Department of Mechanical and Aerospace Engineering

Investigating a Hybrid Solar Photovoltaic and Solar Thermal Energy System, Combined with Improved Load Management for the Loch Lomond and Trossachs National Park Headquarters

Author: Alexander McNally - 201659018
Supervisor: Mr Cameron Johnstone

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Signed: Date:25/8/2017

Abstract

This project looks at how the Loch Lomond and Trossachs National Park Authority (LLTNPA) could maximize the fraction of their energy demand that is met through renewable generation for their Balloch headquarters (HQ). To try and achieve this a hybrid Photovoltaic (PV) and solar thermal energy system was developed, taking load management into consideration.

A combination of onsite data collection and software simulation were carried out for the project. Through simulation it was discovered that maximum coverage of PV could reduce the electrical demand of the HQ building by approximately 25% following an initial investment of roughly £100,000. This would have a payback period of around 10 years. Once solar thermal was added to the computer modelling it was discovered that by installing approximately 50m^2 of evacuated tube collectors, and increasing onsite thermal storage that approximately half of the energy demand currently met by biomass could be met onsite by solar thermal.

To understand how the electrical generation compared to the electrical demand, a detailed high resolution electrical demand profile was created through partial onsite data collection and calculated estimation.

The project found that utilizing a hybrid system alongside improved load management reduced dependency on the electricity grid and reduced the amount of biomass fuel deliveries required.

The future work section concluded that it would be beneficial to model other combinations of renewable generation for a hybrid system alongside striving to improve load management as it is likely to become increasingly important in a future where buildings are required to be more energy efficient.

Acknowledgements

Thank you to all the staff at the Loch Lomond and Trossachs National Park for accommodating my project. I would like to extend a special thank you to the Facilities Manager, Paul Scullion, and his team who were extremely helpful in providing me with access to the site and essential information.

Thank you to my supervisor Cameron Johnstone for providing his guidance throughout.

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Finally, thank you to my family and friends who have provided endless support and taught me so much.

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Nomenclature

BREEAM	Building Research Establishment Environmental Assessment Method
HQ	Headquarters
LLTNP	Loch Lomond and Trossachs National Park
LLTNPA	Loch Lomond and Trossachs National Park Authority
SEPA	Scottish Environmental Protection Agency
SNH	Scottish Natural Heritage
PV	Photovoltaic

1. Introduction

This section describes what the Loch Lomond and Trossachs National Park Authority (LLTNPA) do, where the headquarters are located, information regarding the buildings design and construction, as well as the project aim and objectives.

1.1. LLTNPA

The LLTNPA are a government funded body who look after Scotland's first and largest national park. The park was established in 2002 with the park authority aiming to protect and enhance the Loch Lomond and Trossachs National Park (LLTNP). A critical role of the LLTNPA is to minimize damage caused by the year-round influx of visitors. The LLTNPA focus on conservation, visitor experience and rural development. (*What we do | Park Authority | - Loch Lomond & The Trossachs National Park*, 2017)

Figure 1 LLTNPA Headquarters in Balloch (*Page\Park - Projects - Loch Lomond and Trossachs National Park Headquarters*, no date a)

1.2. Location

The LLTNPA headquarters are situated in Balloch, a village on the south-western shores of Loch Lomond. The building accommodates 130 staff, including staff from Scottish Natural Heritage (SNH) and staff from the Scottish Environmental Protection Agency (SEPA). (*Urban Realm, Carrochan, Loch Lomond and the Trossachs National Park HQ.*, 2009)

Figure 3 Location of the LLTNP within Scotland (*Scotland - Google Maps*, 2017)

Figure 2 Map Showing Location of LLTNPA HQ within the LLTNP (*Balloch - Google Maps*, 2017)

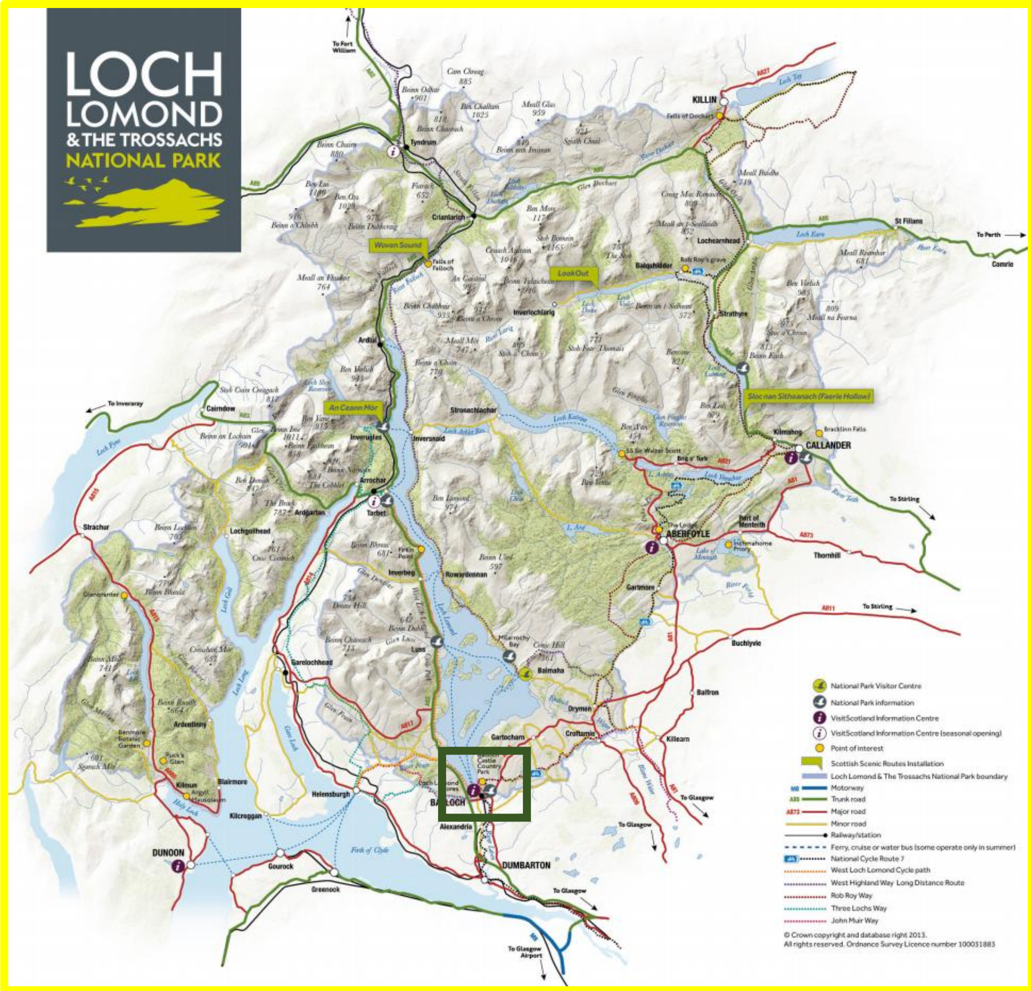


Figure 4 Map of Loch Lomond and Trossachs National Park (*LLTNP*, 2013)

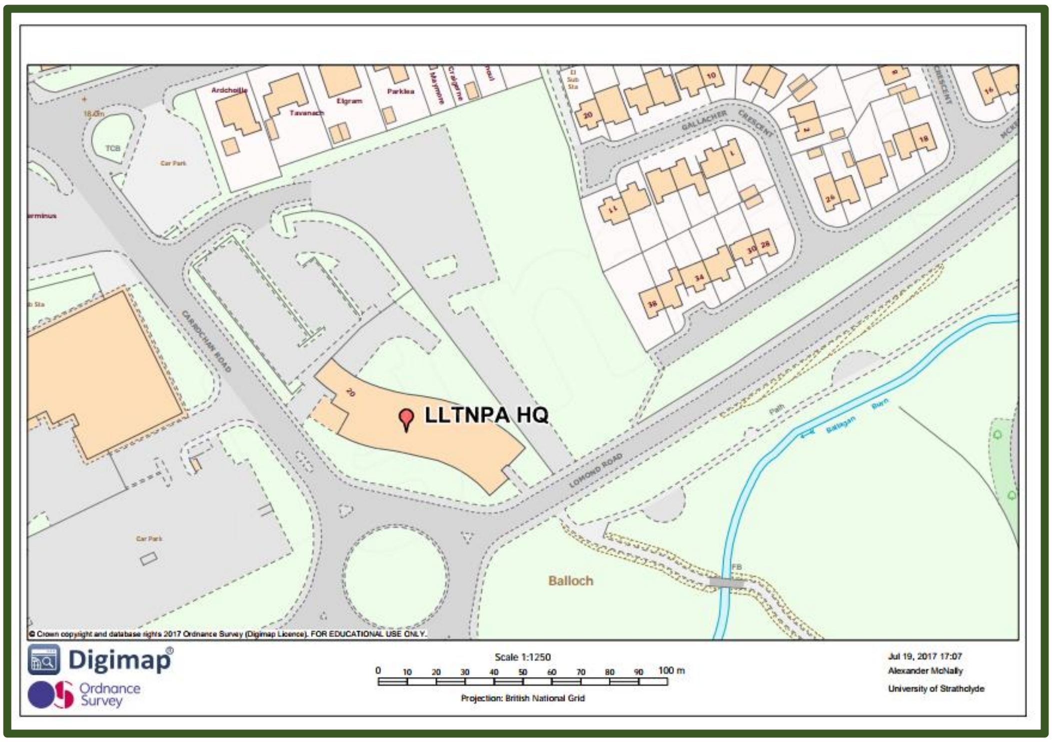


Figure 5 Ordnance Survey Map of LLTNPA HQ and Surrounding Properties

1.3. Building Design

The building is designed to maximize the use of natural daylight and 80% of the building is naturally ventilated with the 20% that is mechanically ventilated, done so using fans with low power consumption. The building is curved to compliment it's setting next to a roundabout and takes the form of 2 parallel, extruded gable forms which have a naturally lit 'street' between which provides access to various office spaces within the building.(*Urban Realm, Carrochan, Loch Lomond and the Trossachs National Park HQ.*, 2009)

1.3.1. BREAAM Standards

BREEAM (Building Research Establishment Environmental Assessment Method) is a sustainability rating scheme considered when planning projects, infrastructure and buildings. BREEAM aims to address challenges such as energy generation and consumption, materials used, management, land use, innovation, health and wellbeing to other key issues such as pollution, transport, waste and water.

As BREEAM standards were adhered to during the design and construction of the LLTNPA HQ, the integration of renewable generation onsite will be less challenging.(*BREEAM*, 2017)

The LLTNPA HQ have a BREEAM rating of 'Excellent' positioning the building within the top 10% of UK new non-domestic buildings, see Table 1.

Table 1 BREEAM Ratings

Outstanding	Less than top 1% of UK new non-domestic buildings (innovator)
Excellent	Top 10% of UK new non-domestic buildings (best practice)
Very Good	Top 25% of UK new non-domestic buildings (advanced good practice)
Good	Top 50% of UK new non-domestic buildings (intermediate good practice)
Pass	Top 75% of UK new non-domestic buildings (standard good practice)

1.4. Building Construction

The headquarters has a timber frame, constructed with locally sourced, green douglas fir. The outer envelope of the building consists of a traditional slate roof, Scottish larch cladding and natural stone walls. Internally, sheep wool is used for insulation.

Figure 6 The buildings timber frame during construction.(*Page\Park*, no date)

1.5. Overall Approach

Introduction

The introduction sets the context of the project, provides basic information regarding the building and contains the project aim and objectives.

Literature review

As a hybrid renewables system consisting of PV and solar thermal was being explored, the literature review contains material on these technologies and reasons as to why they were scoped into the project. Explanation as to why other popular renewable technologies were scoped out of the project are also provided. Various modelling software was used for the project therefore an overview of software is present in the literature review along with explanations as to why each was chosen.

Resource Assessment

This section looks at daily and annual site specific global horizontal irradiance, suitable areas for mounting solar technologies, average temperatures and wind speeds.

Methodology

Data Collection

To start with, the methodology explains how the data required for the project was collected.

Modelling

Details are then provided regarding the various modelling software that were applied, simulations that were run and any assumptions made to do so.

Load Management

Information on how a high-resolution demand profile was created through onsite data collection are then given.

Results

The results section firstly presents the results obtained from PV modelling using, PV*SOL, the solar thermal sizing using, T*Sol, and then the results of modelling a hybrid PV/solar thermal system using energyPRO.

A high resolution daily demand profile developed is presented, followed by a proposal for an improved daily demand profile that utilizes load management to maximize the amount of renewable generation utilized onsite instead of being exported to the grid.

Discussion

The discussion identifies key decisions made throughout the whole process and the key findings of the project. This includes economic analysis, incentives for deployment, barriers to deployment and environmental considerations.

Conclusion

This section refers back to the overall aim and objectives of the project.

Further work

This section describes how the project could be advanced regarding research into hybrid renewable systems in combination with intelligent load management.

1.6. Aim

This project is focused on the Loch Lomond and Trossachs National Park Authority (LLTNPA) headquarters building. The project aims to identify what proportion of the buildings energy demand can be met using a hybrid solar photovoltaic and solar thermal energy system. Furthermore, the project aims to look at the impact that combining such a system with improved load management would have.

1.7. Objectives

- Data collection to determine the current energy usage of the LLTNP headquarters.
- Site and location survey to determine most suitable types of renewable generation to scope into the project.
- Determine what fraction of the energy demand could be met through onsite hybrid renewable energy generation.
- Financial analysis to determine approximately how much such a system would cost to implement, annual savings and payback period.
- Produce a daily demand profile for the headquarters.
- Identify loads that could be shifted/energy saving measures that would allow a greater proportion of the headquarters energy demand to be met by renewables.

2. Literature Review

The literature review focuses on PV and solar thermal. These 2 renewables were deemed to be the most suitable for the LLTNPA headquarters. Reasons for which other renewable generation technologies were scoped out for this project are described in their respective sections.

2.1. Photovoltaics

Photovoltaic materials can convert solar energy to electrical energy. Light is collected using modules of photovoltaic cells and due to the photovoltaic material properties each cell has the ability to absorb photons of light and emit electrons. (*Science Mission Directorate*, no date) (Knier, 2008)

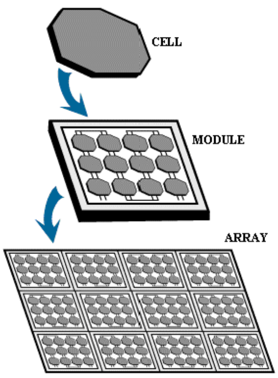


Figure 7 Breakdown of a PV array (Science Mission Directorate, no date)

Solar energy breaks certain bonds in a semiconductor allowing parted electrons and bonds that are missing electrons to flow through p or n-type layers. A field occurs between these 2 layers and with the aid of electrical contacts electrons can flow from the n-type layer to the p-type layer. This induced current from multiple cells in series is then stored or used directly to power loads.(*PV technical summary | Wattcraft*, no date)

PV panels are often featured in microgrid systems, operating in parallel to the main grid or disconnected from the main grid in “island” mode.

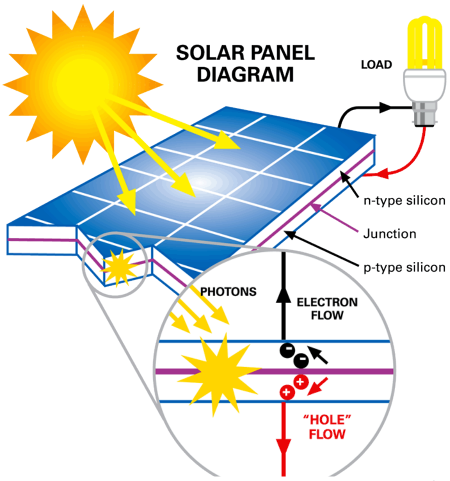


Figure 8 Solar Panel Diagram (Past, Present, and Future of Solar Energy, no date)

There are many variables that influence the power output achieved from photovoltaic systems which include things such as the tilt angle, location, time of year, orientation, ambient temperature and materials.

2.1.1. Tilt angle and Location

PV panel tilt angle impacts the power output with the optimal tilt angle dependent on location and time of year. At the equator, the optimal tilt angle is zero degrees to the horizontal. Figure 9 shows how this angle varies north and south of the equator.

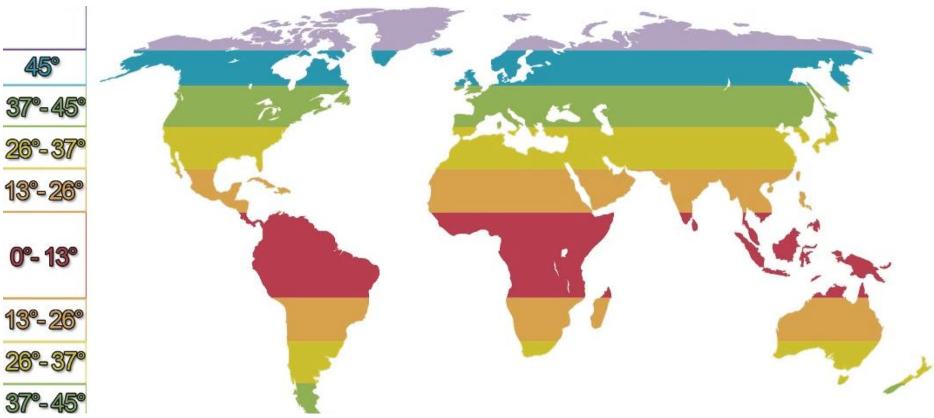


Figure 9 Optimal Angle for Fixed PV Panels Depending on Location(How to find the Best solar panel angle or tilt angle - Solar Panels Photovoltaic, no date)

Away from the equator in the winter, when the sun is lower in the sky, the optimal tilt angle is increased relative to horizontal. Vice versa, in summer months the optimal tilt angle relative to the horizontal is shallower. See

Figure 10 and Figure 11 below which show seasonal tilt angles and optimal tilt angles throughout the year depending on latitude.

Figure 10 Seasonal Solar Tilt Angles (*How to Power Your Home with Solar: Solar Array Tilt Angles* -, no date)

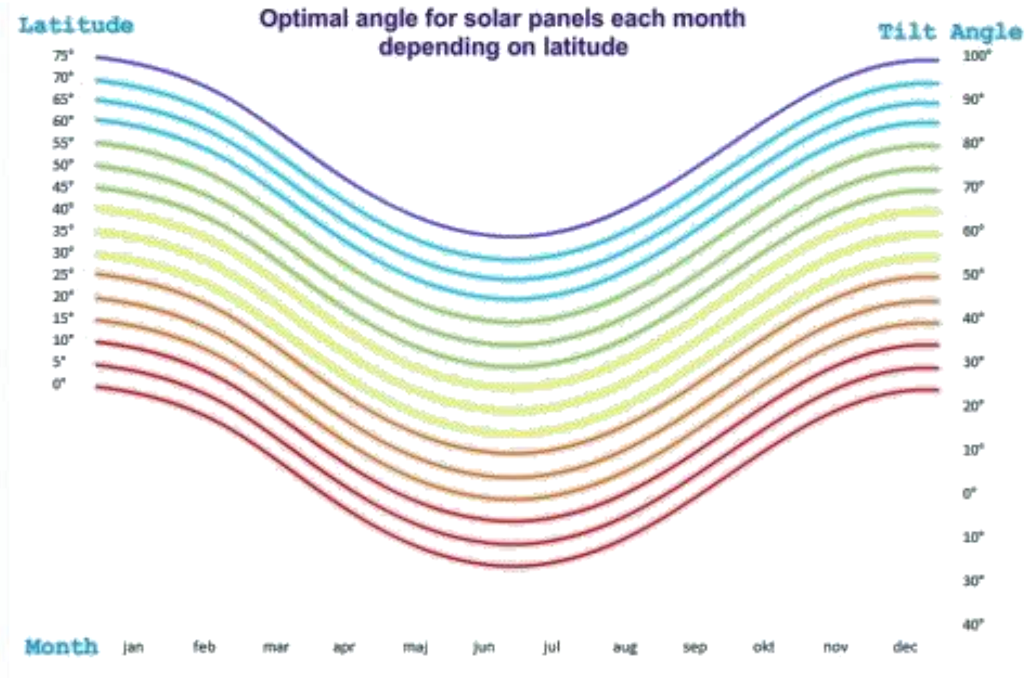


Figure 11 Optimal tilt angle for fixed PV panels for different locations (*Tilt angle: optimizing solar yield | freesolaraudit.com*, no date)

2.1.2. Seasonal Impact

Solar irradiance varies significantly throughout the year as illustrated by Figure 12, 2016 solar Global horizontal irradiance levels for Balloch, obtained from HOMER Energy. (*Solar photovoltaic output depends on orientation, tilt, and tracking - Today in Energy - U.S. Energy Information Administration (EIA)*, no date)

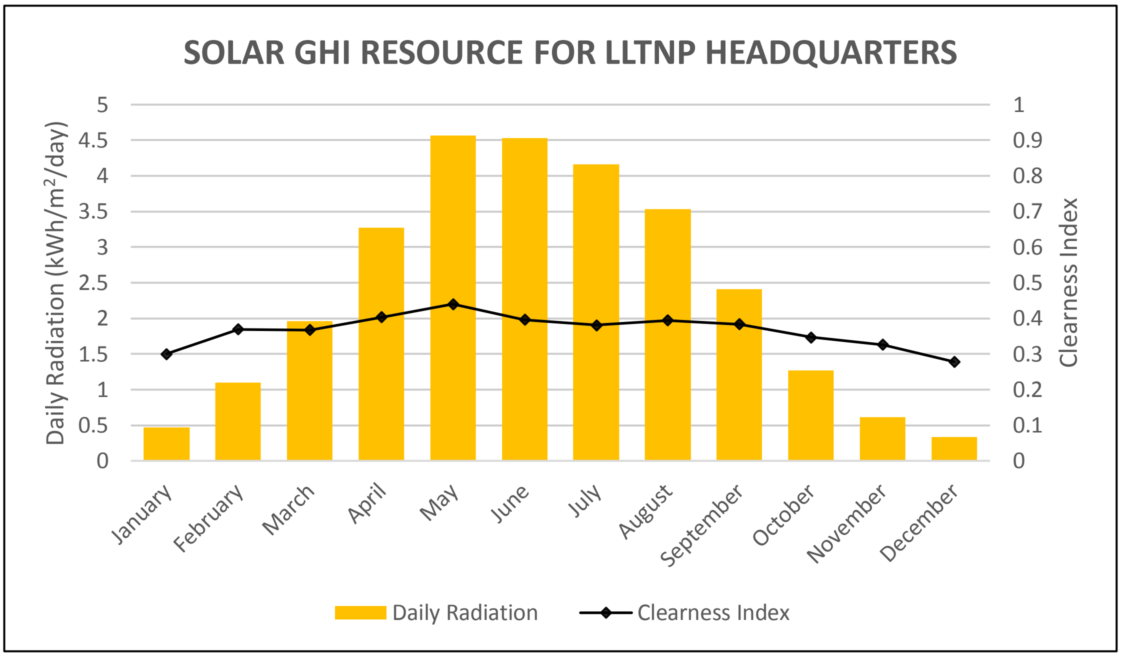


Figure 12 Solar GHI Resource for LLTNP HQ

In the current-voltage plot in Figure 13 it can be observed that the power output is significantly higher for higher values of solar irradiance. However, an increase in solar irradiance results in an increase in temperature which decreases the efficiency of a solar cell. Therefore, to utilise the greatest quantity of solar irradiance measures must be taken to optimise the operating temperature. See section 2.1.4. regarding the impact of temperature on PV cells.

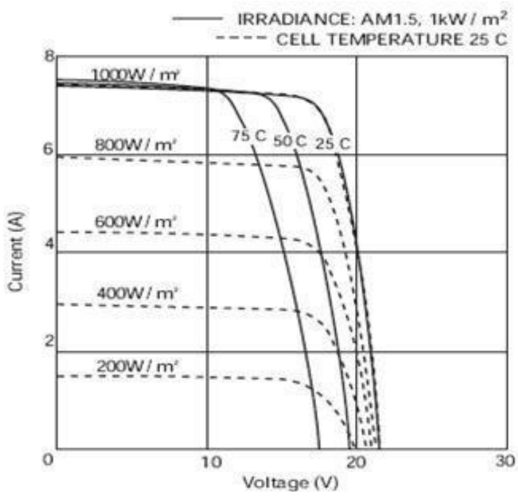


Figure 13 I-V (Current-Voltage) Curve (*Electrical Characteristics of Solar Panels (PV Modules) | altE*, no date)

2.1.2. Orientation

The highest power can be achieved through a tilting PV mount that follows the sun from East to West. Realistically most PV panels have fixed mounts and as a result are orientated south to maximise the yield throughout the day. This is represented Figure 15 below that show power output over time for PV panels facing various azimuths.

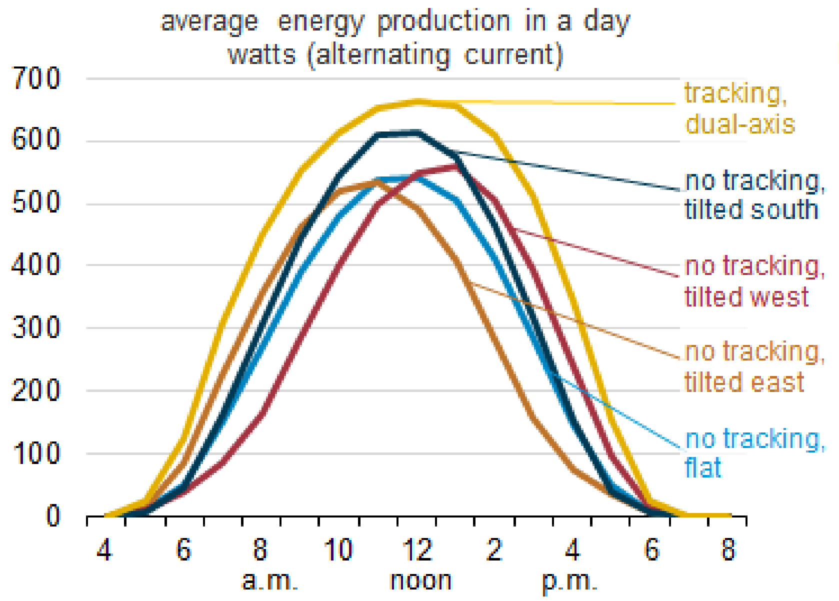


Figure 15 Average Energy Production in a Day for Various Orientations (U.S. Energy Information Administration (EIA), 2014)

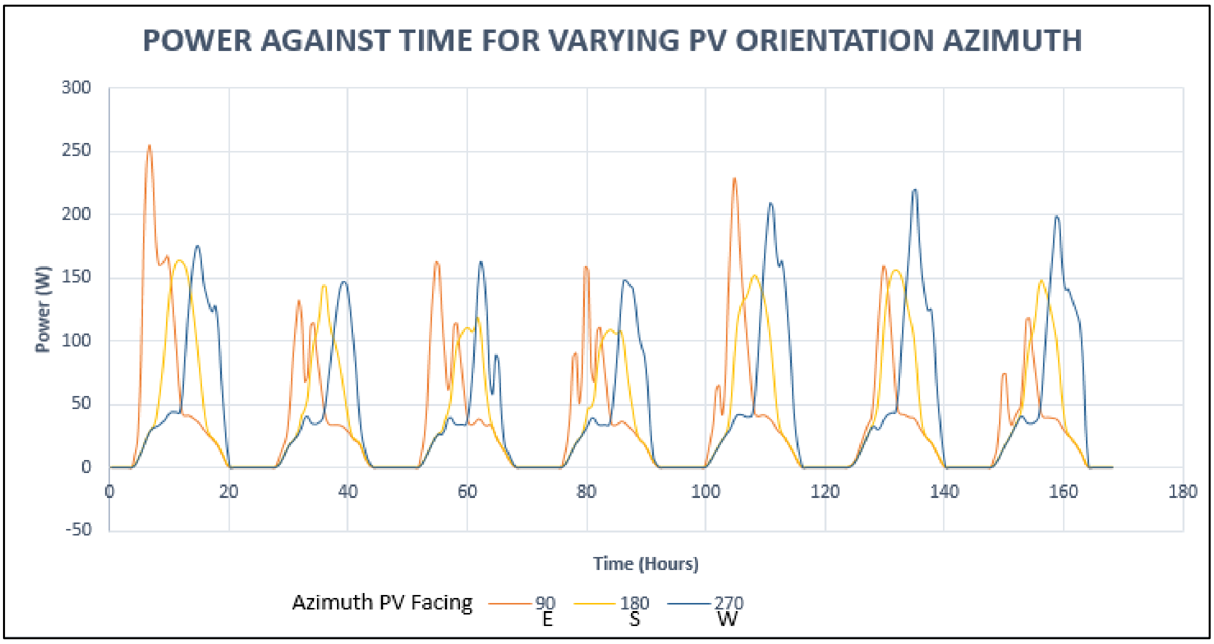


Figure 14 Power Against Time for Varying PV Orientation Azimuth (Generated in E-SPR)

2.1.3. Temperature Coefficient

PV modules have a temperature coefficient, pMax, which illustrates the impact of temperature on power output. This coefficient indicates the decrease in efficiency for every 1 degree Centigrade rise in temperature over the standard test temperature of 25 degrees centigrade. This temperature coefficient is provided by the solar panel manufacturers and the value differs depending on the type of solar cell. (*The Impact of Temperature on Solar Panels - TheGreenAge*, no date)

Type of solar cell	**pMax range (%)**	
Monocrystalline	-0.45	-0.5
Polycrystalline	0.45	-0.5
Amorphous	-0.2	-0.25
Hybrid	-0.32	

2.1.4. Materials

The purpose of this section is to identify the various PV materials currently available that could be applied to the proposed system for the LLTNP headquarters.

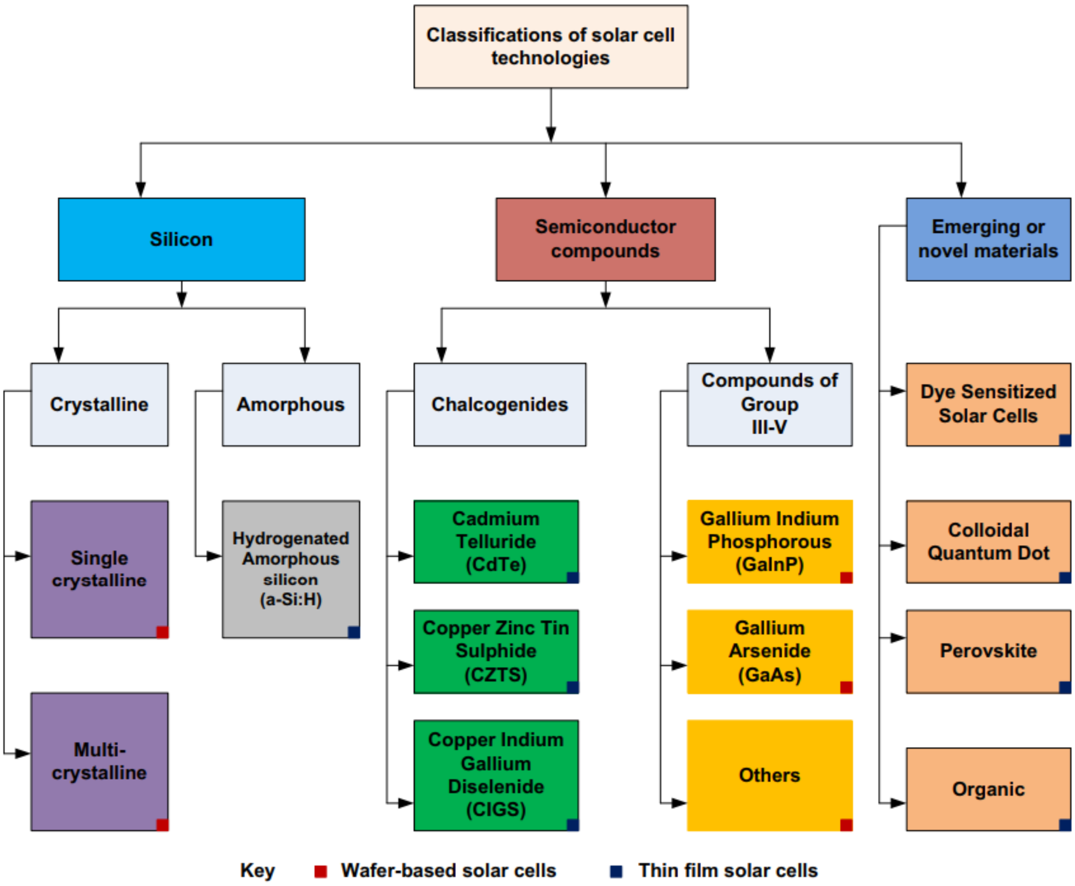


Figure 16 Classification on Solar Cells Based on Primary Active Material (T. Ibn-Mohammeda,b *et al.*, 2017)

PV's are normally classified dependent on the light-absorbing materials used for the solar cells. PV's can be categorized into wafer-based or thin-film technologies.

Wafer based solar cells are made by slicing semi-conductor ingots. Three of the main wafer-based solar cells are crystalline silicon, gallium arsenide, and III-V multijunction.

Thin-film technologies use insulative materials such as glass of flexible plastics for the deposition of semiconducting materials that make up the structure of the device. (T. Ibn-Mohammeda,b *et al.*, 2017)

Power Conversion Efficiencies

Different cell materials yield different efficiencies. The Power Conversion Efficiency (PCE) of a PV cell is the percentage of solar energy shining on the cell that is converted to usable electricity. Advances in technology are increasing this efficiency towards the PCE of some traditional fossil fuels such as coal.

Shown in Figure 17 below is a plot of conversion efficiencies for research cells. The results are separated into their respective families: multijunction cells, single-junction gallium arsenide cells, crystalline silicon cells, thin-film technologies and emerging photovoltaics.

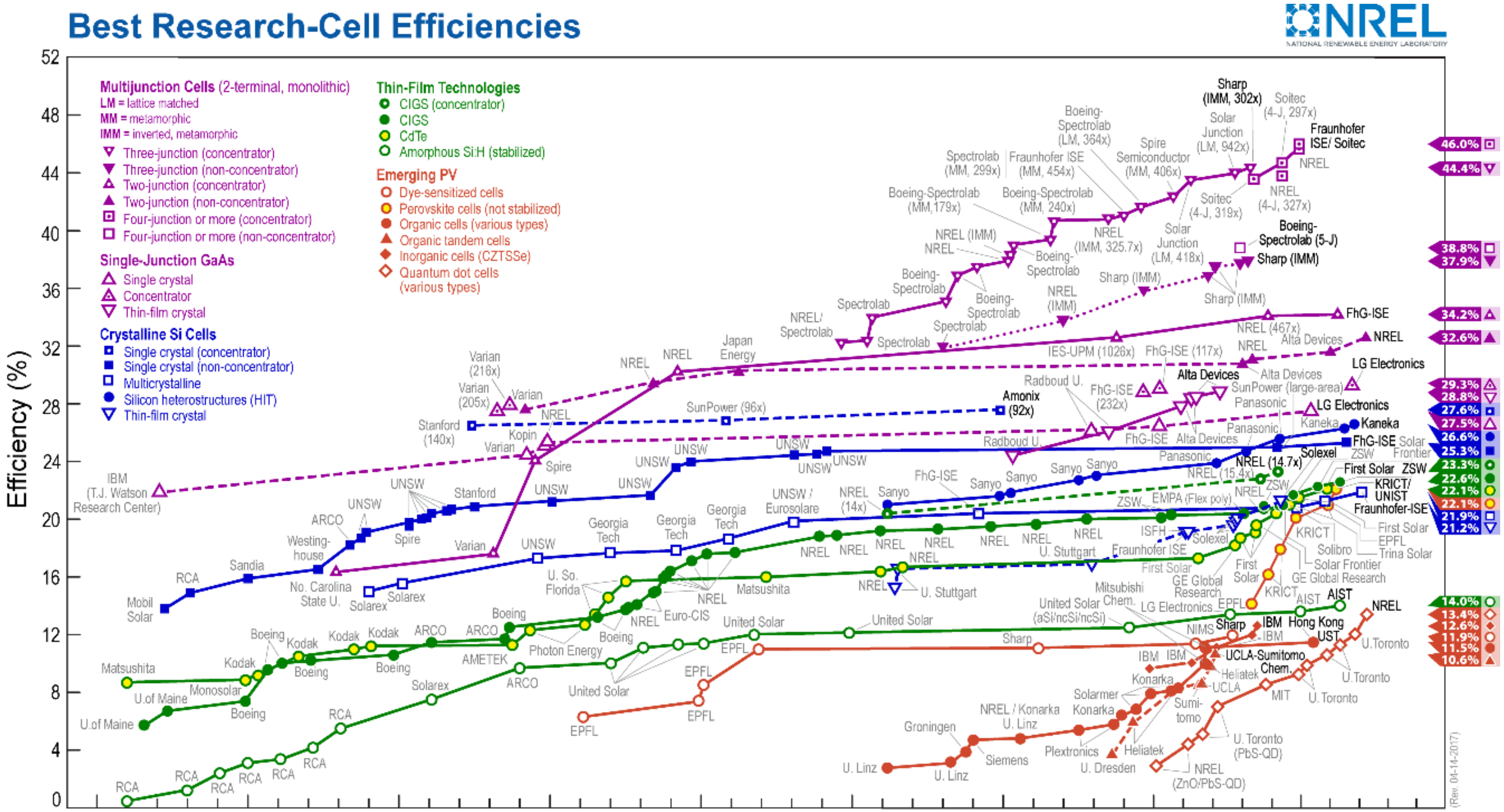


Figure 17Research-cell Efficiencies (*NREL*, no date)

2.2. Solar Thermal Collectors

2.2.1. Evacuated Tube Solar Collectors.

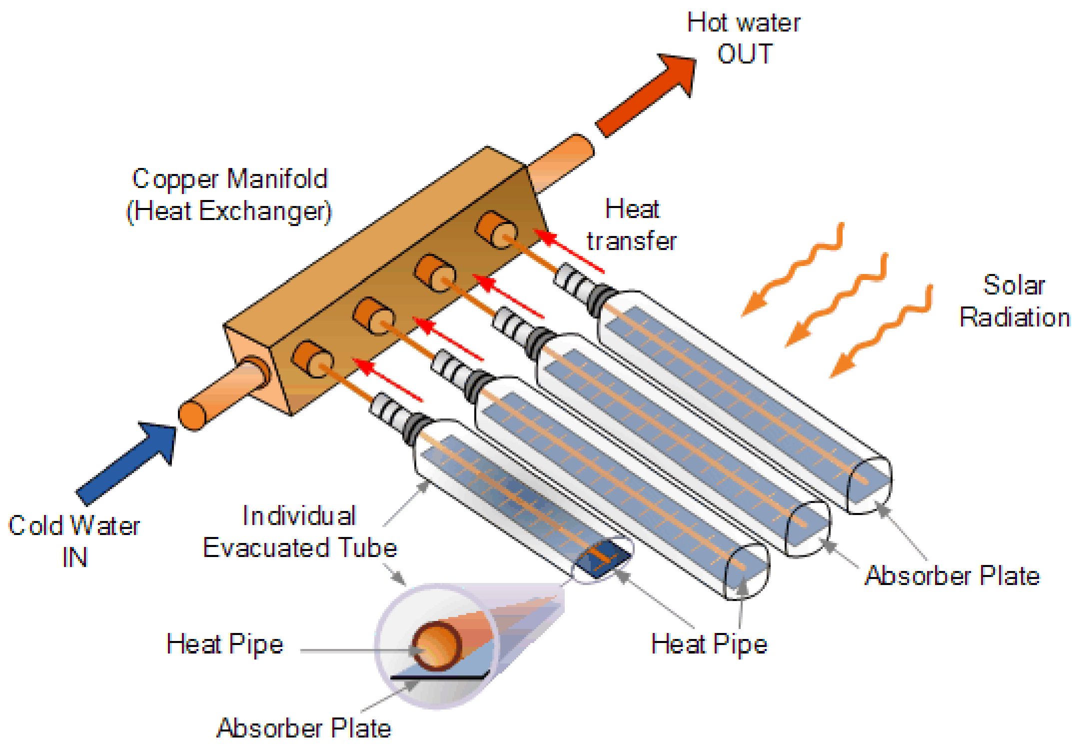


Figure 18 Evacuated Tube Solar Thermal Collector (*Evacuated Tube Collector for Solar Hot Water System*, no date)

An evacuated tube solar thermal system works by collecting solar radiation using absorber plates and heat pipes contained within evacuated glass tubes. The heat collected is transferred to water of a lower temperature via a copper manifold (heat exchanger).

Evacuated tube solar thermal systems can achieve higher temperatures compared to flat plate collector systems. This is because the evacuated tubes reduce conduction and convection heat losses. The round profile also enables the suns incident radiation to be perpendicular throughout more of the day relative to flat-plate collectors.

In terms of pricing, evacuated tube systems are slightly more expensive than flat-plate systems. (*Evacuated Tube Collector for Solar Hot Water System*, no date)

2.2.2. Flat Plate Collectors

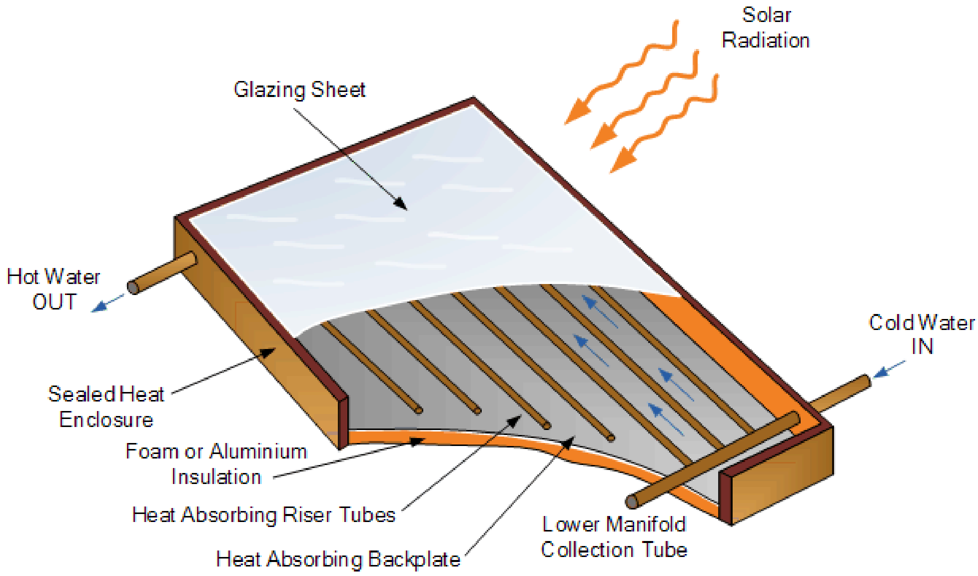


Figure 19 Flat-Plate Solar Collector (*Flat Plate Collector for use in Solar Hot Water System*, 2014)

A flat-plate collector is made from a heat absorbing surface that is blackened to absorb as much incident solar radiation as possible. This heat absorbing surface has a series of (normally copper) tubing running across the surface with a heat transferring liquid. If copper pipes are used the pipes are soldered to the absorber plate to maximise heat transfer by increasing contact area. These pipes and absorbing plate are encased in a box that is insulated on the underside of the absorber plate and around the edges to minimise heat losses. The top of this box consists of a glazing panel to utilise the greenhouse effect and protect the piping within. Flat plate collectors are a cost effective means of producing a large quantity of hot water, they work well with diffuse radiation as well as direct and they are relatively straightforward to install. (*Flat Plate Collector for use in Solar Hot Water System*, 2014)

2.3. Wind

Wind was scoped out for multiple reasons. One of the main reasons being that there is limited physical space to build a substantial turbine with most of the plot taken up with the building, vehicle parking and a natural wastewater drainage area.

Another reason was that within close proximity to the site there are residential and commercial buildings that would negatively impact a wind profile for a turbine and looking further a field there are many hills that enclose Balloch and the Loch Lomond valley that would also impact the wind profile. The presence of residential buildings would most likely result in difficulty attaining planning permission for a turbine due to the visual impact.

SNH and SEPA both have very particular views on siting of onshore wind facilities.

2.4. Software Utilised

Various software packages were used for the project. These included energyPRO, HOMER energy, T*SOL and PV*Sol. Some of the software packages were found to be more suitable than others in terms of modelling a system with multiple components of differing energy form.

HOMER Energy was initially explored and utilised to import details on solar irradiance, wind, and temperatures for the site location. HOMER energy was found to be suitable for modelling the desired PV, however it was deemed not to be the best for a hybrid system including thermal elements. EnergyPRO was found to be flexible for incorporating existing infrastructure as well as PV and Solar thermal collectors.

2.4.1. HOMER Energy

HOMER Energy is a microgrid modelling software used for simulation, optimisation and sensitivity analysis.

2.4.2. PV*SOL

PV*SOL allows for the modelling of a PV system, taking in to account the impact of shading from nearby objects. This was necessary at the LLTNP HQ due to the shading from one of the roof structures on another potential south facing roof surface suitable for PV. The software enabled the production of a 3D model and positioning of the maximum number of PV panels. Using entered location data and an hourly electrical demand profile, the software simulated the yield relative to the demand accounting for losses due to shading.

2.4.3. T*SOL

T*SOL is a software package used to calculate the production from a solar thermal system over a period of time. It allows for the design of solar thermal systems, solar collectors, tanks.

2.4.4. EnergyPRO

EnergyPRO is a modelling software for combined technical and economic analysis and optimization of a variety of thermal, CHP, process and cooling projects. It can be used to model fossil fuel infrastructure and cutting edge renewable technology. (*EMD International A/S energyPRO - Simulate, analyze and optimize operations of energy plants*, no date)

Energy pro has the capability to carry out functions of both PV*SOL and T*SOL in a single modelling software.

It is suitable for also considering existing thermal systems such as the biomass boiler and back up natural gas boiler. EnergyPRO can also incorporate appropriate renewable systems for the LLTNP Headquarters such as solar thermal collectors and Photovoltaic modules.

2.5. Load Management

Currently small scale renewable projects can balance supply and demand using the national grid. However, looking to the future if current trends continue and the number of renewable energy projects increase it will become more challenging for the national grid to provide this balancing service and therefore the grid operators may impose an additional charge for every unit of energy fed into the grid network.

For this reason, it is important that electricity producers carefully consider the profile of generation and demand to avoid undesirable spikes of supply and demand to the national grid.

Careful load management can allow loads to be shifted to times of maximum renewable generation. This relieves stress to the grid and maximises the utilisation of energy generated onsite with the added benefit to the producer of reducing the quantity of energy imported from the grid.

Load management involves firstly identifying what the demand profile is and assessing how certain loads can be eradicated, reduced and shifted to a more desirable time when generation is at its highest.

3. Resource Assessment

The LLTNP has been designed intuitively with the integration of renewables in mind. The building has 2 large south facing roofs, pitched at approximately 40 degrees, aligning well with the optimal tilt angle for the buildings latitude.

3.1. Global Horizontal Irradiance

Global horizontal irradiance is the sum of the direct and diffuse radiation. Below in Figure 20 hourly values are shown. A substantial difference in resource available in the winter months relative to summer can be observed.

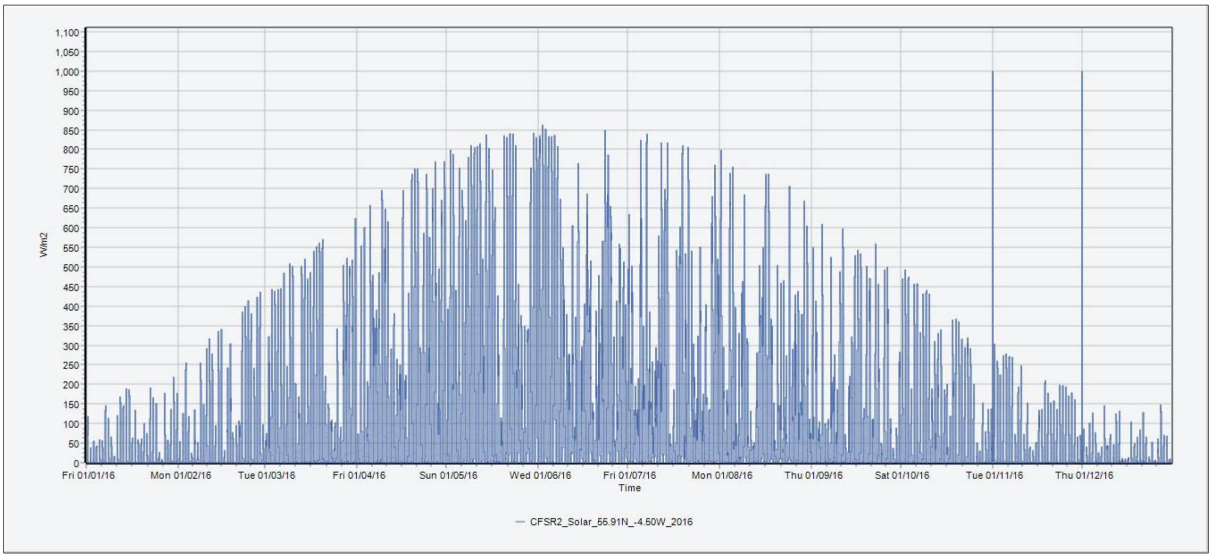


Figure 20 Hourly Global Horizontal Irradiance Values for Balloch 2016-2017 obtained from energyPRO

In Figure 21 below data is shown that has been exported from HOMER Energy. It shows monthly averages of global horizontal irradiance for Balloch. These average values appear to be approximately half of peak values.

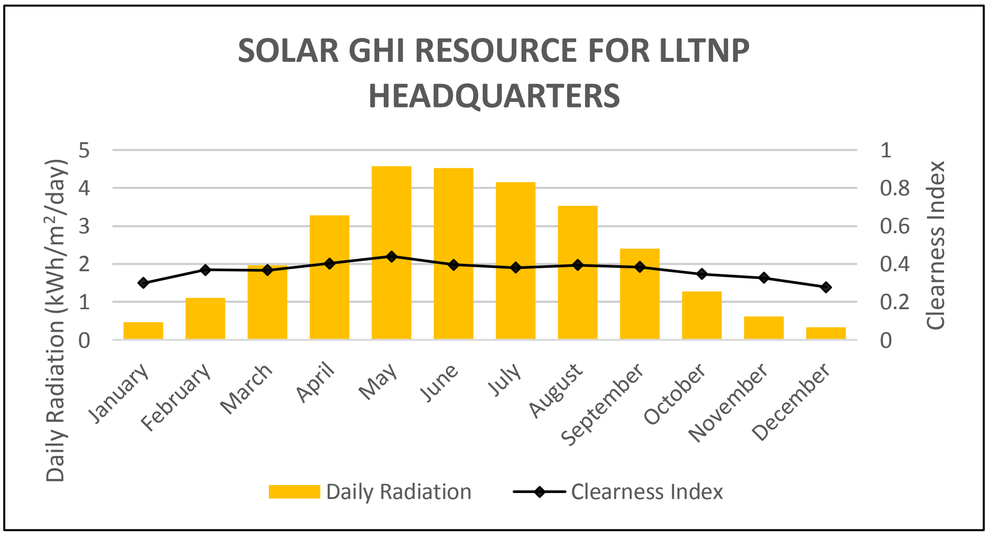


Figure 21 Average Global Horizontal Irradiance Values for Balloch, 2016-2017. Also Shows Clearness Index Values.

Table 2 Solar Data

Month	Clearness Index	Daily Radiation (kWh/m^2/day)
January	0.300	0.47
February	0.369	1.10
March	0.367	1.96
April	0.403	3.27
May	0.44	4.57
June	0.396	4.53
July	0.381	4.16
August	0.394	3.53
September	0.384	2.41
October	0.347	1.27
November	0.326	0.61
December	0.278	0.33

Hourly solar irradiance data was averaged for January and July 2016. A significant difference can be observed between an average day in winter and the average day in summer. This is due to the shorter daylight hours in winter and greater cloud cover.

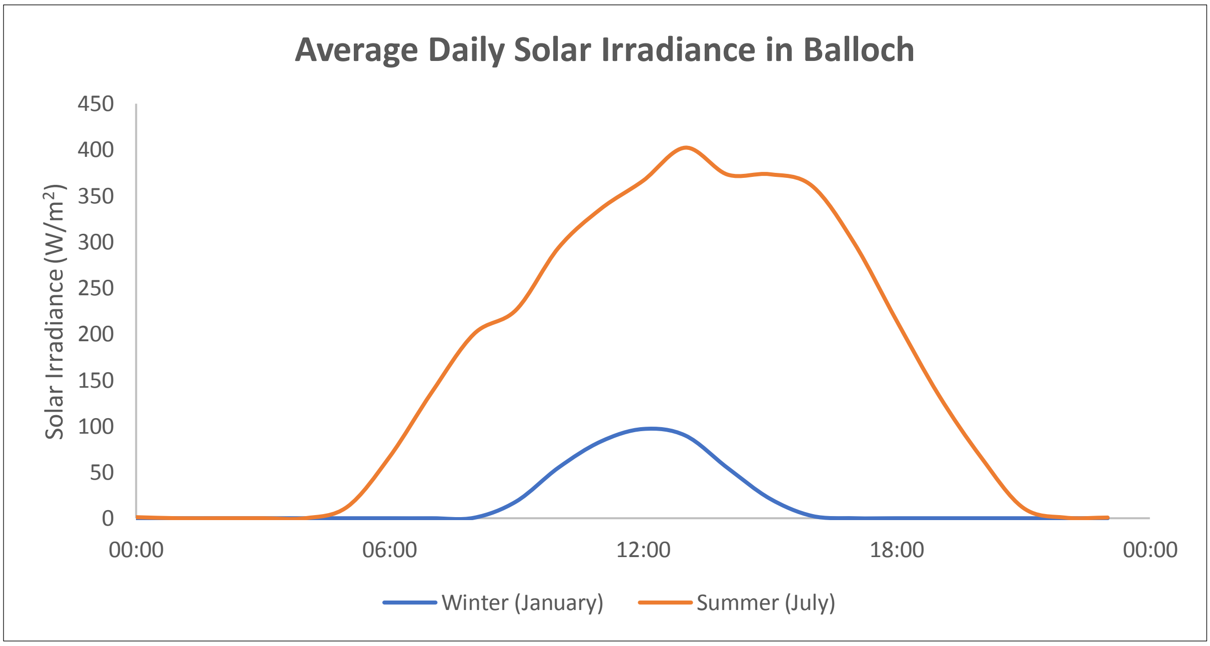


Figure 22 Average Daily Solar Irradiance - Comparison of Winter and Summer

3.2. Mounting Area

Most of the site area is taken up with the building and therefore it would be most appropriate to integrate the solar technologies onto the roof instead of ground mounting.

Two suitable south facing roofs are shown below in Figure 23. The roof areas were attained from google maps with the rear south facing roof having an approximate area of 297m^2 and the front south facing roof having an approximate area of 336m^2. This gives an approximate total area of 633m^2 of south facing roof.

Area 1 has the benefit of having easy access from within the building for installation and maintenance, however has the drawback of shading from the adjacent rooftop, particularly an issue during winter months when the sun is substantially lower in the sky.

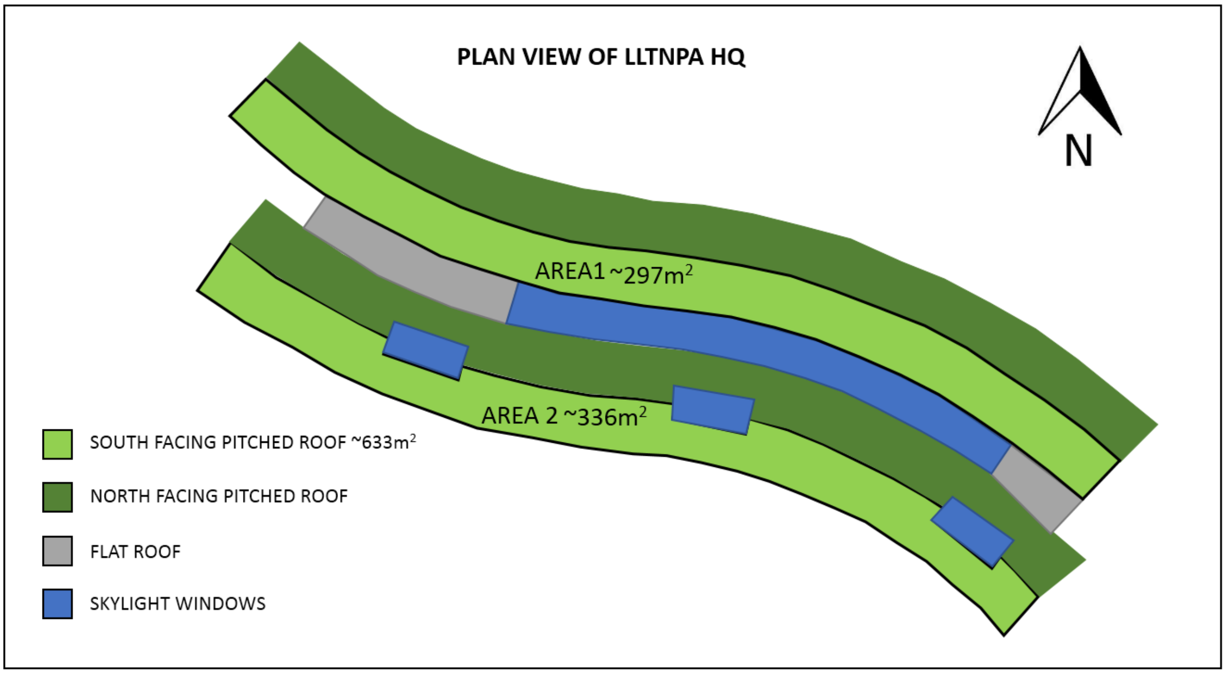


Figure 23 Plan View of Headquarters Roof

3.3. Temperature

The standard test temperature for PV panels is 25 degrees centigrade. The temperature coefficient (specified by respective PV panel manufacturers) determines how the efficiency decreases above 25 degrees centigrade but more appropriately to Scotland the efficiency of a panel increases for temperatures below 25 degrees.

Figure 24 shows average temperatures for the town of Balloch where the headquarters are situated. As the maximum average temperature is 14 degrees in summer and rarely peaks above 25 degrees Centigrade (see hourly data in Figure 25), the site location looks well suited for PV in terms of temperature.

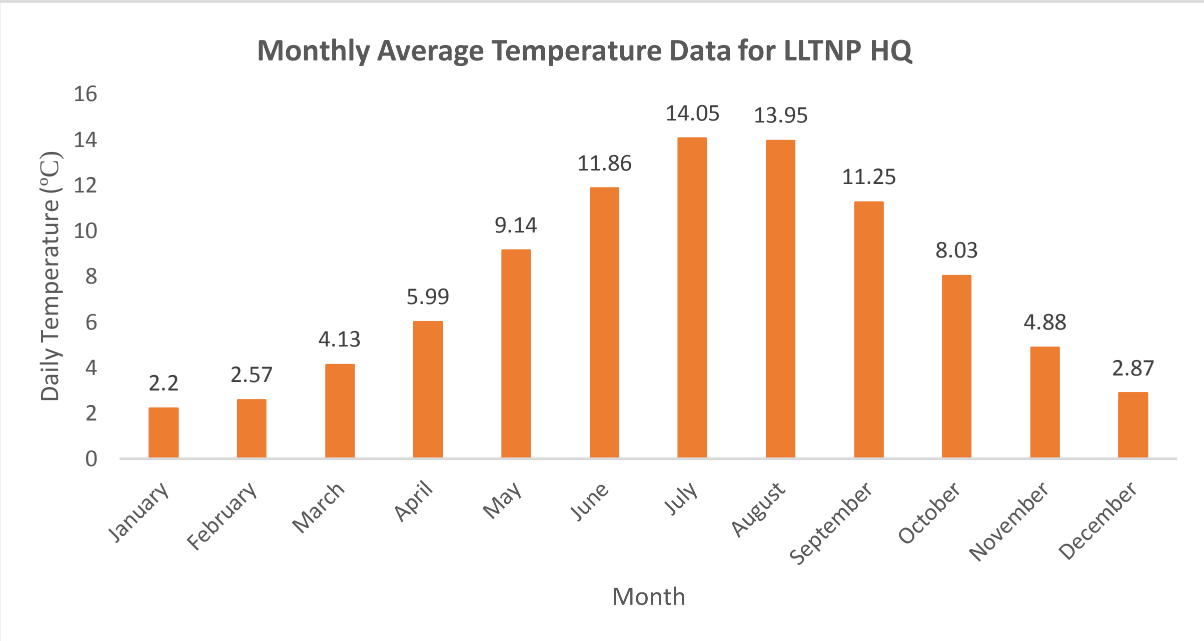


Figure 24 Monthly Average Temperatures for Balloch Exported from HOMER Energy

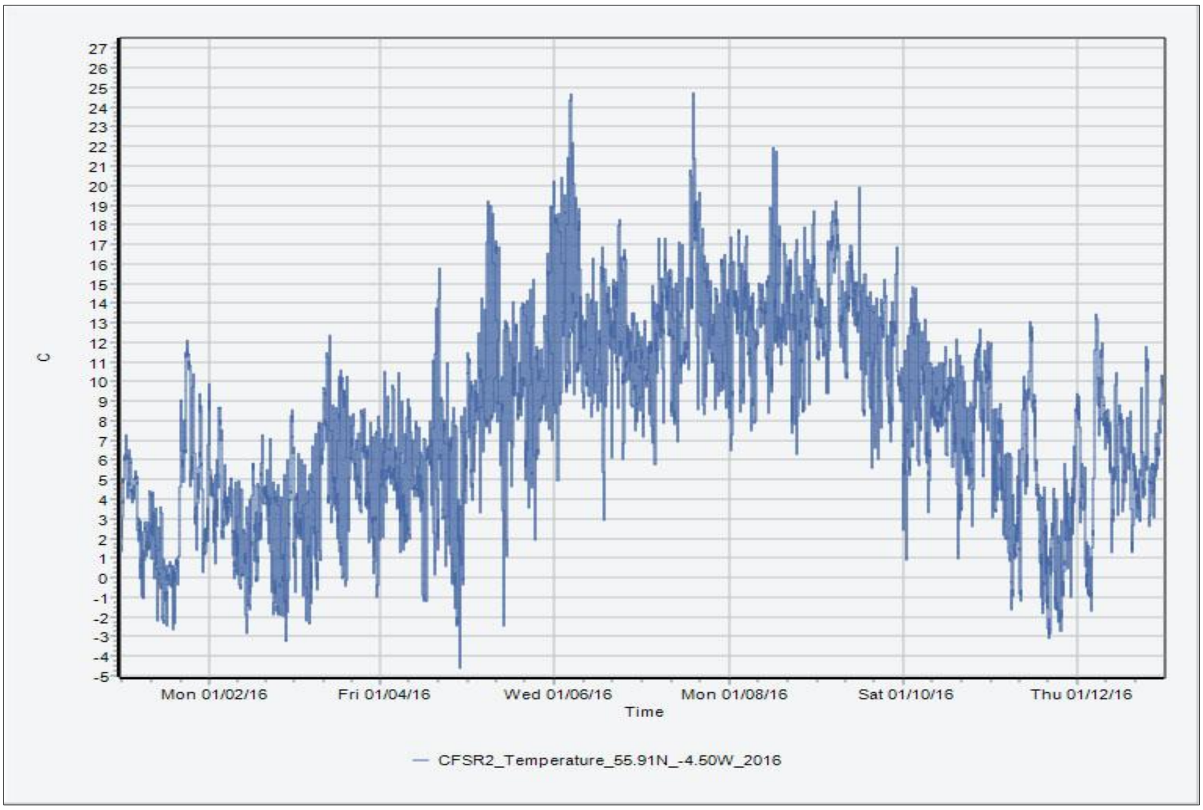
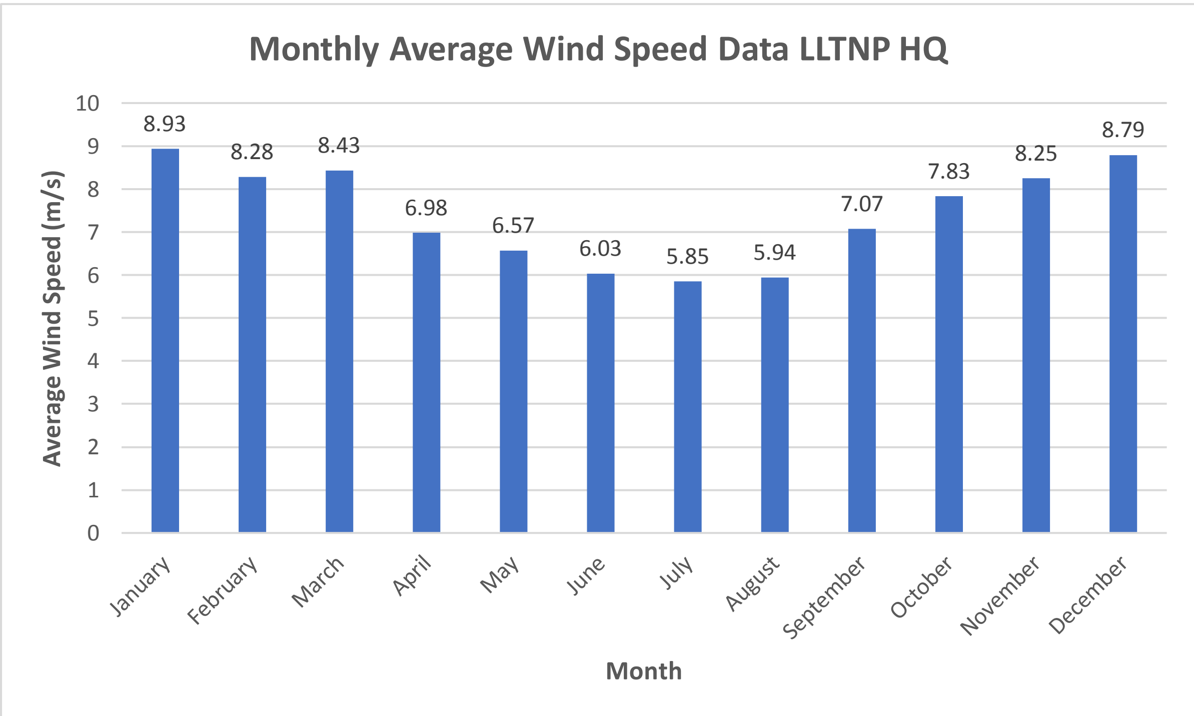


Figure 25 Hourly Temperature Values for Balloch, 2016-2017. Obtained from EnergyPRO

3.4. Wind



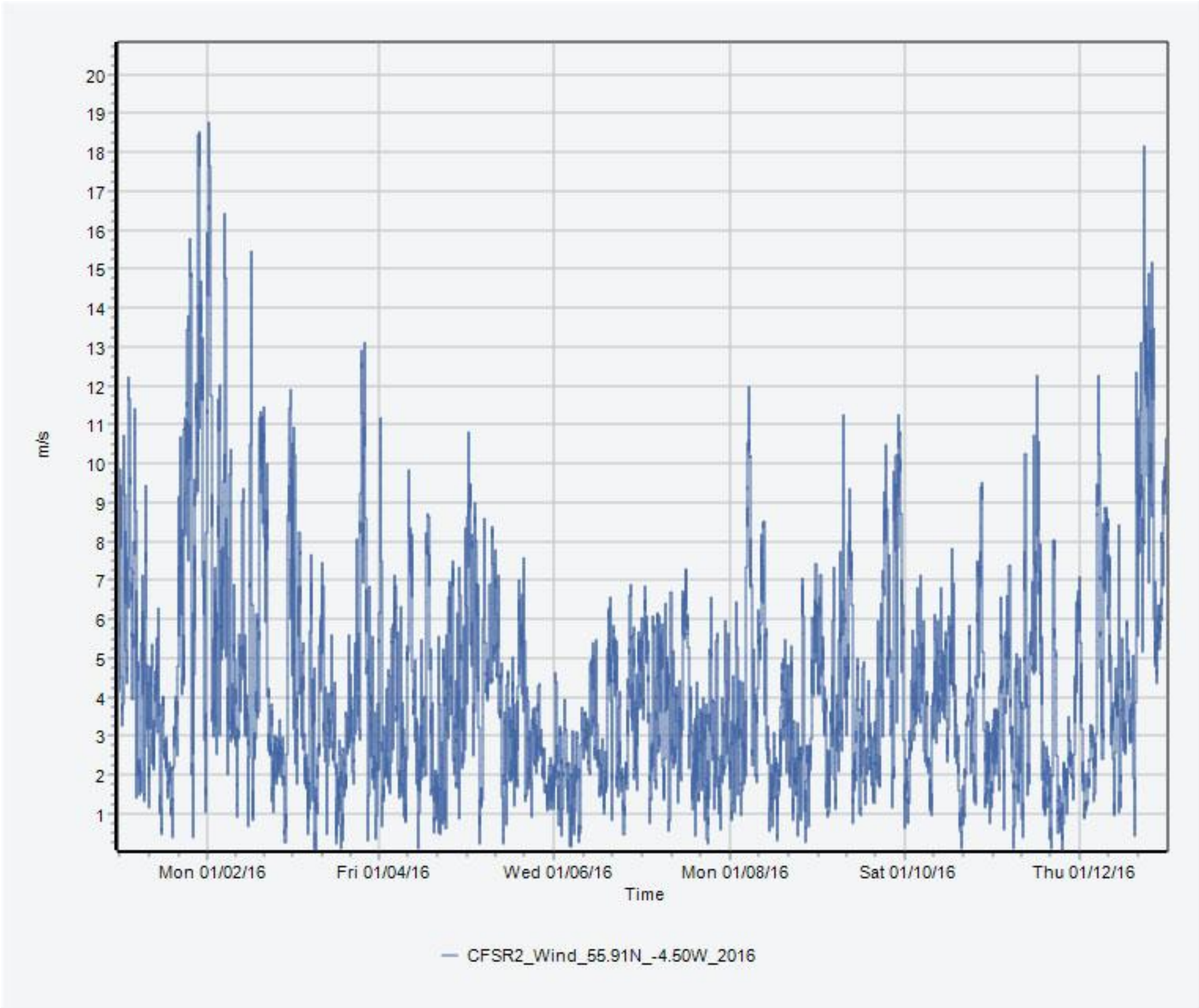


Figure 26 Hourly Wind Speed Data for Balloch Obtained from EnergyPRO

4. Methodology

4.1. Demand Data

4.1.1. Electrical Data

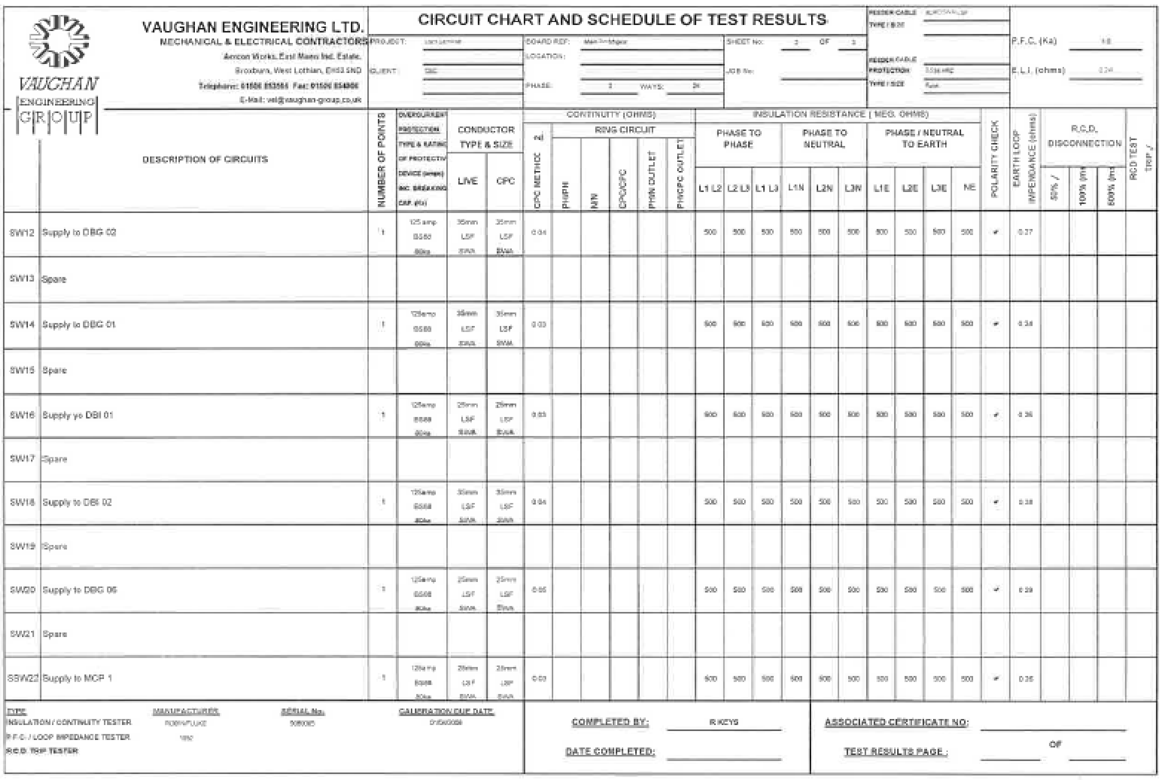
Weekly meter data was obtained from the LLTNPA. To achieve data of a higher resolution, hourly meter data was collected for the working hours of a typical summer day. The meter data collected by the LLTNPA was overall consumption readings however meters are present that allowed individual circuits power consumption data to be read.

Figure 27 Headquarters Switchgear Panel

Figure 28 Headquarters Smart Meter

Through collecting meter readings for a day for each individual circuit, the circuits with the highest energy usage could be identified.

Once the circuits were identified, the circuit charts for the building (see Figure 29) were consulted and analysed to see if any of the loads could be shifted to coincide with times of peak renewable generation.



VAUGHAN ENGINEERING LTD.
MECHANICAL & ELECTRICAL CONTRACTORS
Arncon Works, East Mains Ind. Estate,
Broxburn, West Lothian, EH52 5ND
Telephone: 01506 853555 Fax: 01506 854806
E-Mail: vel@vaughan-group.co.uk

VAUGHAN ENGINEERING GROUP

CIRCUIT CHART AND SCHEDULE OF TEST RESULTS

PROJECT: | CLIENT: | BOARD REF: | LOCATION: | PHASE: 3 | WAYS: 24 | SHEET No: 2 OF 3 | JOB No: | FEEDER CABLE TYPE / SIZE: | FEEDER CABLE PROTECTION TYPE / SIZE: Fuse | P.F.C. (Ka): | E.L.I. (ohms):

	DESCRIPTION OF CIRCUITS	NUMBER OF POINTS	OVERCURRENT PROTECTION TYPE & RATING OF PROTECTIVE DEVICE (amps) INC. BREAKING CAP. (Ka)	CONDUCTOR TYPE & SIZE LIVE	CONDUCTOR TYPE & SIZE CPC	CONTINUITY (OHMS) CPC METHOD	RING CIRCUIT Ph/Ph	RING CIRCUIT N/N	RING CIRCUIT CPC/CPC	RING CIRCUIT Ph/N OUTLET	RING CIRCUIT Ph/CPC OUTLET	INSULATION RESISTANCE (MEG. OHMS) PHASE TO PHASE L1 L2	L2 L3	L1 L3	PHASE TO NEUTRAL L1N	L2N	L3N	PHASE / NEUTRAL TO EARTH L1E	L2E	L3E	NE	POLARITY CHECK	EARTH LOOP IMPEDANCE (ohms)	R.C.D. DISCONNECTION 50% /	100% (ms)	500% (ms)	RCD TEST TRIP ✓
SW12	Supply to DBG 02	1	125 amp BS88 80ka	35mm LSF SWA	35mm LSF SWA	0.04						500	500	500	500	500	500	500	500	500	500	✓	0.27				
SW13	Spare																										
SW14	Supply to DBG 01	1	125amp BS88 80ka	35mm LSF SWA	35mm LSF SWA	0.03						500	500	500	500	500	500	500	500	500	500	✓	0.34				
SW15	Spare																										
SW16	Supply yo DBI 01	1	125amp BS88 80ka	25mm LSF SWA	25mm LSF SWA	0.03						500	500	500	500	500	500	500	500	500	500	✓	0.36				
SW17	Spare																										
SW18	Supply to DBI 02	1	125amp BS88 80ka	35mm LSF SWA	35mm LSF SWA	0.04						500	500	500	500	500	500	500	500	500	500	✓	0.38				
SW19	Spare																										
SW20	Supply to DBG 06	1	125amp BS88 80ka	25mm LSF SWA	25mm LSF SWA	0.05						500	500	500	500	500	500	500	500	500	500	✓	0.29				
SW21	Spare																										
SSW22	Supply to MCP 1	1	125amp BS88 80ka	25mm LSF SWA	25mm LSF SWA	0.03						500	500	500	500	500	500	500	500	500	500	✓	0.26				

TYPE: INSULATION / CONTINUITY TESTER; P.F.C. / LOOP IMPEDANCE TESTER; R.C.D. TRIP TESTER
MANUFACTURER | SERIAL No. | CALIBRATION DUE DATE

COMPLETED BY: R KEYS
DATE COMPLETED:
ASSOCIATED CERTIFICATE NO:
TEST RESULTS PAGE: OF

Figure 29 Example of electrical chart for the LLTNPA HQ

Table 4 below shows all the electrical circuits at the LLTNPA headquarters. The rows highlighted are the circuits which have individual metering. It is assumed that the other loads are relatively consistent and therefore not individually metered.

Table 3 Main Switchgear - Circuit Identification

Main Switchgear	
Description of Circuits	
SW1	Suppy to Window Panel
SW2	Supply to lift
SW3	Condensor
SW4	Condensor
SW5	Condensor
SW6	Condensor
SW7	Supply to DBG05
SW8	Supply to DBG04
SW9	Supply to UPS System
SW10	Supply to DBG03
SW11	Spare
SW12	Supply to DBG02
SW13	Spare
SW14	Supply to DBG 01
SW15	Spare
SW16	Supply to DBI 01
SW17	Spare
SW18	Supply to DBI 02
SW19	Spare
SW20	Supply to DBG 06
SW21	Spare
SSW22	Supply to MCP1
SW23	Supply to Fire Alarm
SW24	Supply to Vesda Panel

4.1.2. Biomass Boiler Data

Wood chip deliveries were recorded by the LLTNP with dates and masses available from the facilities log spreadsheet. A calorific value of 3500kWh per Tonne was also provided by the LLTNPA.

4.1.3. Natural Gas Data

Weekly meter readings were provided by the LLTNPA.

4.2. Modelling

4.2.1. PV*SOL

Simulation was carried out in PV*SOL to find potential yields for various PV panel configurations, taking into consideration the effects of shading. Below is the methodology.

Firstly the type of system was selected. The LLTNPA does own a small fleet of electric vehicles however this was emitted for simplicity in the modelling.

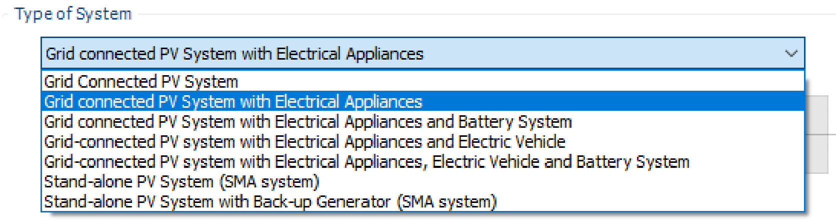


*Figure 30 System Selection PV*SOL*

The location was then selected for the provision of climate data. Glasgow airport was selected as it was the closest data point to Balloch available within the modelling software and was deemed to have a similar climate.

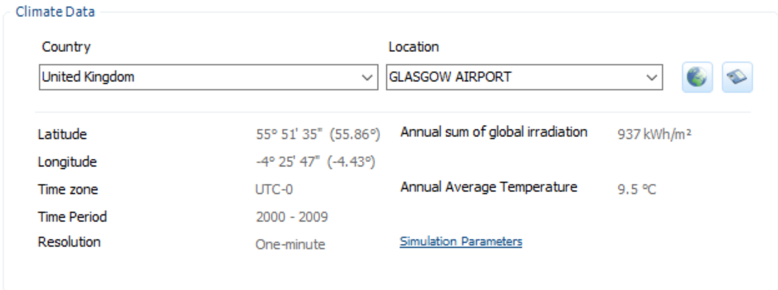


*Figure 31 Climate Data Selection PV*SOL*

A suitable demand profile was selected to reflect as accurately as possible the way the building is utilised. A pre-existing office load profile was selected as this most accurately represents the way in which the building is used. A profile was also developed and imported from MERIT however upon comparing the PV*SOL profile, the built-in office profile selected from PV*SOL seemed more accurate as there was less fluctuation in the winter months. Although there are electric space heaters utilised in the winter months and more lighting is required, the demand profile imported from Merit appeared to fluctuate too much considering most of the heating is supplied from a biomass boiler which would not impact the electrical demand profile throughout the winter months.

*Figure 32 Consumption Overview PV*SOL*

Having selected a demand profile, the overall energy consumption was adapted to the actual energy consumption of the LLTNP HQ for the fiscal year 2016-2017. This value was 215780kWh and attained from the meter data provided by the LLTNPA.

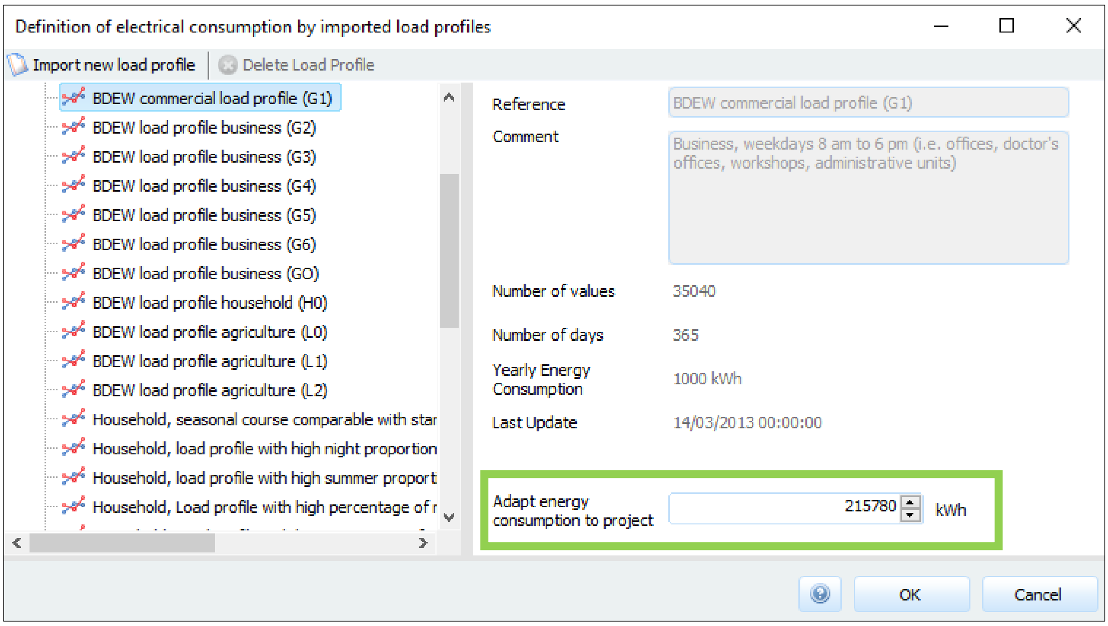


*Figure 33 Load Definition Screen PV*SOL*

A close representation model of the LLTNPA HQ was then developed as shown in below. A straight edged building was simulated to avoid complication and skylight windows positioned to scale. Having selected the roof to have maximum coverage of panels and selected a standard example 200W polycrystalline unit. The simulations were then run. Please refer to the results section for the output from these simulations.

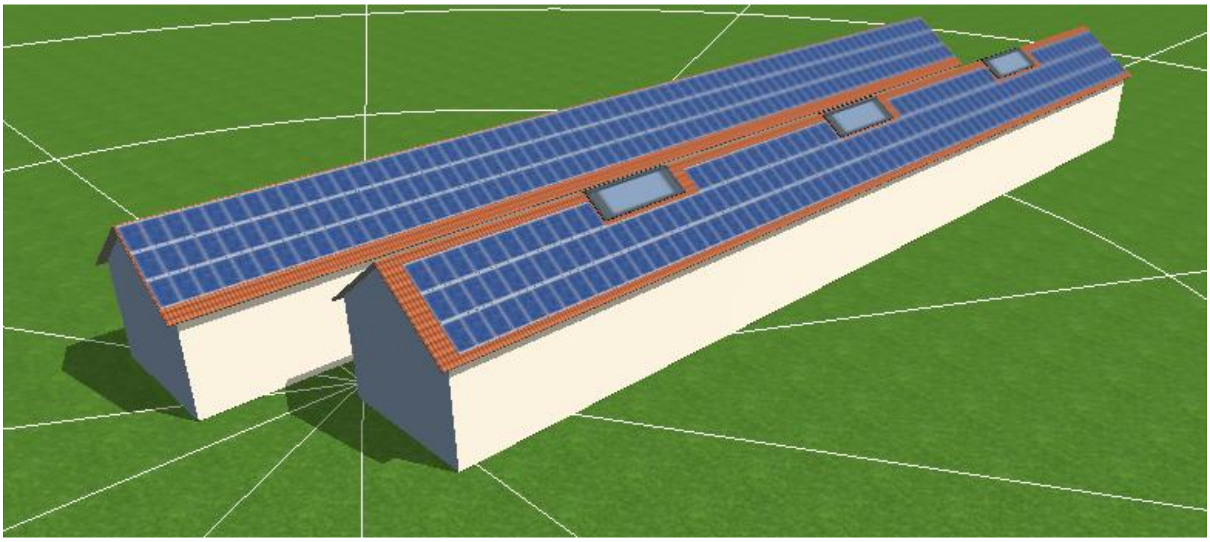


*Figure 34 HQ Model Developed in PV*SOL*

4.2.2. T*Sol Online Sizing Tool

T*SOL allowed for an approximate yield to be calculated for the LLTNPA HQ by allowing basic information to be entered using the user interface shown below in Figure 35. The inputs required were collector orientation, type of collectors (tube or flat plate), area of collectors, pitch that the collectors are mounted at, number of people using the building, water temperature required, location, water tank size, boiler type, usable floor area and level of building insulation. Numbers approximately 1/10th of the LLTNP were entered to allow the outputs to be scaled up due to the limitations of the online tool. Understandably there would be some scaling issues however it was useful to get an approximate idea of yield help validate values obtained from EnergyPRO. Example results are shown in Figure 36.

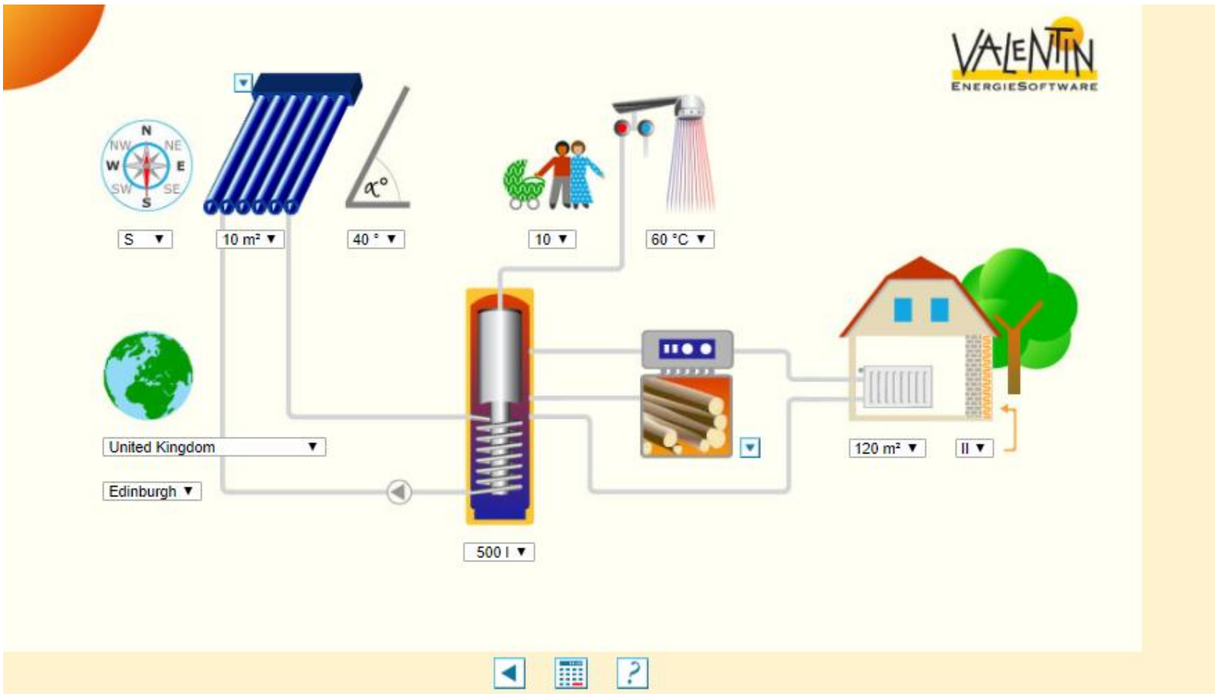


*Figure 35 T*SOL Online Calculator User Interface*

Results

Irradiation:	10.410 kWh/a
System yield:	3.538 kWh/a
Solar fraction:	18 %
CO^2 savings:	0 kg/a

Irradiation:	Solar radiation onto the tilted surface of the collector absorber surface, over one year
System yield:	Solar system's available energy
Solar fraction:	Percentage of the total energy requirement produced by the solar system (= system yield)
Efficiency:	System yield/irradiation
CO^2 savings:	Emissions avoided by use of the system in kg/year

*Figure 36 Example Output from T*SOL Online Calculator*

4.2.3. EnergyPRO

EnergyPRO was used to firstly model the existing energy system in place at the LLTNP HQ. This model consisted of the biomass boiler, back-up natural gas boiler, thermal storage, the heating demand, the electrical demand and connection to the electricity grid. The new proposed hybrid system was then modelled with everything from the first model but inclusive of solar thermal tube collectors, solar PV and increased thermal storage. Figure 37 shows the user interface when starting a new project in EnergyPRO.

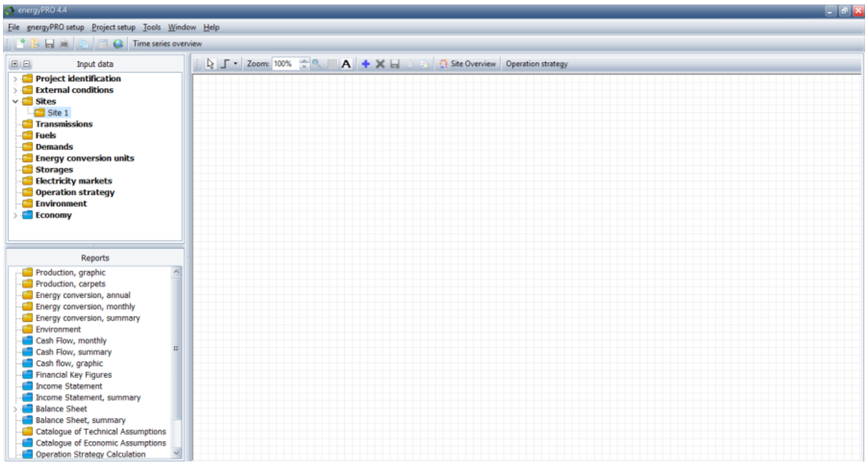


Figure 37 EnergyPRO User Interface

The first important stage of modelling was to select the data collection point nearest/ most suitable to the site location. This allows time series to be imported for air temperature, solar radiation, wind speed, precipitation and humidity. See Figure 38 below. CSFR2 data was chosen that was collected just south of Balloch as it was most recently collected in 2016 and had geographic similarities.

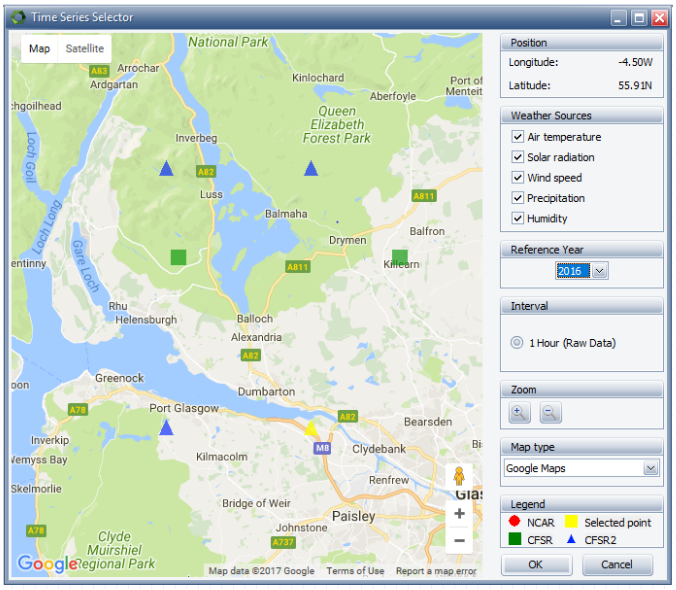


Figure 38 EnergyPRO Time Series Selection Screen

Having imported the time series as described they could then each be individually amended if required and graphically viewed for any given period. An example of the solar time series interface and graphical output are shown below in Figure 39. The two outlying data points visible in Figure 39 below were altered to enable a higher resolution graphical output by decreasing the range of the vertical axis.

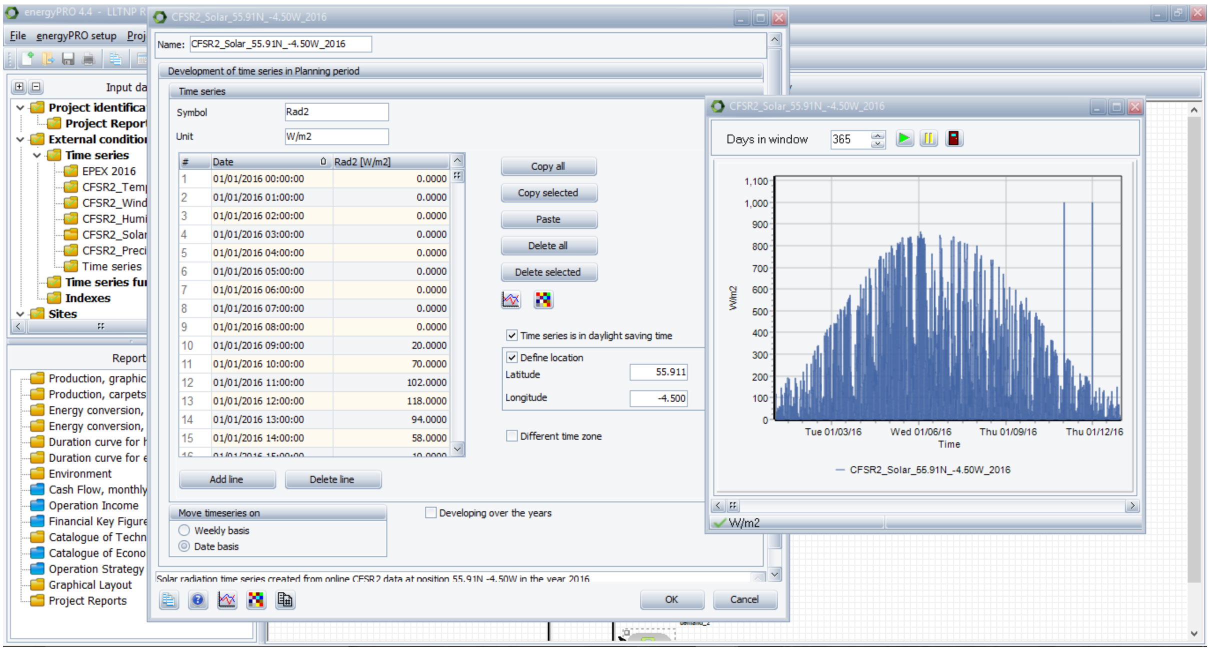


Figure 39 EnergyPRO Solar Time Series Interface

Having sorted the time series, the model of the system was developed with various nodes. Nodes were added for the different fuel types (biomass wood chips and natural gas), energy conversion units (biomass boiler and natural gas boiler), thermal storage (hot water tanks), demands (electrical and heat) and the grid connection. The result is shown below in Figure 40.

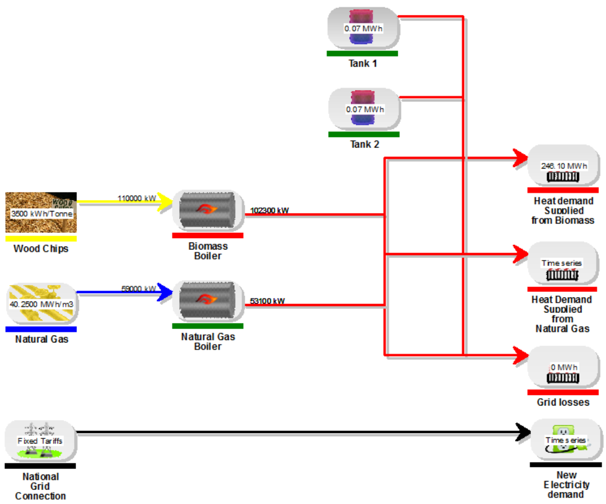


Figure 40 Diagram of Current System at LLTNPA HQ - Developed in EnergyPRO

The system was then modified, see Figure 41 below, to include maximum coverage of solar PV panels and 50m^3 of solar thermal collectors. The thermal storage capacity was increased until the heat demand of the building was completely met. An electric immersion was also added to make use of generation to allow some of the heat demand to be met using electricity. This option was favoured rather than increasing the amount of solar thermal as electricity is a more flexible form of energy meaning that electricity generated from the PV panels can be utilised for both electrical and heat demand.

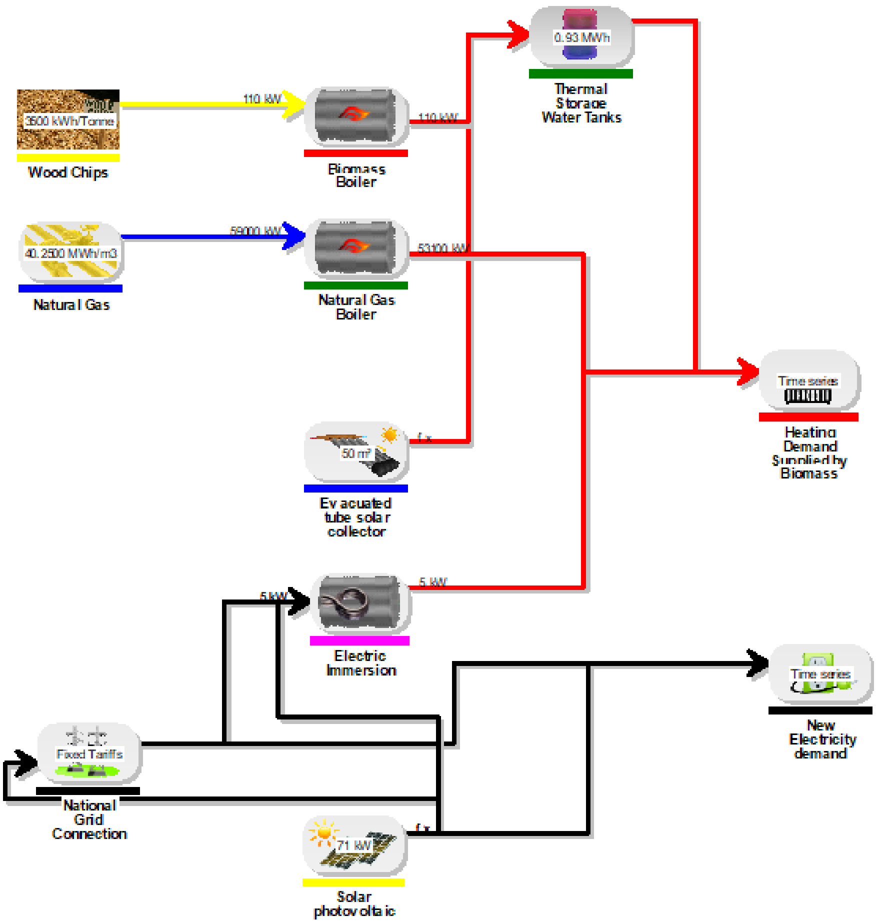


Figure 41 Diagram of Proposed System at LLTNPA HQ - Developed in EnergyPRO

Priority of energy production was set to the PV panels were set to have priority over importing electricity from the grid. Similarly, the solar thermal collectors were set to have priority over the biomass boiler and the natural gas boiler was set to only be used if there was no production available on the biomass boiler. The electric immersion was set to only run on excess solar PV generation therefore it does not place an extra burden on the grid. An example of how the priority for the biomass boiler was set is shown below in Figure 42.

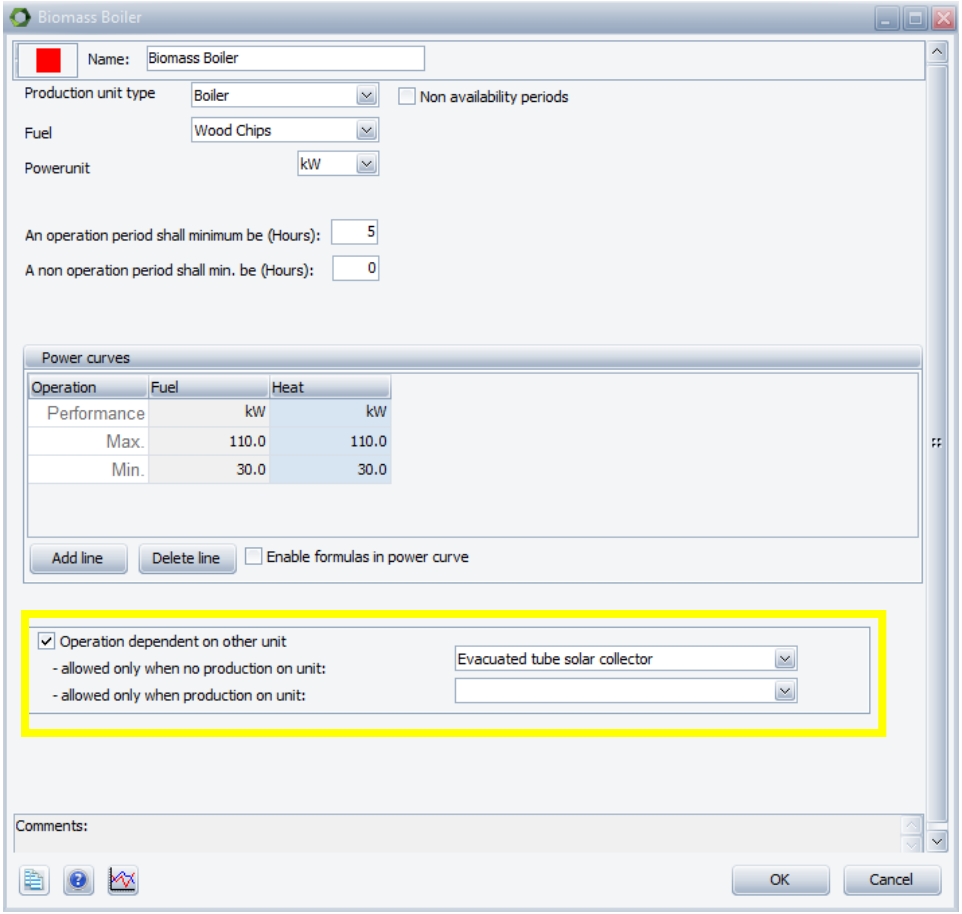


Figure 42 Setting the Operational Priority of the Biomass Boiler

Having modelled the system, various results could then be outputted including generation quantities and percentages relative to overall energy demands. Figure 43 below shows an example of the outputs achieved from EnergyPRO. See section 5 for detailed results.

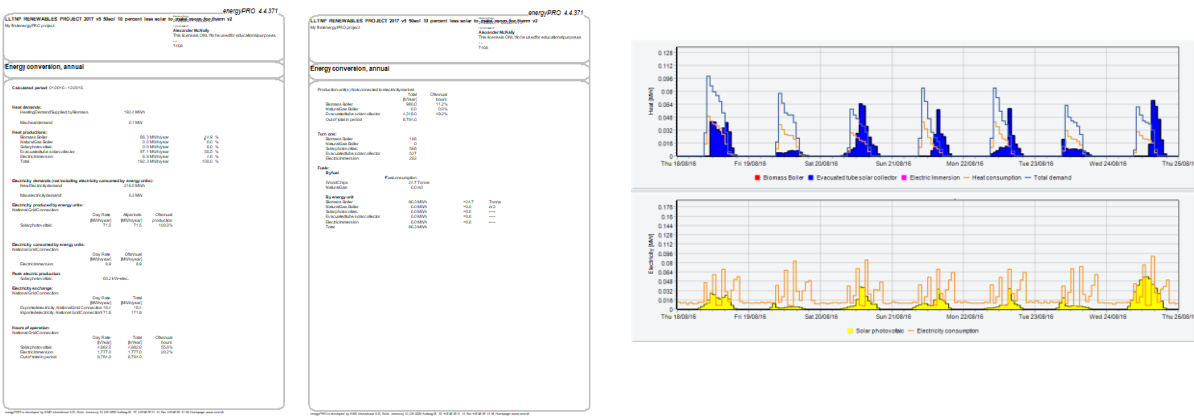


Figure 43 Example outputs from EnergyPRO

5.Results and Discussion

5.1. Data Collection

An overview of the energy consumption in 2016 is shown below in Figure 44 with gas and electricity values obtained from weekly meter data recorded by LLTNPA staff. Wood chip deliveries records were converted to a calorific value. Assumptions made were that the storage bin was always filled to full and therefore the values below give a fair representation of usage throughout the year.

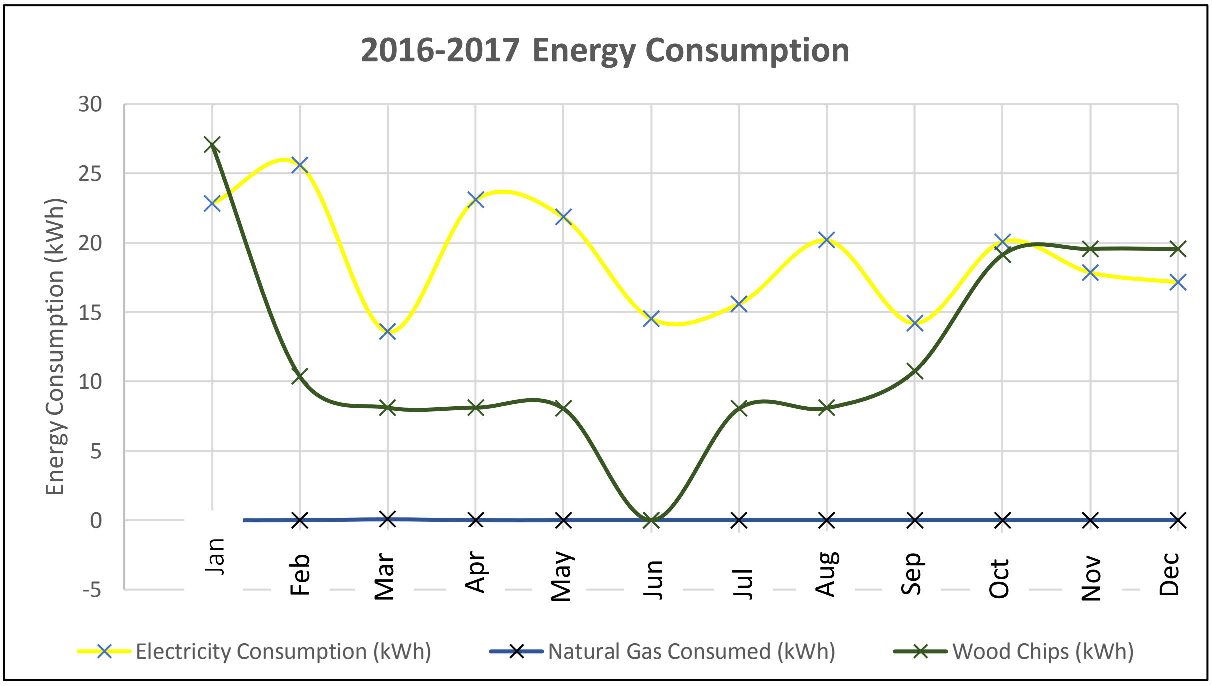


Figure 44 2016-2017 Energy Consumption

Table 4 Monthly Electricity, Gas and Wood Chip Consumption 2016-2017

2016-2017	Electricity Consumption (kWh)	Natural Gas Consumed (kWh)	Wood Chips (kWh)
January	22826	0	27090
February	25592	0	10360
March	13591	67	8120
April	23090	0	8120
May	21838	0	8050
June	14535	0	0
July	15594	0	8050
August	20177	0	8085
September	14208	1	10745
October	20079	0	19134.5
November	17860	0	19565
December	17159	0	19565
Total	**226549**	**68**	**146884.5**

.

The profile above in Figure 44 shows that the heating demand supplied by the biomass boiler is greatest during the winter months. It also shows that there is less fluctuation in the electrical demand. This is because the many of the loads are consistent throughout the year. The higher values are observed in the winter months when there is less natural daylight available and plug in electric heaters are utilized by staff to increase thermal comfort levels.

5.1.1. Electricity

Weekly meter readings were provided by the LLTNPA, *see appendix 1*.

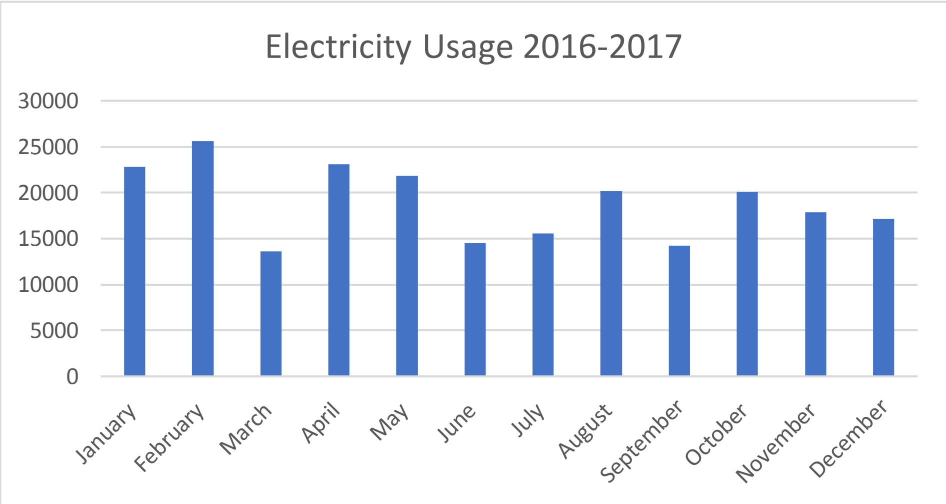


Figure 45Electricity Usage 2016-2017

5.1.2. Biomass

A calorific value for the wood chips used in the biomass boiler of 3500kWh/Tonne was provided by the LLTNPA.

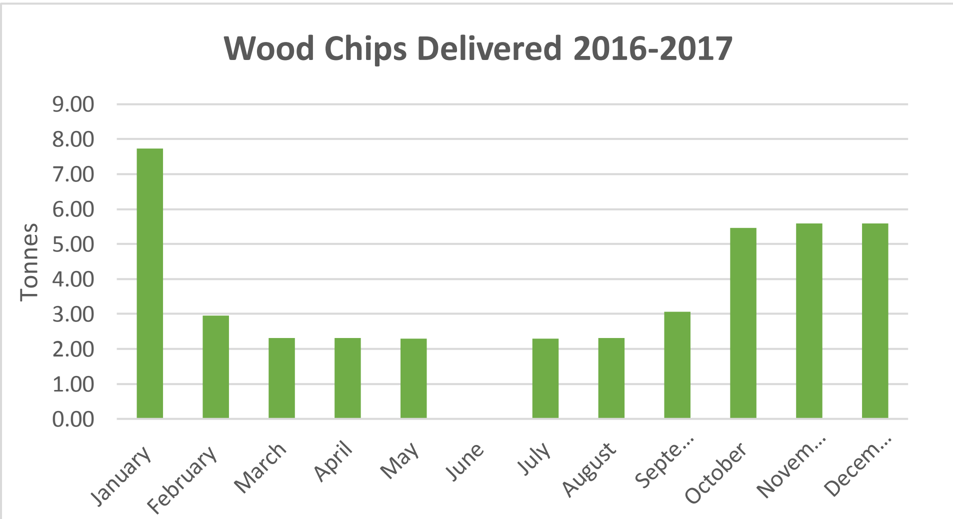
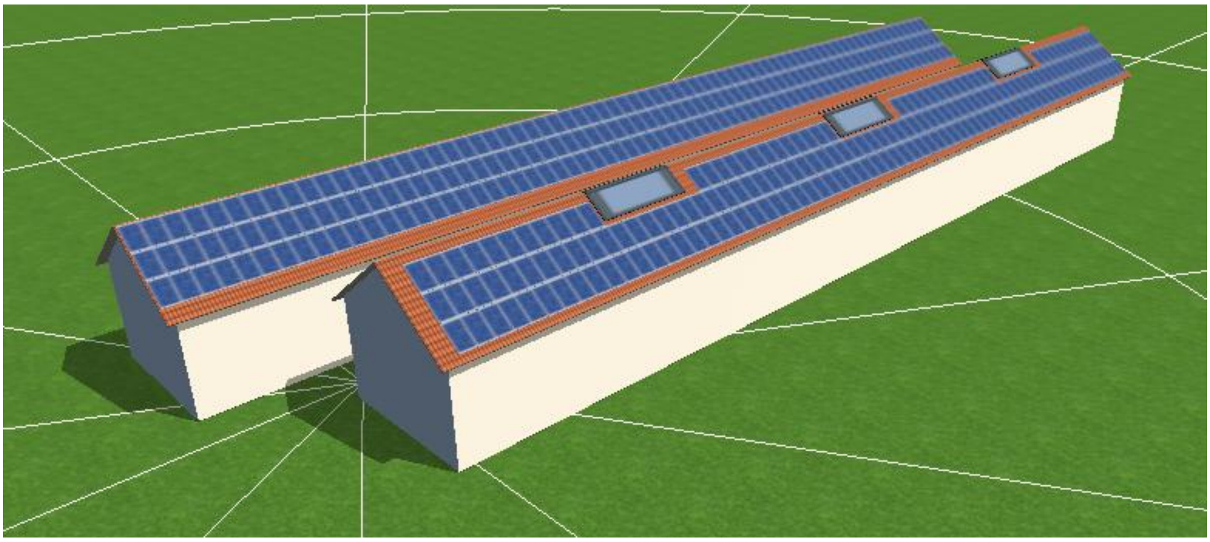


Figure 46Wood Chips Deliveries 2016-2017

5.2. Modelling Results

5.2.1. PV Simulation Results



Climate Data	GLASGOW AIRPORT (2000-2009)
PV Generator Output	79.2kWp
PV Generator Surface	664.0 m^2
Number of PV Modules	396
Number of Inverters	9

Yield		
PV Generation (AC)	70,193	kWh
PV Generation used onsite	54,852	kWh
Grid Feed-in	15,341	kWh
Spec. Annual Yield	886.27	kwh/kWp
Performance Ratio	80.2	%
Own Power Consumption	78.1	%
Calculation of Shading Losses	3.4	%/Year
CO2 Emissions A	42,136	Kg/ year

Gain		
Investment Costs	95,040.00	£
Return on Assets	11.64	%
Payback Period	9.8	Years
Electricity Production Cost	0.09	£/kWh

Consumption		
Total Consumption	215780	kWh
Peak Load	102.8	kW

PV Generator 1 Module Area		
Name	Front Roof Area South	
PV Modules	186 x Example poly 200W	
Manufacturer	PV*SOL	
Inclination	37	°
Orientation	South 180	°
Installation Type	Roof Parallel	
PV Generator Surface	311.9	m^2

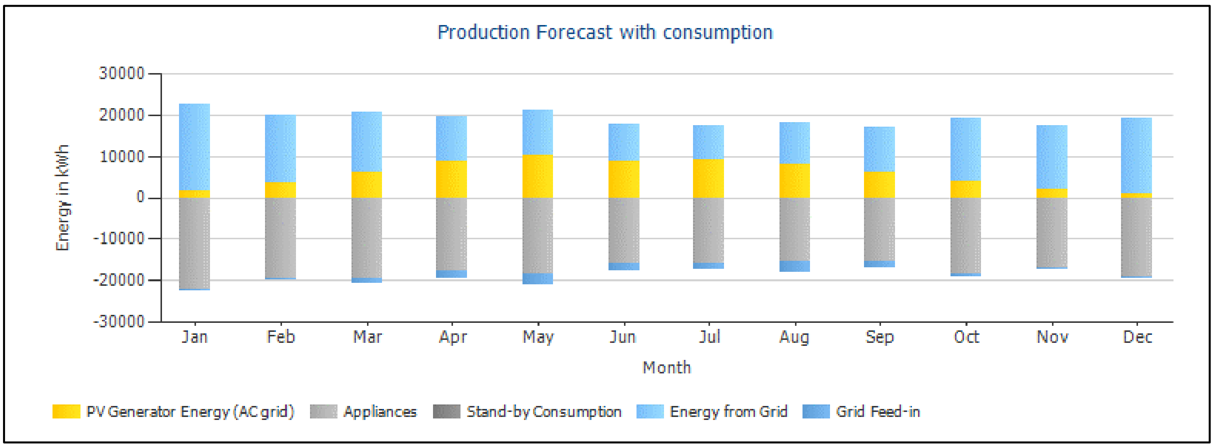
PV Generator 2 Module Area		
Name	Back Roof Area South	
PV Modules	210 x Example poly 200W	
Manufacturer	PV*SOL	
Inclination	37	°
Orientation	South 180	°
Installation Type	Roof Parallel	
PV Generator Surface	352.1	m^2

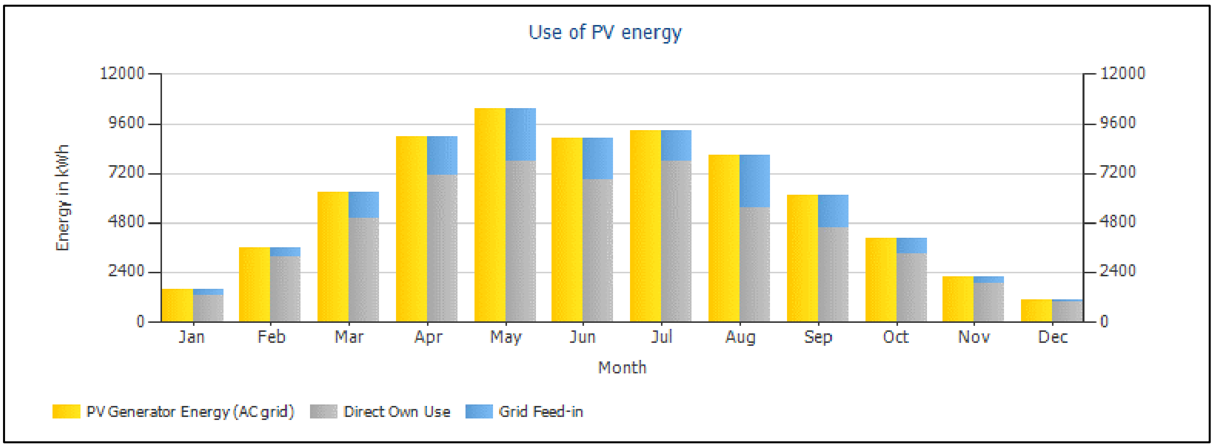
Inverters	
Module Area	**Front-Roof Area South Facing**
Inverter 1	2 x 8.0 kWh ESS AIO
Manufacturer	Hansol Technics Co. Ltd.
Configuration	MPP 1: 1 x 24|MPP 2: 1 x 23
Inverter 2*	2 x 8.0 kWh ESS AIO
Manufacturer	Hansol Technics Co. Ltd.
Configuration	MPP 1: 1 x 23|MPP 2: 1 x 23
Module Area	**Back-Roof Area South Facing**
Inverter 1*	5 x 8.0kWh ESS AIO
Manufacturer	Hansol Technics Co. Ltd.
Configuration	MPP 1: 1 x 21 |MPP 2: 1 x 21

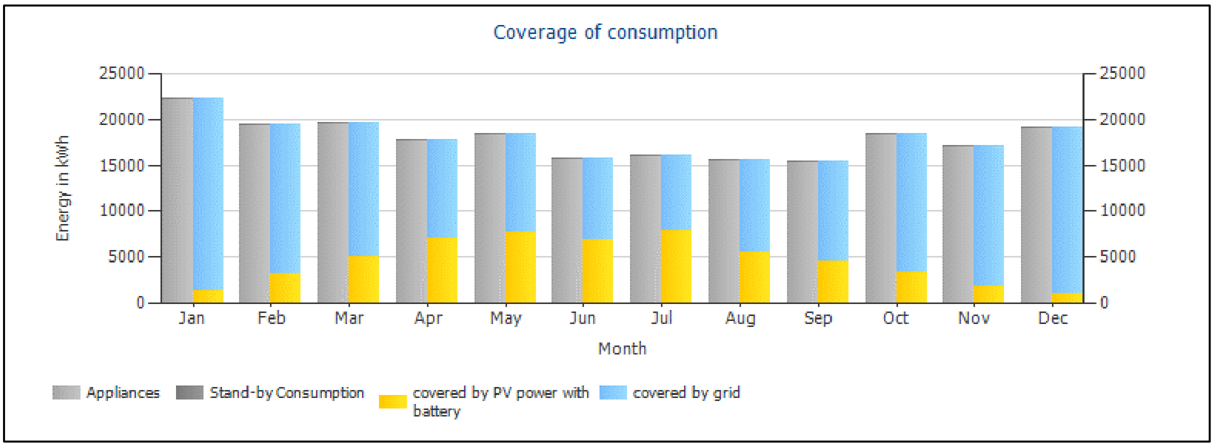
AC Mains		
Number of Phases	3	
Mains Voltage (1-Phase)	230	V
Displacement Power Factor (cos phi)	+/-1	

Simulation Results – PV SYSTEM		
PV Generator Output	79.2	kWp
Spec. Annual Yield	886.27	kWh/kWp
Performance Ratio (PR)	80.2	%
Yield Reduction due to Shading	3.4	%
PV Generator Energy (AC Grid)	70,193	kWh/year
Own Consumption	54,852	kWh/year
Grid Feed-in	15,341	kWh/year
Regulation at Feed-in Point	0	kWh/year

Own Power Consumption	78.1	%
CO_2 Emissions Avoided	42,116	Kg/year
Appliances		
Appliances	215,780	kWh
Stand by Power Consumption	16	KWh
Total Consumption	215,796	kWh/year
Covered by PV power	54,852	kWh/yea
Covered by Grid	160,944	kWh/year
Solar Fraction	25.4	%







Results per Module Area		
Front-Roof Area South Facing		
PV Generator Output	37.2	kWp
Global Radiation at Module	311.9	m 2
PV Generator Energy (AC Grid)	1107.1	kWh/m 2
Spec. Annual Yield	916.4	kWh/kWp
Performance Ratio	82.7	%
Back-Roof Area South Facing		
PV Generator Output	42	kWp
Global Radiation at Module	352.1	m 2
PV Generator Energy (AC Grid)	1103.3	kWh/m 2
Spec. Annual Yield	36104.4	kWh/kWp
Performance Ratio	77.9	%

Global Radiation – Horizontal	936.8	kWh/m^2	
Deviation from standard spectrum	-9.37	kWh/m^2	-1.00%
Ground Reflection (Abedo)	18.68	kWh/m^2	2.01%
Orientation and inclination of module surface	160.95	kWh/m^2	17.01%
Module-independent shading	-2.00	kWh/m^2	-0.18%
Reflection on the Module Interface	-48.9	kWh/m^2	-4.42%
Global Radiation at the Module	1,056.3	kWh/m^2	

1.056.3	kWh/m^2
X 663.96	m^2
= 701,348.1	kWh

Global PV Radiation	701,348.1	kWh	
Soiling	0.00	kWh	0.00%
STC Conversion (Rated Efficiency of Module 11.93%)	-617,648.76	kWh	- 88.07%
Rated PV Energy	83,699.3	kWh	
Module-specific Partial Shading	-1877.84	KWh	-2.24%
Low-Light performance	811.82	kWh	0.99%
Deviation from the nominal module temperature	-1,019.08	kWh	-1.23%
Diodes	-3230.16	kWh	-3.96%

Mismatch (Manufacturer Information)	-1,567.68	kWh	-2.00%
Mismatch (Configuration/Shading)	-149.80	kWh	-0.20%
PV Energy (DC)without inverter regulation	**76,666.6**	**kWh**	
Regulation on account of the MPP Voltage Range	-343.80	kWh	-0.45%
Regulation on account of the max DC current	0.00	kWh	0.00%
Regulation on account of the max DC Power	0.00	kWh	0.00%
Regulation on account of the AC Power/cos phi	-219.20	kWh	-0.29%
MPP Matching	-14.5	kWh	-0.02%
PV energy (DC)	**76,089.1**	**kWh**	

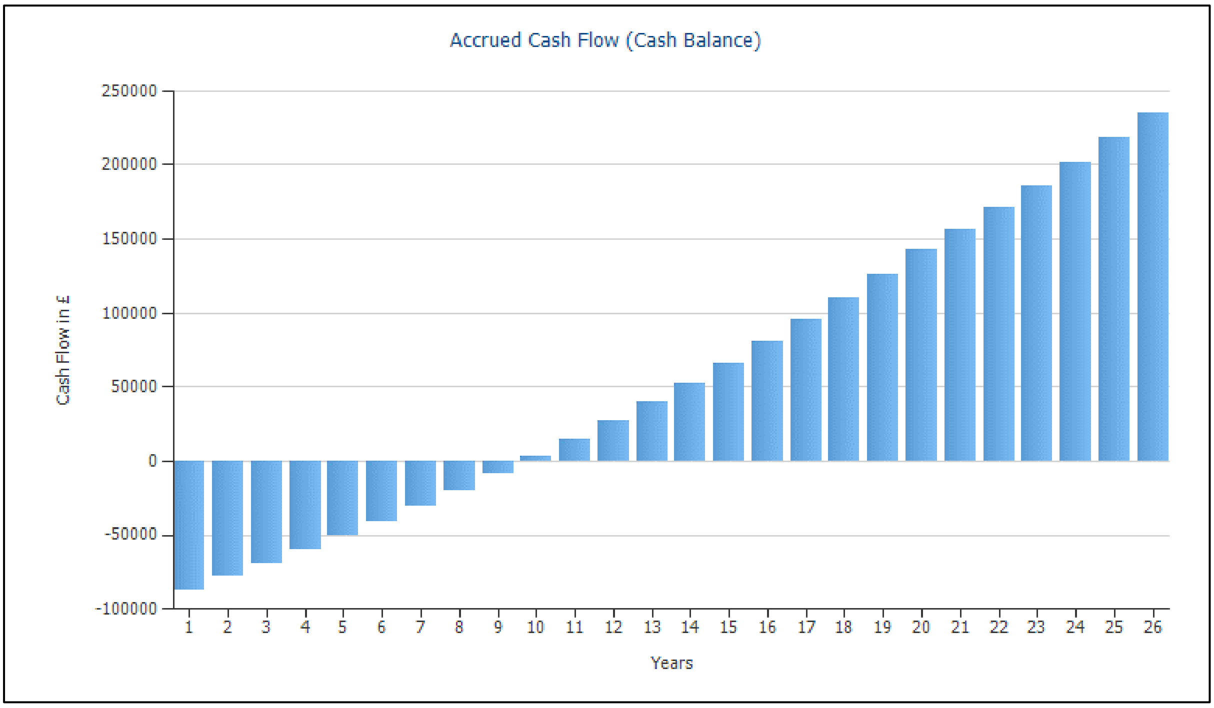
Financial Analysis

System Data		
Grid Feed-in	15,341	kWh/year
PV Generator Output	79.2	kWp
Start of Operation Date	07/08/2017	
Lifespan	25	Years
Economic Parameters		
Return on Assets	11.64	%
Accrued Cash Flow	235,281.13	£
Amortization Period	9.8	Years
Electricity Production Cost	0.09	£/kWh
Payment Overview		
Specific Investment Costs	1,200.00	£/kWp
Investment Costs	95,040.00	£
One -off Payments	0.00	£
Incoming Subsidies	0.00	£
Annual Costs	1900,80	£/year
Other Revenue or Savings	0.00	£/year

Remuneration and Savings

Total Payments from Utility in First Year	3,165.13	£/year
First Year Savings	7,128.71	£/year
FIT 2016 (Oct.-Dec.)Higher Rate-Export tariff with 50% deeming – Building Attached		
Validity	07/08/2017	06/08/2037
Specific generation remuneration	0.0491	£/kWh
Generation Tariff	1,732.53	£/year
Inflation Rate for Generation Tariff	1.00	%/year
FIT 2016 (Oct.-Dec.)Higher Rate-Generation tariff with 50% deeming – Building Attached		
Valididty	07/08/2017	06/08/2037
Specific generation remuneration	0.0203	£/kWh
Generation Tariff	1,432.60	£/year
Inflation Rate for Generation Tariff	1.00	%/year
SDC Example Energy Tariff (Example)		

Energy Price	0.13	£/kWh
Base price	4.47	£/month
Inflation for Energy Prices	5	%/year



	year 1	year 2	year 3	year 4	year 5
Investments	-£95,040.00	£0.00	£0.00	£0.00	£0.00
Operating costs	-£1,881.98	-£1,863.35	-£1,844.90	-£1,826.63	-£1,808.55
Feed-in / Export Tariff	£3,064.40	£3,133.94	£3,134.08	£3,134.22	£3,134.37
Electricity Savings	£7,058.13	£7,337.66	£7,628.26	£7,930.37	£8,244.44
Annual Cash Flow	-£86,799.46	£8,608.25	£8,917.44	£9,237.96	£9,570.26
Accrued Cash Flow (Cash Balance)	-£86,799.46	-£78,191.21	-£69,273.77	-£60,035.81	-£50,465.55
	year 6	year 7	year 8	year 9	year 10
Investments	£0.00	£0.00	£0.00	£0.00	£0.00
Operating costs	-£1,790.64	-£1,772.91	-£1,755.36	-£1,737.98	-£1,720.77
Feed-in / Export Tariff	£3,134.51	£3,134.65	£3,134.79	£3,134.94	£3,135.08
Electricity Savings	£8,570.96	£8,910.40	£9,263.28	£9,630.14	£10,011.54
Annual Cash Flow	£9,914.83	£10,272.14	£10,642.72	£11,027.10	£11,425.85
Accrued Cash Flow (Cash Balance)	-£40,550.72	-£30,278.58	-£19,635.86	-£8,608.76	£2,817.09
	year 11	year 12	year 13	year 14	year 15
Investments	£0.00	£0.00	£0.00	£0.00	£0.00
Operating costs	-£1,703.73	-£1,686.86	-£1,670.16	-£1,653.63	-£1,637.25
Feed-in / Export Tariff	£3,135.22	£3,135.36	£3,135.51	£3,135.65	£3,135.79
Electricity Savings	£10,408.04	£10,820.23	£11,248.76	£11,694.25	£12,157.40
Annual Cash Flow	£11,839.53	£12,268.73	£12,714.10	£13,176.28	£13,655.94
Accrued Cash Flow (Cash Balance)	£14,656.62	£26,925.35	£39,639.45	£52,815.73	£66,471.67
	year 16	year 17	year 18	year 19	year 20
Investments	£0.00	£0.00	£0.00	£0.00	£0.00
Operating costs	-£1,621.04	-£1,604.99	-£1,589.10	-£1,573.37	-£1,557.79
Feed-in / Export Tariff	£3,135.94	£3,136.08	£3,136.22	£3,136.36	£3,136.51
Electricity Savings	£12,638.87	£13,139.43	£13,659.79	£14,200.78	£14,763.18
Annual Cash Flow	£14,153.77	£14,670.51	£15,206.91	£15,763.77	£16,341.90
Accrued Cash Flow (Cash Balance)	£80,625.43	£95,295.94	£110,502.86	£126,266.63	£142,608.53
	year 21	year 22	year 23	year 24	year 25
Investments	£0.00	£0.00	£0.00	£0.00	£0.00
Operating costs	-£1,542.37	-£1,527.10	-£1,511.98	-£1,497.01	-£1,482.18
Feed-in / Export Tariff	£0.00	£0.00	£0.00	£0.00	£0.00
Electricity Savings	£15,347.87	£15,955.71	£16,587.61	£17,244.55	£17,927.50
Annual Cash Flow	£13,805.50	£14,428.61	£15,075.64	£15,747.54	£16,445.32
Accrued Cash Flow (Cash Balance)	£156,414.03	£170,842.64	£185,918.28	£201,665.82	£218,111.14

	year 26				
Investments	£0.00				
Operating costs	-£1,467.51				
Feed-in / Export Tariff	£0.00				
Electricity Savings	£18,637.50				
Annual Cash Flow	£17,169.99				
Accrued Cash Flow (Cash Balance)	£235,281.13				
Degradation and inflation rates are applied on a monthly basis over the entire observation period.					
This is done in the first year.					

PV Module Details:

Manufacturer	PV*SOL	
Electrical Data		
Cell Type	Si Polycrystalline	
Only Transformer Inverters Suitable?	No	
Number of Cells	60	
Number of Bypass diodes	3	
Mechanical Data		
Width	1001	mm
Height	1675	mm
Depth	38	mm
Weight	30	mm
Framed	22	kg
I/V characteristics at STC		
MPP Voltage	28.3	V
MPP Current	7.07	A
Nominal Output	200	W
Open Circuit Voltage	36.1	V
Short-Circuit Current	7.7	A
Increase Open Circuit Voltage before Stabilisation	0	%
I/V Part Load Characteristics (Calculated)		
Values source	Standard (2-diode model)	
Series resistance Rs	7.51e-03	Ω
Parallel resistance Rp	1.802	Ω
Saturation Current Parameters Cs1	195.8	A/K^3
Saturation Current Parameters Cs2	-1.459e-13	A/K^(2,5)
Photocurrent Parameters C1	6.957e-o3	m^2/V
Photocurrent Parameters C2	2.6e-06	m^2/V
Photocurrent	7.732	A
Further		
Voltage Coefficient	-123	mV/K
Electricity Coefficient	2.6	mA/K
Output Coefficient	-0.4	%/K
Incident Angle Modifier	95	%
Maximum System Voltage	1000	V
Spec. Heat Capacity	920	J(kg*K)
Absorption Coefficient	70	%
Emissions Coefficient	85	%

Inverter Details: 8.0kWh ESS AIO		
Manufacturer	Hansol Technics Co.Ltd.	
Available	Yes	
Electrical Data		
DC Power Rating	10	kW
AC Power Rating	8	kW
Max. DC Power	10	kW
Max. AC Power	8	kW
Stand-by Consumption	0.4	W
Night Consumption	0.4	W
Feed-in from	2	W
Max. Input Current	32	A
Max. Input Voltage	1000	V
Nom. DC Voltage	800	V
Number of feed-in phases	3	
Number of DC Inlets	2	
With Transformer	No	
Change in Efficiency when Input Voltage deviates from Rated Voltage?	No	
MPP Tracker		
Output Range <20% of Power Rating	99.9	%
Output Range>20% of Power Rating	100	%
No. of MPP Trackers	2	
Max. Input Current MPP Tracker	16	A
Max. Input Power per MPP Tracker	5	kW
Min. MPP Voltage	320	V
Max. MPP Voltage	800	V

5.2.2. T*SOL Online Calculator Results

Type of Collector	Flat Plate	Tube Collectors	Flat Plate	Tube	Unit
Inputs					
Orientation	South	South	South	South	
Area of Collectors	10	10	50	50	m^2
Pitch	40	40	40	40	º
Number of People	12	12	60	60	
Location	United Kingdom	United Kingdom	United Kingdom	United Kingdom	
City	Edinburgh	Edinburgh	Edinburgh	Edinburgh	
Tank Size	2000	2000	10000	10000	litres
Boiler Fuel Type	Biomass (wood chip)	Biomass (wood chip)	Biomass (wood chip)	Biomass (wood chip)	
Floor Area	240	240	1200	1200	m^2
Insulation level (low or medium)	medium	medium	medium	medium	
Outputs					
Irradiation	10.41	10.41	104.1	104.1	kWh/a
System Yield	3.590	4.333	17.950	21.665	kWh/a
Solar Fraction	10	13	10	13	%
CO2 Savings	0	0	0	0	kg/a
Efficiency	34.5	41.6	34.5	41.6	%

5.2.3. EnergyPRO Results

Calculated period: 01/2016 - 12/2016

Heat demands:

Heating Demand Supplied by Biomass	192.4 MWh	
Max heat demand	0.1 MW	

Heat productions:

Biomass Boiler	86.3 MWh/year	44.9 %
Natural Gas Boiler	0.0 MWh/year	0.0 %
Solar photovoltaic	0.0 MWh/year	0.0 %
Evacuated tube solar collector	97.1 MWh/year	50.5 %
Electric Immersion	8.9 MWh/year	4.6 %
Total	192.3 MWh/year	100.0 %

Electricity demands (not including electricity consumed by energy units):

New Electricity demand	216.0 MWh
Max electricity demand	0.2 MW

Electricity produced by energy units:

National Grid Connection:

	Day Rate [MWh/year]	All periods [MWh/year]	Of annual production
Solar photovoltaic	58.4	58.4	100.0%

Electricity consumed by energy units:

National Grid Connection:

	Day Rate [MWh/year]	Of annual [MWh/year]
Electric Immersion	8.9	8.9

Peak electric production:

Solar photovoltaic	49.2 kW-elec.

Electricity exchange:

National Grid Connection:

	Day Rate [MWh/year]	Total [MWh/year]
Exported electricity, National Grid Connection	12.2	12.2
Imported electricity, National Grid Connection	178.7	178.7

Hours of operation:

National Grid Connection:

	Day Rate [h/Year]	Total [h/Year]	Of annual hours
Solar photovoltaic	4,882.0	4,882.0	55.6%
Electric Immersion	1,777.0	1,777.0	20.2%
Out of total in period	8,784.0	8,784.0	

Production unit(s) Not connected to electricity market:

	Total [h/Year]	Of annual hours
Biomass Boiler	980.0	11.2%
Natural Gas Boiler	0.0	0.0%
Evacuated tube solar collector	4,318.0	49.2%
Out of total in period	8,784.0	

Turn ons:

Biomass Boiler	168
Natural Gas Boiler	0
Solar photovoltaic	568
Evacuated tube solar collector	527
Electric Immersion	262

Fuels:

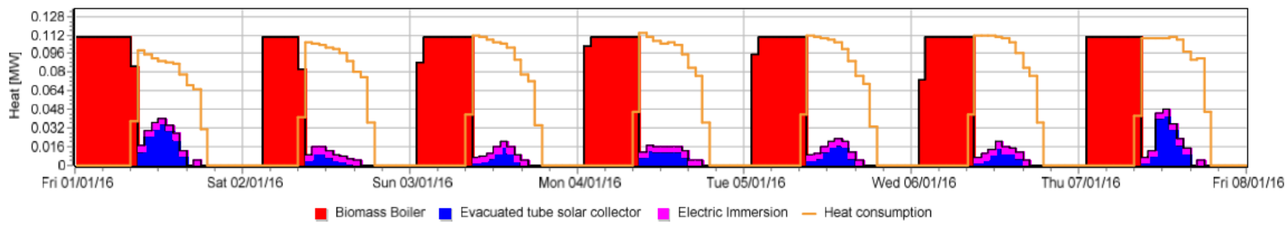
By fuel

	Fuel consumption
Wood Chips	24.7 Tonne
Natural Gas	0.0 m3

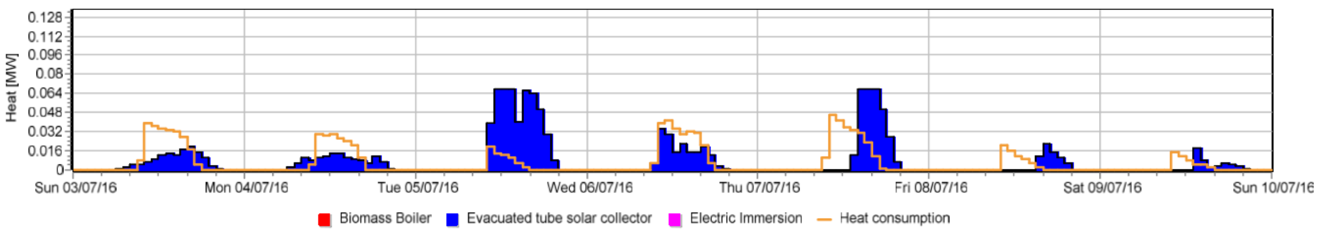
By energy unit

Biomass Boiler	86.3 MWh	=24.7	Tonne
Natural Gas Boiler	0.0 MWh	=0.0	m3
Solar photovoltaic	0.0 MWh	=0.0	----
Evacuated tube solar collector	0.0 MWh	=0.0	----
Electric Immersion	0.0 MWh	=0.0	----
Total	86.3 MWh		

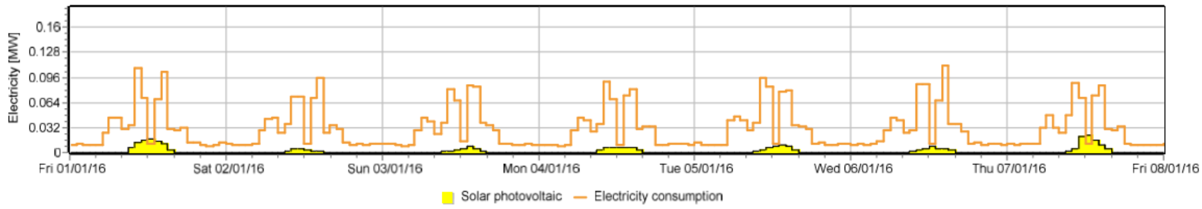
Winter week supply and demand of heat:



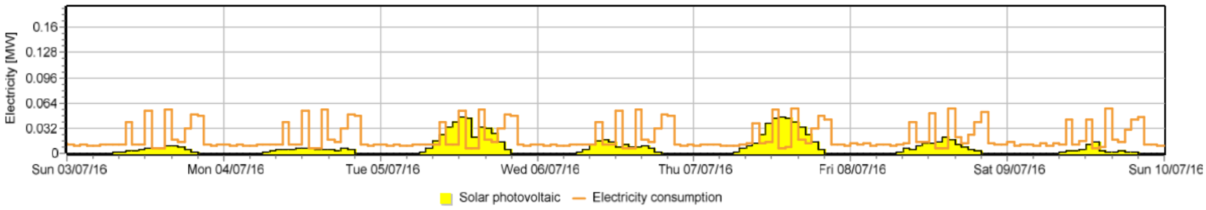
Summer week supply and demand of heat:



Winter week electrical supply and demand profile:



Summer week electrical supply and demand profile:



5.3. Load Management

The first stage in load management requires determining what a typical load profile for the site is. Hourly meter readings were manually taken for a typical summer working week day, *see appendix 2*, and used to generate the load profile shown below in Figure 47.

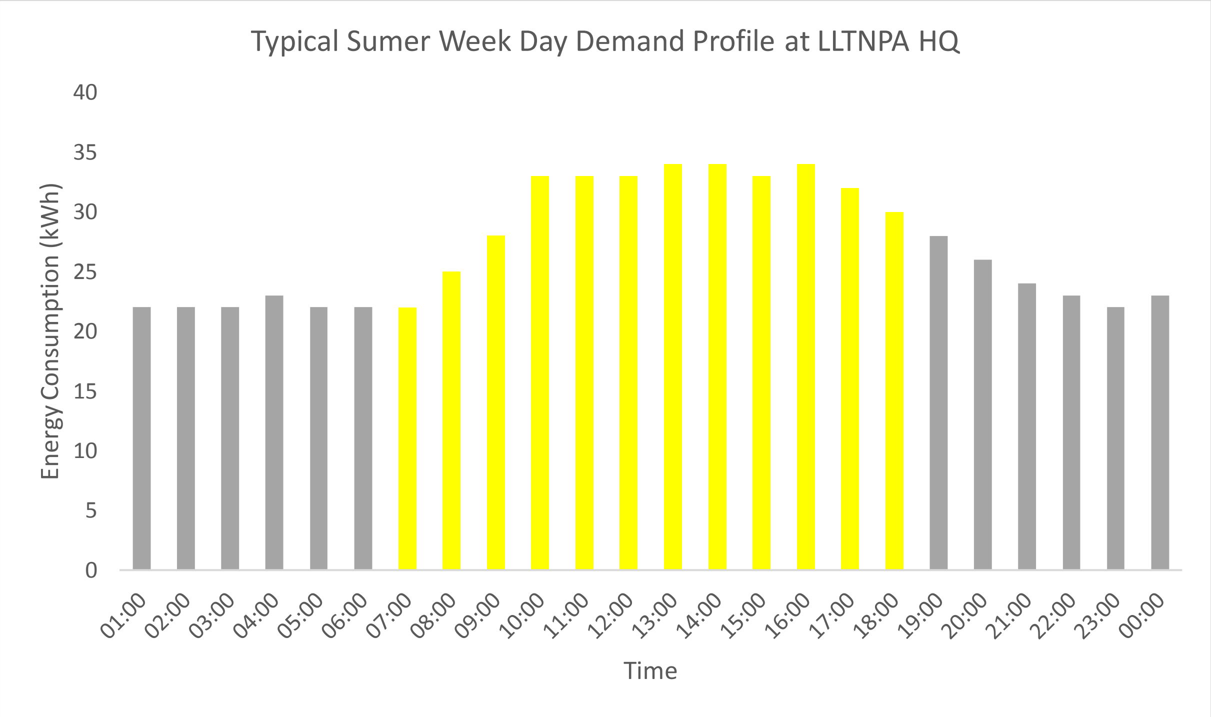


Figure 47 Typical Sumer Week Day Demand Profile at LLTNPA HQ

In Figure 47 the yellow bars represent data collected onsite and the grey bars are estimated values using the following approach.

An average consumption value for the whole day was estimated from August 2016, weekly electricity meter readings provided by the LLTNPA.

The sum of electricity usage recorded whilst onsite between 7AM and 6PM was then subtracted from the estimated daily value. This difference could then be distributed between the hours that were not metered in the day to produce the demand profile in Figure 47.

As shown in Table 4, the electricity consumption for August in 2016 was 20177kWh. This gives a daily average of 650 kWh.

Total recorded usage during hours onsite = 343kWh

Difference to be split between remaining hours =650-343=**307kWh**

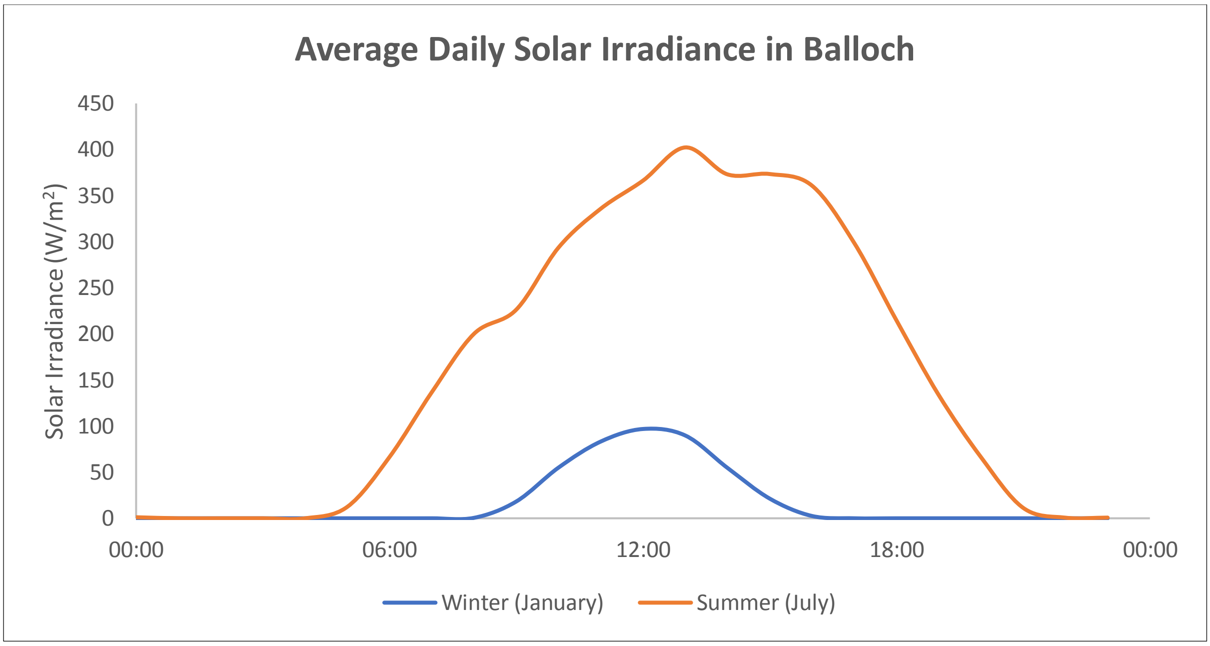


Figure 48 Average Daily Solar Irradiance in Balloch Winter and Summer

The profile of the solar generation in Figure 48 matches relatively well with the electrical demand profile developed in Figure 47 as they rise towards a peak around midday.

To determine where the highest loads were occurring individual meter data was recorded, see appendix 1. Energy usage from the individual circuits was then plotted in Figure 49.

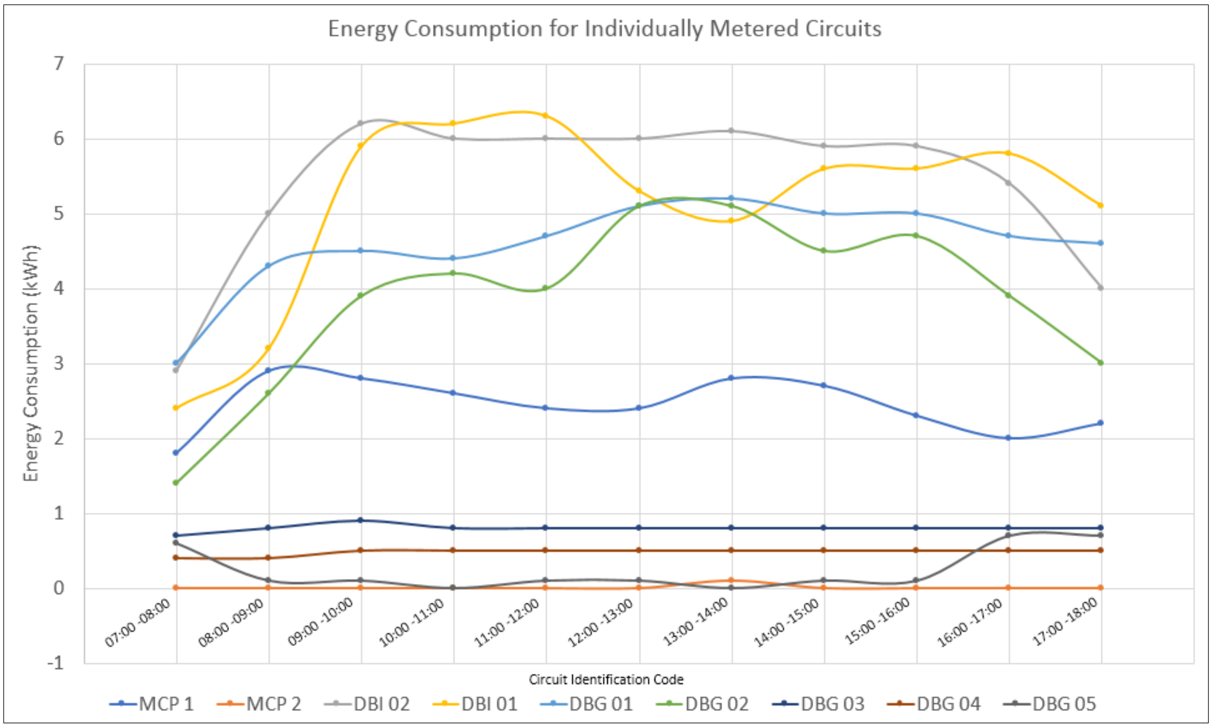


Figure 49 Energy Consumption for Individually Metered Circuits Summer Week Day August 2017

Table 5 Relative Energy Consumption of Individually Metered Circuits

	Circuit I.D.	Energy Consumption (kWh) 07:00-18:00 22/8/2017
Highest Energy	DBI 02	59.4
Consumption	DBI 01	56.3
↓	DBG01	50.5
	DBG02	42.4
	MCP 1	26.9
	DBG03	8.8
Lowest Energy	DBG04	5.3
Consumption	MCP2	2.6

It can be observed from Figure 49 Energy Consumption for Individually Metered Circuits Summer Week Day August 2017 and Table 5 Relative Energy Consumption of Individually Metered Circuits that Circuits that DBI 02, DBI 01 and DBG 01 have the highest energy consumption.

To find out what these loads were likely to be the building electrical charts were consulted along with observations made onsite.

Table 6 Appliances on Highest Power Consuming Circuits and Observations Made On-site at Time of Collecting Energy Consumption Data

Description	**Observations**
DBI 02	
Floor Boxes	Computers and Printers
4 Trench Heaters	Heating not in use
Staircase Liughting	Lighting on - plenty of daylight
Uplights in Planning office/ Visitor area	All uplights on
Lighiting Visitor and Op office	On all day
Floor lights – circulation	On all day
DBI 01	
Floor Socket Boxes	Computers
DBG 01	
Reception supply	
Fitness room	Not in Use
Induction loop reception	Unknown
Ring Circuit - Locker room	Minimally used
Ring circuit planning records	Not in Use
Hand dryer male toilets	Sporadic
Hand dryer female toilets	Sporadic
Ring circuit corridor	
Access controllers	Low powered
Overdoor Heater	Not in Use
Hand dryer disabled toilet	No Hand dryer present?
Touchdown & heating room	Motion controlled lights in use
Lighting - Library	uplighters on although plenty of daylight
Lighting - reception and security	significant and on throughout day
lighting - circulation	-
Lighting - fitness and First aid room	Not in Use

6.Conclusion

The system proposed in the project resulted in approximately 50% of the heat demand being generated from renewable sources on site and approximately 25% of the electrical demand being met with PV. The project also identified that load management could be improved which would further reduce the running costs and environmental impact of the building. Data was successfully collected from the LLTNP HQ to determine the current energy demand. A Resource assessment and site survey were carried out to determine what types of renewable technologies may be suitable. Financial analysis was carried out for the PV, however further work is required to cost the solar thermal system.

A daily demand profile was developed for the LLTNP HQ through detailed meter data collection. Circuits with the highest loads were identified through analyzing this high-resolution meter data and specific load types identified by referring to the respective electrical charts for the building.

7. Future Work

This section is to suggest parts of the thesis that could be built upon. If this work were to be taken further it would be good to carry out deeper sensitivity analysis on some of the variables used for modelling the solar thermal and PV system. It would also be interesting to model a greater number of different renewable technologies alongside load management to optimise a building such as the LLTNP HQ.

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9.Appendices

9.1. Appendix 1: Individual meter readings

Recorded on Tuesday the 22nd of August 2017.

	INDIVIDUAL CIRCUIT METER READINGS									
	MCP 1	**MCP 2**	**DBI 02**	**DBI 01**	**DBG 01**	**DBG 02**	**DBG 03**	**DBG 04**	**DBG 05**	**SUM**
Unit	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh
07:15	137140	69365.4	301014	308612	329393	183784	74240.9	52840.6	92173.1	
08:00	137142	69365.4	301016	308615	329396	183786	74241.6	52841	92173.7	
Δ	1.8	0	2.9	2.4	3	1.4	0.7	0.4	0.6	13.2
09:00	137145	69365.4	301021	308618	329400	183788	74242.4	52841.4	92173.8	
Δ	2.9	0	5	3.2	4.3	2.6	0.8	0.4	0.1	19.3
10:00	137148	69365.4	301028	308624	329405	183792	74243.3	52841.9	92173.9	
Δ	2.8	0	6.2	5.9	4.5	3.9	0.9	0.5	0.1	24.8
11:00	137150	69365.4	301034	308630	329409	183797	74244.1	52842.4	92173.9	
Δ	2.6	0	6	6.2	4.4	4.2	0.8	0.5	0	24.7
12:00	137153	69365.4	301040	308636	329414	183801	74244.9	52842.9	92174	
Δ	2.4	0	6	6.3	4.7	4	0.8	0.5	0.1	24.8
13:00	137155	69365.4	301046	308641	329419	183806	74245.7	52843.4	92174.1	
Δ	2.4	0	6	5.3	5.1	5.1	0.8	0.5	0.1	25.3
14:00	137158	69365.5	301052	308646	329424	183811	74246.5	52843.9	92174.1	
Δ	2.8	0.1	6.1	4.9	5.2	5.1	0.8	0.5	0	25.5
15:00	137161	69365.5	301058	308652	329429	183815	74247.3	52844.4	92174.2	
Δ	2.7	0	5.9	5.6	5	4.5	0.8	0.5	0.1	25.1
16:00	137163	69365.5	301064	308658	329434	183820	74248.1	52844.9	92174.3	
Δ	2.3	0	5.9	5.6	5	4.7	0.8	0.5	0.1	24.9
17:00	137165	69365.5	301069	308663	329439	183824	74248.9	52845.4	92175	
Δ	2	0	5.4	5.8	4.7	3.9	0.8	0.5	0.7	23.8
18:00	137167	69365.5	301073	308668	329443	183827	74249.7	52845.9	92175.7	
Δ	2.2	0	4	5.1	4.6	3	0.8	0.5	0.7	20.9
									TOTAL	252.3

9.2. Appendix 2: Electricity meter reading data 2016-2017 fiscal year.

Date	Meter Reading	Energy Use (kWh)
28/03/16	108666	
04/04/16	117746	9080
11/04/16	124555	6809
18/04/16	126686	2131
25/04/16	131756	5070
02/05/16	135469	3713
09/05/16	139974	4505
16/05/16	143951	3977
23/05/16	148103	4152
30/05/16	153594	5491
06/06/16	156833	3239
13/06/16	157300	467
20/06/16	162000	4700
27/06/16	168129	6129
04/07/16	172106	3977
11/07/16	176007	3901
18/07/16	179009	3002
25/07/16	183723	4714
01/08/16	187568	3845
08/08/16	191742	4174
15/08/16	195314	3572
22/08/16	202927	7613
29/08/16	203900	973
05/09/16	206529	2629
12/09/16	209954	3425
19/09/16	214569	4615
26/09/16	218108	3539
03/10/16	222090	3982
10/10/16	225957	3867
17/10/16	229895	3938
24/10/16	234637	4742
31/10/16	238187	3550
07/11/16	242370	4183
14/11/16	246928	4558
21/11/16	251342	4414
28/11/16	256047	4705
05/12/16	261144	5097

12/12/16	264714	3570
19/12/16	269706	4992
26/12/16	273206	3500
02/01/17	276406	3200
09/01/17	280333	3927
16/01/17	287482	7149
23/01/17	288551	1069
30/01/17	295209	6658
06/02/17	299001	3792
13/02/17	303822	4821
20/02/17	2476	2476
27/02/17	6208	3732
06/03/17	9796	3588
13/03/17	13074	3278
20/03/17	16001	2927
27/03/17	20155	4154
03/04/17	23100	2945

	215780	kWh
1/4/2016 -31/3/2017	215.78	MWh

9.3. Appendix 3: Wood Chip Deliveries 2016-2017 Fiscal Year

Date	Wood Chips Deliveries (Tonnes)
04/01/16	2.54
11/01/16	2.52
18/01/16	2.68
01/02/16	2.62
15/02/16	3.48
22/02/16	3.58
14/03/16	2.96
18/04/16	2.32
02/05/16	2.32
11/07/16	2.3
15/08/16	2.31
19/09/16	3.07
17/10/16	2.93
31/10/16	2.537
14/11/16	3.03
21/11/16	2.56
05/12/16	2.66
19/12/16	2.93
02/01/17	2.25
09/01/17	2.55
16/01/17	2.77
23/01/17	2.55
30/01/17	3.17
13/02/17	3.07
20/02/17	3.13
03/03/17	3.06
06/03/17	2.25
13/03/17	2.11
24/03/17	2.55

Total	**78.81 Tonnes**

9.4. Appendix 3: Natural Gas Usage 2016-2017 Fiscal Year

Date	Meter Reading	Weekly usage (kWh)
04/04/16	28420	0
11/04/16	28420	0
18/04/16	28420	0
25/04/16	28420	0
02/05/16	28420	0
09/05/16	28420	0
16/05/16	28420	0
23/05/16	28420	0
30/05/16	28420	0
06/06/16	28420	0
13/06/16	28420	0
20/06/16	28420	0
27/06/16	28420	0
04/07/16	28420	0
11/07/16	28420	0
18/07/16	28420	0
25/07/16	28420	0
01/08/16	28420	0
08/08/16	28420	0
15/08/16	28420	0
22/08/16	28420	0
29/08/16	28420	0
05/09/16	28420	0
12/09/16	28420	0
19/09/16	28420	0
26/09/16	28421	1
03/10/16	28421	0
10/10/16	28421	0
17/10/16	28421	0
24/10/16	28421	0
31/10/16	28421	0
07/11/16	28421	0
14/11/16	28421	0
21/11/16	28421	0
28/11/16	28421	0
05/12/16	28421	0

12/12/16	28421	0
19/12/16	28421	0
26/12/16	28572	151
02/01/17	28762	190
09/01/17	28869	107
16/01/17	29070	201
23/01/17	29076	6
30/01/17	29076	0
06/02/17	29076	0
13/02/17	29076	0
20/02/17	29076	0
27/02/17	29292	216
06/03/17	29292	0
13/03/17	29292	0
20/03/17	29292	0
27/03/17	29400	108

	Total	**980** kWh