MSc Dissertation Thesis

MSc in Sustainable Energy Systems

A Survey into Energy Demand and the Potential for Renewable Energy on the Isle of Iona

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THE UNIVERSITY of EDINBURGH

Original Mission Statement

THE UNIVERSITY *of* EDINBURGH
School of Engineering

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A Survey into Energy Demand and the Potential for Renewable Energy on the Isle of Iona

Mission Statement

Student: Patrick Miller-Collmann Matric. No.: s2249506

Supervisor: Aristides Kiprakis

Summary and initial literature review

This project will present an approach for estimating the activity on a small Sottish Island, in terms of energy demand, sources and users. The Isle of Iona will be the focus of this study, for which information will be collected, assessed, and categorised to create a detailed survey of Iona's energy use and the available resource for renewable energy.

Iona is a small island in the Inner Hebrides, situated about 1 km off the southwest coast of Mull in westerns Scotland. It is around 2 km wide and 6 km long, with an estimated resident population of 170 across its 68 households [1, 2]. Despite the small resident population, it is reported that the island receives around 130,000 visitors a year, the main reasons being to visit the island's Abbey, which is a historic building.

As reported in a 2015 energy audit, Iona imports almost all its energy, with only a very small proportion being generated on the island by seven roof solar installations [3]. More recent data will be collected through this project. The island is connected to the grid with electricity being supplied by Scottish and Southern Energy (SSE) via an undersea cable from Mull, however, frequent power cuts occur in winter and fuel poverty is estimated at 58% [2, 3].

The island community is proactively working towards finding ways to improve their energy security, whilst moving their energy system towards one that is based on 100% renewables. In response to the 2015 energy audit, Iona Renewables, an island-led charity was formed to protect and enhance the island environment, and promote community development [4]. In 2016, the charity formed 'local energy system roadmap' and has since begun work on a ground-source heat network. Iona has shown keen interest in on-island renewable generation but requires further work to determine its feasibility. Thus, this project would provide the perfect basis for further work in determining the feasibility of on-island renewables.

Main aims and objectives

The aim of this project is to provide a comprehensive review of Iona's energy system, which shall act as a solid basis for further study into the potential for renewable energy generation on the island. The focus of this project will be in creating a methodology for finding, collecting, categorising, and assessing relevant information relating to Iona's current energy system, with the main objective being to create a dataset of information that can be referred to in further work. The secondary objective is to create a dataset of the naturally available resources (i.e., wind, solar, tidal) available for renewable generation on the island. The final objective includes creating suggestions for maximising the use of renewables on the island, using the datasets created in the main objectives. As a *bonus*, a renewable energy system (or part of it) could be designed for the island, although this is not part of the main aim of the project and thus should only be done if time allows for it.

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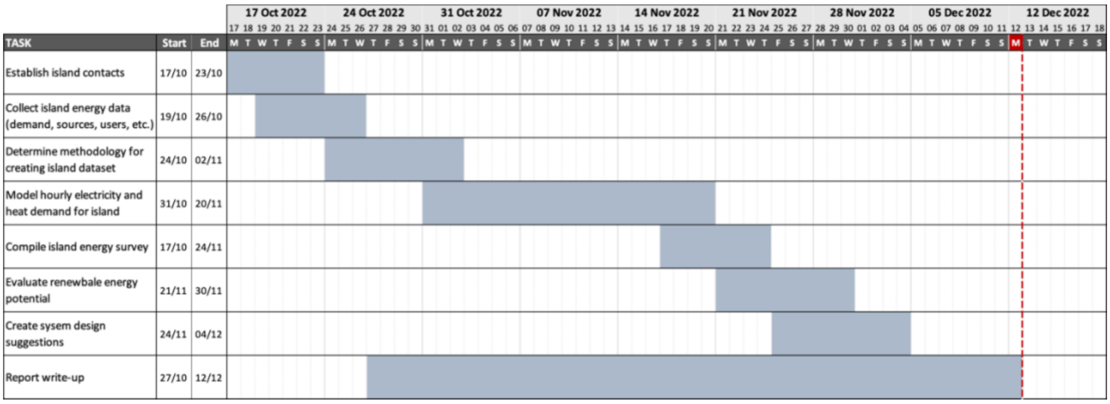
Interim targets

- Establish contacts to obtain recent/updated island data and fact-check sources.
- Obtain data on island energy demand, sources, users, etc.
- Determine methodology for modelling hourly energy demand and creating island dataset.
- Create model for hourly electricity and heat demand on the island.
- Compile model results to create energy demand dataset.
- Create survey of the potential for renewable energy on the island, including wind, solar and tidal.
- Propose system design changes to decarbonise Iona's energy system.

Methodology and draft work plan

- Contact people on the island to get as much updated information as possible. This information includes number and types of residents, number of households, types of buildings, their energy ratings, energy demand, types of energy used, cost of energy bills, etc.
- Retrieve all required data for modelling hourly energy demand and determining the natural resources for renewable energy on the island (i.e., wind, solar, tidal). This will require contacting organisations such as the UK MetOffice for data such as hourly wind speeds for at least the past year but preferably the past decade.
- Model the hourly island energy demand based on the average Scottish consumption for varied household sizes, property types and energy ratings. Also consider local climate and yearly changes in island population (e.g., due to tourism).
- Determine the renewable energy potential on the island for different types of renewables and create detailed maps, chats, etc.
- Assess potential sites for installing renewable energy generation or storage.



Required resources

It would be beneficial to visit Iona to perform an in-person survey of the buildings and infrastructure. However, given time the project's time constraint, phone and video calls to people on the island should suffice. Other required resources may include: Homer Pro, Heating Degree Days, PVsyst (already obtained), and Adobe Photoshop (already obtained).

Health and safety implications

The work will require prolonged computer use for research, design, modelling, and writing. Thus, eye, back and wrist strain should be mitigated by taking regular breaks to look into the distance and to move around.

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[2] M. Georgiev, "Small Islands Energy System Overview," Ricardo Energy & Environment, 2016. [Online]. Available: https://www.hie.co.uk/media/8139/hie-small-islands-low-carbon-energy-overview-final-report-for-publication-pdf-060420-a3410152.pdf

[3] P. Ruhemann, "Isle of Iona: Energy Audit," 2015. [Online]. Available: https://europeansmallislands.files.wordpress.com/2016/03/iona-energy-audit-report.pdf

[4] "Iona Renewables." Iona Renewables Twitter Account. https://twitter.com/ionarenewables (accessed 18/10/2022.

Declaration

The supervisor and the student are satisfied that this project is suitable for performance and assessment in accordance with the guidelines set out in the course documentation.

Signed:

P. M

Supervisor	Aristides Kiprakis	Student	Patrick Miller-Collmann
		Date:	18/10/2022

Abstract

In this project we develop a methodology for extrapolating thermal and electric energy loads from the total energy demand of small energy systems using top-down modelling. We develop a model in Excel for extrapolating monthly thermal load profiles from hourly ambient air temperature measurements, as well as thermal load profiles from seasonal data both the domestic and non-domestic demands. The total mean thermal and electricity demand, as well as the monthly load profiles output by our Excel-based extrapolation model feed into Homer Pro, along with data for the available resources on Iona. Homer Pro is then used to model hourly domestic and non-domestic thermal and electric loads and to run a system design optimisation. The optimal system architecture determined by Homer Pro using a range of renewable technologies is presented and suggestions are made. Results show that Iona has a high potential for renewable energy development from a resources and economic perspective. However, there remain challenges around planning permissions that may prohibit the successful deployment of the renewable system we propose.

Declaration of Originality

I declare that this thesis is my original work, except where stated otherwise. This thesis has never been submitted for any degree or examination to any other University.

P. M

______________________________________(Signature)

Patrick Miller-Collmann

Contents

Glossary

Abbreviations

Abbreviation	Description
AD	Anaerobic digestion
AHD	Annual Heat Demand
AONB	Area of Outstanding Natural Beauty
ASHP	Air Source Heat Pump
B&B	Bed and Breakfast
BUS	Boiler Upgrade Scheme
CARES	Community and Renewable Energy Scheme
CDD	Cooling Degree Day (index)
CHP	Combined Heat and Power
CPI	Consumer Price Index
DHI	Global Horizontal Irradiance
DHLF	District Heating Loan Fund
DNI	Direct Normal Irradiance
DNO	Distribution Network Operator
ED	Electricity Demand
EER	Energy Efficiency Rating
EPC	Energy Performance Certificate
EPR	Energy Performance Rating
GHG	Greenhouse gas
GSHP	Ground Source Heat Pump
HAWT	Horizontal Axis Wind Turbine
HD	Heat Demand
HDD	Heating Degree Days
HDD	Heating Degree Day (index)
HES	Home Energy Scotland
HIE	Highlands & Islands Enterprise
HNSU	Heat Network Supply Unit
PEI	Primary Energy Indicator
POWER	Prediction of Worldwide Energy Resources
PV	Photovoltaic
RHI	Renewable Heat Incentive
SEG	Smart Export Guarantee
SME	Small and Medium-Sized Enterprise
SSEN	Scottish and Southern Electricity Networks
DoD	Depth of discharge

Symbols

Symbol	Description	Units
α	Power law exponent	-
A	Amplitude (cosine function)	-
A_{Adj}	Error-adjusted amplitude (cosine function)	-
B	Vertical shift (cosine function)	-
B_{Adj}	Error-adjusted vertical shift (cosine function)	-
BLC	Building Load Coefficient	-
c	Scale parameter (Weibull)	-
C_p	Specific heat capacity	J/(kgK)
ELP	Final extrapolated load profile	kW
f	Frequency of occurrence (Weibull)	%
h	Hour	hour
i	Day of year	day
k	Shape parameter (Weibull)	-
$L_{\mathrm{AdjReExtr}}$	Adjusted re-extrapolated relative load	%
L_{Extp}	Extrapolated relative load	-
L_{ReExtr}	Re-extrapolated relative load	-
L_{Rel}	Relative load	%
L_{Year}	Weighted annual mean load	kW
Q	Energy required for heating or cooling	W
q_{air}	Heat transfer from air infiltration	W
Q_{Cooling}	Energy required for cooling	W
q_{env}	Heat transfer from building envelope	W
Q_g	Heat transfer related load	W
Q_{Heating}	Energy required for heating	W
Q_{int}	Heat gain from internal sources	W
Q_{sol}	Heat gain from solar radiation	W
Q_{Total}	Total net heat transfer	W
RELP	Final extrapolated relative electricity load profile	-
T_{b}	Base temperature	°C
$T_{\mathrm{b\text{-}CDD}}$	Cooling degree day base temperature	°C
$T_{\mathrm{b\text{-}HDD}}$	Heating degree day base temperature	°C
T_{in}	Indoor temperature	°C
T_{out}	Outside ambient air temperature	°C
U-value	Mean thermal transmittance of building	W/m^2K
UA-value	Total building heat loss	W/K
v	Wind speed	m/s
Y_{YearDay}	Weighted annual mean load of an average day in the week	kW
ΔT	Temperature difference between inside and outside	K
φ	Phase shift (cosine function)	-
ω	Period (cosine function)	-

1. Introduction and Background

1.1 Background

The Scottish Isles are amongst the most remote populated places in the UK, making it challenging to connect them to mainland infrastructure. A total of 93 Scottish islands were inhabited by 103,700 people in 2011, representing two percent of Scotland's population [2], with most of the islands falling into one of four main archipelagos: Shetland, Orkney, Outer Hebrides, and Inner Hebrides [3]. Providing such remote places with reliable and affordable energy poses a significant challenge. A 2016 study analysing the energy systems of 49 remote islands in the Highlands & Islands Enterprise (HIE) region, found that energy costs were generally high due to the frequent use of electricity or oil for heating buildings that are generally below the national average in terms of energy performance. This additional electricity demand to meet heat loads, combined with the higher price of electricity in Northern Scotland compared to the rest of the UK, was found to increase the likelihood of fuel poverty [4]. Consequentially, many Scottish islands experience fuel poverty rates greater than 50%, reaching as high as 92.1% in parts of the Outer Hebrides [5, 6]. Comparatively, the UK national average lies around 15%, where fuel poverty is defined by a household spending more than 10% of its income on fuel [7].

Some Scottish Isles, such as Mull and Foula, have implemented microgrid solutions to improve their energy security by generating renewable energy locally and have shown good success. However, many islands remain fuel poor, requiring extensive system upgrades to bring energy costs down, whilst increasing their energy security. Gaining an extensive understanding of the current energy system, its users, load demands, energy mix, and limitations, is an essential step required to providing design suggestions aimed at improving energy security and reducing emissions. Only then can appropriate design suggestions be made based on the requirements and locally available renewable resources.

In this project we develop a methodology for producing a detailed survey of energy demand and the potential for renewable energy on small island systems and apply it to the Scottish Isle of Iona. We develop a model for estimating hourly energy demand in terms of heat and electricity for a timeseries of up to 10 years using meteorological data and electricity load curves. As detailed energy demand data and load curves are often hard to come by, our methodology aims to require very little input data, with the option of entering more data to obtain more reliable results. Thus, the methodology we present is applicable to various energy systems and is easily adaptable to fit the needs of a system planner.

1.2 The Isle of Iona

Iona is a small island in the Inner Hebrides, located around 1 km off the southwest coast of Mull in Western Scotland. The island is approximately 5.5 km long and 2.5 km wide with an area of 8.55 km^2 (Fig. 1). Iona has a resident population of around 177 people across 69 households [8], however, the population increases significantly during the holiday season due to the influx of visitors and temporary workers [9]. A reported 130,000 visitors step foot on Iona every year; the main reason being to visit the Iona Abbey, which is one of Scotland's most historic and sacred sites [10]. A large portion of the population on Iona is concentrated in the Village of Baile Mòr. The remaining inhabitants live on the northern half of the island, located mainly along the eastern coast and along the road that passes through the island's centre.

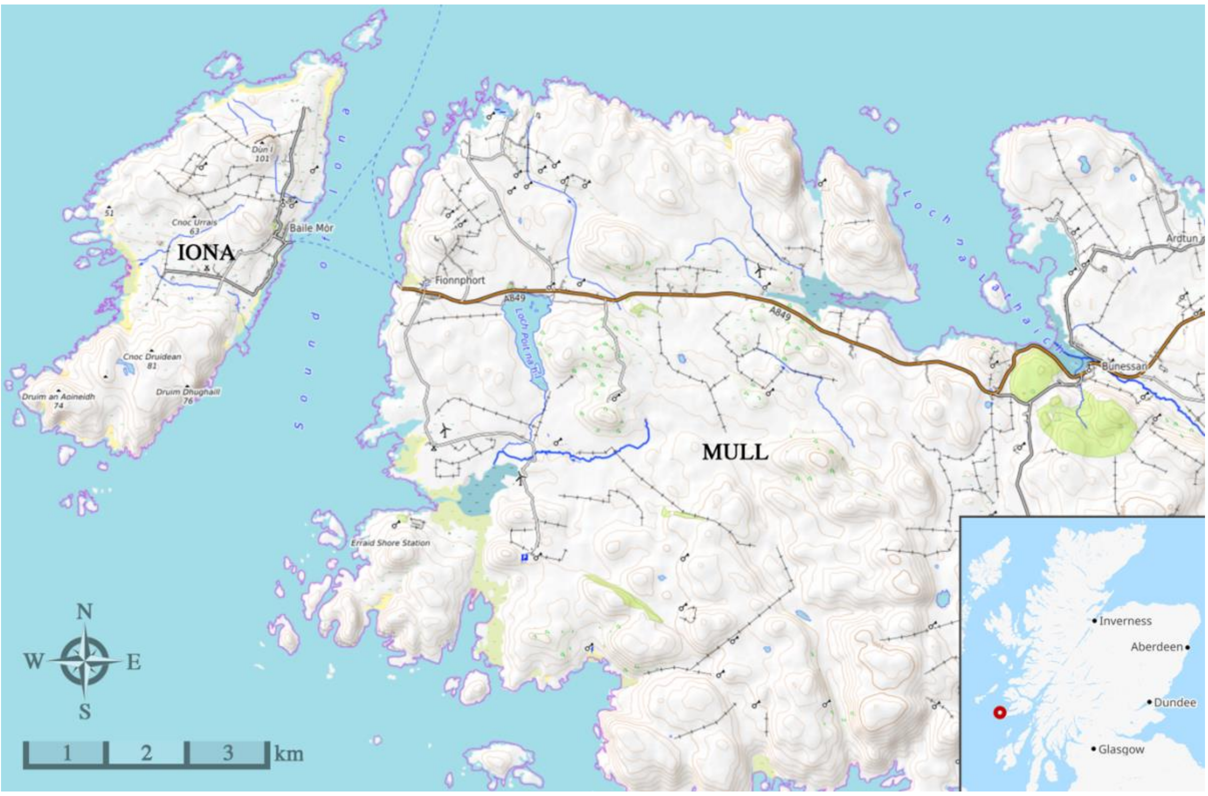


Fig. 1. Map of Iona and the southwest of Mull with wider context. Adapted from [11] and [12].

1.2.1 Access and Restrictions

Access to Iona from Mull is provided by a Calmac Ferry, that leaves from Fionnphort, at the southwestern tip of Mull. Mull, being an island itself, is served by three different ferry routes that connect the Scottish Highlands to the eastern coast of Mull. The ferry routes are: Kilchoan to Tobermory, Lochaline to Fishnish, and Oban to Craignure, the latter being the main route used for access to Iona [13]. Iona's context as 'an island off an island' is a major restriction when it comes to planning and constructing on Iona. Discussions with Philip Ruhemann, chair of Iona Renewables and author of a 2015 'Isle of Iona Energy Audit' (detailed in Section 3.1.1), revealed that the cost of projects on Iona are as much as 45% greater than their equivalents on the mainland due to Iona's location and restricted access. Additionally, Iona is classified as an Area of Outstanding Natural Beauty (AONB), which comes with several restrictions around construction, such as limiting the placement of solar arrays, the height of wind turbines, the locations where trenches can be dug for new cabling, etc. This, combined with the difficulty of access, adds significant cost and complexity to developing renewables on Iona [14].

1.2.2 Building Stock

There are an estimated 145 buildings on Iona, comprising 102 residential buildings, 14 hotels and bed and breakfast establishments (B&Bs), 28 public and commercial buildings, and the Iona Community, which includes the Iona Abbey and various other buildings.

According to 59 Energy Performance Certificates (EPCs) available for Iona [15], the residential sector is mostly comprised of detached (55%) and semi-detached (26%) houses and bungalows, with 13% terrace housing and 6% flats. In the sample of 53 residential buildings, 70% are heated using electricity, 23% use oil, 6% dual fuel (mineral/wood), and 2% coal. Room heaters are the most common type of heating (30%), followed by boiler and radiators (26%), air source heat pumps (23%), storage heaters (15%), with a minimal use of ceiling and portable heaters (2%). The median EPC Energy Efficiency Rating (EER) for residential buildings on Iona is 46, which falls into band E and is well below both the UK national and Scottish medians, coming in at 67, band D [16]. Whilst band D is the most common EER on the island, the ratings are heavily skewed towards the less efficient end, with only seven outliers rated in band B (Fig. 2). Of these seven buildings, five form part of a new island development called 'The Glebe', which consists of semi-detached and detached houses that are all heated by air source heat pumps.

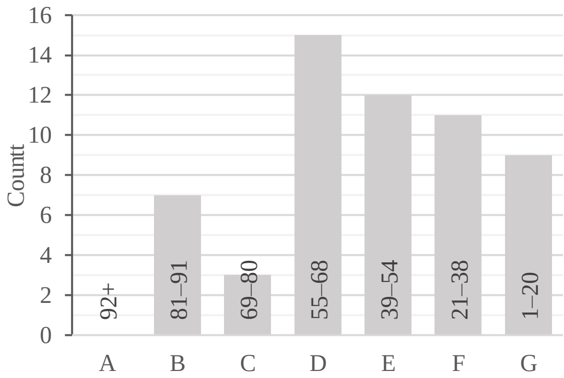


Fig. 2. Residential building EER histogram.

The six available EPC reports for commercial and community buildings on Iona are insufficient to form a representative sample. However, of the six evaluated buildings, four use electricity for heating, one natural gas, and the other oil. The systems used for heating are only known for three buildings, of which all are heat pumps. Included in these buildings are the Iona Abbey and Iona Village Hall which use air source heat pumps, demonstrating the community's enthusiasm towards decarbonisation.

The detailed approach for creating the building stock dataset is described in Section 3.2. An overview of the building stock is given in Table 1. Detailed figures from the 2015 Energy Audit, 2018 Electrical Connections Study, and 2022 estimates, as well as collated data from the 59 available EPC reports are given in Section 4.1.

Table 1
Iona Building Stock and Relative Electricity Demand

Count	Property Type	Percentage of Total Electricity Demand
102	Residential	44.4%
14	Hotel/B&B	14.6%
28	Public/Commercial	8.1%
1	Iona Community (inc. Abbey)	32.9%

1.3 Existing Energy Network

In 2014, 26.2% of the total energy supplied to Iona was in the form of electricity, 35.8% as solid and liquid fuel used for heating, and 38.0% as diesel used mainly for the Calmac Ferry. Excluding transport fuels, Iona's energy demand was around 42.3% electrical and 57.7% thermal for the same period [9]. Almost all of Iona's energy is imported from either from Mull or the mainland.

1.3.1 Electricity Supply

There is an existing network of electrical grid infrastructure on Iona, made up of 11kV lines (Fig. 3). A series of transformers is present, allowing projects to be easily situated near to existing grid connection points, thereby avoiding long and expensive electrical cable runs. Grid electricity is supplied to Iona via an undersea cable from the Isle of Mull by Scottish and Southern Electricity Networks (SSEN), the Distribution Network Operator (DNO) responsible for the northern part of the Scottish electricity transmission system [17].

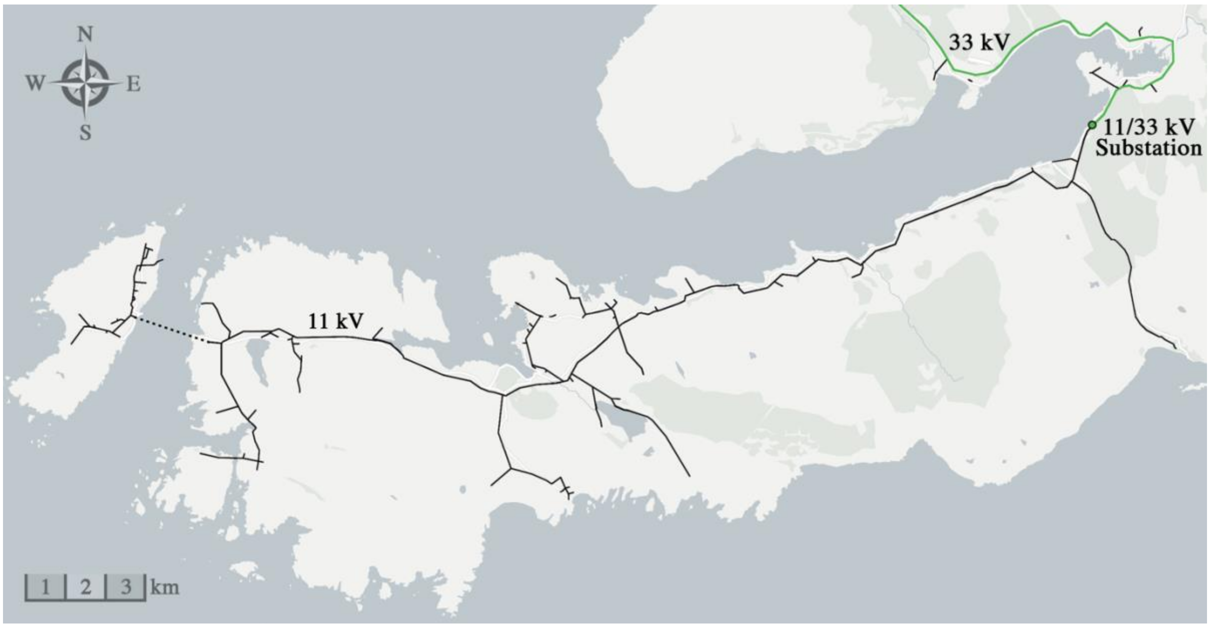


Fig. 3. Electrical grid infrastructure on Iona and the southwestern coast of Mull. Adapted from [18].

A very limited amount of renewable energy generation is present on Iona, estimated at seven rooftop solar installations and six air source heat pumps in 2015. In recent correspondences, Philip Ruhemann reported the addition of five air source heat pumps since the Energy Audit, of which four are residential and one which has been installed to heat the Abbey [9].

1.3.2 Fuel Supply

Liquid and solid fuels are brought onto the island via a small number of local suppliers on the Isle of Mull. Robin McCallum supply coal, LPG and butane, whilst heating oil is provided by Cleaner Oils Ltd in Craignure, Mull. Wood is sold by various suppliers on Mull, and petrol and diesel can be purchased on Mull or the mainland but is not allowed to be transported in containers on the Calmac Ferry [9].

1.3.3 System limitations

Although the grid capacity on Iona is adequate for the island's needs, there is a very limited export capacity of around 50 kW. This limited export capacity poses a risk to electricity generation projects on Iona, as SSEN may not allow connection to its electrical network where there are constraints, even if the aim is not to export the electricity but use it on the island. If connection to the existing electricity network is not possible or prohibitively expensive, an alternative would be to develop a private wire network [17].

The supply of liquid and solid fuels to the island is dependent on the ferry's ability to operate, which is prone to interruptions due to weather conditions, though the timing of deliveries is not critical as fossil fuels are relatively easy to store. However, to achieve long-term energy security and to avoid volatility in energy prices, reducing Iona's dependence on fossil fuels (especially for heating) is paramount. Electrification would also avoid the current emissions associated with the transport of fuel to Iona.

1.4 Energy Users Demand

1.4.1 Total Demand

The total energy demand on Iona in 2014 was estimated at 6,772 MWh. The residential sector is the largest energy user on Iona, representing 36% of total demand, followed by the Calmac Ferry (27.7%), the Iona Community (11.9%), marine tourism (11%), hotels (8.8%), and shops (1.4%). The 45 registered private vehicles are responsible for around 1% of Iona's energy consumption, with agriculture, amenity buildings, delivery transport, primary school, fishing sector, and waste collection (listed in descending order) being responsible for less than 1% of demand [9].

1.4.2 Electricity

In terms of electrical energy demand, the residential sector is responsible for 43% of the total electricity consumption, followed by the Iona Community, which is the single largest electricity user, accounting for 34% of the annual island demand. Comparatively, the combined electricity use of the two island hotels makes up 15% of total demand, followed by 5.5% for shops, 1.6% for amenities and 1% for the school. During the year of 2014, Iona's total electricity demand was estimated at around 1,825 MWh, just shy of 5 MWh per day, corresponding to a mean load of 208.3 kW [9]. Electricity on the island is mostly consumed in buildings, with a reported 80% used for heating and 20% used for appliances in 2018 [19]. The relative and total electricity demand of four different building types on the island, resulting from a simple extrapolation method described in Section 3.2, is given in Table 2.

Table 2
Relative (%) and Total (MWh) Electricity Use by User in 2015 and 2018

		2018 Electrical Connections Study			2015 Energy Audit
Count	Building Type	Appliances	Heating	Total	Total
102	Residential	9.8%	43.5%	53.3%	44.4%
14	Hotel/B&B	6.8%	7.9%	14.7%	14.6%
28	Public/Commercial	0.6%	9.2%	9.8%	8.1%
1	Community	3.0%	19.2%	22.1%	32.9%
145	TOTAL	20.1%	79.9%	100%	100%
102	Residential	150.1	668.8	818.9	835.0
14	Hotel/B&B	104.3	121.5	225.9	274.4
28	Public/Commercial	9.3	141.9	151.2	151.8
1	Community	45.7	294.5	340.2	618.4
145	TOTAL	309.4	1,226.8	1,536.2	1,879.6

Extrapolated using data from [9] and [19].

Since 2014, several heat pump systems have been installed in new and existing buildings on Iona, including the Iona Abbey. This electrification of heating has likely increased the total electricity demand on Iona, as more fuel-based systems are replaced. However, as our methodology allows for a flexible input of energy data, we assume the above figures showcase our energy demand model.

1.4.3 Heating Fuels

The main use of heating fuels (i.e., oil, coal, propane, wood, and butane) on the island is within the residential sector, making up 84% (1,967 MWh) of consumption in 2014, with the remaining fuel used in the public, commercial and community sectors, which combined represented just 16% (374 MWh) of the total fuel use for heating of 2,341 MWh [9]. There are no large single users of heating fuel on Iona. From the limited available data, it seems that a higher percentage of public and community buildings use heat pumps, compared to residential buildings on Iona.

1.4.4 Transport Fuels

The main user of transport fuel is the Calmac Ferry, having consumed 157,137 litres of diesel in 2014, equivalent to 1,713 MWh of energy. Marine tourism consumes 62,600 litres of diesel (688.6 MWh) annually, with land vehicles estimated at 15,434 litres (169.8 MWh). The Calmac Ferry alone makes up 66.9% (1,729 MWh) of the total yearly diesel consumption on Iona of 2,583 MWh, followed by marine tourism at 26.7% (688.6 MWh). The combined commercial, public and community sectors consume 97.1% of all the diesel used on the island, equivalent to 2,508 MWh per year. The remaining 2.9% (75.0 MWh) of diesel is used in domestic vehicles.

Transport fuel use of Iona is not included in our model as there is no clear path for electrification of the Calmac Ferry and marine tourism which make up such a large proportion of total fuel consumption.

1.5 Government Policy and Incentives

In 2015, the Paris Agreement, signed by the UK and 195 other countries, set out to limit the average global temperature to 2°C above pre-industrial levels by the end of the century, preferably staying below 1.5°C if possible [20]. In line with these commitments, the UK has set the aim of becoming net-zero by 2050, meaning all greenhouse gas (GHG) emissions are to be ceased or offset by 2050. The UK's Net Zero Strategy outlines several key targets [21]:

- Net-zero by 2050
- All electricity to be generated by low-carbon sources by 2035
- No new gas boilers to be sold by 2035
- Exceed 600,000 annual installation of heat pumps by 2028

Scotland's targets set out in the Climate Change (Emissions Reduction Targets) (Scotland) Act 2019 [22] are to achieve net-zero by 2045, with a 75% reduction by 2030 and 90% by 2040. This is to coincide with a reduction in fuel poverty to no more than 5% by 2040, compared to an estimated 24.6% in 2019 [23]. The Scottish Energy Strategy, released in December 2017, set out a 2030 target for the equivalent of 50% of the energy for Scotland's heat, transport and electricity consumption to be supplied by renewable sources [24]. The Heat Networks (Scotland) Act 2021 set out statutory targets for heat networks to reach 2.6 TWh of output by 2027 and 6 TWh by 2030, representing 3% and 8% of Scotland's current heat supply respectively. This is equivalent to connecting an additional 120,000 and 650,000 homes to heat networks by 2027 and 2030 respectively [25].

Scotland's key targets are:

- Net-zero by 2045
- Less than 5% fuel poverty by 2040
- Half of heat, transport and electrical energy to be supplied by renewable sources by 2030
- Total heat network output to reach 2.6 TWh by 2027 and 6 TWh by 2030

Several schemes are available to support the UK and Scottish energy transition targets. The UK-wide schemes include the Boiler Upgrade Scheme (BUS) and the Smart Export Guarantee (SEG). Scottish schemes include the Community and Renewable Energy Scheme (CARES), the Small and Medium-Sized Enterprise (SME) loan, the Home Energy Scotland (HES) loan and the District Heating Loan Fund (DHLF).

The BUS provides subsidies towards the installation of low-carbon heating systems and is available from 2022 to 2025. It is the successor to the Domestic Renewable Heat Incentive (RHI) [26]. The BUS offers households grants of £5,000 toward the installation of Air Source Heat Pumps (ASHPs), £6,000 for Ground Source Heat Pumps (GSHPs), and £5,000 towards biomass boilers [27]. The scheme aims to help decarbonise the UK heating sector, which accounts for nearly half of the national energy use, or around 760 TWh per year, of which approximately 70% is met using gas [28].

The SEG is a government-backed initiative launched in 2020 that requires some electricity suppliers (SEG Licensees) to pay small-scale generators (SEG Generators) for the low-carbon electricity they export to the National Grid. The scheme is the successor to the Feed-in-Tarif (FIT) scheme [29]. SEG Generators can have an installed capacity of up to 5 MW for solar photovoltaics (PV), wind, hydro, and anaerobic digestion (AD), and up to a 50 kW for Combined Heat and Power (CHP). The payment rate and terms are up to the discretion of SEG Licensees and thus vary [30].

CARES encourages local and community ownership of renewable energy projects by providing funding and support for developing renewable projects. A wide variety of community organisations and charities are eligible for CARES support; however, applications are only open to non-profit organisations [31].

The SME loan provides unsecured loans from £1,000 up to £100,000 to not-for-profit small and medium-sized businesses for the installation of energy efficient measures. The loan covers the financing of energy efficiency measures, including upgrades to heating, air conditioning, ventilation, insulation, lighting, and the installation of solar panels, wind turbines and wood-burning stoves. Eligible SMEs can also receive cashback grants of up to £30,000 to recover 75% of the cost of energy efficiency measures and renewable heat measures up to £20,000 and £10,000 respectively [32].

HES delivers loan and cashback schemes on behalf of the Scottish Government. The loans are available to home occupiers who live in their property and to self-builders, providing up to £15,000 in funding for energy efficiency measures, £17,500 for up to two home renewable systems, and up to £6,000 for an energy storage system. A maximum cashback of £6,000 and £11,750 is issued to energy efficiency and renewable measures respectively [33].

The DHLF offers loans, as well as pre-capital support which is provided by a Heat Network Supply Unit (HNSU) that can give advice and support on projects. The fund is open to all public and private sector applicants looking to develop a heat network. Loans of more than £1 million are available as low interest (typically 3.5%) unsecured loans with repayment terms of either 10 or 15 years [34].

2. Literature Review

2.1 Modelling Load Profiles

Producing reliable energy load profiles for different building sectors plays a prominent role in the framework of distributed energy planning and electricity demand forecasting [35]. The accuracy of load profile estimates is directly linked to system efficiency and cost [36]. The transition towards smart energy systems requires accurate and detailed knowledge of the energy system to ensure complex hourly energy balances are met by the various components of the system. Additionally, obtaining accurate energy loads is essential for correct dimensioning of system components, from renewable energy generators and storage devices to power electronics [37, 38]. However, as the availability of measured load profiles for buildings at the district level is not widespread, several methods for estimating these have been developed. Two distinct approaches for estimating residential energy consumption have been identified by [39], which are top-down and bottom-up methods. Top-down methods model energy consumption using estimates of the total consumption within the entire residential sector, using pertinent variables to attribute the energy consumption to characteristics of the sector. In contrast, bottom-up models extrapolate the energy consumption of regions or nations using the data from individual or groups of houses. A comprehensive list of over 70 studies on estimating the load profiles of buildings, classified by type of model, energy type (i.e., thermal or electrical), and time resolution is presented by [36].

Top-down approaches do not consider individual end-users, instead treating the residential sector as an energy sink. These models determine the effect of long-term changes or transitions within the residential sector on energy consumption, their primary aim being to estimate supply requirements. They evaluate energy use using variables such as macroeconomic indicators, climate conditions, changes in housing stock, and estimates of appliance ownership. These variables are used to weight the historical energy data in order to predict present consumption. The main strength of top-down models is that they only require top-level input variables and aggregated historic energy data, both of which are widely available. They also benefit from simplicity; however, their reliance on historical data is also a drawback, as they have no inherent capability to model discontinuous advances in technology. Top-down models also cannot be used to identify areas of improvement to decrease energy consumption as they do not provide consumption estimates at an energy uses level [39].

Bottom-up approaches extrapolate the energy consumption of individual end-uses, houses, or groups of houses to represent that of a region or nation based on the representative weight of the modelled sample. All models employing input data from a hierarchical level less than that of the entire sector are classified as bottom-up approaches. Bottom-up models utilise either statistical or engineering methods for extrapolation. Statistical methods establish the relationship between energy consumption and end-uses by attributing the energy consumption of buildings to specific end-uses by relying on historical data and types of regression analysis. Engineering methods consider power ratings, the usage of equipment and systems, and/or thermodynamic relationships such as heat transfer, to explicitly account for the energy consumption of end-uses. Common input data for bottom-up models include dwelling properties, such as envelope (windows, walls, roof, ground floor) materials, geometry, equipment and appliances, indoor and outdoor temperatures, occupancy schedules, and equipment use. The high level of detail of bottom-up models is their main advantage, enabling them to identify areas for improvement for specific energy end-uses, without a reliance on historical data. Their main drawbacks compared to top-down models is their complexity and required level of input data detail [39].

2.1.1 Degree Day Index

The climate is a strong determining factor in heat loads, and as the proportion of heating provided by electricity grows (e.g., by heat pumps), changes in outside temperatures will have an increasingly large effect on electrical loads. Thus, it is important to include climate-driven heating loads in estimates of energy demand, both for thermal and electrical models. The effect of climate conditions is often represented in conditional demand models and large-scale energy forecasts using the Heating Degree Day (HDD) index and the Cooling Degree Day (CDD) index [40]. The HDD and CDD indices are used to quantify the expected relative heating or cooling required for a building to be kept at a desired indoor temperature. Thus, degree days are often used in top-down models to represent the variability in climate conditions [41]. HDD are usually calculated annually, as the sum of the daily departures from the mean outside ambient air temperature (T_{out}) and a base temperature ($T_{\text{b\_HDD}}$), summed only when $T_{\text{out}} < T_{\text{b\_HDD}}$ [42]. This is written as:

$$\text{HDD} = \sum_{i=1}^{365} \left(T_{\text{b\_HDD}} - T_{\text{out\_}i}\right) , \qquad T_{\text{out\_}i} < T_{\text{b\_HDD}} \tag{1}$$

where i is the day of the year. The CDD index is calculated similarly to HDD, however, instead is the sum of the daily departures from T_{out} and a different base temperature ($T_{\text{b\_CDD}}$):

$$\text{CDD} = \sum_{i=1}^{365} \left(T_{\text{out\_}i} - T_{\text{b\_CDD}}\right) , \qquad T_{\text{out\_}i} > T_{\text{b\_CDD}} \tag{2}$$

The base temperatures $T_{\text{b\_HDD}}$ and $T_{\text{b\_CDD}}$ represent the T_{out} at which a building needs to be heated or cooled respectively to achieve a desired indoor temperature (T_{in}). Base temperatures depend on the desired T_{in} and the total net heat transfer (Q_{Total}) between the inside and outside of the building. The main heat transfers (i.e., losses and gains) are from the building envelope (q_{env}), air infiltration (q_{air}), solar radiation (Q_{sol}), and internal sources (Q_{int}) such as electrical equipment and people [43]. Both heat transfers q_{env} and q_{air} depend on the temperature difference between the inside and outside (ΔT), where q_{env} also depends on the UA-value of the building. The UA-value is a measure of a building's total heat loss (in W/K), calculated by multiplying the building's area by its mean U-value, which is used to describe thermal transmittance or rate of transfer of heat through a material or structure [44]. The heat transfer q_{env} is thus calculated as:

$$q_{\text{env}} = \text{UA}\Delta T\,, \qquad \Delta T = (T_{\text{out}} - T_{\text{in}}) \tag{3}$$

where UA is the UA-value for the building. The thermal transmittance q_{air} depends on ΔT, the specific heat capacity (C_p) and the mass flow rate of the air:

$$q_{\text{air}} = mC_p\Delta T \tag{4}$$

The total heating or cooling load depends on the base temperature and the sum of heat transfers Q_{Total} between the interior and exterior of a building, where Q_g is the sum of the Q_{sol} and Q_{int} heat transfers:

$$\begin{aligned} Q_{\text{Total}} &= q_{\text{env}} + q_{\text{air}} + Q_{\text{sol}} + Q_{\text{int}} = \text{UA}\Delta T + mC_p\Delta T + Q_{\text{sol}} + Q_{\text{int}} \\ Q_g &= Q_{\text{sol}} + Q_{\text{int}} \end{aligned} \tag{5}$$

To calculate the total energy required as heating or cooling to maintain a desired T_{in}, we use a Building Load Coefficient (BLC) which isolates the heat transfer related load Q_g from ΔT. This is used to express the relationship between the base temperature (T_{b}), T_{in} and Q_g:

$$\begin{aligned} \text{BLC} &= \text{UA} + mC_p \\ T_b &= \text{T}_{\text{in}} - \frac{Q_g}{\text{BLC}} \end{aligned} \tag{6}$$

where the energy required for heating or cooling (Q) is expressed as:

$$Q = \text{BLC}(T_{\text{b}} - T_{\text{out}}) \tag{7}$$

For our purposes, we are only interested in calculating heating loads for Iona, as buildings on the island do not require cooling due to moderate outside temperatures. We thus continue our derivation for heating demand only, although the process for calculating cooling demand is very similar. Thus, using HDD, the total heating load (Q_{Heating}), given in W, is expressed as:

$$
\begin{aligned}
Q_{\text{Heating}} &= \text{UA}\Delta T + mC_p\Delta T - Q_g\,, \qquad T_{\text{out}} \geq T_{\text{b\_HDD}} \\
&= \left(\text{UA} + mC_p\right)\Delta T - Q_g = \text{BLC}\Delta T - Q_g \\
&= \text{BLC}\Delta T - Q_g = \text{BLC}\left(\Delta T + \frac{Q_g}{\text{BLC}}\right) \\
&= \text{BLC}\left(\left(T_{\text{in}} - \frac{Q_g}{\text{BLC}}\right) - T_{\text{out}}\right) \\
&= \text{BLC}\left(T_{\text{b\_HDD}} - T_{\text{out}}\right)
\end{aligned}
\tag{8}
$$

The resultant expression (8) shows the relationship between base temperature $T_{\text{b\_HDD}}$, the outside temperature T_{out} and the thermal properties (i.e., insulation and heat gains) of a building, described by the BLC. Although our methodology uses a top-down approach, where BLC is implicitly accounted for in the total annual heat demand figure used for extrapolation, it is important to consider the effect of building heat transfers when choosing an appropriate HDD base temperature.

3. Methodology

Detailed energy data for Iona is sparce. However, designing an island energy system that is both reliable and based on renewables requires much more granular energy demand data. Therefore, we will apply methodologies using a range of data sources to model the energy demand on Iona at an hourly interval, in terms of electricity and heat demand (HD). We backcast hourly HD from 10 years of ambient air temperature measurements and island occupancy to create monthly HD load profiles and determine the scaled annual average HD Load (Fig. 4). To model electricity demand (ED) we extrapolate monthly ED load profiles for weekdays and weekends from seasonal profiles, measured ED and occupancy rates for Iona (Fig. 5). The extrapolated monthly ED and HD load profiles, as well as scaled annual average ED and HD loads are input into Homer Pro, to create a more general load demand model of Iona's energy system. The Homer Pro model is then used to run system optimisation models.

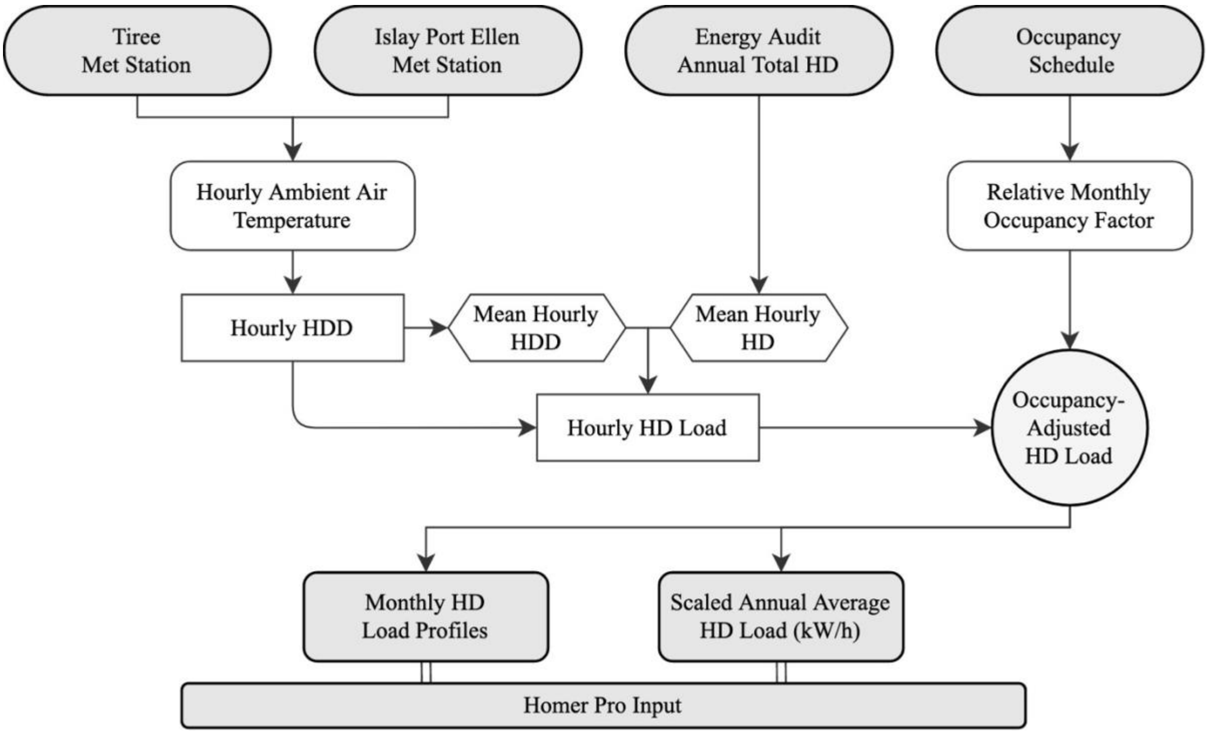


Fig. 4. Flow chart of methodology used to extrapolate daily HD, monthly HD load profiles, and the scaled annual average HD load on Iona. The methodology is repeated for both the domestic and non-domestic sectors.

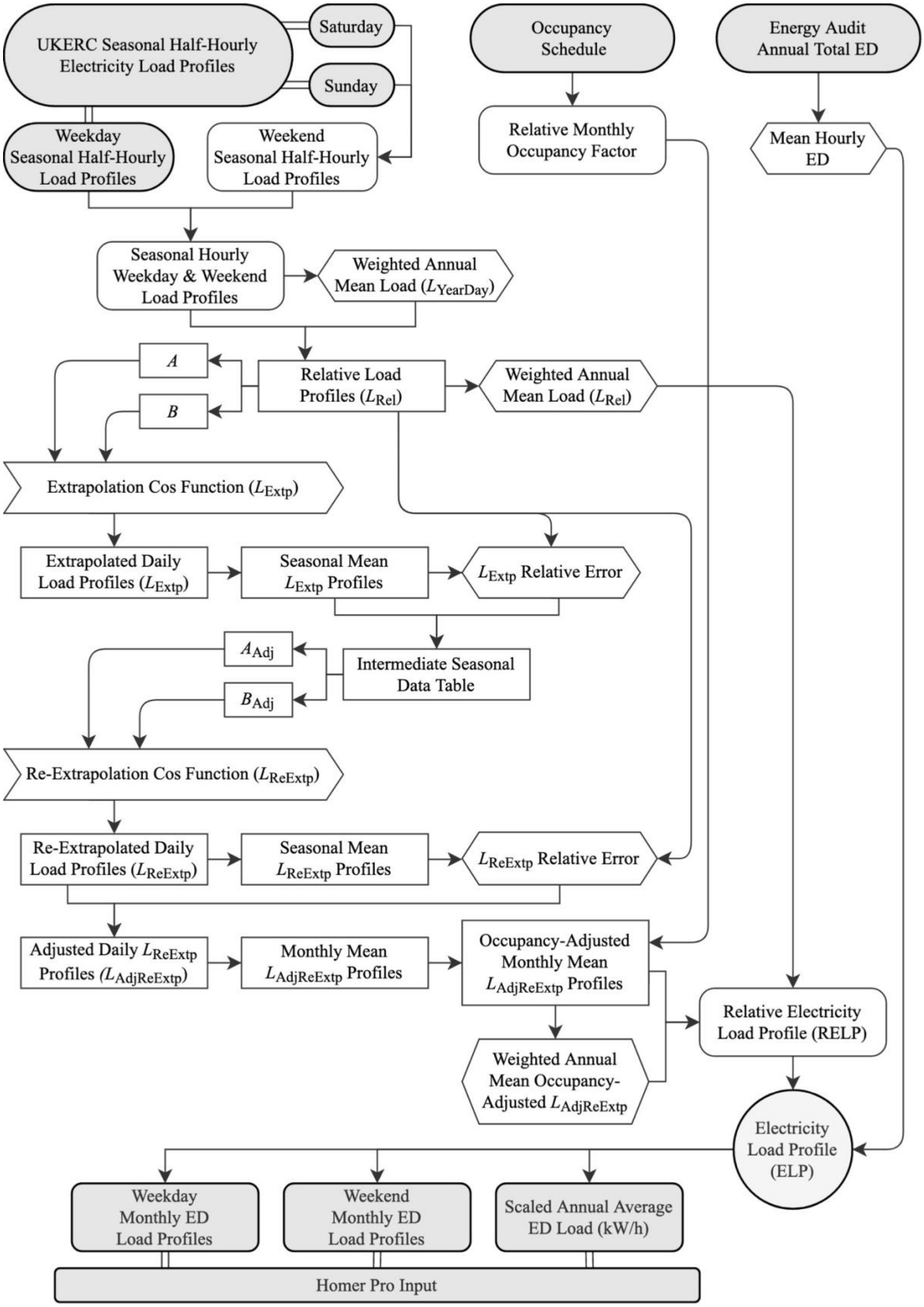


Fig. 5. Flow chart of methodology used to extrapolate monthly weekday and weekend electricity load profiles (ELP) and the scaled annual average ED load on Iona. The methodology is repeated for both the domestic and non-domestic sectors.

3.1 Main Data Sources

The main data sources used in our model for the energy system on Iona are given in this section. All the below mentioned datasets and sources have been added to a GitHub repository [45] to easily allow our methodology to be built upon or replicated.

3.1.1 Isle of Iona Energy Audit

The most comprehensive energy data available for Iona was collected by Philip Ruhemann during a 2015 'Isle of Iona Energy Audit' [9]. The audit provides an overview of the total energy use on Iona by fuel type, consumer, and cost. It also provides a detailed breakdown of all the building types on the island and gives information on the island community, demographics, population and local economy.

The annual energy consumption data given in the audit represent the total import quantities of electricity and a range of fuels to the island during the full year of 2014. The data was provided by the companies which supply energy to Iona. For analysis, all the data given in the Energy Audit was extracted and catalogued according to the categories in Table 3.

Table 3
Categories Used to Catalogue Data from 2015 Energy Audit

Category Type	Sector	Energy Use	Energy Type
Main	All Domestic Community	Total Electrical Heating Vehicles	All Electricity Non-electric Diesel
Sub	Commercial Public Transport Agriculture	-	Heating Oil Coal Propane Wood Butane LPG Diesel

3.1.2 Scene's Connections Study

The 2018 'Iona Renewable Electrical Connections Study' was commissioned by Iona Renewables and undertaken by Scene Consulting. The study provides annual total electricity demand data, split into appliance and heating uses, across four building types: Hotel/B&Bs, Residential, Public/Commercial, and Iona Community buildings. The energy data provided represents the annual consumption for 2017, but excludes 17 buildings, as no known energy data was available.

3.1.3 Scottish Census

The latest census data on Scottish inhabited islands in 2011 [8] and an accompanying report from 2015 [2] provide details on the Iona housing stock in terms of housing type, occupancy and tenure. They also provide information on the island population and demographics.

3.1.4 EPC Register

The Scottish Energy Performance Certificate (EPC) provides access to all the EPC reports available for Iona. The reports contain the results of energy performance assessments for individual buildings on Iona using a standardised methodology. The current and potential Energy Efficiency Rating (EER), Primary Energy Indicator (PEI), and details on the heating systems for 59 buildings (53 domestic and 6 non-domestic) are available for Iona, as well as the type of dwelling and its total floor area.

3.1.5 Electricity Demand Profiles

Average half-hourly electricity demand profiles of eight different UK user profiles for weekdays, Saturdays and Sundays during spring (30/03–02/05), summer (03/05–18/07), high-summer (19/07–31/08), autumn (01/09–25/10) and winter (26/10–29/03) are provided by UKERC [46]. The two user profiles we use in our model are the Domestic Unrestricted (single rate) and the Non-Domestic Unrestricted (single rate) and are based on measured data from 1997.

3.1.6 Meteorological Observations

To determine the climate conditions on Iona for the past decade, hourly mean data from the Tiree and Islay Port Ellen weather stations was obtained from the CEDA Archive [47]. These are the two closest automatic meteorological stations to Iona, with Tiree (56.500N, 6.881W) being 35.3 km away from Baile Mòr and Islay Port Ellen (55.681N, 6.250W) 73.0 km away (Fig. 6). The meteorological conditions measured at the two weather stations are representative of those on Iona, as both stations are located on island systems at altitudes of 9 m (Tiree) and 17 m (Islay Port Ellen), whist Baile Mòr sits between 8 and 20 m above sea level [48].

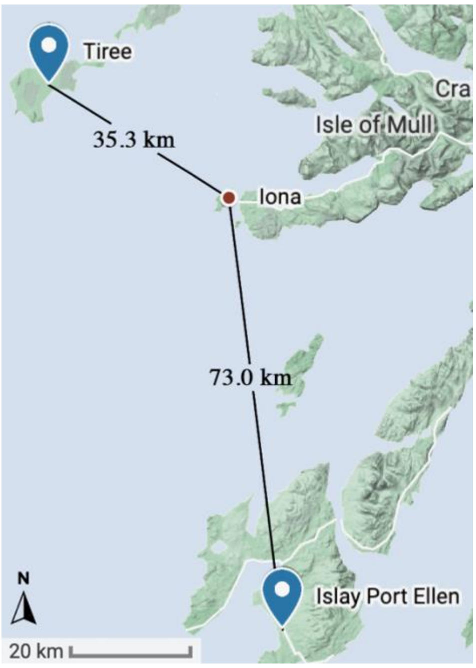


Fig. 6. Location of Tiree and Islay Port Ellen meteorological stations in relation to Baile Mòr, Iona. Adapted from [1].

The data obtained from the two weather stations covers a 10-year period from 01/01/2012 to 31/12/2021 and provide measurements of all the typical meteorological conditions, including ambient air temperature, wind and gust speeds, wind direction, solar irradiation, etc.

3.2 Building StockandUsers

Accurately determining the number of buildings on Iona and their type would best be done through an extensive in-person survey. However, as this is not possible within the scope of this project, a combination of the 2011 census, the 2015 Energy Audit, Scene's 2018 Connections Study, and conversations with Philip Ruhemann are used to compile an estimate.

A total of 97 buildings were reported as being occupied by residents in the 2011 census, which corresponds to figures given in the Energy Audit. According to Philip Ruhemann, at least 4 new builds have been constructed since then, all of which are well insulated 3-bed homes fitted with air-source heat pumps, one having an additional oil-fired aga. In the 2015 Energy Audit, Iona's housing stock is categorised by size and yearly occupancy rate. Adding the 4 new builds to these figures gives an estimated residential housing stock of 101 buildings, consisting of 44 larger permanent homes of multiple occupancy (category 1), 28 smaller permanently occupied homes (category 2), and 29 seasonally occupied homes (category 3), with residents typically staying from May to September.

Figures for non-residential buildings were compiled from the 2015 Energy Audit and Scene's 2018 Connections Study. The audit provides a detailed breakdown of the number of non-residential buildings which were collated and categorised as either Hotel/B&B, Public/Commercial, or Community buildings. As no new non-residential builds were reported on Iona since the energy audit, we assume the 2015 figures apply to the 2018 Connections Study, in which 17 buildings are not assigned a category. Thus, by comparing the total number of buildings within each category (i.e., Residential, Hotel/B&B, Public/Commercial, Community) given in the connections study to that of the energy audit, the remaining 17 buildings were assigned categories. From this we extrapolate the total, appliance and heating electricity use given in the connections study for each of the building categories, by multiplying the reported electricity use by N_2/N_1, where N_1 and N_2 are the number of buildings in a category before and after assigning the remaining 17 buildings respectively. The resultant total, appliance, and heating electricity use is used to obtain the relative appliance/heating use across the different housing types.

3.3 Heat Demand Model

We develop a model for estimating hourly heat demand based on a top-down approach, using the total thermal energy demand given in the Energy Audit. We use the HDD index to represent climate-driven heating loads and combine these with the occupancy rate of the different building types on Iona, to estimate hourly HD for a 10-year timeseries from 2012 to 2021. To calculate the HDD index for Iona, the housing stock is modelled as if it were a single building with a thermal load representing that of the entire island and using a $T_{\mathrm{b\_HDD}}$ that characterises the BLC of an average building on Iona.

3.3.1 Heating Degree Days

HDD are calculated using ambient air temperature measurements from the nearby Tiree and Islay Port Ellen meteorological stations. As some small gaps are present in the two datasets, hourly mean air temperatures from both weather stations were used to make up for this missing data. Throughout the 10-year timeseries (87,672 measurements), Tiree meteorological station is missing 986 temperature measurements, whilst Islay Port Ellen is short of only 44, representing a dataset completeness of 98.88%

and 99.95% respectively. The combined dataset of mean hourly temperatures from the two weather stations was created using the following Boolean statements:

$$\text{AVERAGE}\ \{\text{Tiree temperature}\}, \{\text{Islay Port Ellen temperature}\};$$
$$\text{if}\ \{\text{Tiree temperature}\} = \{\text{number}\}\ \text{AND}\ \{\text{Islay Port Ellen temperature}\} = \{\text{number}\}$$

$$\text{PRINT}\ \{\text{Tiree temperature}\};$$
$$\text{if}\ \{\text{Tiree temperature}\} = \{\text{number}\}\ \text{AND}\ \{\text{Islay Port Ellen temperature}\} = \{\text{“n/a”}\}$$

$$\text{PRINT}\ \{\text{Islay Port Ellen temperature}\};$$
$$\text{if}\ \{\text{Tiree temperature}\} = \{\text{“n/a”}\}\ \text{AND}\ \{\text{Islay Port Ellen temperature}\} = \{\text{number}\}$$

The resultant combined dataset has a completeness of 100%, with 98.83% of values being mean values, 1.12% from Islay Port Ellen only, and 0.05% from Tiree only. We assume air temperatures measured at Tiree and Islay Port Ellen can be used interchangeably, as they are statistically very similar to each other, with a Pearson's Correlation Coefficient r = 0.94 and only a 0.02 °C spread in means (Table 4).

Table 4
Weather Station Datasets Statistics

	Tiree	Islay Port Ellen
Population	86686	87628
Mean	9.62 °C	9.58 °C
Median	9.60 °C	9.60 °C
Standard deviation	3.71 °C	4.24 °C
r	0.94	

This combined ambient air temperature dataset was used to calculate the hourly HDD on Iona for the full meteorological timeseries between 2012 and 2021. A base temperature $T_{\text{b\_HDD}}$ = 15.5°C was chosen, as is standard for estimating the HDD of buildings in the UK [49]. Excel was used to calculate the HDD from the ambient air temperature T_{out} under the following conditions:

$$\text{HDD} = 0\,, \qquad T_{out} > T_{\text{b\_HDD}}$$

$$\text{HDD} = \frac{(T_{\text{b}} - T)}{24}\,, \qquad T_{out} < T_{\text{b\_HDD}} \tag{9}$$

The resultant hourly HDD are summated for each day, month, and year, to provide relative measures of the historical HD on Iona between 2012 and 2021. Using the historical HDD data and the figures for the thermal energy use in 2014, provided in the Energy Audit, HD on Iona can be extrapolated for the full 10-year timeseries. Extrapolation is performed by determining the ratio between the Annual Heat Demand (AHD) for Iona in 2014 and the total HDD for the same year using equation (10). This gives the mean heating load (Q_{Heating}) associated with one HDD for the building stock on Iona. From this we can extrapolate the Q_{Heating} for any hour (h) within the 10-year timeseries relative to the recorded AHD in 2014. The resultant Q_{Heating} values can be summed to provide total historical HD in kWh for any number of hours, days, months or years within the 10-year timeseries:

$$Q_{\text{Heating}}(h) = \text{HDD}(h) \cdot \frac{\text{AHD}(2014)}{\text{HDD}_{T_{\text{b\_HDD}}}(2014)} \tag{10}$$

where AHD (2014) = 2,340,953 kWh [9]. Usually, HD is determined from HDD by multiplying the total number of degree days by BLC, as given in (7). However, as we use a top-down approach, the BLC is already accounted for in the AHD value for 2014 and thus we do not require detailed energy loss data for the buildings on Iona.

Model Inputs and Considerations

At least one full year of HD data is preferable for accurate results; however, our model can extrapolate any length of timeseries, given the measured HD period is covered by the inputted meteorological dataset. If the total HD input covers a period of less than a year, it is extrapolated out to 365 days, whilst accounting for leap days in the total measured HD and respective extrapolation. The data input into the model must cover full days of consecutive hourly values, with non-values being assigned “n/a”. Ambient air temperature measurements must be in °C and HD in kWh.

3.3.2 Occupancy Factor

The effect of building occupancy on HD is factored into our model using a building occupancy schedule, which assigns an occupancy factor to domestic and non-domestic buildings for each month of the year. Once the schedule is defined by a user, our model matches hourly Q_{Heating} values with occupancy factors for the respective months of the year. The Q_{Heating} values are then multiplied by the ratio of the respective occupancy factor over the mean occupancy factor. Domestic and non-domestic buildings can be given different occupancy schedules, which are factored into the model depending on the relative weight of the sectors’ HD. For Iona, we use a relative HD weighting of 84.0% and 16.0% for domestic and non-domestic buildings respectively, determined from the Energy Audit data. Table 5 shows the occupancy schedule used in our model run, which is based on qualitative data from [9] and [13], but which can be adjusted by a user to represent a different system. As 29 of 101 residential buildings are seasonally occupied according to the Energy Audit, the occupancy factor from May to September for domestic buildings is lowered to reflect the reduction in residential population.

Table 5
Occupancy Schedule for Buildings on Iona

Sector	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	HD Ratio
Domestic	1.00	1.00	1.00	1.00	0.86	0.71	0.71	0.71	0.86	1.00	1.00	1.00	84.0%
Non-Domestic	0.80	0.80	0.80	0.90	1.00	1.00	1.00	1.00	1.00	0.90	0.80	0.80	16.0%
All	0.90	0.90	0.90	0.95	0.93	0.86	0.86	0.86	0.93	0.95	0.90	0.90	100%

Mean monthly occupancy-adjusted Q_{Heating} loads for all hours of the day are calculated from the 10-year timeseries for both domestic and non-domestic loads. These form thermal demand load profiles which are later input into our Homer Pro model.

3.4 Electricity Demand Model

Homer Pro is used to create a model of the hourly ED on Iona for both the domestic and non-domestic sectors. Total annual electricity consumption figures for the domestic and non-domestic sectors were obtained by summing all the electricity consumption figures assigned to each respective sector in our Energy Audit data catalogue. Domestic and non-domestic hourly electricity load profiles are calculated for weekdays and weekends, which used in the Homer Pro model. The total annual and daily electricity demands, as well as mean hourly loads for both sectors used in our electricity demand model are given in Table 6.

Table 6
Total Electricity Demand and Mean Electricity Load on Iona

Type	2014 Total (kWh)	Scaled Annual Average (kWh/day)	Scaled Annual Average (kW)	ED Ratio
Domestic	780,000	2137	89.0	42.7%
Non-Domestic	1,044,590	2862	119.2	57.3%
TOTAL	1,824,590	4999	208.3	100%

3.4.1 Load Profiles

Homer Pro offers synthetic load profiles for residential, commercial, industrial and community users; however, we generate custom load profiles for domestic and non-domestic buildings based on the UKERC electricity demand profiles [46]. The UKERC profiles provide weekday, Saturday and Sunday half-hourly values for the spring, summer, high summer, autumn and winter seasons. Homer Pro allows for the input of hourly values of weekday and weekend profiles for 12 months. Therefore, we apply a methodology to convert the 5-season profiles to 12-month profiles, combine the Saturday and Sunday values to obtain weekend values, as well as the half-hourly values to obtain hourly values.

Hourly values were obtained by averaging the two values associated with the same hour (e.g., 10:00, 10:30). Weekend values were calculated by taking the mean of the Saturday and Sunday values for each hour of the day. To estimate the weekday and weekend hourly load profiles for each month from values for the five seasons, we first calculate the weighted annual mean loads (L_{Year}) as follows:

$$L_{\mathrm{Year}} = \frac{34L_{\mathrm{Spr}} + 77L_{\mathrm{Smr}} + 44L_{\mathrm{Hsr}} + 55L_{\mathrm{Aut}} + 155L_{\mathrm{Wtr}}}{365} \tag{11}$$

where L_{Spr}, L_{Smr}, L_{Hsr}, L_{Aut} and L_{Wtr} are the mean loads for the spring, summer, high summer, autumn and winter seasons respectively. Each seasonal load is weighted according to the number of days in its respective season as given in Table 7. The L_{Year} of an average day in the week (L_{YearDay}) is calculated by taking a weighted average of the weekday and weekend L_{Year} values:

$$L_{\mathrm{YearDay}} = \frac{5\left(L_{\mathrm{Year}_{\mathrm{Weekday}}}\right) + 2\left(L_{\mathrm{Year}_{\mathrm{Weekend}}}\right)}{7} \tag{12}$$

Table 7
UKERC Electricity Demand Profile Seasons

Season	Start	End	# Days	Midpoint (*i*-value)
Spring	30-Mar	02-May	34	105.5
Summer	03-May	18-Jul	77	161.0
High Summer	19-Jul	31-Aug	44	221.5
Autumn	01-Sep	25-Oct	55	271.0
Winter	26-Oct	29-Mar	155	11.0

The input load profiles, as well as all the calculated weighted averages, L_{Year} and L_{YearDay}, are converted into relative loads (L_{Rel}) by dividing each respective hourly value across all the seasons by the overall mean L_{YearDay}. The resultant domestic and non-domestic hourly L_{Rel} for weekdays and weekends represent the electric load profile relative to their respective annual mean loads. The UKERC load profiles give respective ratios of 0.98/1.04 between mean weekday and weekend loads for the domestic sector and 1.13/0.68 for the non-domestic sector.

To extrapolate monthly L_{Rel} from the seasonal data, we determine cosine functions to best fit the L_{Rel} data across the five seasons for each hour of the day, where each datapoint is associated with an *i*-value representing the number of days between the midpoint of the season and the beginning of the year (Table 7). In effect we generate 96 different cosine functions to best fit the data across all hours of weekdays and weekend for both domestic and non-domestic loads. The resultant functions give L_{Rel} for any given day of the year (i) and are defined as:

$$L_{\mathrm{Rel}}(i) = A\cos(\omega i - \varphi) + B \tag{13}$$

where A is the (specific) amplitude, ω the period, φ the phase shift, and B the (specific) vertical shift. The cosine function variables are defined as:

$$\omega = \frac{2\pi}{365} \qquad A = \frac{\max - \min}{2} \tag{14}$$

$$\varphi = 11\left(\frac{2\pi}{365}\right) \qquad B = \frac{\max + \min}{2} \tag{15}$$

where A and B are calculated from the max and min values of L_{Rel} for any given hour of the day. The function used to extrapolate L_{Rel} for any hour on any given day of the year is thus written as:

$$L_{\text{Rel}}(i) = A\cos\left(\frac{2\pi}{365}i - \left(\frac{2\pi}{365}\right)11\right) + B \tag{16}$$

Using Equation (14) and (15) we calculate the values of A and B for all 96 cosine functions and use these to extrapolate L_{Rel} for every hour of the day for every day of the year for both weekdays and weekends within the domestic and non-domestic sectors. The daily extrapolated relative loads (L_{Extp}) are then categorised by the UKERC seasons and averaged respectively (Table 7). The seasonal means of L_{Extp} and L_{Rel} are compared to determine the relative error in the extrapolation:

$$L_{\text{Extp}} \text{ relative error} = \frac{L_{\text{Extp}} - L_{\text{Rel}}}{L_{\text{Rel}}} \tag{17}$$

The L_{Extp} relative error is calculated for both weekdays and weekends loads of the domestic and non-domestic sectors, for all hours of the day in each of the five seasons using equation (17).

The cosine function used for this initial extrapolation underestimates max loads and overestimates min loads because A is based on mean seasonal loads and not the actual daily max and min loads. To adjust the amplitude and vertical shift of the original cosine function in order to improve its extrapolation accuracy, an intermediate set of load profiles are created by adjusting L_{Rel} to account for the respective L_{Extp} relative error. The intermediate dataset is used to calculate the error-adjusted amplitude (A_{Adj}) and error-adjusted vertical shift (B_{Adj}) values that are used in a re-extrapolation function (L_{ReExtr}) which better represent the actual yearly max and min loads (Fig. 7).

$$L_{Extp} = A\cos\left(\frac{2\pi}{365}i - \left(\frac{2\pi}{365}\right)11\right) + B$$

$A = 0.538 \qquad B = 1.91$

$$L_{ReExtr} = A_{Adj}\cos\left(\frac{2\pi}{365}i - \left(\frac{2\pi}{365}\right)11\right) + B_{Adj}$$

$A_{Adj} = 0.679 \qquad B_{Adj} = 1.91$

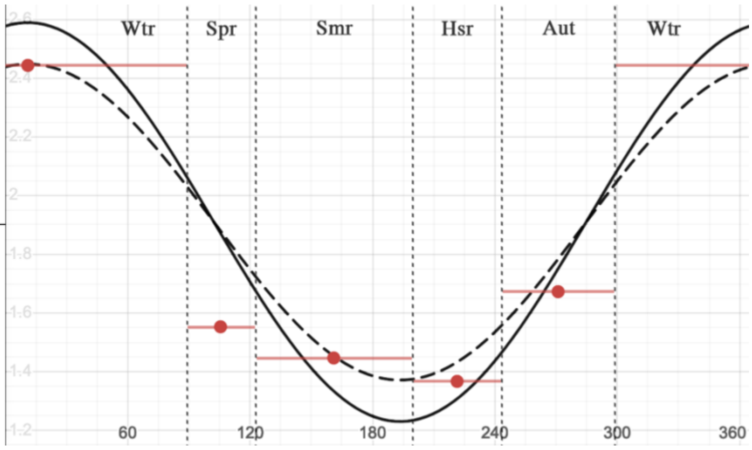


Fig. 7. Example of original (dotted) and error-adjusted (solid) cosine functions fit to mean seasonal L_{Rel} data. Plotted in [50].

The L_{ReExtr} function is used to re-extrapolate loads for each day of the year and hour of the day for domestic and non-domestic weekdays and weekends. The resultant daily L_{ReExtr} are once again averaged to create a seasonal dataset, for which the L_{ReExtr} relative errors compared to L_{Rel} are also calculated.

Whilst this re-extrapolation reduces the relative error in the resultant values, especially for the winter and high summer seasons, some errors remain (Table 8). Therefore, each L_{ReExtr} value is adjusted by the respective L_{ReExtr} relative error associated with its season and hour of the day, to give the final error-adjusted re-extrapolated loads ($L_{AdjReExtr}$). The resultant seasonal mean loads have 0% error compared to L_{Rel}, however, the seasonal error adjustment results in somewhat abrupt changes in loads between months of different seasons. Nevertheless, the improved accuracy of loads estimations is more important than the smoothness of the monthly load transitions.

Table 8

L_{ReExtr} Relative Errors Compared to L_{Rel}

	Domestic Weekday					Domestic Weekend					Non-Domestic Weekday					Non-Domestic Weekend				
TIME	Spr	Smr	Hsr	Aut	Wtr	Spr	Smr	Hsr	Aut	Wtr	Spr	Smr	Hsr	Aut	Wtr	Spr	Smr	Hsr	Aut	Wtr
00:00	2%	-2%	-8%	5%	-1%	7%	1%	-2%	5%	-1%	0%	-6%	-7%	3%	-1%	2%	-3%	-4%	2%	-1%
01:00	2%	-1%	-8%	5%	-1%	1%	0%	-3%	5%	-1%	6%	-11%	-13%	8%	-2%	8%	-10%	-12%	3%	-2%
02:00	0%	-3%	-9%	3%	-1%	-1%	-2%	-7%	4%	-1%	-3%	-14%	-14%	8%	-2%	0%	-10%	-10%	6%	-2%
03:00	2%	-3%	-6%	3%	-1%	1%	-3%	-6%	3%	-1%	-2%	-12%	-13%	8%	-2%	-1%	-12%	-13%	7%	-2%
04:00	0%	0%	-6%	1%	0%	3%	-3%	-7%	2%	-1%	0%	-12%	-12%	8%	-2%	2%	-10%	-14%	7%	-2%
05:00	2%	0%	-6%	1%	0%	-1%	-6%	-9%	3%	-1%	1%	-12%	-12%	8%	-2%	0%	-12%	-14%	7%	-2%
06:00	4%	1%	-1%	4%	-1%	5%	0%	-3%	4%	-1%	9%	0%	-1%	10%	-1%	4%	-1%	-4%	7%	-1%
07:00	3%	-5%	0%	-1%	-1%	1%	-4%	-7%	4%	-1%	13%	2%	1%	4%	-1%	7%	1%	-2%	6%	-1%
08:00	6%	-6%	1%	-3%	-1%	3%	0%	0%	2%	-1%	7%	-3%	1%	3%	-1%	1%	-1%	-3%	6%	-1%
09:00	9%	1%	-1%	5%	-1%	4%	-2%	0%	2%	-1%	3%	-4%	1%	4%	-1%	-4%	-6%	-4%	5%	-1%
10:00	6%	1%	-3%	4%	-1%	3%	-3%	0%	1%	-1%	2%	-5%	1%	4%	-1%	-5%	-10%	-7%	5%	-1%
11:00	8%	1%	-6%	5%	-1%	3%	-2%	0%	5%	-1%	3%	-5%	1%	3%	-1%	-5%	-8%	-5%	5%	-1%
12:00	7%	1%	-3%	4%	-1%	-1%	-3%	0%	4%	-1%	2%	-6%	1%	3%	-1%	-4%	-8%	-5%	5%	-1%
13:00	6%	1%	-3%	4%	-1%	4%	-3%	1%	2%	-1%	2%	-5%	1%	4%	-1%	-6%	-8%	-6%	4%	-1%
14:00	8%	-3%	-5%	2%	-1%	7%	-3%	1%	3%	-1%	4%	-4%	1%	5%	-1%	-5%	-8%	-7%	4%	-1%
15:00	9%	0%	-3%	7%	-1%	8%	-7%	1%	6%	-1%	5%	-3%	0%	6%	-1%	-3%	-7%	-6%	4%	-1%
16:00	13%	-2%	0%	11%	-1%	10%	-4%	1%	8%	-1%	5%	-2%	0%	8%	-1%	-2%	-9%	-9%	5%	-1%
17:00	15%	-6%	-5%	7%	-2%	17%	0%	1%	12%	-1%	5%	-2%	-1%	8%	-1%	-1%	-9%	-9%	5%	-1%
18:00	21%	-5%	-3%	5%	-2%	17%	0%	1%	9%	-1%	8%	1%	1%	5%	-1%	6%	-3%	-2%	5%	-1%
19:00	21%	0%	0%	-5%	-1%	19%	-1%	1%	-7%	-1%	3%	-3%	1%	-3%	-1%	3%	1%	-1%	2%	-1%
20:00	14%	1%	1%	-10%	-1%	13%	3%	1%	-10%	-1%	-1%	-6%	0%	-6%	-1%	1%	0%	0%	-1%	0%
21:00	-3%	1%	-8%	-9%	-1%	-5%	1%	-6%	-10%	-1%	0%	0%	0%	0%	-1%	-3%	0%	-2%	1%	0%
22:00	-2%	1%	-2%	0%	-1%	0%	1%	0%	0%	-1%	0%	0%	-1%	2%	0%	-1%	0%	-1%	2%	0%
23:00	1%	-1%	0%	3%	-1%	0%	-2%	0%	2%	-1%	0%	-3%	-5%	3%	-1%	-1%	-2%	-3%	2%	-1%

All the resultant $L_{AdjReExtr}$ for domestic and non-domestic weekdays and weekends are averaged by hour of day for each month. Building occupancy on Iona is incorporated at this point by multiplying each monthly $L_{AdjReExtr}$ profile by the occupancy factor associated with the respective month (Table 5).

To create the final monthly load profiles, the occupancy-adjusted $L_{\mathrm{AdjReExtr}}$ values are re-adjusted to account for the effect of the extrapolation and occupancy rate calculations on the annual mean relative load, which should be equal to 1. This is done by multiplying each hourly value by the ratio between the mean occupancy-adjusted $L_{\mathrm{AdjReExtr}}$ and the mean L_{Rel} for each weekday/weekend for domestic/non-domestic value. To associate the resultant final extrapolated relative electricity load profiles (RELP) for the domestic and non-domestic sectors, with electricity loads measured on Iona, the RELPs are multiplied by the hourly scaled annual average electrical load for each respective sector (Table 6). This gives the final electricity load profiles (ELP) in kW for domestic and non-domestic weekdays and weekends which we use as inputs into our Homer Pro model.

3.5 Homer Pro

Homer Pro is used to model the electricity demand on Iona for a typical year according to the data we have calculated though our methodology. Homer Pro is the global standard software package used for optimising microgrid design in all sectors, from village power and island utilities to grid-connected campuses and military bases. The ‘Hybrid Optimization Model for Multiple Energy Resources’ nests tools to simulate energy systems, show system configurations optimised by cost, and provide sensitivity analyses [51]. The Homer Pro software has ‘Load’, ‘Components’, ‘Resources’ and ‘Project’ tabs which feed into the ‘Design’ and ‘Results’ views of the model (Fig. 8). The load data input into Homer Pro is used to represent the Iona network requirements. The system design suggestions we make in Section 7 are added as components to our model. The available renewable resources on Iona are also added to the model. Finally, after setting up cost and system constraint parameters, Homer Pro compares a wide range of system compositions to determine the most cost-effective system to meet load requirements using the specified range of components and the available resources.

Fig. 8. Homer Pro model tables collated.

3.5.1 Loads

For Iona, domestic and non-domestic electric loads are modelled separately in Homer Pro as Electric #1 and Electric #2, using the daily scaled annual averages of 2,137 kW for domestic and 2,862 for non-domestic loads (Table 6). The ELPs for weekdays and weekends for the domestic and non-domestic loads are added to the model. As no granular electricity consumption data is available for Iona, we keep the default random variability at 10% day-to-day and timestep of 20%. These could be adjusted to better fit an energy system if daily measurements of electricity consumption were available.

Whilst the heat demand on Iona for the past decade is modelled in Excel using the methodology described in 3.3, Homer Pro is used to create a more general model which is also used for system design optimisation. The 10-year timeseries of estimated HD is used to calculate the scaled annual average HD (in kWh/day) for the domestic and non-domestic sectors on Iona which are entered into the Homer Pro model as Thermal #1 and Thermal #2 loads. As with the electric loads, Homer Pro allows for thermal load profiles to be modelled, for which the thermal load profiles calculated in Section 3.3.2 are used. As weekly heating habits are not known for Iona, the same thermal load profiles are used for weekdays as for weekends. If relative weekday and weekend Q_{Heating} loads were available, they could be input into the Homer Pro model.

3.5.2 Components

All the potential components suggested in Section 7 are entered into the model by adding them to the system as either AC or DC inputs and entering all the required component parameters. Homer Pro includes a library of a variety of specific or generic system components, but also allows for manual entry of components not included in the library. The cost per kW of installed capacity for each component is required by the model, which we determine from a range of sources for our system design. Additional parameters such as capital costs, replacement costs, operation and maintenance costs, fuel costs, expected lifetime, degradation factors and efficiency rating which match the chosen components must also be entered into the model. For sizing components, Homer Pro includes a 'Homer Optimizer' which can automatically size various system components within user-definable limits. Using the optimiser increases the number of possible system variations which Homer Pro can model to further optimise the system design. For this reason, we use the system optimiser to size most of our components.

3.5.3 Resources

All the available resources and fuels on Iona which are required by the chosen system components are added under the resources tab. For our system we add solar DHI (Global Horizontal Irradiance), solar DNI (Direct Normal Irradiance), wind, temperature, and fuel available on Iona. Solar GHI data is downloaded straight into Homer Pro from the NASA Prediction of Worldwide Energy Resource (POWER) database, which covers a 22-year period from 1983-2005 [52]. For the solar DNI, daily mean values are taken from the 2021-2021 10-year timeseries from the nearby Tiree meteorological station and imported into Homer Pro. For wind resource, the measured wind speeds at Tiree for the same timeseries were binned by wind speeds of 1 m/s increments to determine their frequency distribution. This data is then entered into Desmos [50] along with the equation (18) for a two-parameter Weibull distribution [53] to approximate the shape parameter (*k*) and scale parameter (*c*), which best fits the frequency (*f*) distribution of wind speeds (*v*) from the 10-year dataset (Fig. 9).

$$f(v) = \frac{k}{v}\left(\frac{v}{c}\right)^{k-1} \cdot \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{18}$$

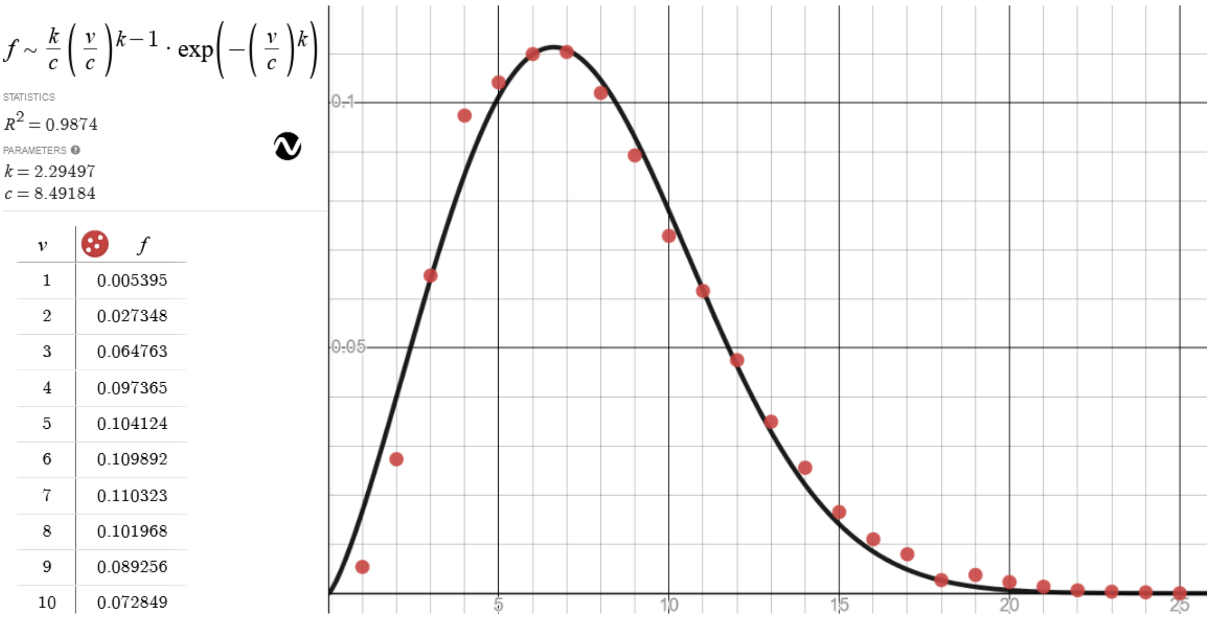


Fig. 9. Weibull distribution which best fits the frequency distribution of Tiree wind speeds during the 2012-2021 period, determined using Desmos [50].

The resultant shape parameter k is entered into Homer Pro, along with the peak hour of wind speeds determined from the Tiree dataset. The measurement altitude of 9 m above sea level and anemometer height of 9 m along with a power law exponent (α) of 0.36 is used to extrapolate wind speeds out to hub height. Commonly, a power law exponent $\alpha = 1/7$ is commonly used for neutral conditions [54], however, $\alpha = 0.36$ has been shown to accurately model wind shear on an island using in-situ measurements [55].

Our complied dataset of T_{out} measured at Tiree and Islay Port Ellen is added to the model by importing daily means into Homer Pro. The ambient air temperatures are added to model temperature effects on solar PV cell efficiency. A cost of heating oil on Iona of 67.2 p/litre is added to the model, obtained by adjusting its price given in the Energy Audit by the relative change in the UK Consumer Price Index (CPI) for liquid fuels between 2015 and 2021 [56]. The cost of electricity is also determined by adjusting the 2015 figures by the relative change in the CPI for electricity. Thus, a grid power price of 24.0 p/kWh with a sellback price of 3.5 p/kWh into the SSEN network [57] is added to the Homer Pro model.

3.5.4 EconomicsandConstraints

Within the 'Project' tab of Homer Pro, we keep the default nominal discount rate of 8% and project lifetime of 25 years. As an expected inflation rate, we use a conservative value of 5.1%, which was the average inflation in the UK between 1960 and 2021, although inflation has been much lower in recent decades before the year 2022 [58]. A fixed capital cost of £50,000 and an operation and maintenance cost of £5,000 per year are also added to cover all expenses related to planning and operation of a potential network upgrade. For reference, Scene's 2017 proposal for an Iona heat network estimated their total project-related costs (excluding components) at £33,000 [17].

Grid purchase capacity has been limited to 1,000 kW in our Homer Pro model for Iona, as the peak electric load is just shy of 1,000 kW and we know the grid is already constrained with a reported export capacity of only 50kW [17].

3.6 Limitations

The level of detail and accuracy of the data input into our model is a major limitation of our methodology. Much of the data used in our model comes from the Energy Audit, which is somewhat outdated, lacks detail and potentially precision as some data given in the audit is already estimated or extrapolated. For example, the island ED data is based on the estimated annual demand for just three housing types (category 1-3), extrapolated out to represent all the buildings on the island. Additionally, the ED values used for our model are from 2014 and thus do not account for the numerous new heat pump installations on the island. The added heat pumps which would result in increased ED and decrease in HD as we have modelled it. In terms of the fuel consumption, which is used to estimated HD, whilst most of the figures are measured values and not estimates, they represent the total fuel imports to Iona and not actual consumption. However, as the fuel use data covers the fuel consumption of a full year and deliveries are made fortnightly, the data should be a good indication of yearly demand for all the buildings on the island. Whilst our model of energy consumption on Iona is limited by the input data from the Energy Audit, our model allows for flexible input data quality and would thus provide more reliable results if fed with better data.

To estimate heating loads we assume an HDD base temperature of 15.5°C as is standard to represent the total net heat transfer of the UK building stock [49]. However, the average EER on Iona is 47, compared to the UK average of 67 [59], meaning the average building on Iona experiences more heat loss than an average UK building. Thus, an appropriate T_b for Iona would likely be above 15.5°C. Although net heat transfer is implicit in the AHD measured in 2014, the relationship between the BLC and T_b means the accuracy of the extrapolated AHDs depends on the suitability of the chosen T_b at representing the mean BLC of the building stock. To overcome this a second year of measured AHD could be used to calibrate the T_b to accurately model the building heat losses, where T_b would be adjusted until the modelled and measured AHD for the second-year match. Alternatively, a detailed heat loss analysis study could be performed on Iona's building stock to determine a more representative T_b.

Another limitation is that whilst the occupancy schedule used in our model functions as intended, the input occupancy data for Iona is heavily based on broad estimates and qualitative data which impacts the accuracy of our results. Additionally, the seasonal UKERC ED load profiles which are merged with the occupancy data are based on UK average data that may not accurately represent seasonal and hourly variations in ED on Iona as they are based on outdated measurements of loads on the UK mainland in 1997. Our output model would benefit from the input of actual measured electric load profiles for Iona or of a more representative set of profiles for a small or island community.

Overall, the biggest limitation to our model is in the quality of the input energy data, being outdated, sparce, largely based on estimates and assumptions, and covering varied timeseries. However, our model of Iona illustrates how our methodology can be used to extrapolate detailed energy data from just a small amount of input data by using a range of available data sources.

4. Results for Iona

In this section we discuss the results from our energy demand extrapolation methodology described in the previous section, as well as the results from our analysis of the buildings stock and users on Iona. The model results which we give in this section for thermal and electric loads on Iona are used as inputs in the Homer Pro hybrid optimisation model, to determine an optimum system setup for the design suggestions given in Section 7. This section follows the same structure as our methodology, starting by giving results for Iona's building stock and users, then energy demand from our Excel model, creating the inputs for our Homer Pro model, for which results are shown at the end. All the model files used to create our results have been added to a GitHub repository [45] to allow for the use of our model and/or the creation of new forks.

4.1 Building StockandUsers

The detailed survey of the building stock on Iona compiled from data gathered in the 2015 Energy Audit [9], 2018 Electrical Connections Study [19] and conversations with Philip Ruhemann in 2022 [14] are given in Table 9. The Energy Audit provides the most detailed overview of all the different buildings on Iona, with the Connections Study proving a more general building type classification. Of the residential buildings classified in the Energy Audit, 44 are considered larger permanently occupied, 28 smaller permanently occupied, and 29 seasonally occupied homes. The data from the three sources are consistent with each other providing one new build was constructed between 2015 and 2018, with the other three being built thereafter.

The results of our survey into the EPCs for buildings on Iona are given in Table 10, compiled from all 59 available EPC reports associated to the PA76 postcodes on the island, from 6SG to 6SW [15]. The resultant dataset for residential buildings is likely representative of the sector as it covers more than half of the residential buildings on Iona. However, too few reports are available for non-residential buildings to properly represent the entire sector. As the available EPC reports for the various buildings on Iona were produced on different dates ranging from 2008 to 2022, they may not accurately represent the present housing stock, yet provide a more general indication of buildings on the island.

Table 9
Count and Type of Buildings on Iona in 2015, 2018 and 2022

2015 Energy Audit				2018 Electrical Connections Study		
Year	Count	Description	Type	Year	Count	Type
2015	62	Residential properties	Residential	2018	87	Residential
	21	Self-catering	Residential		9	Hotel/B&B
	14	Crofts	Residential		27	Public/Commercial
	2	Hotels	Hotel/B&B		1	Community
	11	Bed & breakfasts	Hotel/B&B		17	Not assigned
	1	Hostels	Hotel/B&B			
	4	Retreat Centres	Public/Commercial			
	1	Campsites	Public/Commercial			
	8	Shops	Public/Commercial			
	2	Staffa boat tour companies	Public/Commercial			
	2	Farms	Public/Commercial			
	1	Heritage Centre Cafe	Public/Commercial			
	1	Martyrs Bay Restaurant and Bar	Public/Commercial			
	1	MacLeod Centre	Public/Commercial			
	1	Welcome Centre	Public/Commercial			
	1	Iona Heritage Centre	Public/Commercial			
	1	Village Hall	Public/Commercial			
	1	Fire Station	Public/Commercial			
	1	GP Surgery	Public/Commercial			
	1	Library	Public/Commercial			
	1	Parish Church	Public/Commercial			
	1	Iona Primary School	Public/Commercial			
	1	Iona Community (inc. Abbey)	Community			
	140	TOTAL			141	TOTAL
2022	+4	New builds				Residential
	144	TOTAL				ALL

Table 10
Classification of Buildings on Iona According to EPC

Sector & Building Type				Heating Type		Fuel Source	
53	Residential	21	Detached house	16	Room heaters	37	Electric
		11	Semi-detached house	14	Boiler and radiators	12	Oil
		8	Detached bungalow	12	Air source heat pump	3	Dual fuel (mineral/wood)
		3	Semi-detached bungalow	8	Storage heaters	1	Coal
		2	End-terrace house	1	Ceiling heating		
		2	Mid-terrace bungalow	1	Portable heaters		
		2	Mid-terrace house	1	n/a		
		1	End-terrace bungalow				
		1	Flat				
		1	Ground-floor flat				
		1	Top-floor flat				
6	Non-Residential	2	Library/Museum/Gallery	2	Air source heat pump	4	Electric
		1	Community/Day Centre	4	n/a	1	Natural gas
		1	Residential space			1	Oil
		1	Restaurant/Cafes/Takeaway				
		1	Retail/Financial				

4.2 Total Energy Demand

The estimated mean annual energy demand for Iona using data from 2014 which has been extrapolated out to represent the current housing stock, whilst excluding the Calmac Ferry and leap days, is 4,995,984 kWh, consisting of 3,266,337 kWh domestic and 1,729,647 kWh non-domestic demand. The overall annual energy demand has a 65.4% domestic (3,266,377 kWh) and 34.6% non-domestic (1,729,647 kWh) split. The total daily scaled annual average energy demand is 12,424 kWh/day, composed of 8,495 kWh/day domestic and 3,929 kWh/day non-domestic demand. Of the total energy demand on Iona, 58.5% (7,274 kWh/day) is thermal and 41.5% (5,150 kWh/day) electric. The hourly mean, minimum, maximum and quartile ranges for the total, domestic and non-domestic loads modelled for Iona are given in Table 11 and are plotted in Fig. 10.

Table 11
Iona Hourly Mean Loads (kW)

	All Sectors			Domestic Sector			Non-Domestic Sector		
	Total	Thermal	Electric	Total	Thermal	Electric	Total	Thermal	Electric
Min	111.2	3.5	40.4	37.3	2.5	16.6	38.4	0.7	23.8
1st Quartile	335.8	149.2	124.6	173.8	109.6	56.4	110.6	26.3	62.3
Median	526.1	317.4	181.4	375.5	279.2	78.6	139.8	47.9	94.6
3rd Quartile	653.4	429.1	308.0	506.9	396.0	124.3	215.2	62.4	167.2
Max	996.8	593.4	468.3	779.5	538.8	286.8	381.3	90.0	311.0
Mean	509.8	293.1	214.6	353.8	258.6	95.3	166.0	44.5	119.2

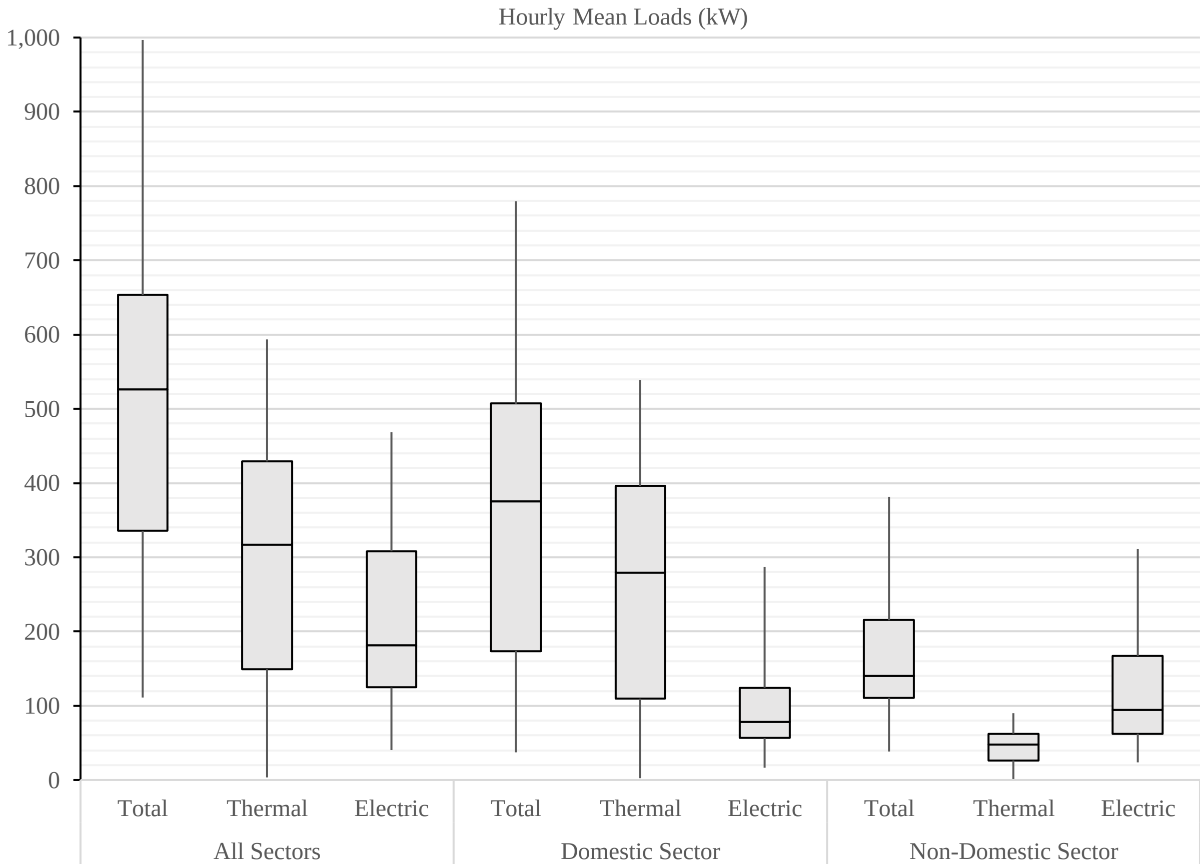
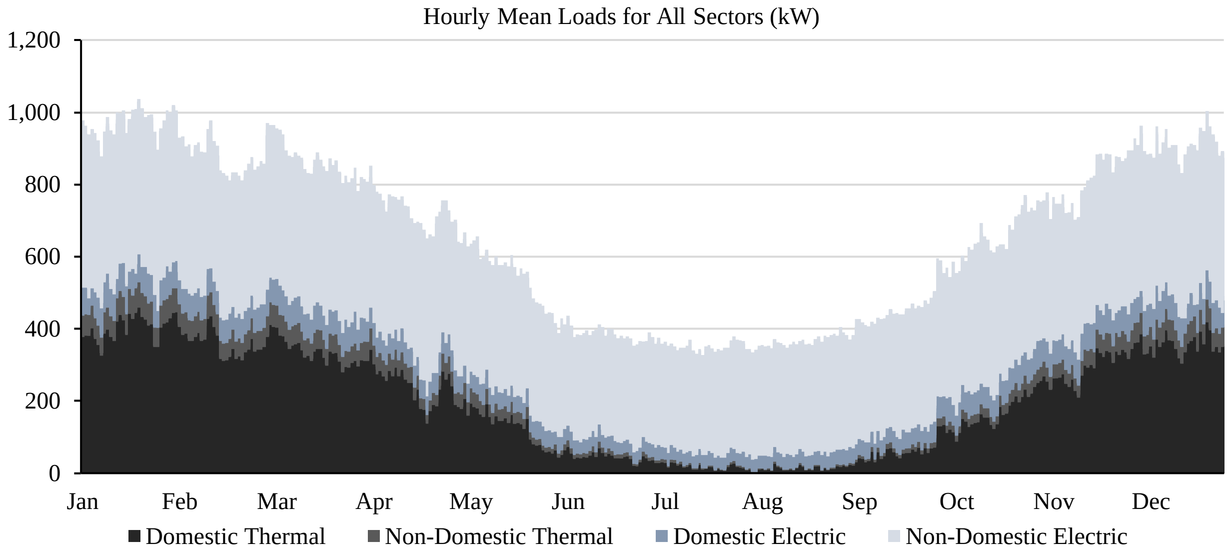


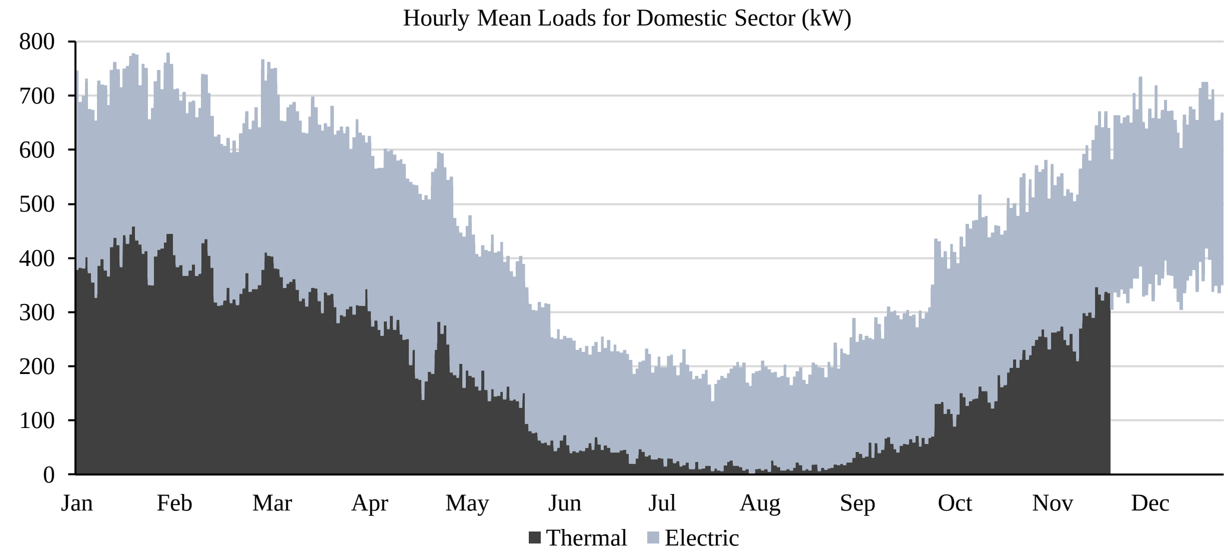
Fig. 10. Box plots of total, domestic and non-domestic thermal and electric loads on Iona for mean hourly model data.

The total mean thermal load on Iona is higher than the electric load, at 293.1 kW compared to 214.6 kW respectively. Electric domestic and non-domestic loads on Iona are somewhat comparable, at 95.3 kW for domestic and 116.6 kW non-domestic; however, the difference between domestic and non-domestic thermal loads is substantial, at 258.6 kW compared to 44.5 kW respectively (Fig. 10).

In terms of variability, both thermal and electric loads fluctuate seasonally, generally peaking in winter and reaching minimums in summer (Fig. 11). Two main factors affecting the seasonal variability of loads are the outdoor climate (i.e., temperature and sunshine hours) and the island occupancy rate (i.e., the variability in population). For domestic sector loads, these two factors add together, as the island occupancy rate is highest in winter when demand naturally tends to be higher (Table 5). However, for non-domestic loads, part of the climate-driven variability is cancelled out by the reduced island occupancy. Nevertheless, both sectors on Iona experience higher loads in winter, although this does explain the larger seasonal differences in loads within the domestic sector compared to the non-domestic sector, particularity thermal loads which are more climate-dependent than electric loads (Fig. 11: mid/bottom). Domestic sector thermal loads show particularly large annual variations, ranging from almost zero in summer to over 400 kW in winter. The overall mean non-domestic thermal load is negligible compared to the sector’s electric load, clearly illustrated in the bottom plot in Fig. 11.

Whilst we make the distinction between thermal and electric loads, it is important to remember that we calculate thermal loads from fossil fuel consumption, without considering the amount of heating provided through electricity consumption. According to data extrapolated from Scene’s 2018 study, approximately 79.9% of the total island electricity consumed in 2017 was used for heating (Table 2). In 2014, the year of our model data, this figure was likely lower as the number of heat pumps on Iona has since increased over the years. Thus, our model likely overestimates Iona’s present thermal load and underestimated electric loads. Whilst we draw a direct comparison between the modelled electric and thermal loads, it is worth noting that thermal loads are based on the total energy released through the combustion of fossil fuels. In reality, oil and gas boilers typically only convert between 60% and 90% of the input energy into useful thermal energy [60]. Comparatively, heat pump systems are much more efficient per kW of energy input. The efficiency of heat pump systems depends on exchange temperature, however, ASHPs in the UK have been found to achieve efficiencies between 245% and 265% [61]. GSHPs reach even higher efficiencies as they operate using higher exchange temperatures. Thus, because the number of heat pumps installed on Iona has risen, the actual energy consumption on the island has likely decreased compared to our model, albeit electricity demand has likely increased.





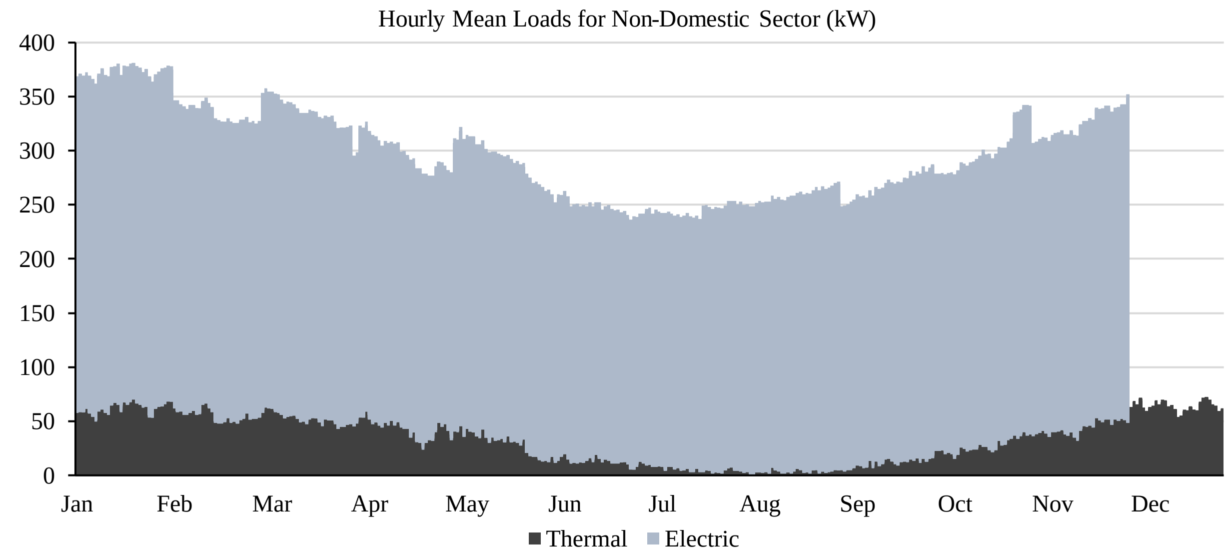


Fig. 11. Extrapolated hourly mean thermal (dark) and electric demand (light) on Iona across all sectors (top), the domestic sector (mid), and the non-domestic sector (bottom), for a typical year. Thermal data consist of mean values from the extrapolated 10-year timeseries. Electric data extrapolated from 1-year monthly demand profiles.

4.3 Heat Demand

The total annual heat demand on Iona is 2,655,031 kWh, comprised of 85.3% (2,265,595 kWh) domestic and 14.7% (389,436 kWh) non-domestic demand, extrapolated using our Excel model based on 10 years of ambient air temperature measurements T_{out} taken between 2012 and 2021. The daily scaled annual average HD is estimated at 7,274 kWh/day, composed of 6,207 kWh/day domestic and 1,067 kWh/day non-domestic demand. The hourly mean thermal load on Iona is 492.8 kW, with a minimum of 105.1 kW and maximum of 1,142 kW. The domestic and non-domestic sectors have mean thermal loads of 258.6 kW and 44.5 kW respectively (Table 11).

Detailed plots of the modelled heat demand for the 10-year timeseries are given in Fig. 12. The hourly mean, maximum and minimum thermal loads across an average year within the timeseries are given in Fig. 13, with the full 10 years of extrapolated hourly loads given in Appendix 1.

As is apparent in Fig. 12, the mean hourly, daily and monthly heat demands vary a lot across the modelled years due to day-to-day T_{out} variability. However, HD (especially daily) follows a clear monthly pattern (row 2), with very little year-to-year variability across the 10-year timeseries. There is also a clear diurnal pattern in the distribution of median, minimum, maximum, and interquartile values for HD (row 3), albeit significant short-term variability (row 4). The data map in Fig. 13 provides a more complete overview of the diurnal and monthly variations in heat demand throughout the modelled period. Thermal loads are lowest in the summer months from July to August, around 13:00, which coincides with UKERC's definition of 'high summer' which is from 19/07 to 31/08 [46].

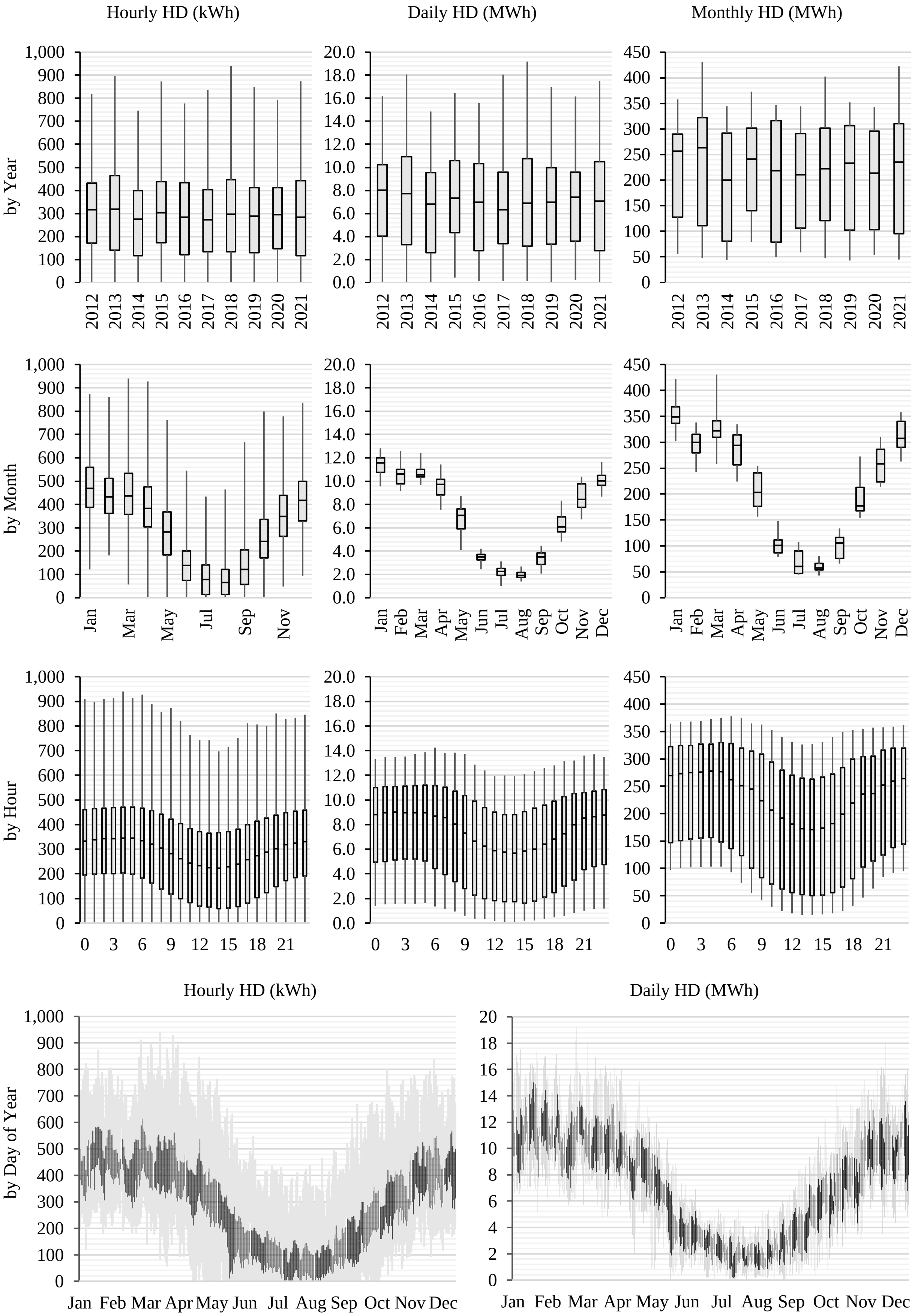


Fig. 12. Box plots of heat demand on Iona extrapolated from the 10-year timeseries of T_{out} between 2012 and 2021. HD given as mean hourly, daily, and monthly figures (across), by year, month, hour, and day of year (along). In the plots by day of year the dark grey areas represent values between the first and third percentile, with max and min values shown as light grey.

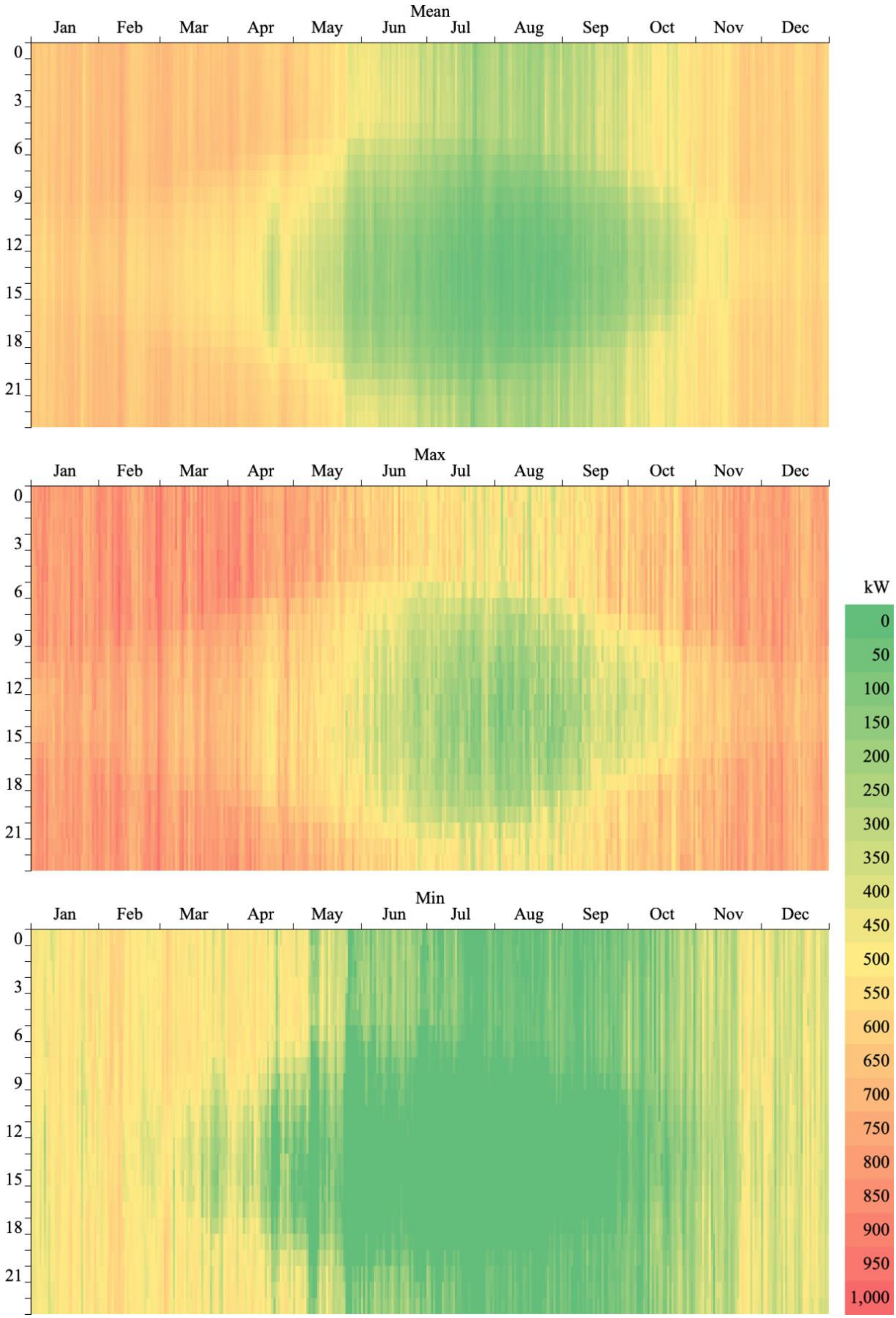


Fig. 13. Hourly mean, max and min total thermal load on Iona. Annual mean extrapolated values from 2012-2021 T_{out} timeseries.

4.4 Electricity Demand

The total annual electricity demand on Iona given in the 2015 Energy Audit was estimated at 1,824,590 kWh/year, comprised of 44.4% (835,000 kWh) domestic and 53.6% (1,044,590 kWh) non-domestic demand. The daily scaled annual average ED using the same figure is 4,999 kWh/day, with 2,288 kWh/day domestic and 2,862 kWh/day non-domestic loads. Thus, according to the Energy Audit, the average hourly electric load on Iona in 2014 for domestic load is 95.3 kW and for non-domestic load 119.2 kW, totalling an overall island electric load of 214.6 kW.

Domestic sector electricity demand shows more variability throughout the year, with much less prominent hourly maximums as those within the non-domestic sector. This is likely due to increased domestic electricity consumption toward the end of the day in winter when businesses are closed. The non-domestic demand shown on the right in Fig. 14 is likely not representative of demands on Iona, as they are based on UKERC load profiles for mainland businesses that have intense operation for specific daytime hours. Businesses on Iona are likely to have much more relaxed opening hours, as well as weekend operation for tourism.

All Sectors Mean Electric Load Profiles

TIME	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00:00	191	169	180	167	132	101	105	110	123	160	176	189
01:00	165	145	151	128	105	78	81	88	100	133	149	162
02:00	149	131	136	116	94	70	72	78	89	120	135	147
03:00	143	125	130	109	91	68	69	73	86	116	129	140
04:00	139	122	128	113	91	68	71	76	90	118	126	136
05:00	72	64	66	56	45	34	35	37	45	60	65	71
06:00	172	151	158	133	110	82	84	87	107	142	156	169
07:00	255	223	230	191	160	119	117	118	156	210	228	250
08:00	175	152	156	123	104	76	74	75	104	142	155	171
09:00	460	402	415	330	275	203	207	218	268	363	412	451
10:00	514	450	464	379	310	229	235	250	304	411	460	504
11:00	260	228	235	187	157	116	120	129	151	205	233	255
12:00	522	457	473	381	319	237	243	259	310	418	469	512
13:00	496	435	451	370	305	227	233	248	299	401	446	487
14:00	236	207	214	168	145	108	110	114	141	190	212	231
15:00	467	409	424	337	285	213	218	230	272	368	421	458
16:00	489	429	441	339	300	223	223	228	272	373	439	480
17:00	265	231	234	167	149	109	109	113	138	193	235	259
18:00	474	412	411	274	246	176	173	181	238	341	415	464
19:00	432	375	375	251	218	155	154	163	246	344	378	422
20:00	201	175	176	127	104	75	74	78	123	169	176	197
21:00	353	309	319	277	202	147	154	169	232	307	316	346
22:00	304	269	285	257	205	156	161	167	206	266	279	300
23:00	134	118	126	112	94	72	73	74	91	116	123	132

Domestic Mean Electric Load Profiles

TIME	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00:00	112	99	105	97	76	57	60	63	71	93	103	111
01:00	81	72	76	66	56	43	45	48	53	68	75	80
02:00	67	60	63	56	47	36	37	40	44	57	62	67
03:00	61	55	58	51	44	34	35	36	42	53	57	61
04:00	58	52	56	52	44	34	36	38	43	53	54	57
05:00	30	27	29	26	22	17	18	19	21	27	28	30
06:00	77	68	72	62	53	41	42	43	51	66	71	76
07:00	125	110	115	96	82	62	61	62	80	106	113	123
08:00	87	76	77	61	51	37	36	36	51	70	77	86
09:00	163	143	149	119	100	75	76	80	98	131	147	161
10:00	156	138	144	119	100	75	77	82	97	129	142	154
11:00	78	68	71	57	49	37	38	41	47	63	70	77
12:00	157	139	145	119	101	77	79	83	98	130	144	155
13:00	158	140	145	120	100	75	77	81	98	130	144	156
14:00	73	65	67	52	45	34	34	36	44	59	66	72
15:00	148	130	134	106	89	66	67	71	85	116	133	146
16:00	182	159	161	121	105	76	75	78	96	134	161	178
17:00	119	103	103	71	62	44	43	45	57	83	104	116
18:00	286	247	243	157	135	92	89	96	132	197	246	279
19:00	280	242	238	155	128	88	86	93	147	213	241	274
20:00	132	114	113	79	62	43	42	45	74	106	114	129
21:00	236	206	209	176	124	88	91	101	143	197	207	231
22:00	204	180	189	168	131	98	101	106	133	174	186	202
23:00	87	77	82	72	60	46	46	47	58	75	80	86

Non-Domestic Mean Electric Load Profiles

TIME	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00:00	79	70	75	70	56	43	45	47	52	67	73	78
01:00	84	73	75	62	49	36	37	40	47	65	74	82
02:00	82	72	73	60	47	34	35	38	45	63	72	80
03:00	81	71	72	58	46	34	34	36	45	62	71	79
04:00	81	70	72	61	47	34	35	38	47	65	71	79
05:00	42	37	37	30	24	17	17	19	24	33	37	41
06:00	95	83	85	70	57	42	42	44	55	76	85	93
07:00	130	113	116	95	78	57	56	57	76	105	115	127
08:00	87	76	78	62	53	39	39	39	53	72	78	85
09:00	297	259	266	211	174	128	130	138	170	232	265	290
10:00	358	312	320	260	210	154	158	169	207	282	318	350
11:00	183	159	164	129	108	79	82	88	104	142	163	179
12:00	364	318	328	262	217	161	164	175	212	288	325	357
13:00	337	295	305	250	205	152	157	166	202	271	303	331
14:00	162	142	147	116	100	74	76	79	97	130	146	159
15:00	318	279	290	231	197	147	151	159	188	252	287	312
16:00	308	270	280	217	195	147	147	150	177	238	278	302
17:00	146	128	131	95	88	66	66	67	80	110	131	143
18:00	188	165	169	117	111	83	83	85	106	145	169	184
19:00	152	133	137	97	89	67	68	70	99	130	137	149
20:00	69	61	63	48	42	32	32	33	49	63	63	68
21:00	117	104	111	101	78	60	63	68	88	111	108	115
22:00	99	88	96	89	74	57	60	61	74	92	93	98
23:00	47	41	44	40	34	26	27	27	33	41	43	46

Fig. 14. Monthly electric loads for all, domestic and non-domestic sectors on Iona, extrapolated from total 2014 annual ED, UKERC load profiles, and occupancy rates.

The electric loads modelled in Excel are only as good as the input profiles which the model was given. This is particularity apparent when comparing the ‘smoothness’ of the electric load profiles to thermal profiles which were extrapolated from hourly measurements instead of seasonal values (Fig. 15).

4.5 Homer Pro Model

The results given in this section are from Homer Pro, which was used to add random variability the extrapolated monthly load profiles, making the synthetic hourly output loads more realistic. The results from our Excel-based extrapolation model given in Fig. 15 are input into Homer Pro as monthly load profiles for domestic and non-domestic thermal and electric loads, along with their respective scaled annual average energy demands.

4.5.1 Input Load Data

Domestic Electricity Demand

Scaled Annual Average 2287.7 kWh/day

Weekday Load Profiles

TIME	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00:00	108	95	101	93	73	55	58	61	68	89	99	106
01:00	77	68	72	63	53	41	43	45	50	65	71	76
02:00	65	58	61	54	46	35	37	39	43	56	60	64
03:00	61	54	57	50	44	34	35	36	41	53	56	60
04:00	57	51	55	51	44	34	36	38	42	53	54	57
05:00	30	27	29	26	22	17	18	19	22	27	28	30
06:00	80	71	75	65	55	42	43	44	53	69	74	79
07:00	136	120	125	104	89	66	65	66	86	114	123	134
08:00	97	84	85	66	54	39	37	38	54	76	85	95
09:00	162	142	147	118	99	74	75	79	96	129	146	159
10:00	146	129	135	112	94	71	73	77	92	121	133	144
11:00	71	63	65	53	45	34	35	38	43	58	65	70
12:00	141	125	131	108	92	70	72	76	89	118	130	140
13:00	142	125	131	109	91	68	70	74	89	117	129	140
14:00	66	58	61	48	41	31	31	33	40	54	60	65
15:00	138	121	126	100	85	63	65	68	81	109	125	136
16:00	177	155	158	119	103	76	75	77	94	132	157	174
17:00	120	104	104	72	62	44	43	46	58	84	104	117
18:00	288	249	244	157	135	93	90	96	132	198	247	281
19:00	280	243	238	155	129	89	87	94	148	214	241	274
20:00	132	114	112	78	62	42	41	44	74	105	113	128
21:00	237	207	210	178	125	89	92	102	145	198	209	233
22:00	205	181	190	169	132	99	102	107	134	176	187	203
23:00	87	77	81	72	60	46	46	47	58	75	80	86

Weekend Load Profiles

TIME	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00:00	123	108	115	106	83	62	65	68	77	101	112	121
01:00	90	80	85	74	62	47	50	53	59	76	83	89
02:00	73	64	68	60	50	38	40	42	47	61	67	72
03:00	64	57	60	52	45	35	36	37	43	55	59	63
04:00	60	53	57	53	45	35	36	38	44	55	56	59
05:00	30	27	29	26	22	17	17	18	21	27	28	30
06:00	70	62	66	57	49	38	39	40	47	61	65	69
07:00	95	85	89	76	67	51	51	50	64	83	88	94
08:00	63	56	59	48	43	33	32	32	42	55	58	63
09:00	166	146	152	123	104	78	80	84	101	135	151	164
10:00	181	159	166	137	114	85	88	93	111	148	164	178
11:00	94	83	86	69	59	44	45	49	56	76	85	93
12:00	197	174	181	147	124	93	96	101	120	161	179	194
13:00	199	175	181	149	122	91	93	99	120	161	180	196
14:00	91	80	82	64	55	41	41	43	54	73	82	89
15:00	174	153	155	120	98	71	72	78	95	132	155	171
16:00	194	170	171	127	109	78	77	80	99	141	171	191
17:00	117	102	102	70	61	43	42	45	57	82	102	115
18:00	282	244	240	155	134	92	89	96	131	195	243	275
19:00	280	242	237	154	127	86	84	91	145	212	240	273
20:00	132	115	113	79	63	43	42	45	75	106	114	129
21:00	232	202	205	172	120	85	88	98	140	192	204	227
22:00	202	178	186	164	128	95	98	103	130	171	183	199
23:00	88	78	82	73	60	46	46	47	58	75	81	87

Non-Domestic Electricity Demand

Scaled Annual Average 2861.9 kWh/day

Weekday Load Profies

TIME	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00:00	79	70	74	70	55	42	44	46	51	67	73	77
01:00	84	73	74	61	48	34	36	39	46	64	74	82
02:00	82	71	72	60	46	33	34	37	44	62	72	80
03:00	81	70	72	58	46	33	33	36	44	62	71	79
04:00	81	71	72	61	47	34	35	38	47	65	71	79
05:00	43	37	38	31	24	17	17	19	24	33	37	42
06:00	100	87	89	73	59	43	43	46	58	79	89	98
07:00	144	125	128	103	85	61	60	61	83	114	127	141
08:00	100	87	89	71	60	44	43	43	60	82	89	98
09:00	351	306	314	247	203	149	151	159	198	272	312	344
10:00	420	366	375	303	244	178	182	195	241	330	373	411
11:00	214	187	191	150	124	91	94	102	121	166	190	209
12:00	429	375	385	307	253	186	190	203	247	337	382	420
13:00	401	350	361	295	241	178	183	195	237	320	358	392
14:00	193	169	175	137	118	88	89	93	115	155	174	189
15:00	381	334	346	275	233	174	178	188	223	300	343	373
16:00	367	322	333	259	232	175	175	178	210	284	331	360
17:00	173	152	156	113	103	77	77	80	95	130	155	170
18:00	211	185	189	130	123	91	91	93	117	161	189	207
19:00	162	142	146	102	94	70	70	73	104	138	146	159
20:00	74	65	67	51	44	33	34	34	51	67	67	72
21:00	121	107	115	104	80	61	65	70	91	114	112	120
22:00	101	90	97	91	75	58	61	62	75	93	95	100
23:00	47	42	45	40	34	26	27	27	33	42	44	47

Weekend Load Profiles

TIME	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00:00	80	71	77	73	59	46	48	50	55	70	75	79
01:00	85	75	77	64	52	38	40	43	50	67	76	84
02:00	82	72	74	62	49	36	37	40	47	65	73	81
03:00	81	71	72	59	48	35	35	38	46	63	72	79
04:00	80	69	71	61	47	34	35	38	47	64	71	78
05:00	40	35	36	30	23	17	17	19	23	32	36	39
06:00	84	73	76	63	52	38	39	41	50	68	75	82
07:00	95	83	87	73	62	46	46	46	60	80	86	93
08:00	55	48	50	41	36	28	27	27	36	47	50	54
09:00	160	141	148	120	103	78	80	83	100	131	146	157
10:00	201	176	183	151	125	94	96	102	123	164	181	197
11:00	104	91	95	77	65	49	51	55	63	84	94	102
12:00	202	177	185	151	128	97	99	105	124	165	183	198
13:00	180	158	166	139	116	88	91	96	114	150	164	177
14:00	85	75	78	62	54	41	42	44	53	70	77	83
15:00	163	143	150	122	106	81	83	87	101	132	149	160
16:00	160	140	146	114	103	78	78	79	93	125	145	157
17:00	78	68	71	52	48	36	37	37	44	60	70	76
18:00	131	115	119	85	82	63	63	64	78	104	119	128
19:00	125	110	115	83	78	60	61	62	87	111	114	123
20:00	58	51	54	42	37	29	29	29	43	55	53	57
21:00	106	94	101	93	72	56	59	63	82	101	98	104
22:00	96	85	92	86	71	55	58	59	71	88	90	95
23:00	45	40	43	39	34	26	27	27	32	41	42	45

Heat Demand

Domestic - Scaled Annual Average 6207.1 kWh/day
Non-Domestic - Scaled Annual Average 1066.9 kWh/day

Domestic Load Profiles

TIME	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00:00	451	427	456	418	282	148	103	91	140	254	347	396
01:00	450	427	460	425	286	152	106	94	142	258	351	396
02:00	450	428	461	427	289	155	109	95	144	261	352	395
03:00	452	430	462	432	292	157	109	96	145	265	352	398
04:00	453	430	467	436	294	157	110	96	149	268	354	398
05:00	455	431	468	439	290	147	106	96	147	269	355	400
06:00	455	431	473	431	259	125	87	89	148	270	357	401
07:00	455	433	469	391	229	109	70	69	137	270	355	400
08:00	456	432	446	352	208	93	57	51	110	254	356	402
09:00	454	421	413	322	191	81	46	39	88	220	346	404
10:00	441	399	388	301	174	69	38	28	72	191	322	394
11:00	426	381	368	281	160	61	30	21	62	174	299	377
12:00	414	369	355	267	149	54	25	16	57	165	288	364
13:00	408	362	344	256	142	51	22	13	52	158	286	358
14:00	409	360	341	252	139	50	21	14	50	160	289	361
15:00	414	365	344	252	140	49	22	15	54	168	300	371
16:00	426	373	351	258	144	52	25	17	60	182	319	386
17:00	437	390	369	272	153	58	27	21	73	208	335	392
18:00	441	409	394	294	167	66	35	30	92	236	338	394
19:00	445	416	426	328	185	77	44	44	117	247	339	396
20:00	447	418	438	369	214	93	59	65	128	250	340	396
21:00	448	420	443	388	248	118	80	79	135	252	344	395
22:00	449	422	449	400	263	136	93	85	138	254	344	397
23:00	451	425	452	408	271	143	98	88	142	256	347	395

Non-Domestic Load Profiles

TIME	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00:00	69	65	70	72	63	40	28	24	31	44	53	61
01:00	69	65	70	73	63	41	29	25	31	44	54	61
02:00	69	65	70	73	64	42	29	26	32	45	54	60
03:00	69	66	71	74	65	42	29	26	32	45	54	61
04:00	69	66	71	75	65	42	30	26	33	46	54	61
05:00	70	66	72	75	64	40	29	26	33	46	54	61
06:00	70	66	72	74	58	34	23	24	33	46	55	61
07:00	70	66	72	67	51	29	19	19	30	46	54	61
08:00	70	66	68	60	46	25	15	14	24	44	54	61
09:00	69	64	63	55	42	22	12	10	20	38	53	62
10:00	67	61	59	52	39	19	10	7	16	33	49	60
11:00	65	58	56	48	36	16	8	6	14	30	46	58
12:00	63	56	54	46	33	15	7	4	13	28	44	56
13:00	62	55	53	44	31	14	6	4	12	27	44	55
14:00	63	55	52	43	31	13	6	4	11	27	44	55
15:00	63	56	53	43	31	13	6	4	12	29	46	57
16:00	65	57	54	44	32	14	7	4	13	31	49	59
17:00	67	60	56	47	34	16	7	6	16	36	51	60
18:00	67	62	60	51	37	18	9	8	20	40	52	60
19:00	68	64	65	56	41	21	12	12	26	42	52	61
20:00	68	64	67	63	47	25	16	18	29	43	52	61
21:00	68	64	68	67	55	32	21	21	30	43	53	60
22:00	69	65	69	69	58	37	25	23	31	44	53	61
23:00	69	65	69	70	60	39	26	24	31	44	53	60

Fig. 15. Results output from our ED and HD model, giving Scaled Annual Average Demands (kWh/day) and monthly load profiles of electric and thermal loads for the domestic and non-domestic sectors on Iona. These are used in our Homer Pro model as input values to represent the thermal and electric loads in the domestic (#1) and non-domestic (#2) sectors.

4.5.2 Output Electric Loads

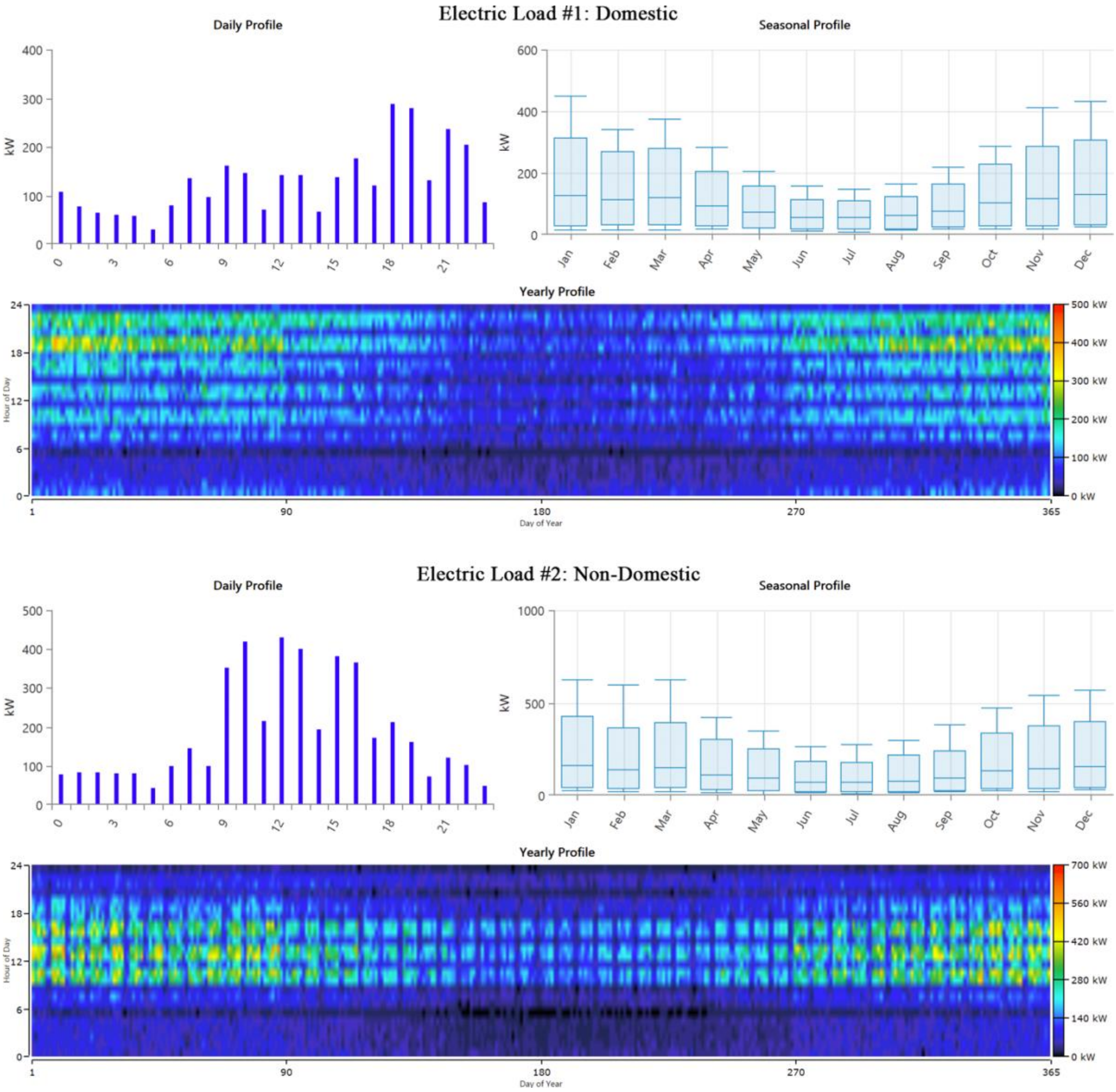


Fig. 16. Homer Pro model outputs for the domestic (#1) and non-domestic (#2) electric load on Iona, using respective Scaled Annual Average ED of 2,287.7 and 2,861.9 kWh/day. Both loads given parameters for 10% day-to-day and 20% timestep random variability. Mean daily electric load profiles are given in the top left of each load, with the seasonal profile on the right. The data maps (below) demonstrate the annual variability in hourly across along the modelled year.

The Homer Pro model provides a much more granular view of typical electric loads on Iona at an hourly resolution using the input annual average ED data and our extrapolated electric load profiles. Homer Pro simulates hourly loads by adding a random variability factor to the mean load to represent potential real-time load fluctuations. Fig. 16 illustrates how domestic electric loads have much more annual variability than non-domestic loads, which have less variability and a more prominent diurnal pattern which follows the opening and closing times of businesses. It is worth noting that the non-domestic load profiles for electric #2 are likely not very representative of actual loads on Iona as its small businesses operate around the community, which would result in higher weekend loads.

4.5.3 Output Thermal Loads

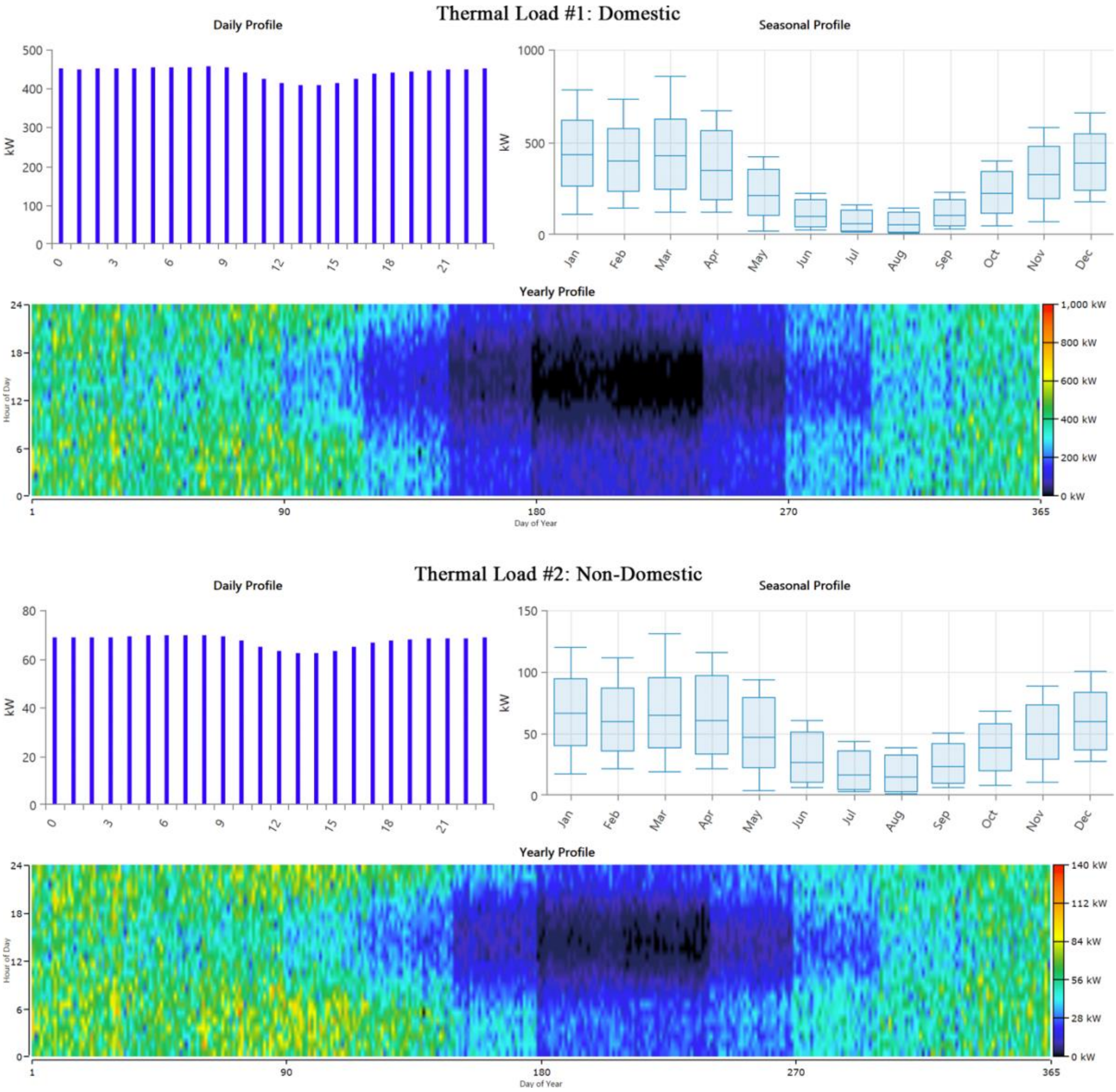


Fig. 17. Homer Pro model outputs for the domestic (#1) and non-domestic (#2) thermal load on Iona, using respective Scaled Annual Average HD of 6,207.1 and 1,066.9 kWh/day. Both loads given parameters for 10% day-to-day and 20% timestep random variability. Mean daily electric load profiles are given in the top left of each load, with the seasonal profile on the right. The data maps (below) demonstrate the annual variability in hourly across along the modelled year.

The thermal loads were also modelled using the default variability parameters. Our results in Fig. 17 show that thermal loads vary significantly more than electric loads across the modelled year. Domestic and non-domestic thermal loads show a very similar annual pattern, peaking in winter nights and reaching minimums as low as zero in summer from July to August near zero. Non-domestic thermal loads spend more time above zero than domestic loads in summer, which is most likely due to the higher occupancy factor within the non-domestic sector compared to the lower occupancy modelled for the domestic sector during this time of the year.

5. Resources on Iona

The available renewable resources on Iona include wind, solar, wave, tidal and potentially some limited hydroelectric from elevation differences on the island. Ambient air temperature is also given in this section as a resource, as it has been added to the Homer Pro model as an input resource, along with wind, solar DNI and solar GHI. Although wave and tidal power are significant resources on Iona, they are not added to the Homer Pro model, as the waters around the island are too shallow for any type of tidal turbines. Wave power on the other hand is not a sufficiently mature technology for this option to be explored in the context on Iona.

5.1 Wind

Wind is the most abundant renewable resource on Iona and thus has good potential for generating renewable electricity from an energy yield standpoint. Wind speed measurements from 2012 to 2021 were taken from the Tiree meteorological station, which is in a comparable island environment to Iona, were used to characterise the probable wind resource in Iona. Fig. 18 shows the frequency distribution of hourly mean wind speeds on the island, with wind speeds ranging from 0.0 m/s to 26.2 m/s with a median wind speed of 6.7 m/s. The wind speeds, measured at 10 m above the ground (9 m above sea level), are below a typical wind turbine cut-in speed of 3 m/s only 9.8% of the time, which does not consider the higher wind speeds at hub height. The interquartile range (mid 50%) of wind speeds lie between 4.6 m/s and 9.8 m/s.

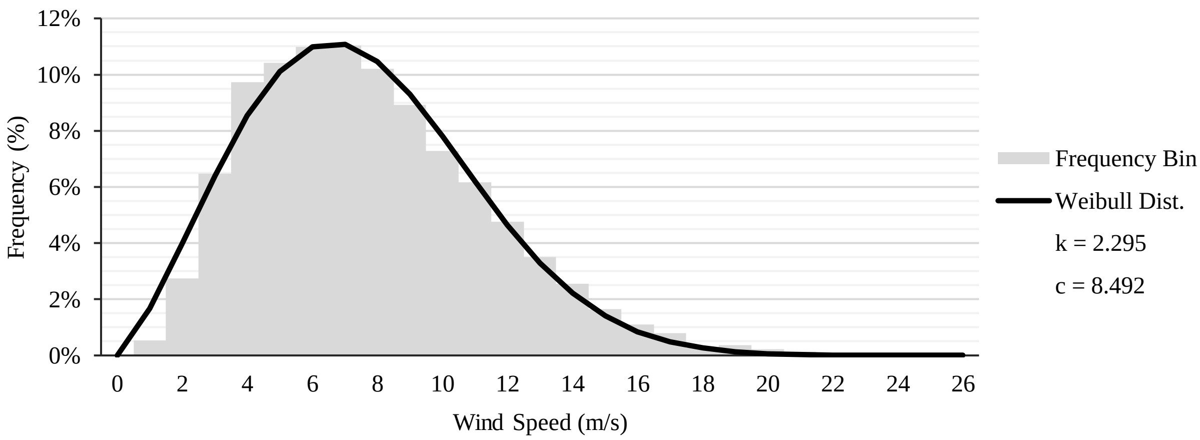


Fig. 18. Hourly mean wind speed frequency distribution in 1 m/s bins for Tiree meteorological station between 2012 and 2021, with best fit Weibull distribution using k = 2.295 and c = 8.492, showing high degree of correlation (R^2 = 0.99).

Using the above Weibull distribution to describe the wind speed distribution measured at Tiree, wind speeds are extrapolated up to hub height using power law exponents α = 1/7 and α = 0.36. Fig. 19 shows the output of the Homer Pro wind resource, with monthly averages from the Weibull distribution shown on the left. The power law extrapolation functions for α = 1/7 (top) and α = 0.36 (bottom) are shown on the right and are added as sensitivity variables in Homer Pro to extrapolate wind hub height wind speeds. The output power of any given wind turbine given by its power curve and is directly linked to wind speed according to the relationship given in (19).

$$\frac{v}{v_1} = \left[\frac{z}{z_1}\right]^{\alpha}$$

$$v_2 = v_1 \left[\frac{z_2}{z_1}\right]^{\alpha} \tag{19}$$

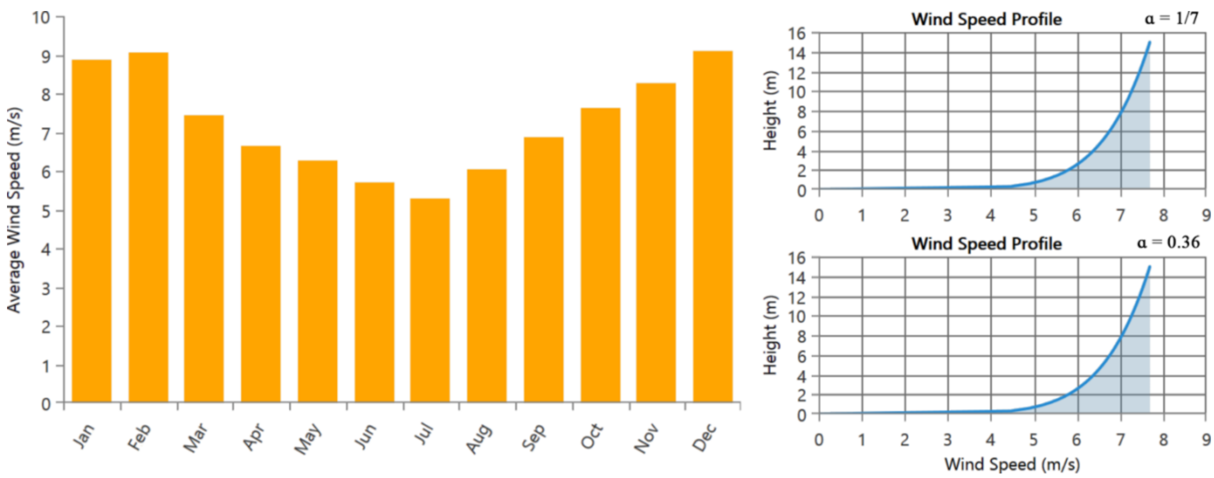


Fig. 19. Homer Pro output of mean monthly wind speeds on Iona (left), characterised by a Weibull distribution with $k = 2.295$ and $c = 8.492$. Right shows the power law functions for $\alpha = 1/7$ (above) and $\alpha = 0.36$ (below) used to extrapolate wind speeds to hub height for both sensitivity cases.

The base wind speed on Iona, represented using data from the Tiree meteorological station, reaches a mean monthly minimum of 5.3 m/s in July and a maximum of 9.1 m/s in December (Fig. 19: left). The diurnal variation in wind speeds is generally characterised with maximums in the night and minimums during the afternoon [62]. This characteristic of wind speeds makes it an ideal source of renewable energy, being particularly well-suited counteract the seasonal and diurnal variability in solar generation. Although wind speeds fluctuate significantly hour-by-hour and day-by-day, the long-term wind speed are quite consistent and reliable.

5.2 Solar

The solar resource on Iona is determined using mean hourly measurements of the solar DNI between 2012 and 2021 taken form the Tiree meteorological station, as well as by monthly solar GHI averages between 1983 and 2005 taken from NASA's POWER database [52]. As expected, solar irradiance peaks in summer around the summer solstice in June and reaches a minimum point in December (Fig. 20). DNI is the main solar resource on Iona with a scaled annual average of 2,728 kWh/m^2/day, compared to a negligible solar GHI of 2.8 kWh/m^2/day (Fig. 21).

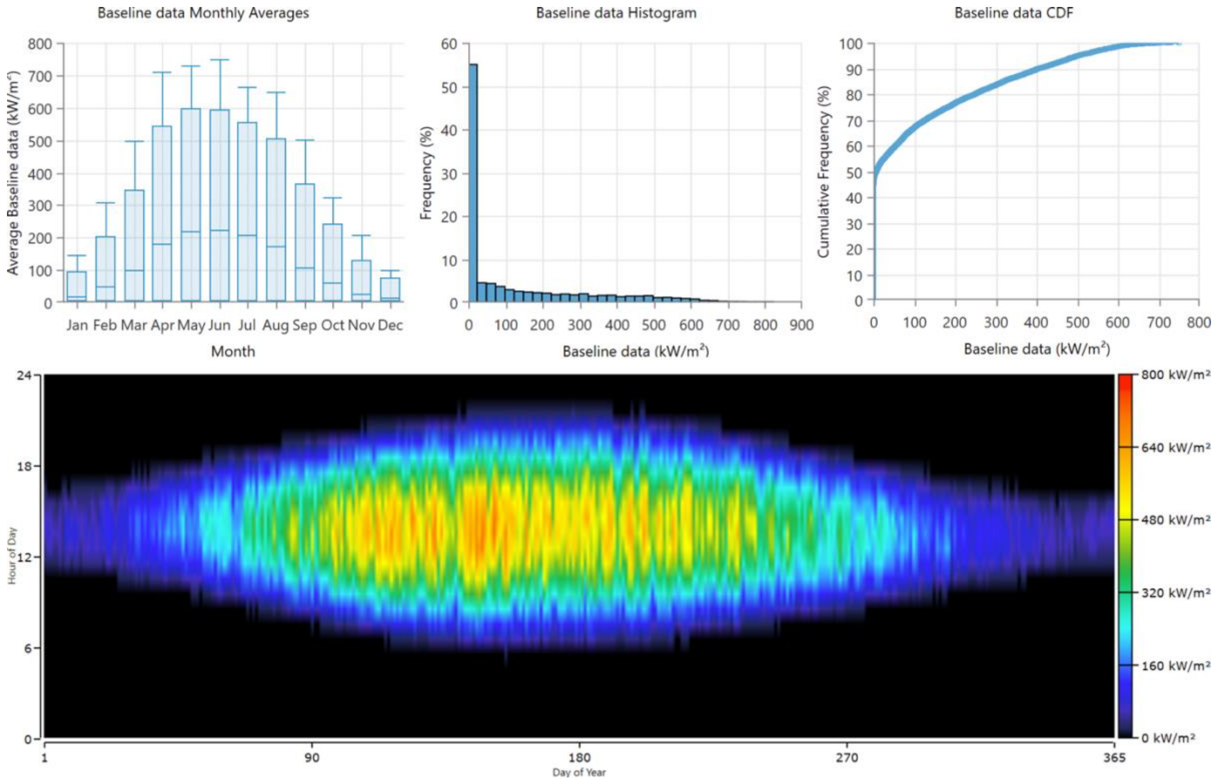


Fig. 20. Homer Pro output of solar DNI using Tiree meteorological station data from 2012 to 2021, with boxplots of monthly averages (top left), frequency distribution (top right) and a data map (bottom) covering the annual mean hourly DNI.

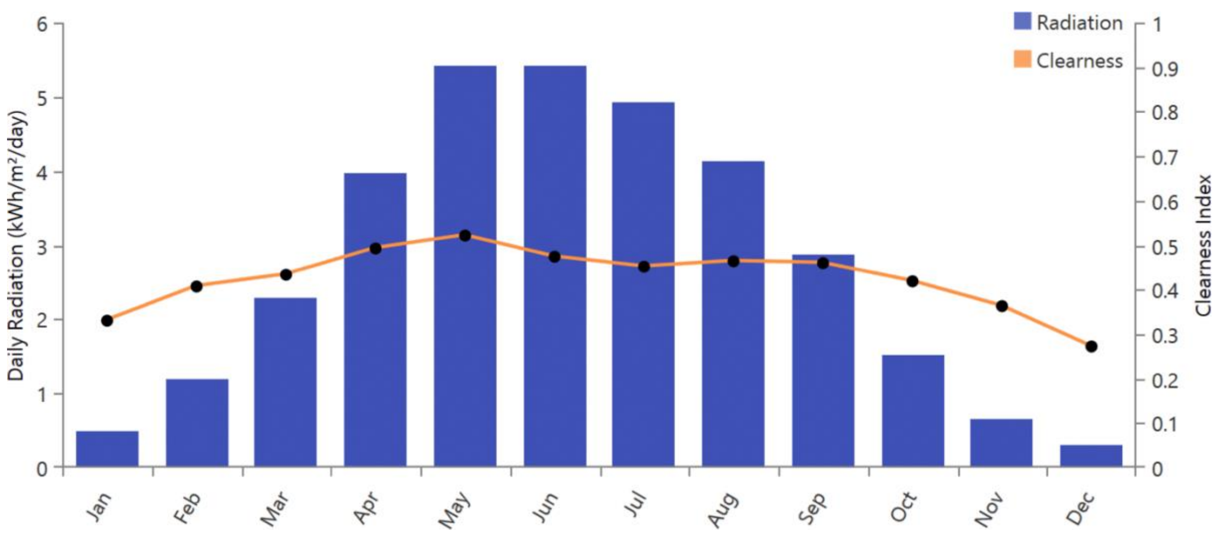


Fig. 21. Homer Pro output of monthly average solar GHI between 1983 and 2005 downloaded from POWER database [52].

At its highest, the average DNI delivers 5,312 kWh/m^2/day of incident solar energy to Iona. DNI reaches a low in December around the winter solstice, providing a daily average of merely 304.5 kWh/m^2/day of energy, which is 94.3% lower compared to summer. The hourly mean DNI peaks at around 750 kW/m^2, between 12:00 and 15:00 during summer, but spends most of the time (54.8%) at zero due to relatively long nights on Iona, shown by the dark areas in Fig. 20.

Whilst there is not much solar energy available on Iona due to the island's high latitude and meteorological conditions, the rapidly declining cost of PV cells, paired with increasing efficiencies make solar installations on Iona viable. The high diurnal and seasonal variability in solar resource means PV installations are best combines with energy storage. Additionally, solar generation tends to work well alongside wind generation as mean solar resource peaks when wind resource is at its lowest and vice-versa.

5.3 Hydroelectric

The potential for hydroelectric energy on the Isle of Iona is very limited. Whilst Iona is surrounded by an abundant tidal and resource, Iona sits on a shallow continental which is insufficiently deep for tidal turbines to be installed (Fig. 22). The maximum ocean depth between Finnphort and Baile is only 5.6 meters, with less than 10 meters of depth around the parameter of Iona.

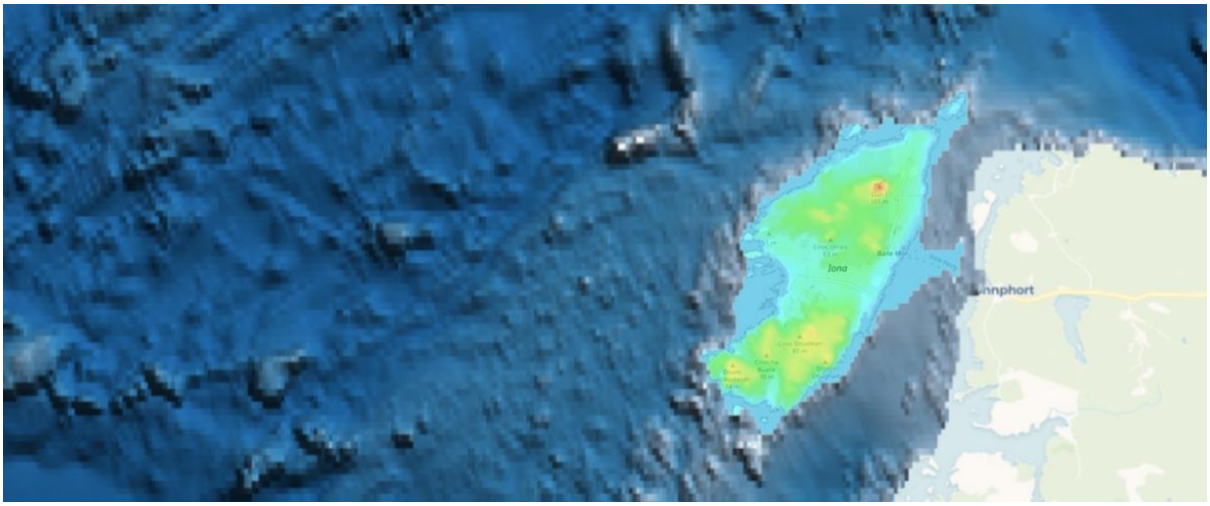


Fig. 22. Combination of ocean bathymetry map and a topographical elevation map of Iona. Adapted from [63] and [48].

Iona's topography, also shown in Fig. 22, illustrates how for the most part Iona is relatively flat with a single peak of 101 meters to the north where a hill named Dùn lies. Additionally, there are no catchment areas on the island to provide sufficient energy through the flow of running water. Thus, the only option for hydroelectric power on Iona would be though a pumped hydroelectric plant, although the lack of height differences on Iona gives the island a very low potential for hydroelectric power.

5.4 Ambient Air Temperature

In the 10-year timeseries of ambient air temperatures, Iona reaches a maximum hourly temperature of around 18°C. Average monthly temperatures peak at around 14°C in July and August, a monthly minimum of 5.7 °C in February (Fig. 23). Mean hourly temperatures on Iona never reach below freezing, which is ideal for ASHP systems as frost negatively effects the efficiency of the condenser units that form part of ASHP systems. However, whilst ambient air temperature shows good potential for ASHP systems, we do not add these to our Homer Pro model. Instead, the below temperature data is used by Homer Pro to determine the effect of temperature on various system components, including PV cells which suffer efficiency losses at high temperatures. The generally low temperatures found on Iona are thus ideal for solar installations, which should achieve higher production than they are rated at, as PV cell efficiency is measured at the standard test conditions temperature of 25°C.

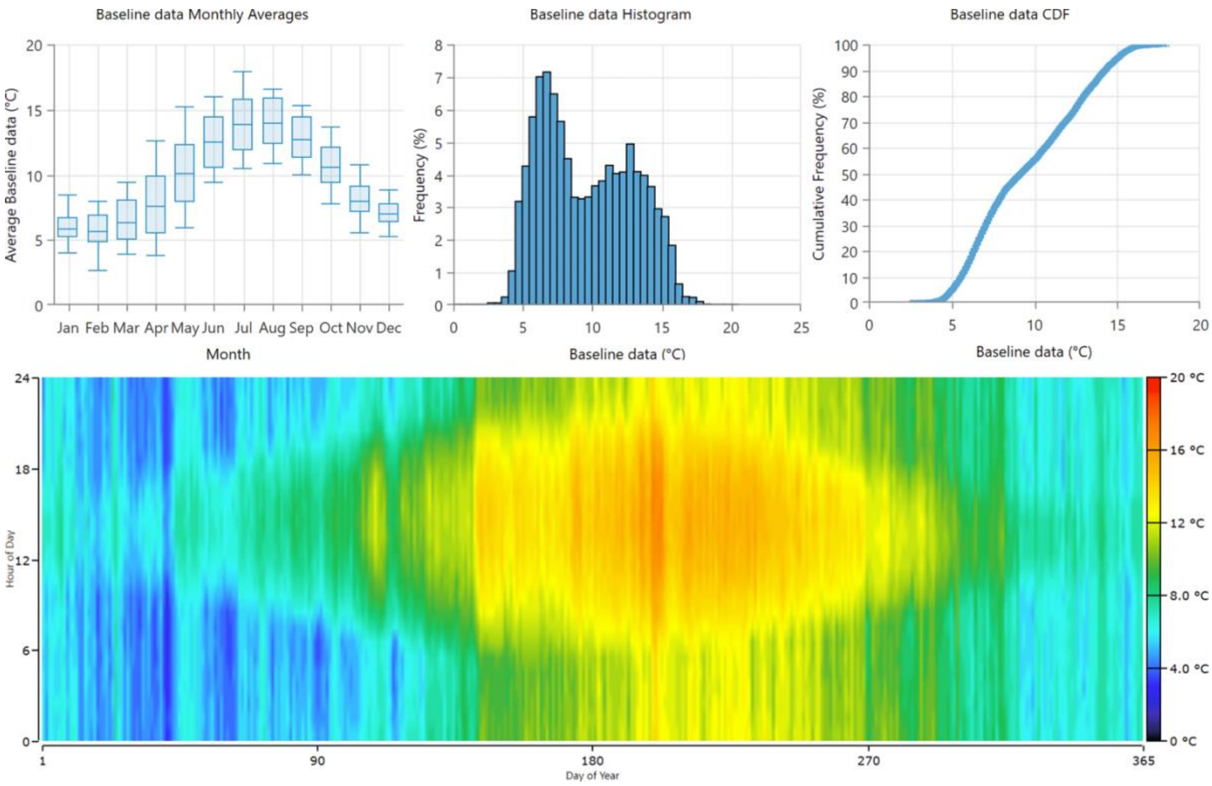


Fig. 23. Homer Pro output of solar DNI using Tiree meteorological station data from 2012 to 2021, with boxplots of monthly averages (top left), frequency distribution (top right) and a data map (bottom) covering the annual mean hourly DNI.

6. Case Studies

There are several examples of Scottish islands installing renewables generation and storage to form micro-grids, from grid-connected to off-grid systems with integrated battery autonomy. In recent years there has been a trend toward an increase in distributed renewable generation within these remote areas to improve the reliability of their local grids and reduce energy poverty, whilst reducing their fossil-fuel reliance. The Isle of Eigg in the Inner Hebrides was one of the first Scottish islands to successfully implemented a range of renewable energy technologies to overcome its main system constraints without connecting to the mainland electricity supply [63, 64]. Many other Scottish Isles have since followed the example set by Eigg to implement their own renewables-based micro-grids. The Isle of Canna, Muck and Fair Island are other key case studies of off-grid systems that have successfully followed Eigg's footsteps [65-67]. The systems employed on these islands use a range of wind, solar and hydro power, combined with battery storage and diesel back-up generation to ensure system reliability, without connecting to the mainland grid. The systems for these four case studies are summarised in Table 12.

Table 12
Summary of Case Study Island Systems

Isle	Wind	Solar	Hydro	Battery	Generator	Inverter	Details
Eigg [63, 64]	24 kW 4×6 kW Proven SD6	170 kW Array 1: 10 kW 60×BP Solar BP3165S Array 2: 22 kW 126×180 W BP Solar BP4180 Array 3: n/a	112 kW 1×100 kW 2×6 kW Head: 100m Length: 800	212 kWh 48 V 2242 Ah (10C) 4×24 Rolls Solar RB 4KS25PS	128 kW Diesel: 2×64 kW	Battery: 60 kW 12×5 kW Sunny Island SI-5048 Solar 1: 6×SMA Sunny Boy SB-3000 Solar 2: 3×SMC-7000HV Solar 3: n/a	Supply: 37 domestic and a few non-domestic buildings Generation excess used for community hall heating Autonomy: 24h
Canna [65]	36 kW 6×6 kW SD6	33 kW 128×270 W REC-270PE		225 kWh 96 V 1740 Ah (10C) 3×48 Rolls Solar 5000	60 kW Diesel: 1×60 kW or 1×60 kW	Battery: 54 kW 9×6 kW Sunny Island SI-80H-12 Solar: 2×20 kW SMA sunny Tripower	Supply: 15 domestic and a few non-domestic buildings
Muck [66]	30 kW 6×5 kW Evance R9000	33 kW 132×250 W		150 kWh 48 V 2242 Ah (10C) 3×24 Rolls Solar 4KS25PS	40 kW Diesel: 1×40 kW or 1×25 kW	Battery: 126 kW 9×SMA Sunny Island SI-5048 Wind: 6×SMA WB-5000A Solar: 6×SMA SMC-5000A	Supply: 38 residents 20 domestic and a few non-domestic buildings ED: 150kW/day

Fair Isle [68]	180 kW 3×60 kW Harbon H60	50 kW 192×270 W REC-270PE	588 kWh 48 V 1949 Ah (10C) 7×48 Rolls RB-2YS27PS	160 kW Diesel: 2×80 kW	Battery: 126 kW 21×6kW SMA Sunny Island SI-80H-12 Solar: 3×15 kW SMA Sunny Tripower	Supply: 55 residents

6.1 Common System Components

All four of the studied Scottish Isles make use of a combination of at least two sources of renewable energy, with wind and solar being used across all systems at varied capacities. Eigg is the only island that additionally makes use of hydropower generators to further diversify its energy generation sources.

6.1.1 Wind Generators

Horizontal Axis Wind Turbines (HAWT) turbines make up a significant proportion of the installed renewable capacity across all case studies, with a range of 3 to 6 turbines of 5 kW to 60 kW rated capacity. Fair Isle has the largest installed capacity of wind energy generation across the four islands, with a total of 180 kW, consisting of three 60 kW Harbon H60 HAWTs [68]. In terms of available renewable resources, wind generation is a great source of energy throughout the year. However, obtaining the planning permission to erect tall wind turbines can be challenging. It is likely for this reason that all the above islands use multiple smaller turbines as opposed to a large single turbine.

6.1.2 Solar PV Panels

Although solar DNI drops off significantly toward higher latitudes, solar PV installations are significant across all the above island systems. Whilst solar DNI is quite low in the Scottish Isles, solar PV cells are an affordable option to help reduce the overall variability in renewable generation. As discussed in Section 5, wind and solar resources have opposing annual and diurnal variability. Thus, implementing both technologies in an energy system, as done on the Isle of Eigg, Muck, Canna and Fair Isle helps mitigate renewable generation fluctuations.

6.1.3 Hydropower Generators

The only island using a hydropower generator is Eigg, with a total installed capacity of 112 kW [64]. Eigg has a favourable topography for hydroelectric power, with elevation differences of up to almost 400 meters [48]. The hydroelectric power plant on Eigg make use of a 100-meter difference in hydrological head over a length of 800 meters to drives its turbines. Hydroelectric power is much less suited for Muck, Canna and Fair Isle due to their respective maximum altitudes of 137, 201 and 217 meters [48], although small hydropower generators may be feasible. Hydropower for these three islands was likely not considered to planning restrictions.

6.1.4 Back-up Diesel Generators

As all four islands have off-grid systems, they all make use of at least one diesel back-up generator for cases when renewable generation cannot meet demand. However, the diesel back-up generators across all the case studies are used only minimally, with Eigg generating around 95% of its energy from renewables [68]. Data on back-up generator use is not available for all the islands, although Canna claims to use its generator less than 10% of the time [65]. The back-up diesel generators are required only to cover infrequent renewable energy generation deficits. By adding back-up generators to their systems, the renewable generators can be sized to meet only 95% of energy requirements and thus system components do not need to be oversized just to remain sufficient during the rarest 5% of climate conditions. This reduces the risk of system overload when renewable generation is unusually high, whilst also reducing costs. In many cases, diesel-generators are already installed on off-grid island systems, so keeping them around in a system based mostly on renewables adds little to no cost.

6.1.5 Battery Storage

As none of the four islands are connected to the national grid, they have no option to export any excess generation. Therefore, all the systems employ battery storage to manage the fluctuations in renewable generation and provide on-demand load power. Rolls lead-acid batteries are used for energy storage across all the studied islands, configured in both 48 and 96 V arrangements, ranging from 1740 to 2242 Ah with storage capacities of 150 to 588 kWh Table 12.

6.1.6 Inverters

Inverters are connected to each of the various renewable generators and batteries across all islands to convert the DC outputs from the batteries and the renewable generators into usable AC grid power. These are sized to match the various system components.

6.2 System Limitations

The limitations across all the island systems are similar given their comparable system components and off-grid nature. The main limitation of the systems is their reliance on diesel generators for back-up power when renewables generation is too low to meet demand. This occurs especially during the summer months when there may be prolonged periods of little wind generation, leading to gradual battery discharge [63]. Whilst solar generation helps in this regard, the drop-off in DNI in the evenings, when ED tends to be higher, means battery storage levels can quickly reach their maximum Depth of Discharge (DoD) of 50%. To avoid potential system overloads on the Isle of Eigg, all outlets connected to the micro-gird have been capped at 5 kW for domestic and small-business users, and 10 kW for larger businesses.

7. System Design Suggestions

7.1 System Components

The system components which were added to the Home Pro model for Iona are based on the renewable resources available on the Iona and the components used within the case study systems discussed in Section 6. It is worth noting that the resident population and thus the electricity demand on Iona is anywhere from four to eight times larger than the ED on the case study islands. Thus, we have sized system components for the Iona model accordingly. Our proposed system for which optimisation is run in Homer Pro, includes wind turbines, solar PV, lead acid batteries, a generic heating oil boiler, auto-sizing (model) inverters, and a limited grid connection (Fig. 24).

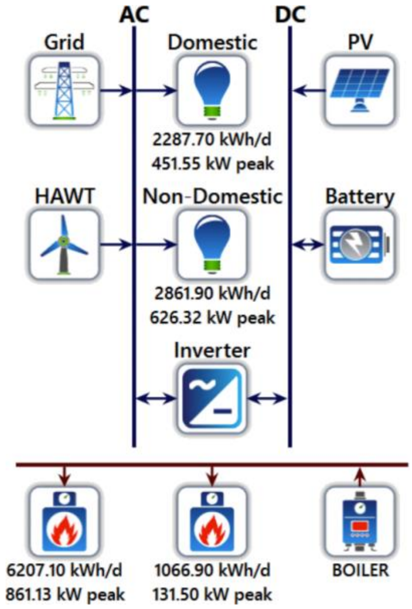


Fig. 24. Layout of system components used within the Homer Pro model for Iona.

Each system component is given an upper and lower limit within the Homer Optimizer to keep the system capacity and cost within reasonable limits.

7.1.1 Wind Generator

We have chosen the XANT M-21 100-kW HAWT for the system on Iona due to its high rated capacity for a hub height of only 23 meters. Having a low hub height helps reduce the visual impact of the turbine, as this has been suggested as one of the main limiting factors in receiving planning permission on Iona [14]. The turbine's power curve is well suited for wind speeds on Iona, with a cut-in speed of 3 m/s and cut-out speed of 20 m/s. Extrapolating the 99th percentile of wind speeds up to hub height using both a 1/7 and 0.36 power law exponent, gives max wind speeds of around 20 and 24 m/s respectively, which is within reasonable range of the XANT M-21 cut-out speed. The capital cost has been set to £350,000 per turbine, with a replacement cost of £300,000 and £2,000 per year of operation and management costs. A maximum of four turbines are optimised for, totalling 400 kW of installed capacity.

7.1.2 Solar PV

LONGi Solar LR6-60 flat plate PV panel are used in the Homer Pro model, having a rated power of 300 W each, with a 18.3% efficiency and 25-year lifespan. A very conservative capital cost of £300 per panel is set to also account for mounting structure, with a replacement cost of £150 as the mounting can be reused. Operation costs are set to £10 per panel.

7.1.3 Battery Storage

The Enersys PowerSafe OPzV 2000 lead-acid battery was chosen for our system model, being comparable to the batteries used across all the case study islands. Each battery has a capacity of 2110 Ah (10C) with a round trip efficiency of 95%, operates at a nominal voltage of 2 V, has 3070 Ah of maximum discharge current, and an operational life of 20 years. The cost is set to £1,200 per unit, with a £1,000 replacement cost, which is around 40% higher than retail to account for the added cost of delivery to Iona [69].

7.1.4 Other Components

Both the system inverter and heating oil boiler are set as generic auto-sizing components, with an inverter capital cost of £400 per kW of installed capacity and a replacement cost of £300. The boiler is given a fuel cost of 0.67 p/litre. The grid connection given a limited purchase capacity of 1,000 kW, an electricity cost of 24.0 p/kWh and a sellback rate of 3.5 p/kWh.

7.2 Optimal System Architecture

The winning system architecture using the input components and capacity ranges, comprises of 217 kW of PV, four XANT 100-kW wind turbines, 82 batteries (181.5 kWh) and 131 kW of inverter capacity. The system would require a capital investment of £1.82M, with a simple payback rate of 5.5 years or discounted rate of 6 years (Fig. 25).

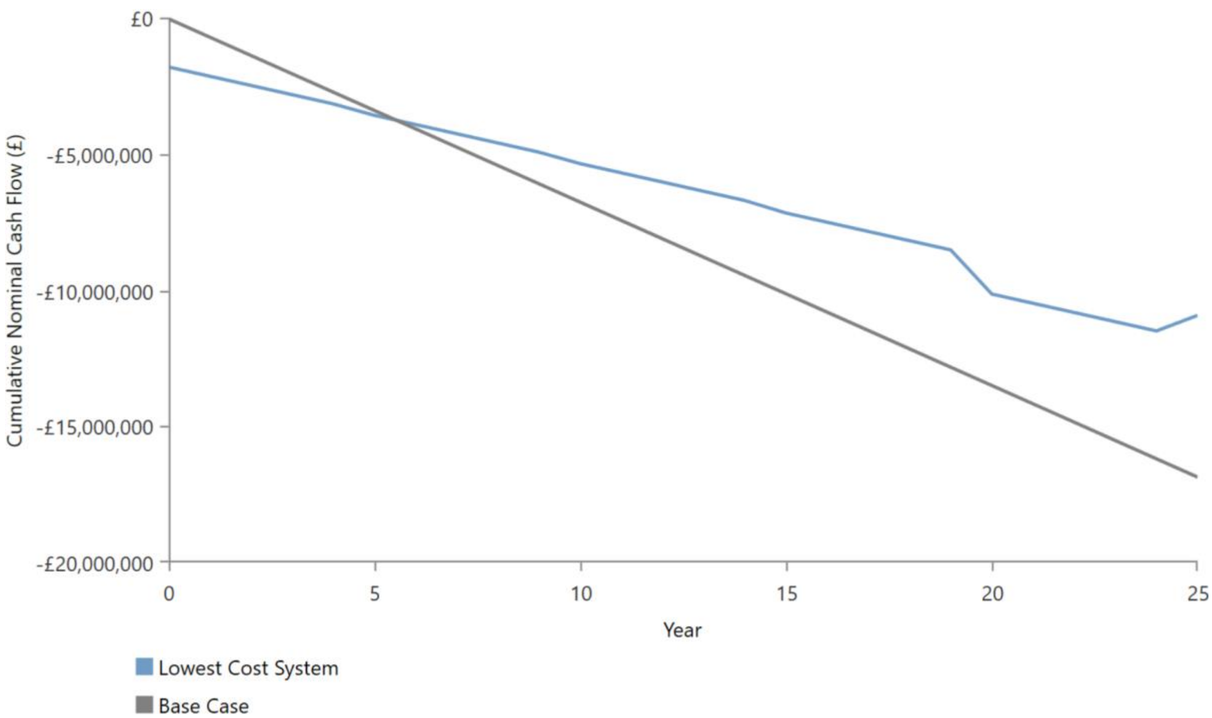


Fig. 25. Cumulative nominal cash flow of the optimised system (lowest cost) and the base case without renewables.

Homer Pro suggests increasing the maximum allowed capacity of both wind and solar PV generation as the optimal size of the systems is near their upper limit. Despite this, renewables penetration remains relatively high throughout the year with grid purchases making up only 20.5% of the total production. The HAWT produces by far the largest amount of electricity, with wind generation dropping off in summer, as solar generation increases (Fig. 26). In the optimal system architecture, 20.6% of generation is sold to the grid, which may be over the 50-kW export capacity threshold on Iona. More battery storage capacity could be added to the system to reduce the amount of electricity export, albeit whilst increasing system costs. However, the added system cost may be worthwhile as it more battery storage would also increase overall renewables penetration. Alternatively, excess generation could be used to heat communal buildings to avoid system overloads, as is the case on the Isle of Eigg.

Production	kWh/yr	%
LONGi Solar LR6-60	207,967	8.69
XANT M-21 [100kW]	1,695,112	70.9
Grid Purchases	489,277	20.5
Total	2,392,357	100

Consumption	kWh/yr	%
AC Primary Load	1,879,604	79.4
DC Primary Load	0	0
Deferrable Load	0	0
Grid Sales	486,244	20.6
Total	2,365,848	100

Quantity	kWh/yr	%
Excess Electricity	2,541	0.106
Unmet Electric Load	0	0
Capacity Shortage	0	0

Quantity	Value	Units
Renewable Fraction	37.4	%
Max. Renew. Penetration	1,244	%

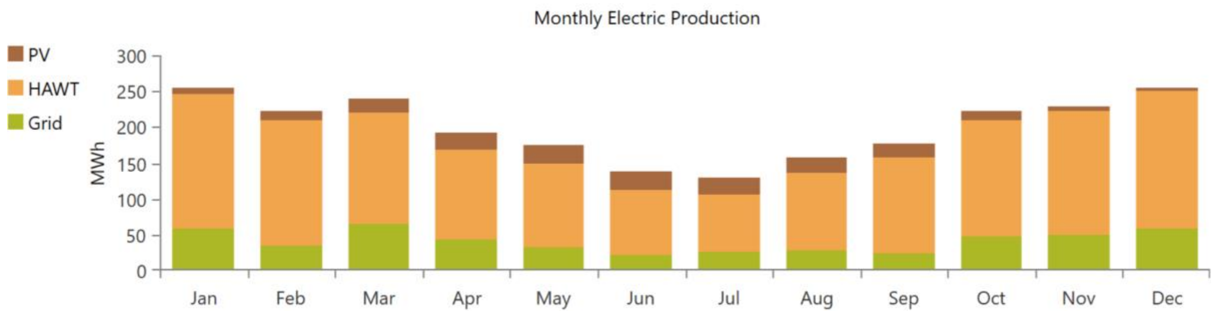


Fig. 26. Homer Pro electrical simulation results, showing the electricity production (below) from wind and solar, as well as grid electricity use. Key system data is given in the tables above.

The optimal system has a relatively small battery storage capacity compared to the case study islands, with an autonomy of only 1.7 hours (Fig. 27). However, as Iona is connected to the grid, the system does not require much battery autonomy to ensure loads are met. If battery storage were to be increased to reduce electricity exports, this would also result in longer battery autonomy.

Quantity	Value	Units
Batteries	82.0	qty.
String Size	1.00	batteries
Strings in Parallel	82.0	strings
Bus Voltage	2.00	V

Quantity	Value	Units
Autonomy	1.69	hr
Storage Wear Cost	0.149	£/kWh
Nominal Capacity	453	kWh
Usable Nominal Capacity	362	kWh
Lifetime Throughput	566,308	kWh
Expected Life	4.95	yr

Quantity	Value	Units
Average Energy Cost	0	£/kWh
Energy In	117,148	kWh/yr
Energy Out	111,487	kWh/yr
Storage Depletion	201	kWh/yr
Losses	5,863	kWh/yr
Annual Throughput	114,383	kWh/yr

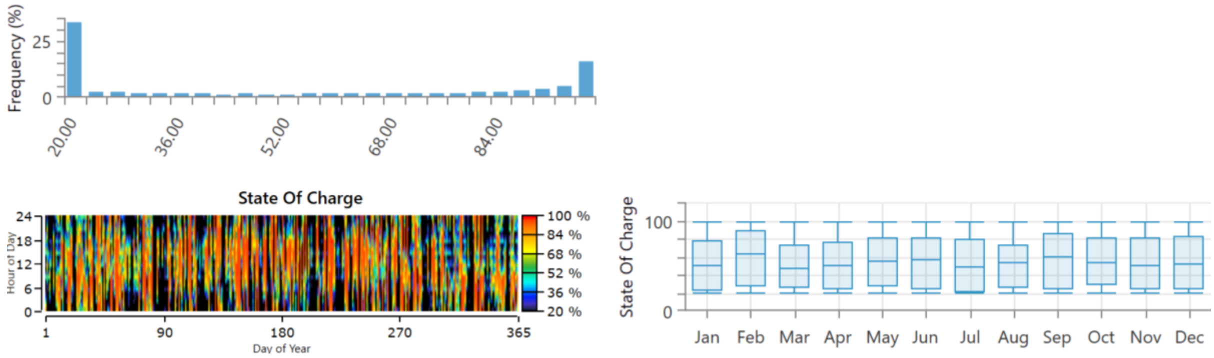


Fig. 27. Homer Pro simulation results for battery system use.

The expected life expectancy of the battery cells for the modelled system is only 5 years. The cell life could be prolonged by decreasing the maximum DoD of the batteries from 20% to 50% for example. With a maximum DoD of 50%, the Homer Pro model estimates the expected life of the batteries at 5.9 years, almost a full additional year, although this does change the resulting winning system architecture.

As our Homer Pro model uses a heating oil boiler to provide thermal loads on Iona, a significant amount of cash flow goes toward fuel costs every year, accounting for around 2/3 of the typical yearly cashflow (Fig. 28). After the initial up-front capital investment, the system operates at minimal cost for the remainder of its lifetime. Additional component replacement costs can be expected every 5 years for batteries, with the expected replacement of the wind turbines after 20 years.

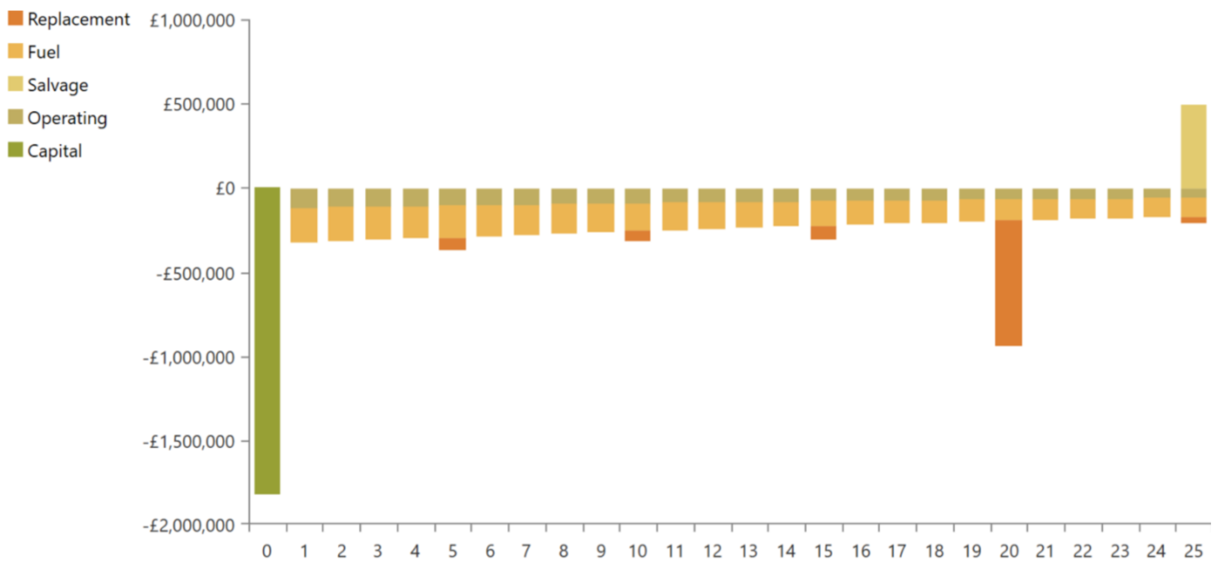


Fig. 28. Discounted cash flow for the winning system architecture given by our Homer Pro model, by type of cost.

8. Discussion and Conclusion

In this project we have developed models to extrapolate instantaneous energy loads from the total electricity and thermal demands of small energy systems, in terms of domestic and non-domestic demand. The methodology we have developed using both Excel and Homer Pro shows good promise for representing the energy demands of small island systems and determining their potential for the implementation of renewable energy.

To illustrate our methodology and demonstrate the functionality of our model, we apply it to the energy system on the small Scottish Isle of Iona. Our model shows promising results, being successfully used to determine a realistic optimal system architecture using a combination of renewable technologies, including wind turbine, solar PV panels and chemical battery storage. As there is no detailed energy data available for Iona, it is not possible to determine the precise accuracy of our model. However, given the reasonable outputs from our energy extrapolation process, we believe the outputs of our model are sufficient to be used for system planning applications. Our survey of the energy demand on Iona revealed that the main limitation of our model is in the detail and accuracy of the input data used. Additionally, as we use a top-down approach for energy demand extrapolation, our model cannot account for changes to the energy system or demand uses and users over time. This is a main drawback of top-down models, which can only use historic data to estimate future loads. In the case of Iona, the measured demand which is extrapolated and used in our Homer Pro model is quite outdated. Whilst energy systems do not change much year-over-year, there have likely been significant changes to the way energy is consumed on the Isle of Iona since 2014. For example, the heat demand which we model using figures of total fuel use is likely not very representative of today's energy demand on Iona, as an increase in heat pump systems replacing traditional fossil fuel-based heating would have shifted a portion of the modelled heat demand towards the electrical side.

Overall, our model more accurately represents short-term changes in thermal loads on Iona than electric loads, due to the use of hourly temperature measurements to determine thermal loads, whilst variations in electric loads are extrapolated from much less representative mean seasonal load profiles. Moreover, a portion of electric loads are used for heating, making electric loads somewhat temperature dependant. However, compared to thermal loads, electric loads output by our model only considers climate effects on electric loads through the use of mean seasonal load profiles where the effects of changes in climate are implicit. However, as the effect of climate on loads is proportional to the ratio between electric heating and appliance use, the difference in electricity uses between the housing stock used to measure the UKERC load profiles and the housing stock on Iona likely result in an under or over-representation of climate effects on electric loads. This can be overcome by using load profiles that are measured on the system being analysed or which are at the very least measured in a comparable energy system to the one being analysed.

Further work is needed to determine the actual accuracy of our model by applying our model to energy systems where load demands have been precisely measured. Only then would it be possible to compare modelled loads to actual loads to determine the error in our model. Our Excel model could be improved by adding bottom-up modelling to determine base temperatures which are more representative of the housing stock being analysed. This could be based on building EPC ratings or actual measurements of building heat losses to model the HDD index more accurately. Temperature-related electricity demand could also be added to the model by comparing the ratio between heating and appliances electricity uses and factoring in changes in heating demand on electrical loads. However, if climate-driven loads are integrated directly into the Excel model, electric load profiles would need to be appropriately adjusted to remove the climate-driven variability implicit in the load profiles.

In terms of the potential for implementing renewables into the energy system on Iona, our model determined that the optimal system configuration uses wind, solar and battery storage to achieve around 80% renewable penetration for a reasonable cost and return on investment. Whilst our Homer Pro model uses component sizes which are more likely to be granted planning permission in the future, current restrictions make it very difficult to implement any type of renewable generation on the island. However, as our model allows for flexibility, a system planner could easily apply our methodology in the future to determine the feasibility of renewables from a resources standpoint.

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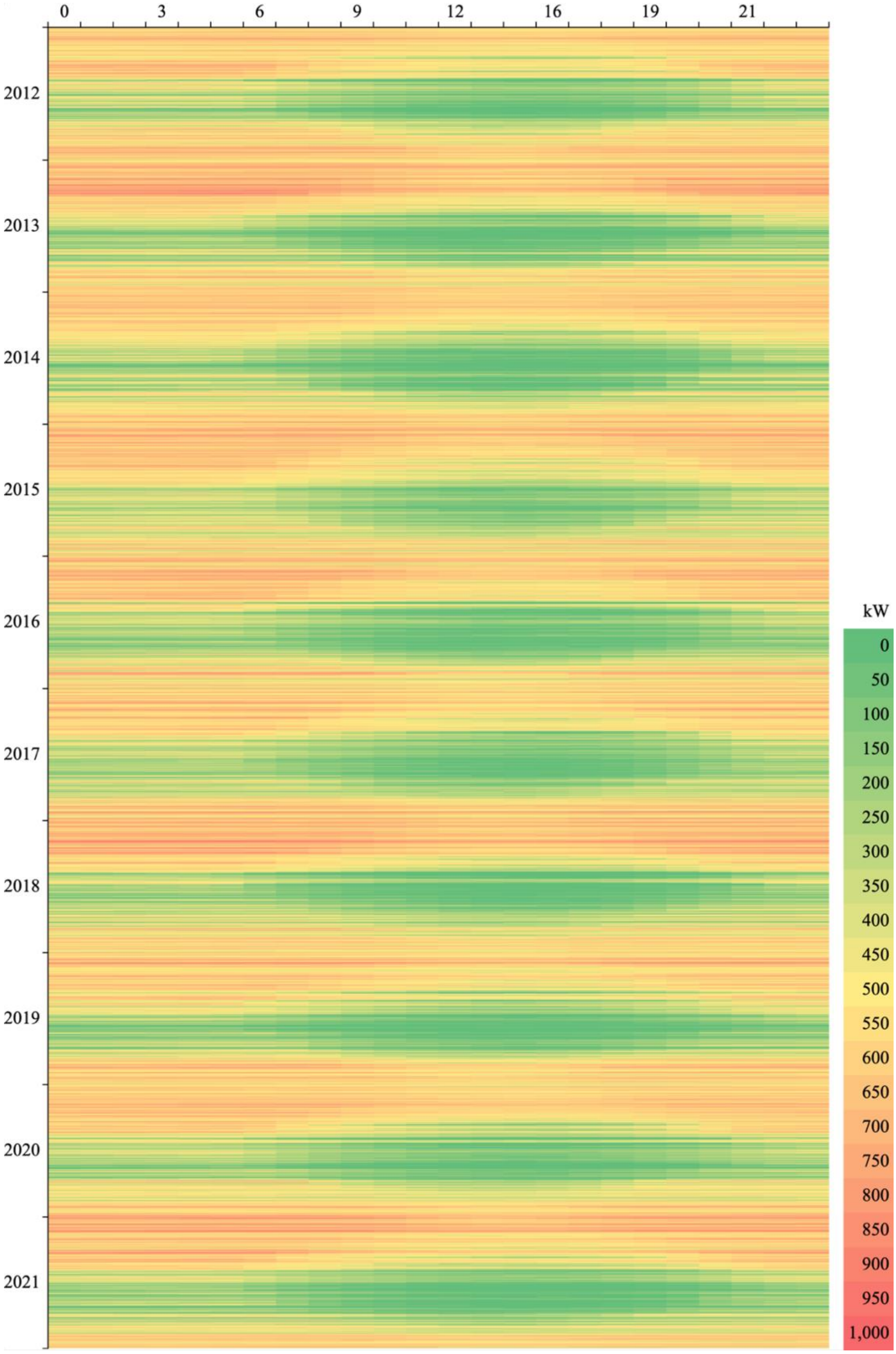
Appendices



Appendix 1. Extrapolated hourly thermal load for full T_{out} timeseries from 2012 to 2021.