends, as well as relevant Scottish energy policy, while Section 3 outlines the methodology used in this study. Section 4 summaries the results of the sustainability indicator analysis, while Section 5 provides discussion points with recommendations to be taken forward by mini-grid managers, policy makers, and researchers.

2. Mapping the Global and Scottish Mini-grid Ecosystem

This section introduces the definitions and components of a mini-grid system, and offers high level insight into global mini-grid trends. Relevant Scottish island and energy policy is discussed, in order to identify and summarise key drivers and players in the Scottish mini-grid eco-system.

2.1. Mini-grids: Definitions and Global Trends

The International Renewable Energy agency (IRENA) classifies a mini-grid as a form of integrated energy infrastructure with distributed energy generation resources and loads, providing autonomous capability to satisfy electricity demand through local generation, mainly from renewable energy sources (3) although several other definitions also exist (4). Mini-grids comprise of power generation technology, storage to account for intermittent renewable resources, a distribution grid providing electricity to load demand (customers), and protection and control elements. Mini-grids also have the option of interconnecting with other mini-grids and connecting to a central grid network. In the Scottish case, all seven mini-grids are “off-grid”, they are disconnected from the main National Grid and are not subject to the same regulatory requirements as commercial energy companies. Figure 1 illustrates a prototypical mini-grid structure and the components that can be found on each of the mini-grid systems investigated as part of this study.

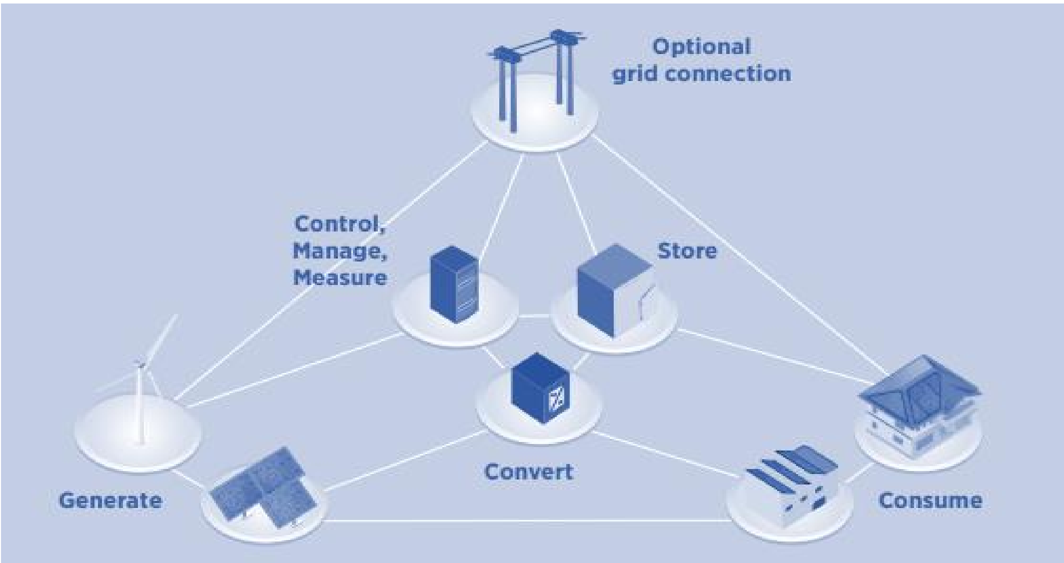

Figure 1 Mini-grid components adapted from (3)

According to the International Energy Agency (IEA) mini-grids currently provide electricity to nearly 90 million people and have the potential to serve 212 million people globally (5). The mini-grid market is on the rise in the Global South, mainly due to decreasing cost of renewable energy technologies (specifically solar PV modules) and battery storage (6). Operating distributed renewable energy assets can now therefore be considered commonplace in developed and emerging economies due to the proliferation of decentralised solar, wind and hydro generators internationally. However, the distributed nature of these generators requires new approaches to their long-term operation and maintenance.

2.2. Policy drivers and trajectory for mini-grids in Scotland

The Scottish Energy Strategy (2017) targets a diverse, well-balanced energy supply portfolio required to decarbonise heat, transport and electricity systems, guided by principals of a whole system view, an inclusive energy transition and a smart local energy model (7). Scottish Enterprise estimate the local energy systems market in Scotland could be worth £637 million by 2030 and this area continues to be a focus through the recent (2019/20) Scottish

Government consultation in this area (8). The Islands of Rum, Eigg, Muck, Canna, Foula and Fair Isle and the peninsula of Knoydart are all 'off-grid', not connected to the national electricity network, and have been supported by Highlands and Islands Enterprise (HIE) to become part of the EU Clean Islands Network (9) with pledges to develop a Clean Energy Transition Agenda. The support programme provides a platform for collaboration on an international scale, enabling strong linkages to be built across international islands in a similar situation and allowing communities to share knowledge, expertise and resources to develop one overarching off-grid Transition Agenda with specific recommendations for each island within this.

The Scottish Energy Strategy (7) also includes provision for islands which are both off and on grid, with key strategic themes including developing a route to decarbonise the islands in line with a 2045 national decarbonisation policy, and energy security. Moving from renewable electricity to renewable heating and transport solutions are noted challenges and the Scottish Government is currently obtaining baseline information and scoping high-level management to inform an Islands' Energy Policy which is under development.

There is an expectation that decarbonising the islands is going to be expensive, and that island energy policy needs to be future proofed and aligned to the National Islands' Plan (10), which states that if the low carbon energy potential of islands was fully realised the effect on the island economy could be transformational and the islands can become hubs of energy innovation and climate change leaders. The renewable and low carbon energy provided by the mini-grids and the community role of the mini-grids ties in well with the Scottish Government meeting its challenging Heat in Building Strategy (11) designed to reduce greenhouse gas emissions from Scotland's homes, workplaces and community buildings and to ensure that they remove poor energy performance as a driver of fuel poverty.

Island policy strategy regarding energy has traditionally relied on HIE with overall key strategic objectives guided by the Scottish Government's economic strategy, including providing support to businesses, supporting communities to build resilience, and regional development.

The HIE Off-grid Collaboration Network was established to bring these seven islanded electrical networks together, share problems, ideas and solutions. The network fosters a collegiate approach allowing for knowledge sharing drawing on the skills and experiences of the mini-grid managers on the islands, allows them to see how they fit into the national picture and is beneficial for them to understand they are not alone in facing challenges. The network shares examples of good practice from other communities, with a shared low carbon agenda and a move away from fossil fuels.

3. Evaluation Methodology

The evaluation follows a multidisciplinary methodology through collection of primary quantitative and qualitative data to gain a comprehensive picture of each mini-grid's performance and sustainability, correlated to operational strategies and experiences as well as input from government agencies and expert technology installers. The evaluation utilises a sustainability indicator framework to provide insight on mini-grid performance in terms of technical, economic, social, environmental and organisational sustainability, adapted from a framework presented by Ilskog (12) and adapted by Yadoo and Cruickshank (13).

3.1. Research Methods

A summary of the research methods deployed in the study is outlined in Table 1. Relevant project and technical reports were analysed, with targeted expert interviews carried out with microgrid managers, installers and representatives from Scottish Government and HIE. Consumer surveys were also carried out online to triangulate data and gain a customer's perspective. An overview of the experts that were interviewed can be found in Appendix 1. Table 1 summarises the research methods employed in this study.

Table 1: Research Methods

Project & Technical Reports	Each mini-grid has produced several technical reports related to the design, installation, operation and business model specific to their mini-grid. As well as technical reports, information was gathered on financial performance of the mini-grids, documenting income and expenditure over the projects lifetime. The reports have been assimilated to gain an understanding of operational practises and challenges faced during the project's lifetime.
Expert Interviews	Interviews were held with key contacts for each mini-grid to gain a clear picture of how communities operate their energy systems; discover technical, social and economic challenges that the mini-grids have faced; and understand how these challenges have been surmounted. Cross-referenced with the other data sources, this information provides insight into factors affecting mini-grid sustainability. The interviews followed a semi-structured informal approach, where a list of questions was covered with the interviewer using probing to gain sufficient level of detail. Additional expert interviews were held with Highlands and Islands Enterprise, Scottish Government, and system installers to gain a clearer understanding of the enabling environment or mini-grid ecosystem under which the mini-grids have been operating. Interviews were held remotely and recorded and transcribed, with interview transcripts shared with stakeholders for approval and validation prior to analysis.
Consumer Survey	Gaining the perspective of end-users of the mini-grids allows for a clearer understanding of how the system performance affects end-users. The survey was designed to discover opinions on the impact of the mini-grid in the community, cost of electricity, experience of mini-grid down-time or quality issues and the impact, and consumers understanding and opinion of the ownership and operational practises of the mini-grid. Such external views complement the insider perspectives gained through the expert interviews. The survey was intentionally kept short and simple to ensure a higher completion rate and restricted to ten questions. The questionnaire was hosted on Kobocollect (14) and a link sent to each consumer by the mini-grid manager.

3.2. Sustainability Indicators

Each mini-grid was evaluated utilising the sustainability matrix presented in Table 2 to assess the extent to which the electrification systems are sustainable, defined in a holistic sense of technical, economic, social, environmental and organisational sustainability. The purpose of the evaluation was to use the data collection tools and methods presented in Table 1 to provide sustainability indicator insight for each mini-grid, identify which systems are not achieving all sustainability indicators, identify reasons why, and make suggestions for methods and frameworks to achieve them.

Table 2: Mini-grid Sustainability Indicators

Technical: 1. Service is reliable, disruptions are minimal 2. Service meets current and future demand capacity requirements 3. System is efficient and technical losses are minimised 4. Support infrastructure (expertise, supply parts) is readily available 5. System is well maintained and advance notice about planned service disruptions is given to users 6. Service is safe to use and operate
Economic: 1. Service is affordable for users 2. System breaks even 3. A share of the profits is re- invested in the electricity service 4. Electricity is used by local industries 5. Electricity is used by a broad range of micro-enterprises 6. Local employment opportunities have increased due to electricity 7. Profits from micro- enterprises or livelihoods have increased due to electricity
Social: 1. Electricity is used in schools 2. Electricity is used in health centre 3. Electricity is used in community centre 4. Tele communications have improved due to electricity 5. All households who want it have access to electricity service
Environmental: 1. Electricity is generated from a low carbon source 2. Electricity has replaced diesel or other fossil fuels for heating 3. Electricity has replaced diesel or other fossil fuels for cooking 4. Electricity has replaced diesel or other fossil fuels for equipment 5. No adverse local environmental impacts have occurred
Organisational: 1. Electricity service management organisation is efficient and effective 2. Project documentation is easily accessible and efficient 3. The management team is a good representation of the customer demographic 4. Low level of non- technical losses or payment defaults 5. Users are satisfied with the electricity service 6. Transparent financial accounts are kept 7. There is an effective channel through which complaints about the service can be made

4. Sustainability Evaluation Results

This section provides an overview of the mini-grids, including geographic location and key technical parameters. A summary of the findings for each indicator theme is presented, with detailed insight for each mini-grid presented in Table 4 to Table 8.

4.1. Overview of Mini-grids

The seven mini-grids are geographically located according to the map in Figure 2, and a summary of the key parameters for each mini-grid is outlined in Table 3 allowing for an understanding of the operating conditions for each community energy company. Both demand and generating potential on these islands is relatively small and because of the distance from the mainland the cost of sub-sea cables makes connection to the national grid prohibitive in the medium term. As a result, the seven islands have developed energy solutions that are self-contained.

Energy demand on the islands is met by a range of complementary technologies such as wind, solar and hydro generation, with diesel generation to balance supply and demand. The electrical networks are owned by community companies (apart from Rum, which is owned and operated by NatureScot[1], an executive non-departmental public body of the Scottish Government but the community is considering an asset transfer process).

According to HIE, operational considerations for the islands are challenging, with key themes in their view summarised as financial and human capacity. The networks are generally expensive to run with supply being costly, and although well-trained individuals exist, there are not many of them. HIE commissioned a Small Islands Energy Systems Overview audit in 2018, following receipt of the audit HIE developed an ongoing workstream to identity what activities may be required to solve resilience issues, reduce the risk of catastrophic weakness in the future, and address issues restricting growth and development in communities.

A secure energy network is fundamental to any community's resilience and energy concerns are of primary importance to HIE. A "sticking plaster" approach has been used to provide money when needed, and there is a need to plan ahead before some of the systems are coming to their end of life.

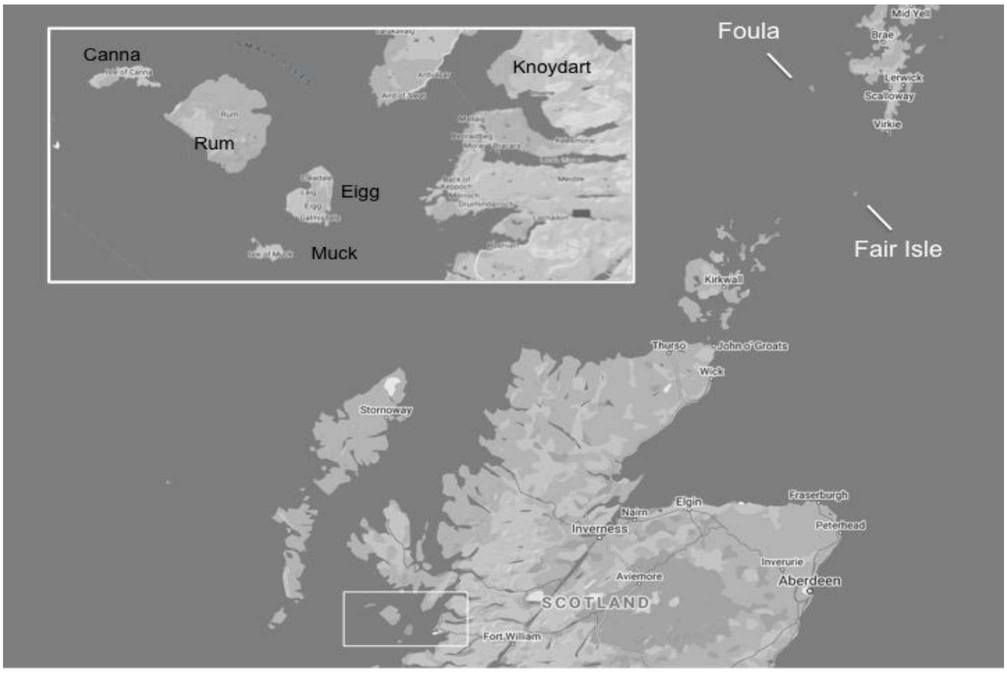

Figure 2 Location of the mini-grids (Source: Google Maps)

[1] NatureScot is the operating name of Scottish Natural Heritage

Table 3: Summary of key mini-grid parameters

	Canna	Eigg	Foula	Fair Isle	Knoydart	Muck	Rum
Installed	2018	2008	c1985,refurb 2004-15	2018	1978, refurb 2001,2015,2021	2013	c1900 refurb 1980,2010-12
Renewable Generation	70 kW	304 kW	75 kW	225 kW	280 kW	66 kW	45 kW
Generation Technology (kW/kVA)	Solar PV (40) Wind (30) Diesel (45)	Solar PV (50) Wind (24) Hydro (115) Diesel	Solar PV (25) Wind (18) Hydro (20) Diesel (65)	PV Array (45) Wind (180) Diesel (160)	Hydro (280) Diesel (160)	Solar PV (36) Wind (30) Diesel	Hydro (40) Diesel (96)
Battery Size	159kWh	316 kWh	80 kWh	1174.66 kWh	190,000 kWh (loch storage)	45 kWh	150 kWh when installed
Storage Technology	Vented lead-acid battery	Lead-acid battery, Flywheel, ultra-capacitors. storage heaters, loch storage	Vented lead-acid battery, seasonal loch storage, residential storage heater	Vented lead-acid battery, storage heaters	Loch storage, R&D flow battery, storage heaters	Lead-acid batteries	Lead-acid batteries, dump load to castle heating.
Connections	28	86	25	34	70 (50 residential)	40	52 (25 residential)
Population (inc tourists)	17 (34)	110 (250)	34 (50)	55 (130)	110 (200)	40 (40)	40 (90)
Tariff	Standard: 25p/kWh Dump load: 5p/kWh standing charge: £25	Standard: 25p/kWh Business: 40p/kWh Standing charge: 12p daily	Residential: 25p/kWh Business: 55p/kWh	Standard: 16p/kWh Heating rate: 4p/kWh Commercial: 22p-28/kWh Standing charge: £25-£50 quarterly	Standard: 20p/kWh after VAT, Heating rate: 10p/kWh other variable tariffs	Standard: 25p/kWh Dump load: 7p/kWh Standing charge: £25 quarterly	Standard: 18p/kWh Standing charge: None
Billing	Quarterly meter readings & bills BACS & Cheque	Domestic by pre-paid card. Public service /business by meter reading	Quarterly meter readings & bills	Quarterly meter readings and bills	Quarterly meter readings and bills	Quarterly meter readings and bills	Pre-paid cards and meter readings and bills
Legal Entity	Company Ltd by shares	Community owned, trading subsidiary of Heritage Trust	Charity (legal status currently under review)	Company Ltd by Guarantee	Company ltd by Shares	non-profit company limited by guarantee	Owned by NatureScot
Paid maintenance team (size)	No (6)	Yes (4)	Yes (4)		Yes (2)		Yes (1, looking to increase to 4)
Installation Cost	£1.31m	£1.6m	£850,000	£3.4m	10 year £1 million	£978,000	£633,000 (2012 upgrade)

4.2. Sustainability Indicator Framework

4.2.1. Technical Indicators

The main technical challenges noted by the installers and mini-grid managers were due to the remote locations of the mini-grids, resulting in logistical issues involved in getting installation and maintenance crews to the islands and then waiting for weather windows to carry out maintenance tasks. Renewable generators on islands can have shorter lifespans, higher operational costs and higher levels of maintenance than on the mainland due to higher wind speeds resulting in greater maintenance requirements for wind turbines and salt rich sea air increasing the rate of corrosion on exposed metals.

Installers stated that bespoke engineering solutions are required due to the integration of various renewable energy generation and storage technologies, and there is a need to find reliable contractors, as well as securing guarantees on equipment. Some mini-grids have had challenges with wind turbine companies going out of business or not honouring warrantees. Mini-grids have taken advantage of technology advancements such as battery upgrades, as well as cheaper equipment for solar PV and batteries.

Both installers and mini-grid managers stated the benefits of remote access to the mini-grid Supervisory Control and Data Acquisition (SCADA) and monitoring systems to support troubleshooting and for providing remote assistance, allowing installers to log in remotely to provide support from a distance. On-going support is generally ad-hoc and often provided for free, which is not considered sustainable.

Despite these challenges, most mini-grids indicated they offered a reliable service. The service meets current demand, with some having spare capacity but most needing additional generation to meet expected increases in demand. Grid voltages are not recorded so exact system efficiencies and power quality is unknown. All mini-grids give advance notice to users regarding planned service disruptions and most mini-grid managers indicated the mini-grids are safe to operate.

The Scottish Government (SG) noted the need for contingency planning in the event of a catastrophic failure, noting that there was a “gap” in who would be responsible for providing emergency cover in the event of a catastrophic failure. Such responsibility usually falls to the network operator but in off gird communities that is not an option. The SG Contingency Planning team has offered advice on how such a situation should be dealt with included as a starter, having in place an up-to-date contingency plan. A suggestion was made regarding an obligation to establish a guaranteed supply, such as a contract between the community organisations and a back-up generator (e.g. Aggreko) in case of a catastrophic failure. Details of technical sustainability indicators for each mini-grid are outlined in Table 4.

Table 4: Technical Indicators

Service is reliable, disruptions are minimal	All mini-grids indicated the service is generally reliable with minimal outages, apart from Rum which has issues with the hydro inlet, pipeline and lead acid batteries which are at the end of their life (currently at 15kWh from an installed 150kWh). A Community and Renewable Energy Scheme (CARES) funded project is in development. For Knoydart, geese hitting the overhead 11kV line cause the majority of outages, and the existing hydro pipeline and turbine are coming to their end of life with government funding obtained for replacement. Canna has a new community owned system installed in 2018 replacing a system previously owned by National Trust for Scotland, with no issues to date. Foula now has a reliable system, although previously very unreliable where maintenance was a big issue with common faults relating to the inverter and battery system. Rum has a very old system, with some fundamental design flaws in the hydropower system and the battery storage system has reached its end of life. Muck has generally good service but short

	power cuts occur when switching loads from renewables to diesel generator. Fair Isle has experienced several problems with recently installed wind turbines. Eigg has minimal disruptions, faults are recorded which are usually diesel generator and fuel related. *"Currently the system is reliable, but in the past it has been very unreliable for long periods of time"* – Foula
Service meets current and future demand capacity requirements	All mini-grids meet current demand, some with power limits installed on properties (Rum, Muck, Eigg). Rum has a 20A property supply limit with a keyed circuit breaker, Muck's domestic properties are limited to 5kW, while Knoydart is using 60A or 100A cut out fuses. Most have excess capacity for future demand, which is currently unutilised (Canna, Fair Isle, Knoydart, Fair Isle). Some have limited capacity (Rum-through additional diesel generation or hydro if batteries are replaced, Foula) or no additional capacity (Eigg). Knoydart is working towards a plan to optimise hydro resource utilisation with flexible heating and productive uses of energy. Foula indicated that customers would like to consume more on heating and machinery, and that to meet demand growth additional renewable generation and/or battery storage systems would be needed. The following appliances were noted in consumer surveys as desired but unable to be currently powered: electric shower, car charging, electric heating, freezer, tumble dryer, electric kettle, and toaster. Some indicated that they have to be mindful of electricity use and not switch everything on at once. *"(the mini-grid) just meets the demand and service requirement currently, but more battery capacity is needed for summer period when hydropower systems have lower power output. We have no capacity for future connections until infrastructure is improved."* - Eigg
System is efficient and technical losses are minimised	Apart from Canna, who estimate distribution losses on their Low Voltage network to be 14%, none of the mini-grid managers are aware of the actual losses on the system. This is either because they do not have the equipment to measure (Knoydart, Muck, Rum), the monitoring system is broken (Foula) or they have the data but haven't studied it (Fair Isle). Some indicated they would be interested in more understanding and monitoring of overall system efficiency (Canna, Foula). Knoydart said they have too many other issues to worry about, Foula said monitoring is more human based "having a feel for the system" rather than data based. Rum has good data on hydro and battery performance but unknown distribution efficiency. Fair Isle records all performance data, but specific system efficiency is unknown. *"I've got more to do than look at figures, as long as the lights are on and its working"* – Fair Isle
Support infrastructure (expertise, supply parts) is readily available	All mini-grids have different frameworks in place for supporting maintenance and troubleshooting on the mini-grids, mostly on a bespoke or ad-hoc basis, relying on the experience of directors to support management decisions. Canna and Knoydart said they needed more experience on the island. Knoydart utilise ad-hoc consultant support with no on-going operations contract, as well as two experienced operators resident in the community. Canna have a 10 year maintenance contract with Wind and Sun for their solar PV, inverters and batteries and receive remote support from Community Energy Scotland. They also have a 10 year service agreement with SD Wind but are disappointed with the service. Rum has one paid onsite operator,

	supported by both voluntary and paid offsite management, it is a bespoke system that requires familiarisation. Fair Isle has a critical spares inventory but are concerned about transformer faults or failures, and stated it is difficult to get spare parts to the island. Some mini-grids rely on others for advice (Canna, Eigg and Muck). *"We have limited operational support, a bespoke system with several different types of technologies, suppliers want to sell new products rather than fix old. It requires someone local to really get involved in the maintenance."* Foula
System is well maintained and advance notice about planned service disruptions is given to users	All mini-grids have a detailed maintenance schedule in place, with varying degrees of documentation (see organisational). Knoydart record outages and faults, but have no remote SCADA system, they stated there is room for improvement on the maintenance strategy. Canna has digital documentation on drop box and digital documents on a tablet in the inverter shed, no outage or fault events are recorded, and remote access to a SCADA system is possible. For Rum an inspection and maintenance list is in place but it is unknown if this is strictly adhered to, there is good operating knowledge on island but the system currently relies on one person with daily off-island remote monitoring and advice. Muck has a service routine including annual wind turbine service and transformer oil checks, daily inverter checks, monthly PV checks. Fair Isle do regular service inspections and records. Eigg have regular servicing checks, an operations team in place, daily checks both online and physically at the control shed. All mini-grids give advance notice to users regarding planned service disruptions by email apart from Foula who do it by phone. *"We have had a long road to our current O&M structure it was very bumpy, maintenance was a big issue previously"* – Foula
Service is safe to use and operate	All mini-grids reported the system is safe to operate, although some would prefer training or more knowledge of regulations (Knoydart, Foula). Knoydart is unsure of the specific regulations the company should be working to and Rum have a low voltage distribution network deemed safe to operate but indicated a significant investment is required. Foula regard their system as safe in as far as the operators know their limits, however note it's a complex area that requires attention. *"Everything seems fine, until it isn't. Needs a holistic review."* – Knoydart

4.2.2. Economic Indicators

The majority of customers consider the tariffs to be affordable, and cheaper than previous diesel generators, however some complaints of high tariffs were stated within the consumer surveys, and not all mini-grids have uniform tariffs causing conflict between customers. All mini-grids except Rum bring in sufficient income to cover operations and maintenance costs, however none provision funds to replace capital assets at their end of life. The majority of mini-grids reinvest their profits to improve the electricity service, often through a parent company such as the local community development trust. Electricity is used for local enterprises in all mini-grids, and most mini-grids have paid operational roles. It was not possible to estimate whether employment opportunities had increased from the supply of mini-grid electricity, as often customers were on diesel generators before, however most mini-grid operators expressed plans to initiate new businesses, some using surplus renewable generation, which would likely create jobs.

All mini-grids except Rum have relied on grants for capital funding for new equipment, which is a trend that will continue if current income from electricity sales remain unchanged, as annual income is insufficient to meet operational costs as well as provision income for capital replacement. The Rum mini-grid relies on funding from NatureScot's core budget for new equipment. Several stakeholders highlighted a need for strategic, long term holistic planning that considers both the operational requirements and also expansion planning for the networks. Several mini-grid operators suggested that different forms of productive energy uses and anchor clients, with time insensitive demand would increase the economic viability of their systems. Other suggestions included regular donations from the electricity company to the parent charity to create a future infrastructure loan fund, and sharing accounting, administrative and insurance functions across mini-grids to reduce costs.

HIE noted the regulations and support for off-grid energy can be a grey area, as there is no organisation that has any direct responsibility for them (e.g. not Ofgem or UK government). However, they note that people have a right to an electrical supply. SG noted the challenges faced by off-grid communities, particularly in terms of costs to upgrade energy infrastructure and made available up to £3M in FY 20/21, to support infrastructure upgrades in off-grid communities. The same level of funding will be available in FY 21/22. They posit that it is challenging but not impossible to make the energy systems work on a commercial basis, given a suitable scale, design and support structure. One mini-grid manager made the point regarding the financing of replacement infrastructure by the mini-grids to find a way of exempting taxation on profit put to one side for future replacement, otherwise, there is little incentive to be self-sustaining and reduce reliance on Scottish Government grants.

The obvious preference for both SG and HIE is for these communities to have a secure energy supply, as the national grid connection is not an option currently being considered, it is therefore vital for the mini-grids to be independently financially viable in the long term. HIE are conducting in-depth modelling to answer questions regarding financial feasibility.

These community energy companies arguably have challenges that other mainland generators do not have, for example they are limited by demand and cannot readily sell surplus renewable electricity and experience higher capital installation costs due to the remote nature of the sites. Details of economic sustainability indicators for each mini-grid are outlined in Table 5.

Table 5 Economic Sustainability Indicators

Service is affordable for users	The consumer surveys indicated that all customers found the service affordable, apart from the following: Eigg (only just), Foula (no, it is very expensive and some people struggle to pay their bills, it is excessive), Knoydart (just, too expensive, it encourages people to install backup generation, expensive to heat home during winter months using electricity). Knoydart's prices have increased gradually over the past 10 years to account for asset replacement costs and the reduction of ROCs in 2022. They indicated that price consultations are difficult, with many different views from the community, resulting in different tariffs for different customers. Rum's domestic properties have card meters for sale from NatureScot and via the shop, some NatureScot properties are not metered. The price per unit is set at the meter, which means increasing tariffs requires a visit into someone's property, or adjusting the charge made for the card. .
System breaks even (O&M costs are met)	Knoydart meets O&M costs with a turnover ranging from £100-£120k and operating costs of £86k per year, however £30,000 of turnover is from ROCs which will end in 2027. Canna has an income of ~£26,000 per year with expenses of £20,500 including £6,000 insurance costs per year, they have a maintenance fund into which £1000 is put every year for when current maintenance contracts come to an end in

	10 years time. Foula has an income of approximately £50-£60k per year, which breaks even, and any surplus profit is used to reduce electricity costs. Rum's network is subsidised by NatureScot, the government agency that owns the electrical network. Muck's income covers operation and maintenance with turnover ranging between £18,000 - £30,000 per year, funds are provisioned into a sinking fund in the annual accounts. Fair Isle's system was designed to cover annual O&M noting insurance costs of £10,000 is prohibitive. Eigg has a £95,805 turnover and operating cost of £80,862. *"£10K is the cost of full insurance coverage including PV, wind turbines, and the building (which is prohibitive). If we have a fire or lightning strike its gone. You've got 7 islands, you could do one big insurance liability for all the islands and split the costs".* – Fair Isle
Income is provisioned for capital replacement	None of the mini-grids have excess income to provision for capital replacement. Knoydart have currently limited provisions for long term asset replacement, however energy capacity exists within the hydro system to allow for long term financial viability if demand increases. Canna's system is profitable excluding capital costs and needs to review the scale of system, they sets aside £10,000 per year into a decommissioning fund to a limit of £50,000 which is to be used in the event of the project failing, and estimate a profit of around £20,000 over 5 years. Rum needs to sell more electricity to cover overhead costs and capital replacements. Fair isle indicated they had no provision for asset replacements, and muck has no surplus for capital costs. Eigg stated it is not possible to provision income for future replacements until an existing loan is paid off in 2025. *"After 39 years of operating the mini-grid, we are no further forward in provisioning income for future asset replacement."* - Foula
A share of the profits is re- invested in the electricity service	5 out of 7 mini-grids reinvest their profits (all except Rum and Canna). Canna are investigating options to donate surplus income to their parent charity. Foula indicated that if surplus was available, then it would be used to reduce the high price of electricity. Fair Isle said it was done where possible. Eigg's aim has always been to save funds from their income to support replacement / repairs but the reality is these funds are spent more quickly than anticipated. *"Our financial modelling illustrates that our mini-grid in a small community cannot provide an income large enough to be self funding - long term, we will always need financial support to replace and expand major components of our system. Our present CARES funding means the batteries can be replaced after almost 15 years of use and we can expand capacity by installing more PVs."* - Eigg
Electricity is used by local industries and enterprises	All mini-grids indicated that this was the case, as follows: Knoydart in restaurants, a café, workshops, soon a brewery; Canna in the BT exchange, camp site, new fish farm under development; Foula in ferry services, airfield, water production, agricultural maintenance, with yarn production and future 4G telecom mast soon to be added; Rum in the bunkhouse, internet services, rum production, fish farm offices, B&B, Shop, tea room, BT exchange, and some craft businesses; and Fair Isle in internet and online business, telecommuting, and Eigg for local businesses. *"It's circular: the more electricity we have, the more people move the island. We need more customers to bring in more income, but then we need more generation, or load management. Having the system feeds into longer term plans for the island, provides critical infrastructure for growth".* - Fair Isle
Local employment	Knoydart employs 3 part time staff members and ad-hoc engineering support. Foula electric company employs a part time manager/accountant and 3 part time operators.

opportunities have increased due to the mini-grid	Rum has one onsite contractor (down from an initial 2) to maintain the system, but NatureScot are looking to increase the size of the team to 4. Muck have a volunteer maintenance team, Eigg electric company employs a team of 5 people. Fair Isles Electric Company now has 3 part time workers as opposed to 2 previously All except Foula, Knoydart and Canna were unable to estimate if employment opportunities had increased from the supply of mini-grid electricity, as often customers were on diesel generators before, however there are some plans to initiate new businesses which would provide jobs. Knoydart indicated many businesses did not exist pre-2001, before the first electrical renovation project. Foula has a new yarn businesses that is considering expanding, and the Canna Development Plan has several projects underway that are made possible by a reliable power source that will create employment and new business opportunities including an event and business space, bunkhouse extension, and a visitor hub. Muck stated there were no new businesses due to electrical service improvements.

4.2.3. Social Indicators

Electricity is generally used for schools, health centres and community centres on the islands, providing social impact and essential services to the communities. Bills for community buildings are often subsidised, or paid for by the Highland Council or Community Development Trusts. The majority of islands have increased levels of telecommunications due to the mini-grids, increasing connectivity and access to digital commerce, work, education and entertainment, while providing an anchor customer to the mini-grid. All mini-grids indicated that all customers who want a connection to the mini-grid have one.

Positive impacts of the mini-grids were listed as reduced noise and pollution, 24 hour power allowing flexible work patterns (especially for IT businesses), new employment opportunities, community skills development and "making life more like the mainland with continuous power". Other positives mentioned included cohesive communities using their own electricity generation, reducing costs over fragmented and dispersed systems and independent household power systems. Few negative impacts were noted, other than more blackouts being experienced than on the mainland, a 20A supply limit in some cases, stress for mini-grid managers and volunteer directors, as well as a loss of community spirit, remoteness or self-sufficiency due to the mini-grid. Details of social sustainability indicators for each mini-grid are outlined in Table 6Table 5Table 4.

Table 6: Social Sustainability Indicator Results

Electricity is used in schools	All mini-grids utilise electricity in schools
Electricity is used in health centres	Two mini-grids power health centres (Fair Isle, Eigg) while four do not (Rum, Canna, Knoydart and Muck)
Electricity is used in community centre	All mini-grids have power in a community centre, or community hall. Additionally Canna and Knoydart power a community Shop, while Fair Isle powers a fire station, community museum, chapel and kirk.
Tele communications have improved due to electricity	All indicated telecommunication has improved directly because of the mini-grid, apart from Canna and Fair Isle. Fair Isle stated that the communication tower had its own generator as they didn't want to take on the liability of providing 24 hour power. Rum and Knoydart both mentioned the biggest improvement coming from HEBNET broadband.

	"Telecommunication and the island Wi-Fi network require and are contingent upon Knoydart Renewables, as do waystations in a national emergency network" - Knoydart
All households who want it have access to electricity service	All mini-grids indicated this is the case, with Knoydart stating that anyone within reasonable distance can connect, with external subsidies needed if they are too far away.

4.2.4. Environmental Indicators

All mini-grids have some elements of low carbon generation in the form of wind, hydro or solar power, however the majority have diesel back up, with various estimates of renewable penetration. Fossil fuel (oil, diesel, paraffin or kerosene) heating remains on most islands with some biomass wood heating. Cooking is generally by bottled gas although some electric cooking is being used through dual fuel cookers and microwaves. Power capacity constraints were stated as the main reason for lack of electric cooking and heating, however most customers and mini-grid managers indicated a desire to switch to cleaner solutions, and some have explored grants for research solutions that will address this.

Generally minor, or no adverse environmental effects have been observed while operating the mini-grids. With respect to wind turbines, bird strikes have not been a problem, and few complaints have been made on the visual impact from wind turbines. Noise from hydro and wind turbines, diesel or grease spillage and visual intrusion from distribution poles were all noted as small negative environmental consequences. The consumer surveys indicated most customers had no concerns, while some noted concerns regarding the use of diesel generation for the mini-grid, or oil for heating, demonstrating a desire for a cleaner energy source than fossil fuels. Communities are closely connected to their energy source and have an increased awareness of the environmental issues and operational limitations of their energy supply. There was a general awareness of climate change and the affects this may bring to water/wind/solar output and planning for future infrastructure. Details of environmental sustainability indicators for each mini-grid are outlined in Table 7.

Table 7: Environmental Sustainability Indicator Results

Electricity is generated from a low carbon source	All use renewable generation, estimates of fossil fuel use as follow: Canna 7%, Foula 50%, Knoydart 10%, Eigg 15% and Muck 15%. Rum indicated that this year was the worst (92%) due to problems with their hydro, but has been as low as 3% when batteries were first installed
Electricity has replaced diesel or other fossil fuels for heating	All mini-grids use some fossil fuels (diesel, paraffin, kerosene) or biomass (wood burners) for heating. Knoydart has some customers using electric heating and Fair Isle have storage heating fed by wind turbines but are currently not working. *"I would not use solid fuel if electricity was cheaper"* – Foula customer *"Uncertainties of future energy supply prevent people moving more wholesale into electric heating."* - Knoydart
Electricity has replaced diesel or other fossil	All mini-grids use gas or propane for cooking. On Rum some customers use microwaves, and on Knoydart some customers have a mix of electricity and gas

fuels for cooking	*"the supply is currently and with proposed improvements will be insufficient to support electric cooking."* - Rum
Electricity has replaced diesel or other fossil fuels for equipment	All mini-grids indicated that mini-grids have replaced diesel for domestic equipment (Muck, Knoydart, Eigg, Canna, Foula). Foula stated that most agriculture and fishing activity is still based on diesel, but a yarn company uses mini-grid electricity. Knoydart has replaced a diesel generator for a VHF and HEBNET mast, and that the Forest Trust is considering electricity for wood milling. For Rum, when the battery inverter and automation was installed it reduced diesel generation from approximately 33% to 3%., with an electrical heater that could heat the castle with surplus hydropower output. *"We were at 80% Fossil fuels before the upgrade and costs were very high."* - Foula
No adverse local environmental impacts have occurred	Most mini-grids indicated no adverse environmental impacts (Foula, Canna, Fair Isles, Eigg, Muck), apart from running the diesel generators when renewable resources are low. Mini-grids with wind turbines (Canna, Fair Isles) indicated an initial worry about complaints on visual intrusion or impact to birds but these have not materialised. Canna completed an Environmental Impact Assessment, which included a bird and archaeological survey. Rum indicated increased diesel generation and pollution due to faults requiring extended diesel runs, and installation of the pipeline requiring excavation. Knoydart suggested potential impacts from diesel, such as grease falling into watercourses as well as being in a national scenic area, infrastructure such as poles is intrusive into areas where people expect uninterrupted sight lines, and noise from hydro turbine and generator. *"If there was a pipeline breach it would lead to erosion, de-watering, uncontrolled flow of water into sensitive river environment and could have catastrophic downstream consequences."* Knoydart

4.2.5. Organisational Indicators

Mini-grids are managed by a team of volunteers from the communities who have little or no formal qualifications relevant to managing mini-grids, but have learnt the requirements on the job. Most indicated that the team would benefit from more formal training, especially in technical aspects. There is a perceived risk of directors or volunteers leaving the islands and taking their hard learnt system knowledge with them. Having paid positions was suggested as an option to retain staff and knowledge.

Although some mini-grids had efficient documentation systems, they were often not being used, and many stated a desire to implement one, well organised centralised system for sharing information between the operations team, directors and external contractors. Inadequate or lost operational and maintenance documentation can be a challenge, there is a general need to improve documentation and maintenance records across the mini-grids. Installers noted that contractors often do not provide adequate manuals or documentation, although HIE have started data sharing with a central repository. There was a stated need for each mini-grid to have a consistent and backed-up form of technical and business record keeping that is kept up to date, is searchable and accessible to those managing each micro-grid, not just at the present time, but also going into what is often a future spanning decades. Knowledge vital to each mini-grid cannot risk being lost because the holders of that knowledge move on.

The need for external support such as project management was highlighted as extremely useful, as it can be a lot of work for a community company to plan, deliver, install and maintain the electrical infrastructure. Suggestions for improving the organisational aspects included "pooling" the administrative functions across the seven mini-grids: performance reports, accounting and insurance. Where one specialised person can perform these functions for all of the mini-grids, and also identify opportunities to share knowledge between them. Many mini-grid managers suggested an external company providing maintenance services would take the pressure off of volunteer managers.

Maintaining knowledge and skills to operate and maintain these networks was noted as a challenge, related to population retention and growth. Retention is less of a problem although the islands have a mostly aging population. The problem is circular, as to attract people to the island, requires adequate infrastructure and a reliable electricity service. A point was raised regarding volunteer directors being in place for a number of years to allow the build-up of a temporal knowledge and understanding of each mini-grid spanning the long term. There is also a need for volunteer director succession strategies to be in place for micro-grids so that hard won knowledge is not lost when directors retire or move on.

For HIE the initial focus on the island networks is financial, with skill development a lower but important priority. They indicated that obtaining and maintaining a knowledgebase and skillset on the islands is a different challenge, and that although a case can be made for the business model and financial support needed, finding the right people to be in the right place is difficult.

HIE has provided technical and facilitation support, by bringing the mini-grids together to share knowledge and skills, while visiting other sites. Training and support has been given to the board of directors, including online-based training support. However, there can be a problem with voluntary boards of directors as there is a high turnover of members and knowledge and skills can be lost.

Private businesses invest in training and capacity building to ensure employees stay with the company, however community organisations have it written into constitutions that board members should be periodically replaced. Additionally, volunteers are not reimbursed for their time and often leave. These problems still occur despite there being a smaller turnover of population on the islands, a strong mentality that problems need to be solved by the community, and the same people rotating around organisations. Details of social/organisational sustainability indicators for each mini-grid are outlined in Table 8.

Table 8 Social Sustainability Indicator Results

Electricity service management organisation is efficient and effective	All mini-grids indicated that the management team generally have skills and capacity needed to run the energy company but this is based on experience rather than formal qualifications. Most indicated that they would benefit from additional capacity and training (Knoydart, Fair Isle, Canna). Some mini-grids have a concern that a succession plan is not in place (Fair Isle, Knoydart, Muck), while some indicated board members avoid responsibility for fear of liability (Foula, Knoydart). Canna take whoever is interested to get involved, and with a small population they are likely to stay on for a long time. Knoydart indicated a challenge in finding volunteers, while Eigg said there are a range of experiences on the board including technical, managerial, administrative and renewables. The question is not applicable to Rum as the system is not currently community operated. *"We have "hard won" experience, but need more technical knowledge"* – Foula
Project documentation is easily accessible and efficient	Most mini-grids use only digital storage such as Dropbox, google docs, OneDrive (Canna, Rum, Foula, Eigg, Muck), while some only have paper copies (Fair Isle). Knoydart use cloud storage, emails and printed documents. Rum indicated that not many people look at the online files, Muck has a different system depending on the operators, and Knoydart had a desire for more efficient document storage solutions. *"Miscommunication is a problem, there is no formalised, efficient system. Need to have one well organised system."* Knoydart

The management team is a good representation of the customer demographic	Most mini-grids indicated they recruit anyone who is available, active and interested, and that they don't have a wide pool to choose from (Eigg, Foula, Canna). Canna and Eigg have two female leads, while the majority of mini-grids are majority male. The majority of mini-grid board members are in their 50s or 60s. Foula stated their board is about 20% of the population, so not a concern, while Muck said their representation could be better. Rum don't have a management board but are in the process of investigating the formation of a Community Energy Company. *"Diversity on board is recognised as an issue"* - Knoydart
Low level of non- technical losses or payment defaults	Most mini-grids indicated this was not a problem (Canna, Rum, Eigg, Muck). Rum indicated that historically they had trouble getting some people to pay their bills but the installation of pre-payment meters has helped. Foula have had some issues, indicating that the island is an extreme place to live and it is difficult to make a living for some folk, and Knoydart have had non-payment issues with a handful of customers. Canna have not had issues yet, but need to establish a system to check for non or late payments, Muck said there are sometimes delays. Fair Isle have had some payment default in the past but not for many years.
Users are satisfied with the electricity service	100% of Canna (n=10) are satisfied. 80% of Eigg (n=20) are satisfied, with 2 saying "mostly", 1 saying they could be better informed, and indicating fault fixing not quick enough and infrastructure maintenance needs improving. 63% of Fair Isle (n=8) responses were satisfied, with dissatisfaction being expressed at the wind turbines not working and being unable to have electric heating as a result. Only 25% of Foula (n=5) responses were satisfied, with dissatisfaction stated as cost of tariffs, reliability and quality of supply, causing some customers to install backup systems. Knoydart has 86% satisfied (n=15), with some indicating that the charging structure could be innovated in order to sell more power and increase sales income which could be spent on paying the full cost of running the system and thereby not relying on volunteers and professional goodwill, as well as a suggestion to consider extending grid to outlying settlements. Muck has 33% of satisfied customers (n=9), with some saying its pricey, power cuts are a problem, and that communication to customers could be improved. For Rum, 50% of customers were satisfied (n=10), with all negative responses relating to power cuts. *"We need access to higher usage of power, we need less blackouts, we need more renewable production. We need to attract more development domestic and commercial and lack of power is a limiting factor."*- Rum customer
Transparent financial accounts are kept	All mini-grid managers indicated that this is the case. In Rum's case, NatureScot manages the financial and accounting system
There is an effective channel through which complaints about the service can be made	Most mini-grids have informal channels for complaints, indicating customers can get in contact through emailing directors (Muck, Eigg, Foula, Canna), or verbal (Muck). Only Knoydart stated that they have a complaints policy, but it hasn't been used. Rum stated that people can complain to NatureScot. Fair Isle have a contract which stipulates grievance procedures for every connected property and any grievances to date have been resolved quickly through dialogue with directors. *"Yes, but be realistic, we don't have resources and can only do what is possible".* Foula

5. Discussion and Recommendations

This section provides a holistic analysis of the primary data collected and summarises the challenges and opportunities associated with the islanded mini-grids in Scotland into three themes that could improve the long-term sustainability of these energy systems, namely: optimum scale, collaboration and asset management planning.

5.1. Optimum Scale & Usage of Renewable Resources

In six of the mini-grid cases in Scotland, the community energy companies appear to generate sufficient income to cover their annual operating expenses, with varying levels of volunteer management and operational support. However, most are not in a position to provision funds for future end-of-life asset replacement or major repairs. This means, in the current operating situation, these community energy companies will continue to rely on government financial support or donations to maintain their energy infrastructure. To ensure long-term financial sustainability, the community energy companies might consider the optimum scale of their business that is necessary to generate sufficient income to cover both annual operating costs as well as end-of-life asset replacements. In all cases this is likely to require a significant increase in electrical demand from a variety of customer types.

The mini-grids in Scotland face identical challenges and opportunities to other mini-grid deployments around the world regarding stimulating demand, and would benefit from one or more economic “anchor” loads (15), which are customers that generate both increased electricity sales as well as job opportunities locally through productive use of mini-grid energy. The long-term financial viability of the Scottish mini-grids will depend on increasing residential demand as well as commercial, economic anchor loads. Table 9 highlights a number of commercial opportunities to increase the electrical demand on the network and could potentially be structured at different times of the day, when spare renewable electricity capacity is available.

Table 9: Overview of commercial opportunities to increase network electrical demand

Anchor Client	Overview
Telecoms	4G mobile providers require 24/7 power to their towers and can provide a useful source of revenue for the electricity company.
Fish Farming	Most fish farm operations rely on diesel generators to power feeding pumps and floating barges. A cost effective shore based supply would allow near shore fish farms to connect to mini-grids.
Wood Processing	Production of wood fuel and building materials requires drying, chipping and milling services. All of which can be supported with an electrical supply.
Wool Processing	Wool processing requires hot water to clean fleeces and several mechanical stages to create the yarn. Modular wool production systems are becoming available and this may create opportunities for small-scale production.
Food Processing	Production of beer, whisky, rum, jam, chocolate, cured meat/jerky could all create a commercial opportunity and utilise electricity at different times of the day.
Local Food Production	Green house lighting and heating could support the development of local food production, reducing the carbon content of food for the remote communities and creating employment opportunities.
Heating	Heating is an excellent “dump load” for excess renewable generation. Identification of oil heating offset opportunities should be exploited and an appropriate tariff applied.

Technical system modelling software such as HomerPro (16) can support the design of new and improved mini-grids, which can in turn help to determine the per unit price of electricity that is necessary to sustain the community energy company indefinitely. Such modelling should consider the company's annual operating costs, asset replacement costs, financing and the option to utilise spare renewable energy capacity as a flexible tariff for time insensitive demand. Most technical design studies for mini-grids consider the sizing of the system based on expected user electrical demand. It could be argued that the design process should consider the administrative costs of operating an energy company and therefore the need for additional electrical sales to meet these costs, as well as the equipment maintenance and asset replacement costs. This may require a simultaneous increase in electrical demand as part of the infrastructure design process to generate sufficient long-term revenue to cover company overheads.

5.2. Collaboration & Portfolio Management

Until recently, each of the seven islanded mini-grids in Scotland had operated largely independently. However, a new initative from HIE has implemented a nascent collaboration network, which was viewed by all participants in the survey as a valuable and welcomed support mechanism.

This collaboration network may wish to consider a portfolio management approach to operating and maintaining these networks. A portfolio approach could help deliver a level of standardisation across the networks in terms of technical design, performance monitoring, documentation, training, safety, insurance and accounting. The portfolio approach may benefit from external expertise or management. If the operations for the mini-grids were collectivised there may be benefits such as economies of scale through bulk procurement and contractors conducting annual maintenance at the same time, saving on transport costs. This notion suggests that working together will provide better commercial options, but a need exists to scope out opportunities before putting them into practice. One of the installers indicated that

"*Community groups would 'bite their hands off' to have an external company that provided a maintenance service for the mini-grids, if it was affordable. A lot of people do power systems operation because they have to, not because they want. Having a company you could call on who was employed to keep the system going would be attractive".*

Additionally, one of the mini-grid managers suggested that it may be worth establishing a small "secretariat" to co-ordinate the mini-grids and build on the work done by HIE, either within HIE or co-ordinated by the mini-grids themselves.

In the 1930's the United States implemented the Rural Electrification Administration which supported rural farmers and home owners in establishing electric cooperatives in regions where investor lead utilities had no interest (17). Over 75 years this organisation has grown into the National Rural Electric Cooperative Association (NREA) which supports over 900 cooperative members throughout the United States. In the UK, the Energy Networks Association (ENA) is the industry body for electrical network owners. It may prove feasible to establish a UK mini-grid working group within the ENA structure to learn from the regulated networks but also to share mini-grid operational experience at a national level and with other international organisations such as New Energy Solutions Optimised for Islands (NESOI), NREA, Indigenous Clean Energy and the Africa Mini-grid Developers Association.

The operational experience and structure of these mini-grids may also offer opportunities for both academic and industrial research collaboration, using the mini-grids as a testing environment with active customers. Active research teams at the UK Power Networks Demonstration Centre (PNDC) (18) and Centre for Research into Energy Demand Solutions (19) may find these mini-grids useful environments for testing. By supporting research teams in testing products and control software safely, quickly and while ensuring the security of supply for the communities, these mini-grids may play a valuable role in supporting the national energy decarbonisation efforts.

5.3. Asset Management Strategy

These mini-grid networks are complex systems containing several different asset types from generators, electrical cables, transformers, meters, batteries and the buildings that house these assets. Each of the seven mini-grids surveyed would benefit from a more structured asset management plan that ensures consistency in performance reporting, documentation, maintenance, decision-making and future planning.

The International Standards Organisation (ISO) maintains documentation relating to best practice asset management strategies (ISO 55000). These documents outline potential structures that organisations may wish to implement to ensure their critical assets perform cost effectively while minimising operational risks and recognising potential opportunities for the organisation.

Table 10 highlights the structure and documentation that a mini-grid operational company may wish to consider implementing. By taking a collaborative approach to mini-grid management, a standardised approach to asset management could be established across the group of Scottish mini-grids and potentially more widely.

Table 10: Asset Management ISO requirements mapped to the Scottish Context

ISO 55000 Asset Management Requirements	Scottish Mini-grid Context
Organisational Context: *Vision, mission, culture, environmental and regulatory aspects of the business.*	Most of the Scottish mini-grids are community owned and a subsidiary of a parent charity. The objectives of the energy company should therefore align closely with the parent charity. Regulations relating to HSE, electrical safety and pollution should be understood and defined within the organisational context. Short term and long term company objectives should be established.
Leadership: *Clearly defined roles, responsibilities and authorities.*	Most of the Scottish mini-grids are managed by a group of volunteer board members that are tasked with making decisions on behalf of the community energy company. The expectations and time commitment for board members should be defined and the communication lines established between a paid operations team and board to facilitate decision-making. Continuity planning between successive board members and access to company documentation should be considered.
Planning: *A "Strategic Asset Management Plan" sets out the way in which assets will be managed during their asset lifetime. This also outlines the structure and roles necessary to operate the plan effectively.*	The asset management plan might consider each of the assets (generators, distribution network, metering, communication systems) and the maintenance/servicing schedules necessary to ensure long-term operations. Upkeep of key documentation should be considered, such as, general power system operations manuals, inspection schedules, new connection policies, regulatory reporting. Where and how this information is stored could be mapped-out in a documentation diagram.
Support: *Wider organisational input to the asset management system. Information exchange with other organisational functions.*	For the Scottish mini-grids, financial management with the wider parent charity is required to ensure sufficient funds are provisioned each year for future asset replacement. Involvement in wider community development discussions will also inform electrical network expansion planning.

Operations: *Operating the asset management system will require regular reviews to ensure the plan is being followed and to manage changes to the plan as required.*	These community energy companies are small and resource constrained, therefore the asset management system should be simple to follow and operate. Operating the asset management system should be the responsibility of the operations team, suggestions for improvements should be taken to the board for approval and the board should have responsibility to ensure it is being followed.
Performance Evaluation: *Monitoring of both the technical and financial performance of each asset to inform effective management and decision making. Regular audits of the asset management system itself.*	The specific performance data that is collected will depend on the type of asset and the cost of replacement. Ultimately, the energy company will want to know that each asset is performing satisfactorily and if any performance degradation is occurring. A set of performance metrics for each asset should be established and monitored on a monthly or quarterly basis. This performance data should be considered as an asset class that needs to be collected and stored securely for future analysis and decision-making.
Improvement: *Opportunities for improvement to each asset and the asset management system come from ongoing performance evaluations. Documentation of incidents, faults or emergencies that have occurred and their lessons should be captured in future asset management system iterations.*	Asset performance improvements may be actioned based on regular reports on the key asset performance metrics, perhaps during monthly operations meetings or quarterly board meetings. A standard form of reporting should be established for these meetings to ensure effective decision-making. Incidents and faults should be recorded to learn from and to minimise the risk of these events recurring.

By combining these three themes: optimal scale, collaboration and asset management, Table 11 presents the common operational areas that a collaborative portfolio of mini-grids may wish to develop and standardise.

Table 11: Common areas for future mini-grid portfolio collaboration and standardisation.

Organisational: • Board structure • Board training • Ops .Team Structure • Ops. Team Training • Asset Management Plan • Engagement with industry groups • Documentation storage • R&D opportunities	**Operations** • Performance data • Operations manuals • Annual service checks • Consumables • Fault resolution • Network model / planning • Standard electrical equipment
Finance • Best practice accounting for utilities • End of life asset provisions • Meter/Bill Tracking • Insurance • Procurement • Business planning	**Policies** • HSE Regulations • Outage planning • Business resiliency • New connections • Wayleaves • Supply agreement • Tariff price setting

6. Conclusions

The sustainability evaluation of seven Scottish Islanded mini-grids has revealed that they provide a mostly reliable electricity supply to remote communities allowing social impact in a low carbon manner. However, several technical challenges exist, operational frameworks are often conducted in an ad-hoc manner, with economic uncertainty on their future sustainability.

Results indicate that additional support is required in the area of technical expertise, management support and long term business planning and that in the absence of professional support and additional resource capacity the electrical service, maintenance of the assets and donor investment money for these networks is arguably put at risk. Business recovery plans should therefore be in place as should plans to address the catastrophic failure of any system.

Analysis of economic indicators has found that income generation is currently insufficient to provision for end-of-life asset replacement costs, and therefore regular injections of government/donor funding will continue to be required. In order to allow for surplus cash to be provisioned for end-of-life asset replacement, these energy systems require new consumers and flexible productive uses of energy to generate additional income from spare renewable energy capacity.

Recommendations have been given to improve the long-term sustainability of these energy systems in the themes of optimum scale, collaboration and asset management planning. Delivering improvements in these three areas requires further research to fully analyse the most profitable scale and most efficient system design for each mini-grid. A coordinated effort is also required to develop a uniform asset management system for the seven mini-grids through a collaborative framework.

The findings suggest that the long-term sustainability of the mini-grids requires an integrated economic development plan to create communities that have sufficient scale to be independent and resilient. A collaborative, portfolio management approach can be used to pool resources and operational costs, reducing the burden on mini-grid managers and achieving economies of scale, while increasing economic sustainability. Accordingly, strategic development plans need to be in place for each mini-grid that tie in with an economic plan for each island and the energy needs of that plan. Future economic development may be constrained if the availability of electricity proves to be a limiting factor due to lack of forward planning.

The results of this study should be used by policy makers to inform future strategies for island energy security that enhance economic growth and social impact. A commercial opportunity exists to develop efficient management strategies for mini-grids in Scotland, which could be replicable with other mini-grid operators around the world. Establishing appropriate management processes, decision-making and financial accounting now will put these mini-grids in a strong sustainable position for future, more complex decarbonisation efforts.

This study is the first step towards future research to model in detail the financial, technical and operational strategies in a detailed asset management framework, and should be the basis of an on-going dialogue between mini-grid managers, customers, installers, and policy makers to plan and implement a long term strategy for the islanded mini-grids focussed on holistic sustainability.

7. References

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8. Appendix 1- List of Expert Interviews

Highlands and Islands Enterprise	Ian Philp: Account manager for HIE. Works in an area office that covers western seaboard with a portfolio of clients and a range of projects. Not an energy specialist but working with local businesses to strengthen and grow them.
Scottish Government	Simon Gill: Part of the policy team in SG, supports electric vehicle, heat networks, generation and hydrogen network projects. Interest in local and community energy. Christine Mckay: On the local energy team working with community renewables. Manages the CARES contract coordinated by Local Energy Scotland. Developing a Local Energy Policy statement.
System installers	• Ruth Kemsley: Russet Engineering, Econnect, Amber Control • Steve Wade: Wind and Sun • Jamie Adam: Community Energy Scotland • Alex Fraser: SSE
Knoydart	Frank Atherley, John Cocker
Rum	Tom Cane, Stewart Sandison
Muck	Ewan MacEwan
Canna	Isebail MacKinnon, Geraldine MacKinnon
Eigg	Sue Hollands
Fair Isle	Robert Mitchel, Ian Best
Foula	Magnus Holbourn