Department of Mechanical and Aerospace Engineering

Assessment and Selection Process of Energy Technologies for a Future Energy System for the HALO Sustainable District

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Abstract

The project's aim is to develop an energy system for a residential and working district in the town centre of Kilmarnock. The district is planned by the HALO initiative that aims to revitalise urban areas in the UK. In order to supply clean and reliable energy, a system consisting of renewable electricity supply technologies, district heating, passive cooling as well as electrification of transport was developed.

Energy systems for ecovillages and comparable sustainable town districts vary worldwide. To begin, different demonstration projects in the UK and Germany as well as state-of-the-art technologies were researched with regard to an implementation for the HALO Kilmarnock project. This was followed by a site-specific assessment of the technologies in order to evaluate technical and public restrictions on the specific project site. The subsequent modelling methodology consisted of two parts. The first part was the development of demand profiles in order to create exemplary future energy consumption. For this the profile designer in a software called Merit was used. The second part was an investigation on the ideal combination of different technologies which can match the before-mentioned demand profiles. The energy system modelling software energyPRO was used in a scenario-based approach to match and investigate the demand of electricity, heating and cooling of the energy system, respectively.

This high-level scoping study concluded that a combination of PV panels with additional grid connection can supply enough electricity for the town quarter buildings and the planned 30 electric vehicles. A district heating system with an air source heat pump can supply sufficient heat for the district and therefore the electrification of heat was possible to be incorporated without exceeding the on-site grid limitation. Passive cooling was considered to be the most energy efficient option. Since the PV panels produce a high surplus in summer the installation of electric chillers would be a feasible option as well. In the end, future work needs to be carried out in order to investigate in detail the performance of the heat pump and to define component sizes. Cooling requirements for the non-domestic buildings need to be specified and considered while designing the buildings of the residential and working district in Kilmarnock.

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Table of contents

List of figures

List of tables

Acronym definitions

AC	Absorption chiller
ASHP	Air source heat pump
BAT	Battery
BREEAM	Building Research Establishment Environmental Assessment Method
CHP	Combined heat power
CIBSE	Chartered Institution of Building Services Engineers
COP	Coefficient of Performance
CO_2	Carbon dioxide
CS	Cold storage
EB	Electric boiler
EC	Electric chiller
ESRU	Energy Systems Research Unit
EV	Electric vehicle
GSHP	Ground source heat pump
HP	Heat Pump
HSA	Hot sedimentary aquifer
KPI	Key Performance Indicator
LEED	Leadership in Energy and Environmental Design
PV	Photovoltaic
ST	Solar thermal
SWSHP	Surface water source heat pump
TS	Thermal storage
WSHP	Water source heat pump
WSPT	Wind Speed Prediction Tool

1 Introduction

1.1 Background

Today's world experiences a shift towards a more sustainable way of living. Reasons for that are the increasing CO_2 emissions, poor air, soil and water quality as well as the depletion of finite resources. To tackle and even extend these issues people all over the world gather together in so-called ecovillages to live a sustainable life.

Figure 1 The four dimensions of sustainability [1]

Ecovillages are communities that dedicate their development towards a sustainable way. They decided to regenerate the environment they live in while fulfilling the four dimensions of sustainability that are ecology, economy, social and culture (Figure 1). Today, these settlements serve as demonstration sites for a sustainable and harmonious way of living. The holistic understanding of sustainability can be executed in different ways. Some ecovillages focus on a traditional way of living using techniques for electricity and food production from a century ago. Other communities use state-of-the-art technology to reduce the environmental impact as much as possible [2]. One well-known example is Findhorn ecovillage in Scotland that started refurbishing their village several years ago and enjoy high reputation since then. But there are also other enterprises that seek to be a role-model in sustainable town design, one of which is HALO. HALO is an innovative revitalisation and regeneration initiative that aims to refurbish urban and depleted old industry areas all over the UK. In Scotland the first of four planned site refurbishments started in the town centre of Kilmarnock, the former production site of the Johnnie Walker distillery. In order to support the local economy as well as approaching economic transformation the project seeks to create a town quarter that is dedicated to living, leisure and work. The 28-acre area will consist of an Enterprise and Innovation Hub, 210 dwellings, additional live and work studios and some more leisure and working areas. The HALO initiative intends to stimulate entrepreneurial businesses, facilitate learning and attract young people to work and live in this innovation centre [3].

The vision of the HALO initiative goes along with the current trend of building and refurbishing town quarters to innovative and sustainable ecovillages. To tackle the idea of decreasing the energy footprint of each inhabitant ecovillages need to integrate a reliable energy system in order to provide electricity, heating and cooling as well as the electrification of transport. Besides the reduction of emissions, there are additional factors that support the integration of a district energy system to benefit the environment like increasing conversion efficiency and usage of heat that would have been wasted otherwise [4]. For that reason, an assessment and selection process for energy technologies was established to create an energy system for the HALO sustainable district. Future possibilities include on-site electricity production, a low-carbon district heating and cooling system as well as electric vehicles (EV). To this stage a district heating network consisting of a geothermal well with a depth of 2,000 m (in combination to a heat exchanger or ground source heat pump) and a grid connection with a limitation of 2,000 kVA for electricity supply were planned. The investigation in this thesis considered those technologies and focused on even more sustainable solutions for the future energy system. The Kilmarnock project itself is divided up into two phases. This master project focused in detail on solutions for Phase I that includes the Innovation and Enterprise Hub and 70 dwellings. After gaining results for this phase, the adaptability of the system was appraised in order to incorporate more buildings (Phase II). An energy system that can be easily expanded is the preferable outcome.

1.2 Overall Aim

The overall aim of this master thesis was the development of an energy system for the HALO sustainable district in order to harness the integration of renewable and sustainable energy technologies in ecovillages. The energy system will consist of energy supply from renewables (besides an available grid connection) as well as district heating technologies, cooling strategies, storage options and electric vehicles (EV). The following objectives were met in order to achieve the aim:

- Screen energy technologies for an energy system in terms of availability and usability.

- Assess energy technologies towards their suitability for a specific location in order to develop feasible energy system configurations.
- Create demand profiles for the Kilmarnock quarter to display sufficient energy consumption.
- Evaluate the energy system configurations with an energy modelling software in order to assess the technical feasibility and align the demand and supply match for a future integration into the HALO sustainable district.
- Select feasible technologies and recommend a future energy system in order to supply clean and reliable energy for the sustainable district.

The research subject for this master thesis was an energy plan for the HALO sustainable district. The research question set the framework for the master thesis to be able to achieve the objectives. The master thesis aimed to answer the following question:

What would a future on-site energy system for the HALO sustainable district look like?

The rationale for the energy system is strongly sustainable and only the cleanest technologies were considered for the application in a future energy system. The focus of this thesis is placed on the technical rather than the economic feasibility of the energy system.

This work can be classified as an accompanying study to the planning of the energy system done by Wood. Potential configurations of a future energy system were assessed. Besides, the usage of the results for the planning and execution of an energy system for the HALO Kilmarnock project, this study serves as an information and decision tool for potential other future projects that need to establish an energy system.

1.3 Methodology

The aim of this master thesis was the development of an energy system for a sustainable district in Kilmarnock. The following paragraphs explain the methodology to reach this aim step by step.

1.3.1 Background and Literature Review

First of all, information about the HALO Kilmarnock project was gathered. Therefore, several project calls and meetings with the engineering company in charge, Wood, were conducted. This gave the opportunity to fully understand the project scope and timeline as well as having a continuous communication exchange. Additionally, there was some exchange with two PhD. students from the University of Strathclyde to develop skills in software modelling and initial technology assessment.

To deepen the understanding of ecovillages and energy systems, a detailed literature review was carried out. The literature review provides a general overview of ecovillage visions and incentives for sustainable building design in order to show the benefits of creating a sustainable living environment. Since this master thesis focused on the development of an energy system in a potential future ecovillage, demonstration projects in UK and Germany were presented with a main focus on their energy supply systems. Afterwards the Kilmarnock project site was investigated to get an overview of site and climate conditions. Finally, a state-of-the-art technology screening was carried out to present potential options for the energy system as well as exclude first possibilities with regard to the conditions at the project site presented before.

1.3.2 Initial technology assessment

As per objective in this thesis, a detailed site-specific assessment was carried out (chapter 3.1). The site-specific initial assessment was executed for renewable on-site energy production as well as district heating technologies. The cooling and storage options were not assessed since the literature review already offered a sufficient comparison.

The site-specific viability of electricity supply technologies in Kilmarnock was assessed in two steps. First by taking technical restrictions like available wind speed, solar insolation or topography into account and secondly by more superior and public related restrictions like land ownership. The following table (Table 1) shows the assessed restriction criteria for wind and solar power. The information for this investigation was gathered from different publicly available tools and maps as well as from data collections provided on the internet [5].

Table 1 Restriction criteria energy resources [5]

Technical Restrictions	Relevance to wind turbines	Relevance to solar panels
Wind speed	x	
Solar insolation		x
Ambient temperature		x
Topography	x	x
Land cover	x	x
Electrical lines and substations	x	x
Radar and airspace restrictions	x	x
Roads, railroads, and paths	x	x
Potential Restrictions		
Natural heritage (national parks, urban areas, wildlife etc.)	x	x
Cultural heritage (world heritage sites, scheduled monuments, listed buildings)	x	x
Land ownership	x	x
Land use and amenity (enjoyment from physical outdoor space)	x	x
Administrative boundaries	x	x

The site-specific viability of heating technologies (heat pumps) was structured differently. Ground source heat pumps were assessed towards the geothermal situation and ground temperatures in Kilmarnock, while air source heat pumps were assessed towards the local climate. Surface water source heat pumps were assessed with regard to available water bodies and their water flow rates as well as temperatures to work out the heat capacity of the water. For all heat pump types, different first-hand calculations were executed to identify the potential of the technologies. Information for that was gathered in different reports and maps from the internet.

1.3.3 Modelling approach

The modelling approach for the development of an energy system was divided into two parts. Part one consisted of the creation of energy demand profiles that display potential future consumption of the Kilmarnock sustainable district. Part two consisted of the development and assessment of different energy systems in an energy system modelling software. This thesis focused on the development of an energy system for Phase I. In the end the adaptability of the system for an extensive demand in Phase II was assessed.

1.3.3.1 Part One – Creation of energy demand profiles

In order to create energy demand profiles for a future town district, yearly generic energy demand profiles were obtained from different sources.

Electricity demand

Generic electricity demand profiles for domestic and non-domestic buildings were obtained from Elexon, an electric utility company from London, and from the Energy Systems Research Unit (ESRU) network of Strathclyde University. These generic profiles were inserted into the profile designer of an ESRU software called Merit. Merit is used at the University of Strathclyde to model renewable energy schemes by matching user specified demand profiles with different supply technologies. The software allows to scale and modify generic demand profiles by using annual consumption data and peak power. Values for the peak power were delivered by Wood and annual consumption was calculated with Benchmark values from the Chartered Institution of Building Services Engineers (CIBSE). In cases where more units of one building were planned, e.g. the domestic buildings, the unit peak load was used to create a single demand profile of that building type. Single unit demand profiles can easily be scaled up and down depending on the number of units planned.

For the Urban and Lorry Park in Phase II, a 24-hour electricity demand profile was self-developed. The profile takes into account seasonal sunrise and sunset times [6] to find out when lighting is required. The lighting load during night time was provided by Wood. Afterwards the profile was edited in Merit as well.

EV demand

The EV demand profile was developed by using average annual mileage covered in UK and average EV battery capacities and ranges of most popular EV models. With the given capacities and ranges the energy consumption of these car models was calculated and the average of all models was taken in order to calculate the annual electrical energy consumption per year. This number was then used to calculate the electrical power demand per car [7]. The electrical power demand was assumed to be met with a standard charging speed of 8-12 hours, e.g. during overnight parking at a building or in a parking area in the period from 19:00 – 07:00.

Heating Demand

The heating demand profiles for each planned building were provided by a colleague who worked on the same project [8]. The procedure of creating these demand profiles was the same as described for the electricity demands. Generic heating demand profiles were obtained from the ESRU network and then modified with predicted peak loads provided by Wood and calculated annual consumptions with Benchmark values from CIBSE.

Cooling Demand

Cooling demand was assumed to arise only in non-domestic buildings. It is highly dependent on building features, like glazed areas that can influence cooling requirements heavily. To investigate active cooling technology and since the building design was not existent at this stage, a generic cooling demand taken from the Technology and Innovation Centre building at Strathclyde University was modified in Merit with given peak loads provided by Wood. The created demand profile was used for investigation purposes of active cooling in the Innovation and Enterprise Hub of Phase I only. Since for the non-domestic buildings of Phase II no information were available, an extension of the cooling system was not modelled.

All in all, the energy demand profiles used for the modelling procedure display no real-life consumption of the sustainable district in Kilmarnock since the project is still in its design phase. Nevertheless, with this modelling approach it was possible to create yearly energy demand profiles for all buildings or installations of Phase I and II in an adequate way.

1.3.3.2 Part Two – Modelling of energy systems

Modelling software and input data

For the modelling of different energy systems, a software called energyPRO was used. EnergyPRO is an independent software solution from EMD International A/S. It is used for more than 20 years to model energy systems and analyse these in a techno-economic way. With energyPRO it is possible to simulate a complete energy system for a full year on an hourly basis. It provides insights into the best operation strategy and analyses costs and investments. The hourly balance of not only electricity but also district heating and cooling can be displayed. Since the energy system for the HALO district was still in its design phase energyPRO was chosen to be able to model, simulate, analyse and optimise various energy systems in terms of their capability for the project site [9]. A more detailed description of energyPRO can be found in Lyden et al., 2018. This paper compares 13 energy system modelling tools in detail with regard to their capabilities to select a suitable software for a specific situation. In this selection process energyPRO scored well and shared the first place with two other softwares [10]. EnergyPRO is not a freeware and has to be bought from EMD.

EnergyPRO models the electricity, cooling and heating side of an energy system with additional storage and electricity market options (Figure 2).

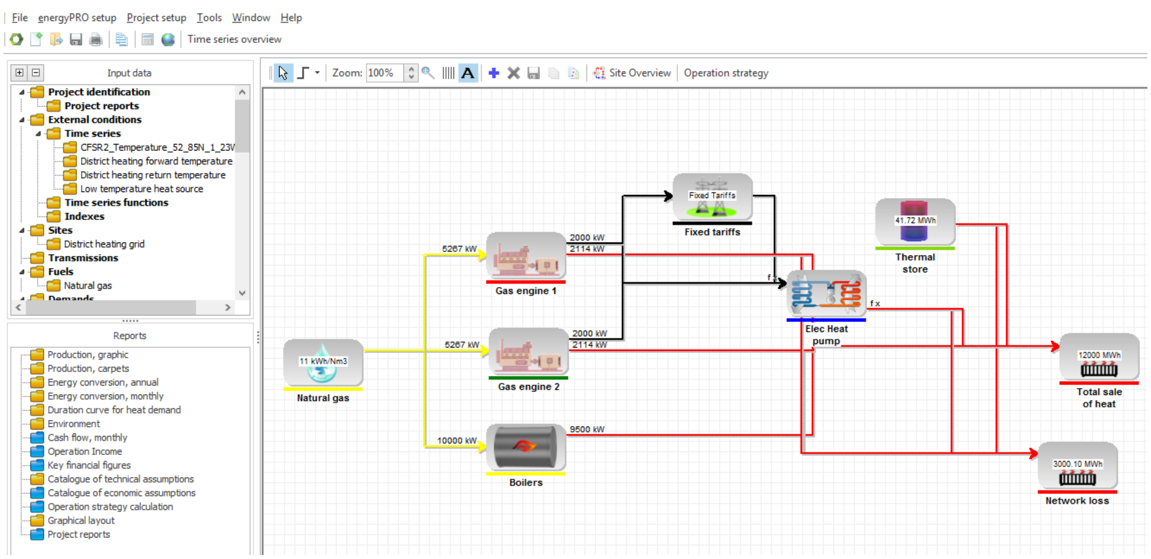


Figure 2 Exemplary project: A cogeneration plant and electric heat pump on fixed tariffs - Screen shot from the energyPRO software version 4.5.179

Input data to set up the production and storage units in energyPRO were taken from technology specification sheets, manufacturer manuals and best practice numbers from pre-installed energyPRO projects. Rarely, own assumptions were taken. An overview of the input data can be seen in the Appendix to this master thesis and was submitted additionally to this thesis. Climate data was obtained from the energyPRO online database for an exemplary year that was 2017.

Modelling procedure

A scenario-based approach is taken for the modelling of the renewable energy supply and storage technologies. The three different scenarios can be seen in Table 2.

Table 2 Scenarios and energy system configurations for the software modelling [own demonstration]

		Scenario 1 Renewabale penetration District heating:Geothermal well with heat exchanger Passive cooling	Scenario 2 Grid connection (+PV) District heating: Heat Pump or Solar thermal Passive cooling	Scenario 3 Grid connection + PV District heating:Heat Pump Active cooling	
Configuration					**Demands**
C1	**PV**	x			Electricity Demand Phase I
C2	**PV + BAT**	x			Electricity Demand Phase I
C3	**PV + BAT + GRID**	x			Electricity Demand Phase I
C3+	**PV + BAT + GRID**	x			Electricity Demand Phase I + EV Demand
C4	**PV + WIND + BAT**	x			Electricity Demand Phase I + EV Demand
C5	**PV + ASHP + TS**		x		Heating Demand Phase I
C6	**PV + BAT + ASHP + TS**		x		Heating Demand Phase I
C7	**PV + BAT + GRID +ASHP + TS**		x		Electricity + Heating Demand Phase I
C7+	**PV + BAT + GRID +ASHP + TS**		x		Electricity + Heating + EV Demand Phase I
C8	**PV + BAT + GRID +WSHP + TS**		x		Electricity + Heating Demand Phase I
C8+	**PV + BAT + GRID +WSHP + TS**		x		Electricity + Heating + EV Demand Phase I
C9	**PV + BAT + GRID +GSHP + TS**		x		Electricity + Heating Demand Phase I
C9+	**PV + BAT + GRID +GSHP + TS**		x		Electricity + Heating + EV Demand Phase I
C10	**ST + TS**		x		Heating Demand Phase I
C11	**PV + GRID + HP + TS + EC +CS**			x	Electricity + Heating + Cooling + EV Demand Phase I
C12	**PV + GRID + HP + TS + AC +CS**			x	Electricity + Heating + Cooling + EV Demand Phase I

*BAT = Battery, HP = heat pump, TS = thermal store, ST = solar thermal, EC = electric chiller, AC = absorption chiller, CS = cold store

For each scenario, assumptions were made how the three energy streams (electricity, heating and cooling) are met in the new sustainable town district:

1. Scenario
   - Electricity supply was modelled in energyPRO in order to find out if the demand can be met with renewable energy sources and how high potential grid imports were.
   - The heating demand was assumed to be met by the planned geothermal well in combination with a heat exchanger in a district heating scheme and was therefore not displayed in energyPRO.
   - The cooling demand was assumed to be met by passive cooling and was therefore not displayed in energyPRO.

2. Scenario
   - Electricity demand was assumed to be met by the planned grid connection; additional PV panels were inserted for power supply for the heating

technologies. The electricity demand of the Phase I buildings and EV’s were not displayed in energyPRO unless a grid power supply for the heating technologies was incorporated. This was needed in order to identify if the grid limitation on-site would be exceeded.

- Heating supply was modelled in energyPRO in order to find out if the demand can be met with power-to-heat and solar thermal technology in a district heating scheme.
- The cooling demand was assumed to be met by passive cooling and was therefore not displayed in energyPRO.

3. Scenario
    - Electricity demand was assumed to be met by the planned grid connection and additional PV panels.
    - The heating demand was assumed to be met by power-to-heat technology in a district heating system.
    - Cooling supply was modelled in energyPRO in order to find out if the demand can be met with active cooling chiller technology.

In each scenario different energy system combinations were modelled, called energy configurations. The configurations started with a basic model and incorporated more technology in every step in order to ensure a demand and supply match. The system configurations for each scenario as well as the energy demands that needed to be met can also be seen in Table 2.

The modelling process investigated a full year that is 2017. In order to see daily conditions in more detail, for each configuration not only yearly profiles of demand and supply trends were displayed but also one winter (01/01/17) and one summer day (12/07/17).

1.3.4 Analysis

In order to assess and analyse the quality of the different system configurations a number of Key Performance Indicators (KPI´s) were determined during the modelling procedure. The demand and supply match rate was the critical value of this investigation. A system configuration was only identified as being feasible when the demand and supply match rate accounted for at least 100%. In every other case the configuration was extended with additional supply technologies. As soon as the critical value was met, several other KPI's were assessed that can be seen in Table 3.

Table 3 Assessed KPI's [own demonstration]

Key Performance Indicators			
Renewable Electricity Production (MWh/year)	Imported Electricity from Grid (MWh/year)	Renewable Penetration Factor (%)	Electricity Peak (MW)

The renewable penetration factor is the relation between renewable electricity produced and electricity consumed in total:

$$RPF = \frac{electricity_{produced}}{(electricity_{produced} + electricity_{\ imported})}$$

Since the future grid connection on the HALO Kilmarnock site will have a limit of 2,000 kVA (that correspond to 1,900 kW with a power factor of 0.95) the imported electricity peak is another important KPI that was considered.

1.3.5 Discussion

In the Discussion part of this thesis the results from the initial site assessment as well as from the modelling procedure were discussed and reviewed in the context of the HALO Kilmarnock project. Each energy stream and the result of feasible supply technologies were presented and recommended in a combination that can be implemented in the HALO sustainable district. Additionally, the limitations and validation of this work were mentioned and their impact was evaluated.

1.3.6 Conclusion and Future Work

In the conclusion an overview of the whole master thesis, the approach taken and assessments carried out was given. In the end, the results and recommendations were displayed.

Since there are always time and scope limitations to each work the future work chapter shows the areas that need to be specified. It also addresses open questions that have to be answered in order to draw final conclusions.

2 Literature Review

2.1 The Vision of ecovillages and incentives for sustainability

Ecovillages itself and the life within these settlements are realised according to a vision that includes more than providing clean energy. The sustainable principles as well as incentives for implementing sustainability in a future town district design project were discussed in this chapter.

2.1.1 The Vision

In recent years, an ongoing worldwide trend for setting up ecovillages can be observed. Figure 3 shows an overview of ecovillages that are members of the Global Ecovillage Network [11].

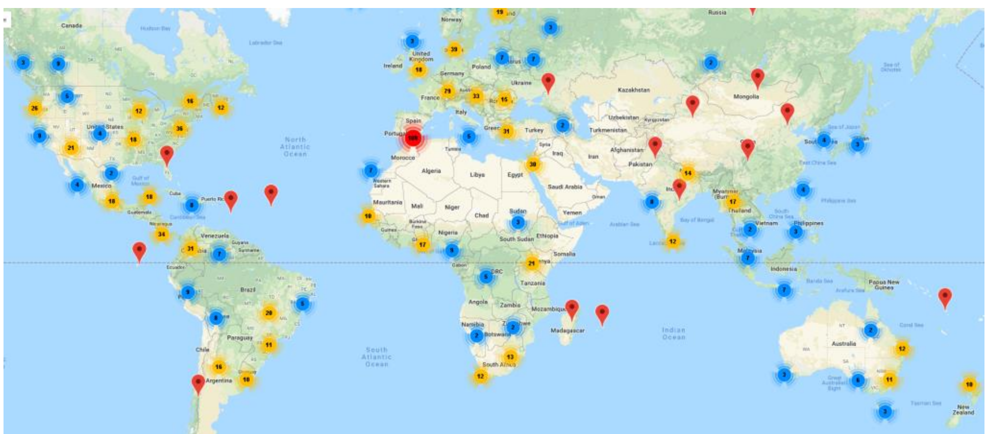


Figure 3 Ecovillages worldwide [11]

GEN aims to create an international network for ecovillages in order to educate and advocate the vision of sustainable living to bring forward the idea of a regenerative world [12]. Ecology, economy, social and culture are the four dimensions that are focused in these settlements to provide a sufficient level of sustainability [1]. Each of these dimensions consists of even more principles that are also represented in the “One Planet Living” initiatives by Bioregional (Figure 4).

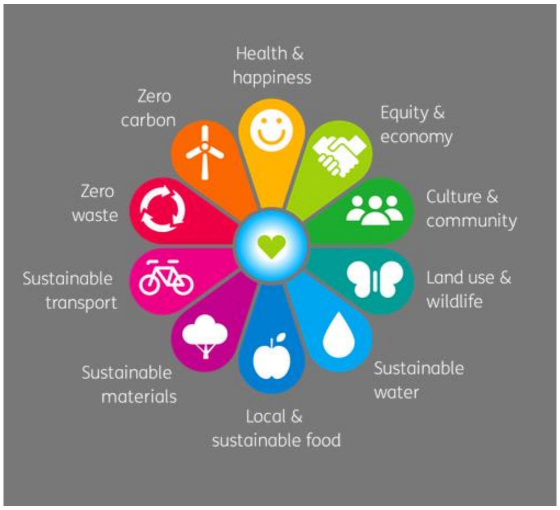


Figure 4 One Planet Living framework [13]

The framework provided by this initiative helps to communicate and execute sustainability. It shows that sustainable development consists of more factors then just using renewable energy (zero carbon goal). As represented in that picture, the criteria an ecovillage is supposed to follow are much broader incorporating for example also equity, local food production and zero waste [13].

In this master thesis, only the energy part of an ecovillage is focused (zero carbon goal). Nevertheless, ones should know that ecovillages define themselves about more areas, e.g. health, equality and economy.

2.1.2 Incentives for sustainable design

There are several incentives for building new town quarters in a sustainable way as well as integrating renewable energy. In order to provide a certain standard for new sustainable building design, certification systems like BREEAM and LEED are existent.

The Building Research Establishment Environmental Assessment Method (BREEAM) was one of the first environmental assessment mechanism for building design. It was introduced in 1990 by BRE Global Limited and has been updated ever since. As an individual third-party approval body BRE Global Limited offers a range of standards, certifications and assessment methods to increase quality, safety and sustainability. BREEAM is used in over 50 countries and it is based on a balanced scorecard system to reach optimal environmental standards for building design. For ecovillage projects a certification after BREEAM is more than beneficial. It is recommended to involve an assessor at an early stage of the project design process in order to fulfil the BREEAM Communities scheme in the best possible way [14].

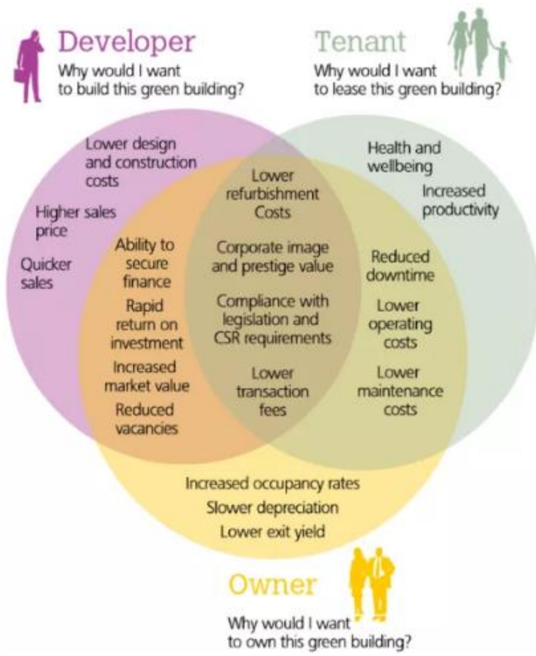


Figure 5 Reasons for Green Building development from different perspectives [15]

Incentives for incorporating BREEAM principles to build sustainable housing are shown in Figure 5. Examples that are beneficial for the tenant and owner are e.g. lower operating and maintenance costs, while for the developer quicker and higher price sales are possible. All in all, BREEAM is the leading environmental assessment method in building design and empowers building design projects to be recognised towards their sustainability [15].

Another widely used green building rating system is called Leadership in Energy and Environmental Design (LEED). LEED addresses principles like cost-effectiveness, health and efficiency to building design processes. The LEED certification scheme helps to evaluate different buildings based on a rating scale for various factors such as air quality and energy consumption. Building green buildings by using LEED does not only improve the building condition and environment but also benefits the image of the developer or owner [16]. The US Green Building Council even stated that buildings with LEED certification are leased faster, ensure higher property values and are sold for higher prices [17].

All in all, it can be stated that sustainable certification schemes are favourable for new building design projects in order to attract future tenants and buyers as well as to increase the value of the properties.

2.2 Demonstration projects

To see what already established ecovillages look like, the following paragraphs cover some of the most innovative and well-known ecovillages in the United Kingdom and Germany. For this master thesis these two countries were chosen due to the high standards and developments both made in the field of sustainable housing and living. Although, sustainable development covers more than using renewable energy, the focus of this review was based on the renewable technologies used in these ecovillages. In the end the applicability of these energy systems with regard to the HALO project side was assessed.

2.2.1 Findhorn Ecovillage

Findhorn Ecovillage is a community project close to the town of Findhorn in the north-east of Scotland. In 1982 the ecovillage project was established and land purchase initiatives started. Since then the community carried out many sustainable modifications starting with an intensive building programme in 1990 [18]. In order to reduce CO_2 emissions old buildings were retrofitted as well as new zero carbon buildings constructed. The refurbishment and new building strategy involved the usage of natural materials and breathing wall constructions to increase indoor air quality. Until now 61 ecological buildings were built, using environmentally friendly materials (see Figure 6) [19].

One state-of-the-art example is the Moray Art centre which was opened in 2008. Photovoltaic panels were installed for the electricity production while ground source heat pumps cover the heating demand. Another example is the Soilse, a cohousing construction with own biomass district heating. Other technologies used are solar panels for hot water heating or a district heating system consisting of gas boilers with high fuel efficiency [19].

Figure 6 Ecological building in Findhorn Ecovillage [20]

The community owns four wind turbines with a power capacity of 750 kW that result in almost constant surplus electricity. The exceed electricity is fed into the public grid, after passing a substation for flow metering, switching purposes and voltage transmissions. For that reason, Findhorn ecovillage can call itself “net exporters of electricity”. About 50% of the electricity is used on-site and the rest is exported. In case of insufficient wind availability, the ecovillage can import electricity from the public grid. To support research of load management, Findhorn ecovillage serves as a demonstration site using equipment that supports demand and supply matching. To reduce coal usage the ecovillage uses solar panels and wood combustion for space and hot water heating. In some cases, oil is substituted with propane to decrease pollution levels further. All in all, Findhorn produces 28% of their energy use from renewables. This share is supposed to increase in the coming years. Initiatives like exploring the potential of hydrogen and fuel cell usage already started. A study in 2006 identified that inhabitants of this ecovillage had the lowest ecological footprint of all measured communities with a number of 2.71 hectares per capita. As a comparison, the UK average is 5.4 hectares. The sustainable picture is completed by their organic food production and ecological waste water treatment [20].

2.2.2 BedZED London

BedZED is a large-scale settlement of 100 dwellings, offices, leisure facilities and a college in the south of London. It was completed in 2002 and the main aim of this community is to reduce CO_2 emissions and water use. BedZED has an on-site car club to save energy for transport [21].

Figure 7 Buildings of bedZED community [22]

The passive houses are heated through solar thermal installations and are highly insulated as well as ventilated with colourful wind cowls (see Figure 7). For the whole complex an underground district heating system composed of a gas-fired boiler supplies hot water. In connection to this, every dwelling has a large water tank for storing the warm water. All roofs are coated with photovoltaic panels, in addition to the solar thermal panels, facing south and providing some of the electricity that is used on-site. When the production exceeds the electricity demand, the surplus is exported to the public grid. BedZED has the approach of creating a sustainable and zero carbon environment. However, some technologies have not performed effectively and were replaced. One example is a combined heat and power plant (CHP) that was originally installed to produce clean electricity and heat from tree waste.

After performance problems the CHP has been substituted with a gas boiler [22]. To reach the target of reducing the usage of fossil fuel in transport by 50% a green transport plan has been established. Besides walking or using public transport, a car pool has been introduced. Thus, BedZED introduced the first low-car environment in the UK [21].

2.2.3 The Vauban district, Freiburg

The Vauban district in Freiburg in the south of Germany was opened in 2000 to become a role model for a new way of environmentally friendly living. Experts from Fraunhofer Institute for Solar Energy Systems and Passive House Institute in Darmstadt have developed the plans for the community. The settlement set the focus on clean transportation since it accounts for many environmental impacts. Cars almost never drive through the community and parking is only permitted at the outskirt of town. Almost 70% of Vauban’s inhabitants have no car [23].

Figure 8 The Vauban district in Freiburg [23]

All buildings meet low energy consumption standards and 42 even meet passive house standard. Around 100 dwellings produce more energy than they consume which results in public grid exports and paybacks. Heat is supplied via a district heating system composed out of a combined heat and power generator powered by woodchips. For cooking biogas is used produced by an on-site anaerobic digester with waste. In order to control and monitor the energy and material flows a software called GEMIS is used. For the first time ever, a whole district is analysed in terms of energy supply, water and waste, buildings and infrastructure as well as traffic. This scientific evaluation has already shown that the increased investment in energy-efficient houses pays off after a few years. Moreover, using a CHP plant for areas with several buildings is one of the most efficient forms to generate energy. All buildings in the Vauban district have rooftop solar panels (see Figure 8) that produce local electricity as well [23].

2.2.4 Bramwich, Hamburg

Bramwich Ecovillage is a part of the solar power residential area situated in Karlshoehe in the southeast of Hamburg. Karlshoehe was established in 1996 by a consortium of universities and Hamburg Gas Company. All in all, 124 buildings form this settlement from which 40 households constitute the Bramwich Ecovillage (see Figure 9) [24].

Figure 9 Bramwich Ecovillage [24]

Solar panels are installed on all buildings on the southern part of the rooftop to collect maximum solar power for heating purposes. In total 3,000 m^2 of the roofs are covered with solar panels. The solar energy heating system is integrated for every building in the Karlshoehe settlement and consists, apart from the solar collectors, of a heat distribution network as well as a heating centre and thermal storage (see Figure 10). The thermal storage is a big underground tank accommodating 4,500 m^3 of water. The hot water arrives through a piping network in each building. The advantages of a centralised solar power heating system instead of having a system for each building is the high efficiency, the convenience factor and economic benefits [24].

All in all, the heating system was expected to save 8,000 kWh energy and 158 tons CO_2 per year while supplying around 50% of the thermal energy needed in this community. However, the last evaluation by a research institute found out that more heat losses in the piping system occur than expected resulting in 30% heat demand coverage by the system. The Bramwich houses are also all

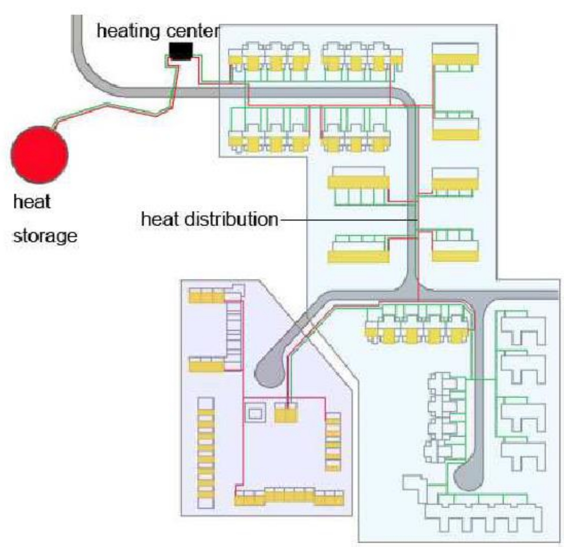


Figure 10 Centralised solar power heating in Karlshoehe [24]

low-energy buildings with an energy consumption below 59 kWh/m^2 and make use of biological purification technology [24].

2.2.5 Hannover-Kronsberg

The Hannover-Kronsberg project was carried out due to the World Exposition exhibit in 2000 on the subject of "Humankind-Nature-Technology". Besides advancements in building design, transport as well as water, soil and waste management, the whole district was considered for energy efficiency optimisation [25].

Figure 11 Hannover-Kronsberg [26]

One goal was to reduce CO_2 emissions by 60% compared to standards at that time. In order to reach that aim two decentralised gas-powered cogeneration plants were introduced for a district heating network [25]. In addition to an already existing smaller turbine two big wind turbines of 1.5 and 1.8 MW were installed to cover most of the electricity demand [27]. PV panels, solar thermal panels and a seasonal super insulated storage tank of 2,750 m^2 were installed as well. In case the demand exceeds the energy supplied by the CHP plant a central gas boiler was installed as a backup. For three years from 1999 – 2001, energy flows and consumption were monitored to find out if a CO_2 reduction of 60% has been achieved. The evaluation indicated that space heating, hot water and electricity led to a reduction of 28% of CO_2 emissions. In combination with 19% savings from the CHP plant and another 28% by the wind turbines it resulted in an overall reduction of 75% of CO_2. In total, the CO_2 emissions decreased from approx.1.7 tonnes per year to 0.4 tonnes [25].

2.2.6 Energy systems in demonstration sites and application for the HALO district

All demonstration projects make use of different technologies in order to provide sufficient and mostly clean energy. It is striking that all four out of five demonstration projects make use of solar radiation with PV panels in order to produce electricity. Although the climate in the UK and Germany is not well-known for many sun hours, this technology seems like a reasonable electricity supply source. Another renewable supply technology that is used in Findhorn and in Kronsberg is wind energy. Findhorn ecovillage owns a wind turbine rather than installing one on-site as the Kronsberg district did it. This community ownership of a turbine is a common practice to incorporate wind energy into an energy system of a district. All demonstration ecovillages also have a grid connection to export surplus energy or import electricity when deficits occur. For the HALO Kilmarnock project both technologies are promising options for a future energy system and were screened and assessed in the upcoming chapters.

The heating side shows more technology variation in the different demonstration projects, e.g. solar thermal, combined heat and power with woodchips, gas boilers, biomass and ground source heat pumps. Most systems are carried out as district heating systems and some are combined with thermal water storage. For the HALO Kilmarnock project only clean heating technologies with a minimum of emissions like solar thermal and heat pumps are interesting. A district heating is also a viable possibility and was considered for the HALO district.

In the following chapters these technologies and more options were screened and assessed in more detail.

2.3 Kilmarnock Site Assessment

The site assessment of the area in Kilmarnock, where the HALO project is planned, was carried out in order to get an overview of local climate, geography and other characteristics that could be important for feasibility studies of renewable energy technology.

Kilmarnock is a town in Ayrshire in the south-west of Scotland. The latitude is 55° 36' 42.16" N and longitude is -4° 29' 44.92" W. The altitude is 49.0 m above mean sea level. Kilmarnock is around 22 miles away from Glasgow (see Figure 12) and has a population of approx. 46,350 people. It is situated in a lowland area with no mountains, only 16 km from the coast. The river Irvine runs through the eastern part of the town. The distance between river and site is 1.5 km. Kilmarnock water, a smaller water body, runs 0.5 km away from the project site from north to south becoming a tributary of the river Irvine [28].

Figure 12 Kilmarnock in south-west Scotland (left) and the project site in the town centre (right) [28]

The project site in Kilmarnock itself is a brownfield site of 28 acre in the middle of Kilmarnock town centre (Figure 12). Before, the Johnnie Walker distillery was situated here. Most of the area consists of concrete, some minor parts are mantle rock with a few trees. The surrounding area is a mix of housing and grassed area. In the south, there is the Ayr College with a football field and parking lot. The east and north-east is determined by housing and the north-west by grassed area and trees. In the south-west, there are rail tracks. The site shows good infrastructure and no major obstacles for construction and renewable energy installations [28].

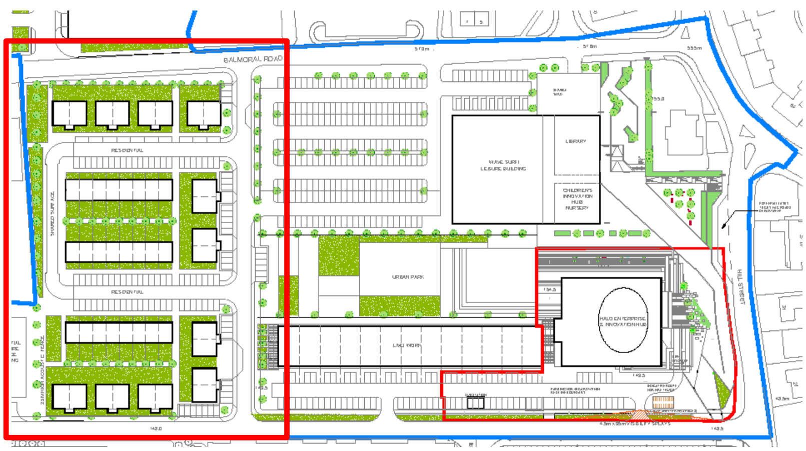


Figure 13 Phase 1 – Location of Enterprise and Innovation Hub and 70 dwellings (circled red) [29]

This thesis focusses on an energy system for Phase I that consists of an Innovation and Enterprise Hub, 44 duplex and 26 terrace dwellings (Figure 13). In the end the recommended energy system was investigated with regard to its adaptability for Phase II that includes more live/work studios, speculative offices, a leisure and an energy centre as well as a religious facility, an urban park and a car park.

Climate data for Kilmarnock can be seen in Figure 14 to Figure 16. The graphs were obtained from the energyPRO online server. The closest location to Kilmarnock that contain climate data is located east of Prestwick (-4,5W and 55,50N). The obtained Climate Forecast System Reanalysis 2 data is available since 2010. For this thesis the database from 2017 was used.

Temperatures range in 2017 between -6°C to 22°C and can be seen in Figure 14. The average annual ambient temperature over several years is 9 °C [30].

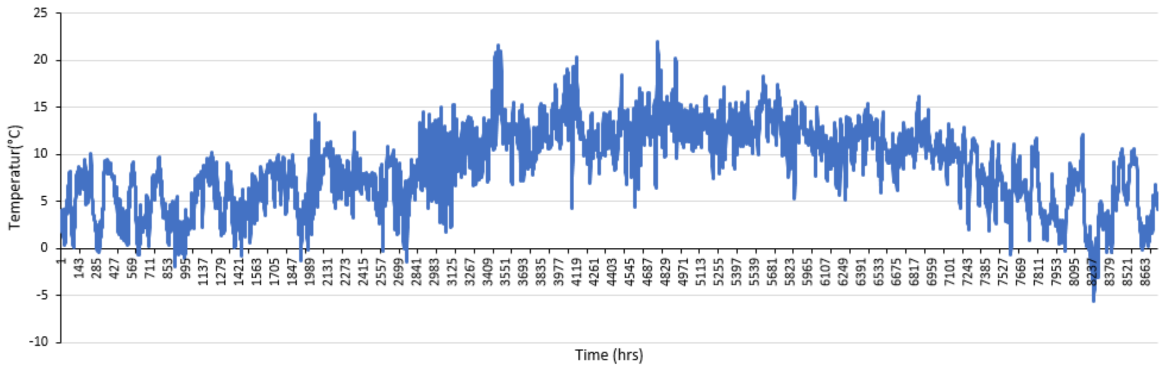


Figure 14 Ambient temperature profile in 2017 used for Kilmarnock area [own demonstration]

Kilmarnock has approx. 1,439 hours of sunshine per year [30]. The yearly trend of the solar radiation in 2017 can be seen in Figure 15.

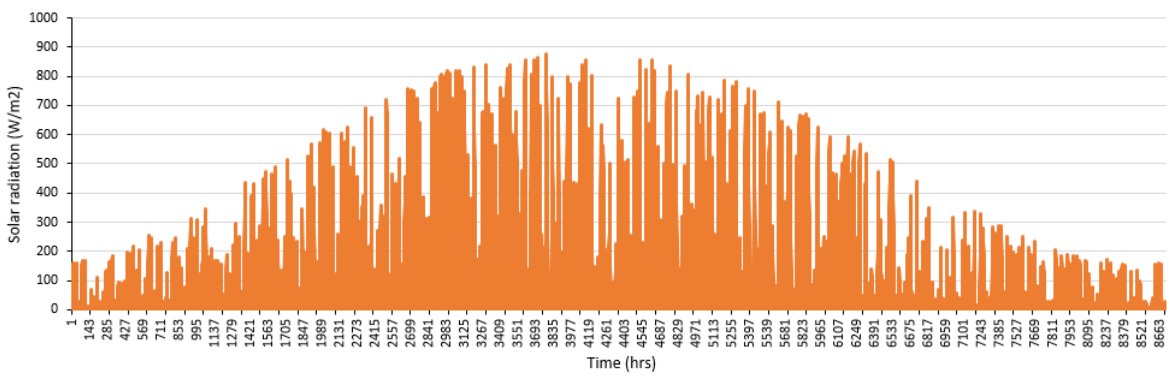


Figure 15 Solar radiation profile in 2017 used for Kilmarnock area [own demonstration]

The average wind speed in this area is around 9.7 m/s [30]. The yearly trend in 2017 can be seen in Figure 16.

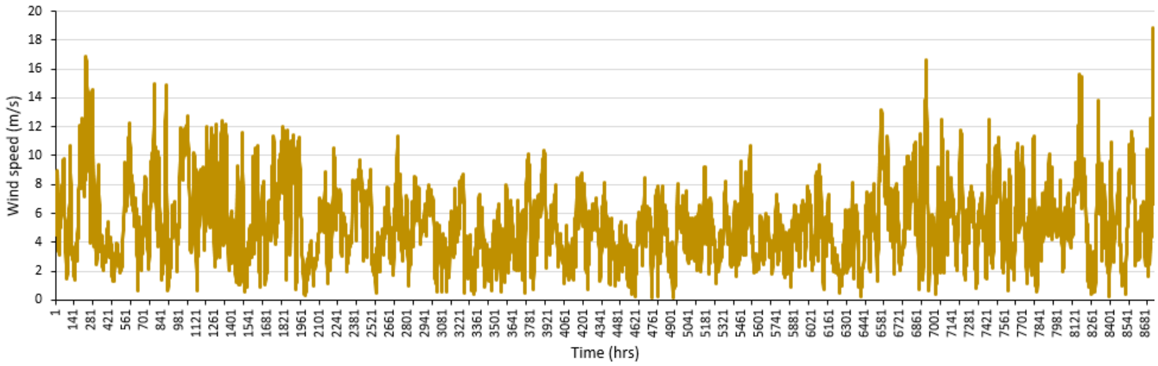


Figure 16 Wind speed profile in 2017 used for Kilmarnock area [own demonstration]

In summary, the conditions on the project site indicate that several technologies can have a potential for a future energy system. The sun radiation and wind profile seem reasonable to install PV panels and wind turbines. A reason against wind energy is the location in the middle of the town that comes along with potential obstacles like buildings. The quality of the wind resource would be better on an open field. With the Irvine River and Kilmarnock water two potential thermal resources for a water source heat pump are available. However, an initial site-specific assessment was carried out in chapter 3.1 to confirm or to refuse the potential of these technologies.

2.4 Technology selection

Today there are many renewable technologies available that can be combined with each other in energy systems. This chapter gives a broad overview in order to show available options and exclude first possibilities with regard to the conditions on the project site or the sustainable rationale behind this thesis.

2.4.1 Renewable energy sources for electricity production

<u>Solar</u>

In the UK the deployment of solar energy increased rapidly in the last 7 years (see Figure 17). Mostly in the micro-generation sector of 0-4 kW and in installations with a capacity of 5-25 MW [31]. Reasons for that are different renewable incentive schemes like Feed-In-Tariffs which supported the installation of micro PV or other incentives that resulted in a development of around 10 GW of solar farms in total in the last years [32].

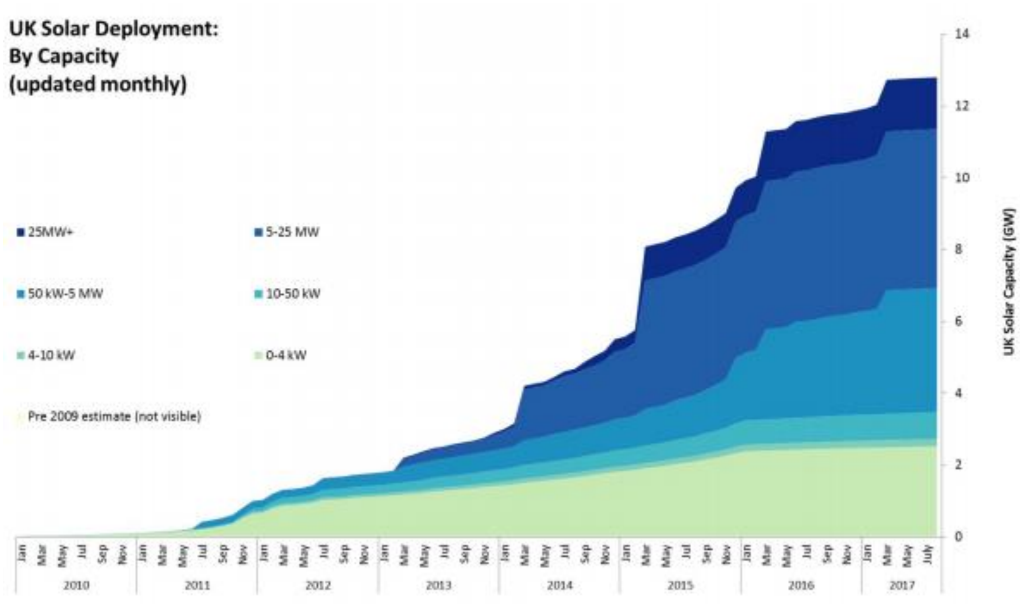
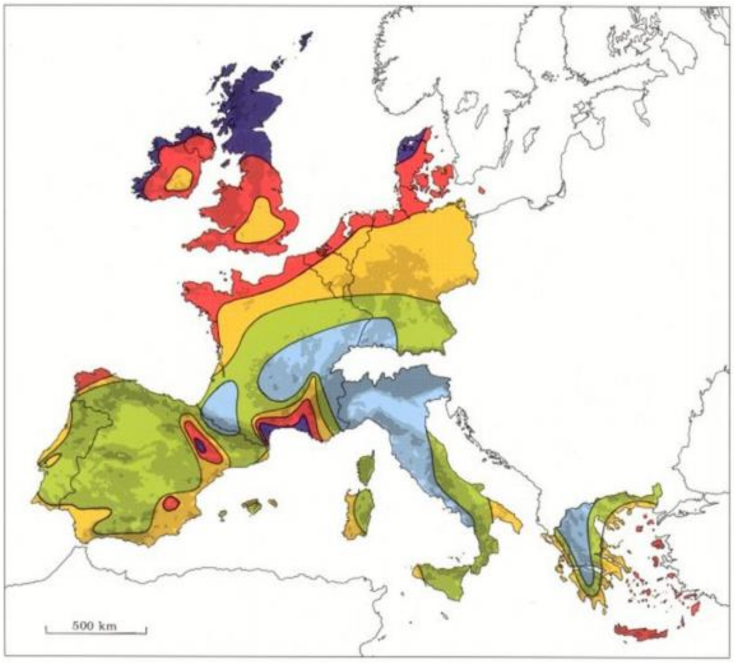


Figure 17 UK solar deployment [32]

The main drawbacks of solar power are the fluctuating production as well as dependencies on weather conditions and solar angles [33]. However, the costs have fallen in the last years. Actually, the levelised cost of electricity from photovoltaic solar range between 0.1 – 0.35 $/kWh [34]. Concentration of solar power combined with storage allows to scale the power supply quickly up and down in order to provide energy for peak demands even when the weather conditions are not optimal [33]. In the case of Kilmarnock sun hours per year are 1,439 hrs with adequate solar radiation in summer (see chapter 2.3). Therefore, solar power was considered as a potential solution for on-site electricity production.

Wind

Wind power is one of the fastest growing renewable energy sources although its intermittency is a major drawback and requires a combination with dispatchable energy sources or storage [33]. Levelised costs of electricity of onshore wind range between 0.05 – 0.15 $/kWh [34]. There are parts in the world where wind is fairly predictable due to thermal effects.



Wind resources[1] at 50 metres above ground level for five different topographic conditions										
	Sheltered terrain[2]		Open plain[3]		At a sea coast[4]		Open sea[5]		Hills and ridges[6]	
	$m s^{-1}$	$W m^{-2}$	$m s^{-1}$	$W m^{-2}$	$m s^{-1}$	$W m^{-2}$	$m s^{-1}$	$W m^{-2}$	$m s^{-1}$	$W m^{-2}$
(purple)	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
(red)	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
(yellow)	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
(green)	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0- 8.5	400- 700
(blue)	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400

Figure 18 European wind resources [35]

In Europe Scotland is the area with the highest wind speeds which can be seen in Figure 18. Consequently, the UK had 5,106 onshore turbines (8,285 MW capacity) and 1,452 offshore turbines (5,054 MW capacity) already installed in 2015 [36]. The same applies for Kilmarnock: wind speeds are fairly high with an average of 9.7 m/s (see chapter 2.3) which is in the purple spectrum. For that reason, wind energy was considered for the following evaluations.

<u>Hydro</u>

For the current global electricity production from renewables hydropower plays the major role. Advantages that come with hydro power are reliability and the possibility to balance fluctuating renewable energy like wind and solar [33]. The costs range between 0.05 – 0.15 $/kWh [34].

Due to the Scottish landscape there are some hydro plants already in place like the Loch Sloy power station with 150 MW rated output or the latest power station in Glendoe with 100 MW rated power output. Besides these huge power installations also mini and micro-hydro systems can be installed with a rated output from a few kW upwards [37]. The Hydro potential in the Kilmarnock area is assumed to be small since the topography does not provide high heads for efficient hydropower generation. The river Irvine could be assessed for run-off-river installations, however due to the distance to the site this option was neglected (see chapter 2.3).

Others

Ocean and tidal power generation were discounted in this master thesis since the distance to the sea is too far and these generation methods are too complex and costly. Energy production through biomass were scoped out due to the pollutants that come within the combustion of biomass that do not go along with the rationale of this thesis and the clean energy provision vision of the HALO initiative.

2.4.2 Heating and cooling systems

District Heating Systems

District heating systems are mostly associated to **Combined heat and power technologies (CHP)** that are used to recover heat not only from traditional fossil fuel fired power plants but also from renewable power plants or in form of micro-CHP (e.g. Stirling engine). With a future perspective of zero carbon technologies and the aim to prevent as much emissions as possible, these technologies were not considered in this thesis.

Besides CHP another version of district heating is **power-to-heat-technology**. Power-to-heat technology makes use of surplus electrical power from intermittent renewable energy production. This excess power can be used for installations like heat pumps or electric boilers which are able to produce heat in order to warm up open spaces [38]. The basic mechanism behind **heat pumps** is that they transfer thermal energy from one location to another one. There are three types of heat pumps that are ground source heat pumps, air source heat pumps and water source heat pumps. Depending on the type, the heat pump extracts potential thermal energy from the air, ground or water, feeds it into a compressor and coils that transfer the heat into the open space. The major advantage of heat pumps is that they use only a small amount of electricity while being highly efficient. Although heat pumps are quite dependent on climate they work well in a moderate climate like the UK and can ensure heating in winter even at -20 degrees Celsius [39]. Descriptive examples for heat pumps as part of a district heating system are the 13 MW ammonia water source heat pump (WSHP) in Drammen, Norway and UK's largest air source heat pump (ASHP) with 700 kW for the Glasgow Housing Association. The WSHP in Drammen provides heat for 63,000 inhabitants and already achieved a decarbonisation rate of 85% [40]. With a coefficient of performance of 3 the ASHP in Glasgow provides heat for 350 homes [41]. **Electric boilers** are comparable to a water kettle used in a kitchen. They work exactly like typical gas boilers but instead of burning gas to heat up water, electricity is used. The boilers have an efficiency of almost 100% [42]. The major drawback of this technology is that electricity is more expensive than gas or oil and electric boiler consume more electricity than heat pumps. Furthermore, electric boilers are not feasible in a district heating scheme since volumes and capacity are limited. On that account only heat pumps were considered in the further investigation of a district heating system for the HALO sustainable district.

Cooling Technologies

Cooling can be implemented in an active or passive way. **Passive cooling** is used since ancient time and can be carried out through mass effects, movement of air and evaporative cooling. The mechanical interaction with passive cooling methods is minimal. High mass of walls is a common procedure to prevent heat to flow rapidly into buildings during the day. The walls need low reflectivity and good thermal conductivity. This in combination to night ventilation is a common practice in hot climates. Night ventilation supports the exchange of heat and cold air and increases indoor air quality just through air movement. Since Scotland is a windy place, this passive cooling method has a good potential. The last method is called evaporate cooling. Here hot air streams are guided over a wet surface where heat is eliminated through evaporating water. It increases the moisture content and is more effective in places where dry and wet bulb temperature have an adequate difference [43]. **Active cooling** can be incorporated as a district cooling scheme consisting of a heat exchanger or a chiller and a cold store. Heat exchanger make use of natural cold resources like sea or lake water and cold winters. Absorption chillers use waste heat from industrial processes and electric chillers use surplus electricity. With cold storage the demand and supply match rate can be increased [44]. For the future energy system in Kilmarnock passive and active cooling in form of electric and absorption chillers with cold storage were considered. The chiller technologies are only dependent on surplus electricity and heat that can possibly be made available on the project site.

2.4.3 Storage technologies

Since renewable energy production is intermittent and cannot ensure a constant demand and supply match, storage technologies are indispensable. Storage technologies can be categorised into chemical storage that encompasses different types of batteries, hydrogen and EV, into mechanical storage that comprises flywheel storage, pumped hydro and compressed air, as well as thermal storage [45].

<u>Electro-chemical and -mechanical storage</u>

Connolly (2009) has carried out a review of storage technologies as part of his PhD project. The technologies were compared in consideration of technical factors like response time, efficiency and lifetime as well as of economic factors and environmental issues. Table 4 shows the technical suitability of the storage technologies in different applications reviewed in this paper. It states that lead acid batteries, flow batteries and hydrogen fuel cell are the most adaptable storage options [45]. Considering that lead acid batteries are a well-proven and mature technology that is reasonably priced this technology was chosen as a storage option for the future energy system.

Table 4 Technical suitability of storage technologies to different applications [45]

	Storage Technology	Pumped hydro	Compressed air	Flywheel	Supercapacitors	Superconducting magnets	Lead-acid batteries	Advanced batteries	Flow batteries	Hydrogen fuel cell	Hydrogen engine
Storage Application				X	X	X	X		X	X	
Transit and end-use ride-through				X	X	X	X		X	X	
T&D stabilisation and regulation						X	X		X	X	
Peak generation		X	X	X			X	X	X	X	X
Fast response spinning reserve				X			X	X	X	X	X
Conventional spinning reserve		X	X	X			X	X	X	X	X
Uninterruptible power supply				X			X	X	X	X	X
Renewable integration				X			X	X	X	X	
Load levelling		X	X				X	X	X	X	X
Load following							X	X	X	X	X
Emergency back-up			X				X	X	X	X	X
Renewables back-up		X	X				X	X	X	X	

<u>Electric Vehicles</u>

Electric vehicles (EV) can be connected to the public grid to directly charge electricity. Advantages of EV's are the potential international wide reduction of fossil fuel use and CO_2 emissions as well as large-scale deployment of battery storage and associated more flexibility of the whole energy system. There are also EV's available that are able to feed power back to the network [45]. In this master thesis the incorporation of 30 EV's were considered as part of the electricity demand that has to be met rather than as storage option.

Thermal Storage

Thermal storage can be categorised into sensible heat storage, latent heat storage and thermochemical heat storage. The main characteristics can be seen in Table 5. Depending on the temperature range, a cold tank works at 7-15 ˚C, a warm tank between 40-50 ˚C and a hot tank at 80-90 ˚C. Sensible heat storage is the most common form of thermal storage and is based on heat storage in a solid or liquid without any reactions. Examples are water, concrete and molten salt storage. Water is the most proven form of thermal storage and it is reasonably priced (Table 5) [46]. A form of latent heat storage is heat batteries that rely on a phase change from a solid material to a liquid phase. For the Kilmarnock project thermal water storage were investigated since it is a commonly used thermal storage system. Thermochemical storage has the advantage of storing large heat amounts in small volumes. However, this technology requires large reactors and is therefore the least developed one [47]. In summary, latent heat storage and thermochemical storage was scoped out from this thesis.

Table 5 Parameters of thermal energy storage [46]

TES System	Capacity (kWh/t)	Power (MW)	Efficiency (%)	Storage Period	Cost (€/kWh)
Sensible (hot water)	10–50	0.001 – 10.0	50–90	days/months	0.1–10
Phase-change material (PCM)	50–150	0.001 – 1.0	75–90	hours/months	10–50
Chemical reactions	120–250	0.01 – 1.0	75–100	hours/days	8–100

2.4.4 Smart control

All technologies chosen and considered for this thesis are depending on renewable sources or electricity supply rather than fossil fuel combustion. Building up a distribution network with intermittent renewable energy sources like wind or solar power that provide electricity for consumers like heat pumps can increase peak demands subsequently and have a direct impact on the grid performance. To ensure the safe and reliable energy supply through the distribution network smart control schemes need to be considered. Control schemes vary from increased storage usage and demand side management to smart network control. Pudjianto et al. (2013) state that with full penetration of heat pumps and EV's the daily electricity consumption in the UK will increase by 50% while also doubling the peak demand.

This can result in grid shortfalls and collapses. Incorporating a flawless demand-response management can limit that peak to 29%. Solutions for a reduction of electricity consumption could be achieved with EV charging, smart heat pump control systems and voltage regulators that are incorporated in the distribution network [48].

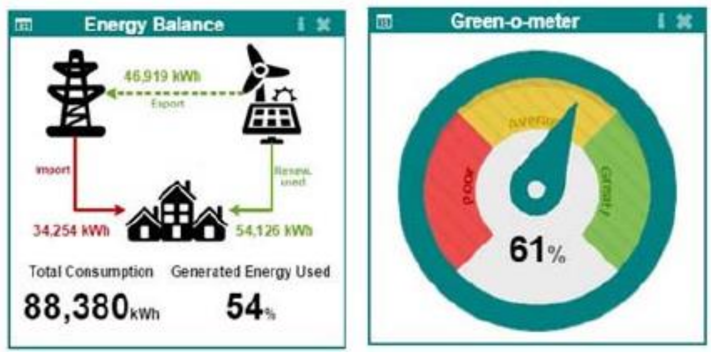


Figure 19 ORIGIN information output - energy balance and Green-O-meter [49]

In order to investigate smart control schemes in an ecovillage, the so-called ORIGIN (Orchestration of Renewable Integrated Generation in Neighbourhoods) project was established in Findhorn. The aim of this project was to increase renewable energy used and decrease grid imports through load shifting and shaping. For that a control system consisting of different algorithms was developed that can take climate and tariff information into account. A direct control of smart plugs can switch off remotely when energy needs to be saved [49].

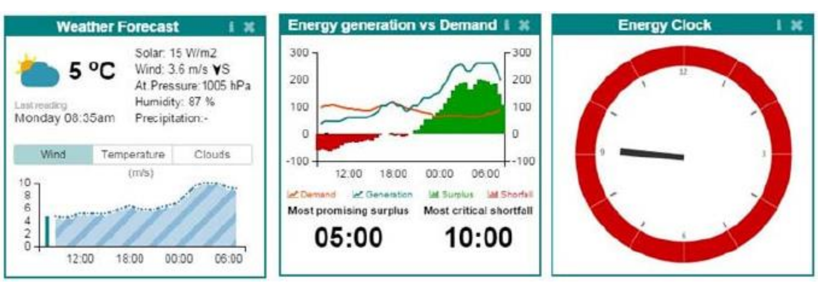


Figure 20 ORIGIN widgets for behaviour change [49]

Information and control outputs like availability of renewable energy and tariff levels can be viewed by the consumer via phone or internet. An example of the customer output is shown in Figure 19. The usage of renewable energy at a certain time can be viewed via the Green-O-meter widget. Performance and consumption feedback can be displayed as well. Widgets that give information about the time when the renewable penetration is high or imports from the grid costs more were included to influence consumption behaviour (see Figure 20) [49].

For the future energy distribution network as well as for the consumer itself it is essential to improve energy performances and consumption. Future grid balancing through smart control is an important aspect to increase intermittent renewable energy supply as well as the electrification of heat. For the HALO Kilmarnock project a smart control scheme should be incorporated to ensure sustainable energy consumption in the future.

2.4.5 Result of technology selection for the HALO sustainable district

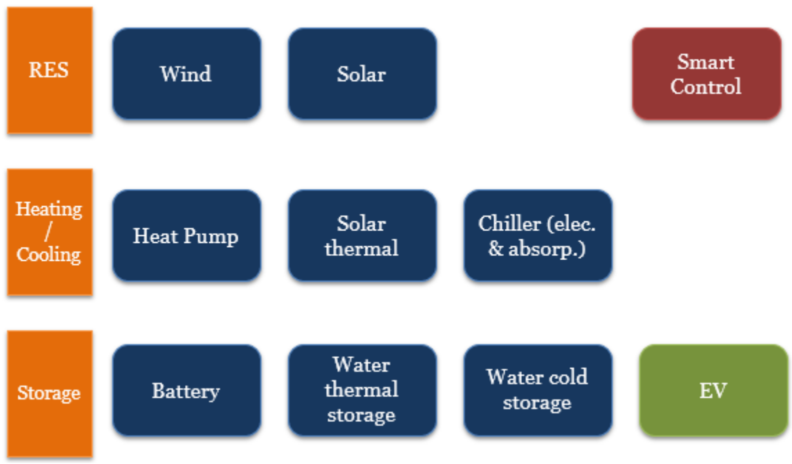


Figure 21 Chosen technologies for further investigation [own demonstration]

In this chapter different renewable technologies were screened and some were chosen for further investigation. Figure 21 shows the technologies that were considered for the investigation and modelling processes following in the next chapters. For renewable electricity supply wind and solar power were considered while for heating and cooling heat pumps, solar thermal installations and chiller technology were eligible. For storage batteries and water tanks were chosen while EV's were not modelled as storage option rather than incorporated as additional electricity consumer. The modelling software energyPRO automatically includes a control scheme in form of an operation strategy that can be modified towards e.g. high renewable technology usage.

3 Comparative analysis of technologies and scenario modelling in the context of the HALO sustainable district

In this chapter the analysis and selection process of energy technologies as well as energy system configurations was carried out. The screened and chosen technologies in chapter 2.4 were further assessed in this chapter. One part of this further investigation was an initial site-specific assessment of wind and solar power as well as of heat pumps. The technologies were assessed using the criteria catalogue or the calculation approach mentioned in chapter 1.3.2. The feasibility of each technology at the specific project site was analysed. The chosen cooling and storage technologies are not dependent on external conditions and were already set as possible options for the modelling scenarios. EV's perform as an additional electricity consumer. For the software modelling procedure, demand profiles for all energy streams (electricity, heat, and cold) were developed. The following modelling approach was scenario-based to highlight each energy stream and its potential supply technologies. The aim was to analyse and select energy technologies in order to develop an energy system for the sustainable district in Kilmarnock.

3.1 Initial site-specific assessment of technologies

3.1.1 Wind power

For wind power some technical restrictions (Table 6) are existent. The average wind speed needs to be at least 5 m/s for small-scale and 6.4 m/s for medium-scale turbines [50]. Three different free tools are available to initially assess potential wind speed in an area that are the Wind Speed Prediction Tool (WSPT) [51], the NOABL Wind Speed Map [52] and the DTU Global Wind Atlas [53] [5]. Except from the WSPT, both other tools predicted a wind speed between 5.2 m/s and 9 m/s dependent on the height of the wind turbine. WSPT only predicted 3.2 m/s on the site in Kilmarnock. However, with two out of three showing sufficient wind speed, this criterion was assumed to be fulfilled. Wind usually comes from the southwest in the UK and that part of the site is open. Cliffs and sharp ridges do not exist that favours good wind resources as well. The infrastructure consisting of grid connection and roads is good. Since the site is in the town centre, access to enlarged streets and the public grid is present. Obstacles like airfields, TV transmitters and ATC towers that can interfere with the wind turbine are not existent, only a substation site is located in the periphery of the project site [28].

Table 6 Initial assessment wind power - technical restrictions[own demonstration and [5]]

Technical Restrictions	Relevance to wind turbines	Condition on Kilmarnock Site	Feasibility
Wind Speed	Average must be at least 5m/s for small-scale and 6.4m/s for medium-scale	3.2 m/s	
		wind projects around Kilmarnock: no infos on renewable map	n/a
		at 45m -> 6.9 m/s at 25m -> 6.2 m/s at 15m -> 5.3 m/s	
		9 m/s	
Other wind parameters	wind shear, inflow angle, turbulence intensity	need on-site investigation	n/a
Topography	- Good: higher, exposed, open ground with a smooth slope leading up to the turbine - No cliffs and sharp ridges due to turbulence issues	No cliffs or sharp ridges, however in town centre and no open ground	
Land cover	Preferably: - be clear of buildings and trees - clear to the south west (direction of prevailing wind in UK) Restrictions: - Buildings and other structures may require setbacks – usually WTs must be a minimum of 400m from any dwelling - set turbine at a distance of at least 10x the height of potential obstacle away from it	South west direction is open, however there are trees and buildings close	
Electrical lines and substations	- Overhead power lines cannot be within falling distance. This is hub height + rotor length + 30m. - Close grid connection can be useful (FITs)	A grrid connection is available	
Radar and airspace restrictions	Airfields, TV transmitters, ATC tower can all be restrictions	Not existing	
Roads, railroads, and paths.	Access to the site for construction vehicles i.e. large articulated lorries, and maintenance is required. This can be built but will increase costs and visual impact.	The infrastructure is good due to location in town centre	

Besides wind speed there were also other wind parameters to be considered, e.g. turbulence intensity, wind shear and inflow angle while assessing a site. Based on these variables the industries standard procedure is to define a project site as a so-called “class”. A turbine model also has a “class” and both classes need to match to prevent mechanical failure [54]. The wind parameters as well as the classification of the site and the turbine cannot be evaluated without an on-site assessment and were therefore not discussed any further. The restrictions coming from topography and land cover are not favourable. The project site in Kilmarnock is in the middle of the town centre and not on open ground. Therefore, it is likely that the wind resource will be highly turbulent. There are buildings and some trees around which give restrictions to the height of the turbine. A safety distance of the turbine height times 10 m has to be considered to ensure no damage in case the turbine collapses. Therefore, the conditions for a wind turbine are in total not favourable at that location.

Other possible restrictions that have been taken into consideration have a more public character (Table 7). The site in Kilmarnock is not a natural or cultural heritage site and the soil does not consists of peat whose structure can be problematic for a wind turbine installation [55] [56] [57]. Kilmarnock itself is classified as low or un-known ecological sensitivity site when it comes to bird appearances [58]. In terms of potential scheduled monuments or listed buildings there are no restrictions to the HALO initiative since the town quarter is going to be built on the old production site of the Johnnie Walker distillery [59]. Due to the fact that the site is within one town there are no interferences with different administrative boundaries [60] [61]. The site is classified as an industrial and commercial area [62]. The Development Plan of the town of Kilmarnock sees the area for "miscellaneous opportunities" [63]. The land ownership is already discussed, HALO can develop the site, but without installing a wind turbine. Wind turbines would require extra planning permission [29] and an extensive permitting process that involves parts of an environmental impact assessment and resident involvement. Although, the location is favourable for industrial operation, the installation of a wind turbine was denied beforehand.

Table 7 Initial assessment wind power - potential other restrictions [own demonstration and [5]]

Potential Restrictions	Relevance to wind turbines	Condition on Kilmarnock Site	Feasibility
Natural heritage (national parks, urban areas, wildlife etc.)	- Permissions in these areas are harder to obtain - No construction on peat soil	No habitat or protected nature sites, the area around Kilmarnock is calssified as low, un-known ecological sensitivity site for birds/ wind farms The soil in this area is classified as non-soil/unknown soil	
Cultural heritage (world heritage sites, scheduled monuments, listed buildings)		No heritage, scheduled monuments or listed buildings present.	
Land ownership	Required for permissions, lease of site and access	Former industry site; HALO can develop site but not with wind turbine	
Land use and amenity (enjoyment from physical outdoor space)		Project site is calssified as an industrial and commercial area. Development plan of Kilmarnock says for this area "misc. opportunity". Installation of wind turbine would cause planning permission	
Administrative boundaries		Within one town	

This initial assessment has shown that there are restrictions for the installation of a wind turbine on-site. Before ruling out this possibility, the implementation of wind from other sources was considered. The first option is called community ownership and means that a community owns a share of the production of a wind turbine or of a whole wind park. Studies show that the acceptance of wind parks increases when the inhabitants know that a fixed share provides energy for their town [64]. The other option is to purchase wind power from a close wind park that would be Whitelee windfarm in the case of Kilmarnock. Whitelee is situated on Eaglesham Moor that is an area 20 km north of Kilmarnock and generates 539 MW from 215 turbines [65]. With regard to the development of the distribution network (discussed in chapter 2.4.4), it would be favourable to purchase or even own an isolated wind power supply. A more detailed observation of these possibilities is out of the scope of this master thesis. However, ones should consider these options and compare grid import costs with wind power purchases or ownership as part of future work following this thesis. Furthermore, a detailed assessment of the surrounding area can even re-define the available wind parameters and planning permissions for an on-site wind turbine. In the upcoming modelling procedure, wind power was assessed as a part of one modelling scenario to display a 100% renewable electricity supply for the HALO sustainable district.

3.1.2 Solar power

Table 8 shows the technical criteria catalogue for solar power. In order to know how viable solar power can be at one location the existing solar insulation and a potential PV output were investigated. For both there is no minimum requirement, due to the fact that the main electricity will come from the public grid. Therefore, this criterion was not crucial for deciding on solar power installations. Nevertheless, the online available PV*Sol tool offers the chance to initially invest potential insulation and PV outputs for certain locations [66] [5]. Potential restrictions from topography or land cover can be prevented by installation. Solar panels should be installed facing south without any obstacles which may cast shadows. As said before, the infrastructure is advantageous since the site is in the middle of a town centre and airspace restrictions, due to reflection problems for airplanes are not existent.

Table 8 Initial assessment solar power - technical restrictions [own demonstration and [5]]

Technical Restrictions	Relevance to solar panels	Condition on Kilmarnock Site	Feasibility
Solar insolation	No minimum required insolation but potential PV output can be calculated	Test again with demand data	n/a
Ambient temperature	Required to calculate energy output for PV	Tmean =9.7 degrees Celsius	n/a
Topography	Should be south facing and free of shading	Need to be cosidered in construction phase	
Land cover	-Should be clear of obstacles and shading - On roof: adjacent building no shading - south-facing is ideal (or south-east or -west) - Areas covered in trees, or steep hills/cliffs problematic	Need to be cosidered in construction phase	
Electrical lines and substations	Close grid connection can be useful (FITs)	A grid connection is available	
Airspace restrictions	Panels located close to a flight path can cause visual problems by reflecting the sun's rays.	Not existing	
Roads, railroads, and paths.	- Access to the site for construction vehicles i.e. large articulated lorries, and maintenance is required. - This can be built but will increase costs and visual impact.	The infrastructure is good due to location in town centre	

The public criteria that was already assessed for wind power show no restrictions for the development of solar power on the site (Table 9). In summary, solar power has a potential for future on-site electricity production or in a solar thermal system and was considered as part of a future energy system and modelled in energyPRO.

Table 9 Initial assessment solar power - potential other restrictions [own demonstration and [5]]

Potential Restrictions	Relevance to solar panels	Condition on Kilmarnock Site	Feasibility
Natural heritage (national parks, urban areas, wildlife etc.)	- Permissions in these areas are harder to obtain - a roof mounted panel in an urban conservation area may have problems gaining permission - visual impact in some areas problem	No habitat or protected nature sites, the area around Kilmarnock is calssified as low, un-known ecological sensitivity site	
Cultural heritage (world heritage sites, scheduled monuments, listed buildings)		No heritage, scheduled monuments or listed buildings present.	
Land ownership		Former industry site; HALO has permission to develop it	
Land use and amenity (enjoyment from physical outdoor space)		Project site is calssified as an industrial and commercial area. Development plan of Kilmarnock says for this area "misc. opportunity"	
Administrative boundaries		Within one town	

3.1.3 Heat pumps

In this chapter shallow and borehole ground source heat pumps (GSHP) as well as surface water source (SWSHP) and air source heat pumps (ASHP) were initially investigated with regard to climate parameters and geothermal conditions.

Shallow ground source heat pumps are drilled to a depth of 1.5 m [67]. At this depth the ambient temperature still has an impact on the subsurface temperature. These impacts are displayed in a formula developed by Kusuda and Achenbach (1965) [68] [5] for calculating the shallow ground temperature including a phase shift:

$$T = T_{mean} - T_{amp} * e^{\left(-x*\sqrt{\frac{\pi}{365a}}\right)} * \cos\left[\frac{2\pi}{365} * \left(t_{now} - t_{shift} - \frac{x}{2} * \sqrt{\frac{365}{\pi a}}\right)\right] \qquad \textit{(Equation 1)}$$

where

T = temperature (°C)

T_{mean} = annual mean air temperature (°C)

T_{amp}= amplitude of air temperature ($\frac{T_{max}-T_{min}}{2}$)

x = soil depth below surface (m)

a = thermal diffusivity (m^2/day)

t_{now} = current day number of year (1-365)

t_{shift} = day number of the year with minimum air temperature (1—365)

Table 10 Technical data required for ground temperature calculation [demonstration: [5]]

Technical data required	Condition on Kilmarnock Site
Mean temperature, T_mean(°C)	8.8 °C
Temperature amplitude, T_amp ((T_max-T_min)/2, °C)	5.7 °C
Soil depth below surface, x (m)	1.5 m
Thermal diffusivity, α (m2/day)	0.042 m2/day
Thermal Conductivity (W/m/K)	1.07 W/m/K
Current day number of year, t_now (1-365)	177 (26/06)
Day number of the year with minimum air temperature, t_shift (1-365)	18

The required input data for Equation 1 was found in the internet at MetOffice [30] and with Thermomap [69]. Thermomap is an estimation tool that allows to create a report that provides the dominant soil properties, the heat conductivity, climatic conditions and geothermal situation of a certain site [5]. It is based on geoscientific datasets and therefore does not unconditionally display real on-site situations. In order to ensure the real geological conditions experts have to be consulted. Table 10 shows the obtained data required for calculating the shallow ground temperature at the Kilmarnock site. In order to find the thermal diffusivity Table 11 was used.

Table 11 Thermal properties of typical soil [70]

Soil Type	Thermal Diffusivity (m^2/day)	Thermal Conductivity (W/m/K)
Sand (gravel)	0.039	0.77
Silt	0.05	1.67
Clay	0.046	1.11
Loam	0.042	0.91
Saturated sand	0.079	2.5
Saturated silt or clay	0.056	1.67

The shallow ground source temperature calculated with those numbers were:

$$T = 8.8 - 5.7 * e^{\left(-1.5*\sqrt{\frac{\pi}{365*0.042}}\right)} * \cos\left[\frac{2\pi}{365} * (177 - 18 - \frac{1.5}{2} * \sqrt{\frac{365}{\pi*0.042}})\right] = 5.91\ °C$$

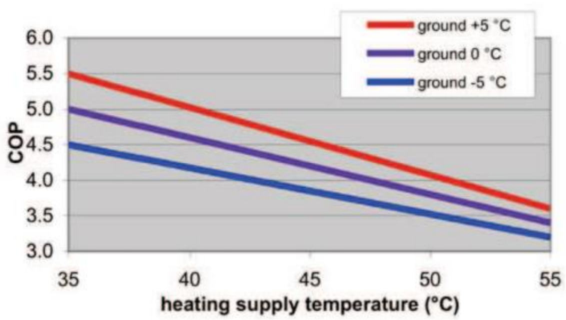


Figure 22 COP in relation to heating supply temperature [71]

For a shallow ground source heat pump this temperature value is satisfying. Figure 22 shows that with decreasing ground temperature the COP decreases as well. Depending on the heating supply temperature the COP with a ground temperature around 5 °C range between 5.5 and 3.5. Consequently, shallow ground source heat pumps were considered to be an option for the HALO Kilmarnock site.

Borehole closed-loop ground source heat pumps consists of a vertical loop in which water can circulate to extract heat from deep geological formations. Mostly the boreholes are drilled to a depth range between 15 and 122 m [72]. The HALO initiative plans a geothermal well with a depth of 2,000 m in combination to an open-loop ground source heat pump or a heat exchanger. For the sake of completeness, the closed-loop heat pump type and its initial assessment was broadly displayed in this section as well. Below 15 m the ground temperature falls by 2.6 °C every 100 m on average [70]. However, this can fluctuate heavily depending on the location. The following equation could be used to initially assess ground temperatures between 15 – 100 m. The map in Figure 23 gives an initial idea about the temperature of boreholes at 100 m [73] [5].

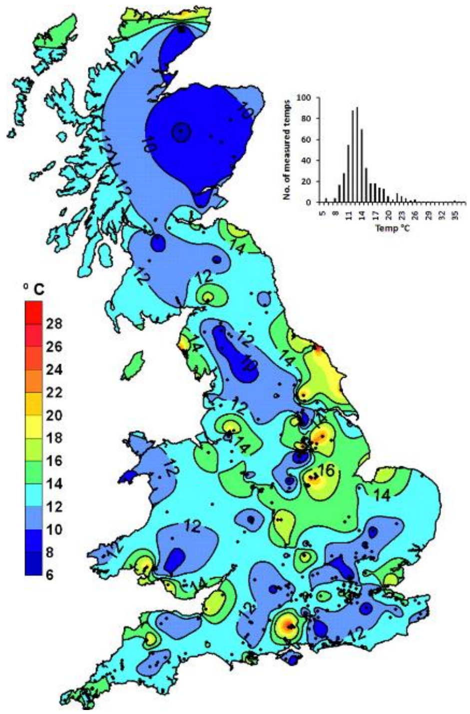


Figure 23 Ground temperatures at depth of 100 m [73]

$$T_d = T_m + 0.026d \qquad \textit{(Equation 2)}$$

where

T_d = temperature at depth d (°C)

T_m = mean air temperature (°C)

d = borehole depth (m)

Since the plan for the HALO Kilmarnock project involves a deeper open-loop system this option was not further assessed. The equation for a first-hand calculation displayed above could help to estimate potential ground temperatures. Though, also in this case experts need to be consulted to identify real data of the geothermal conditions.

Open-loop ground source heat pumps or water source heat pumps extract water from deep geothermal formations via borehole and circulate it up to the surface.

Many factors can influence the performance, even the feasibility of a deep borehole GSHP project. Examples are temperatures, rock formation, groundwater bodies, thermal conductivity and diffusivity [73]. Since no real geothermal data were available, an initial assessment of the geothermal situation through research as well as estimations for the temperatures were carried out. In order to get real on-site data test wells, have to be drilled and experts need to be consulted.

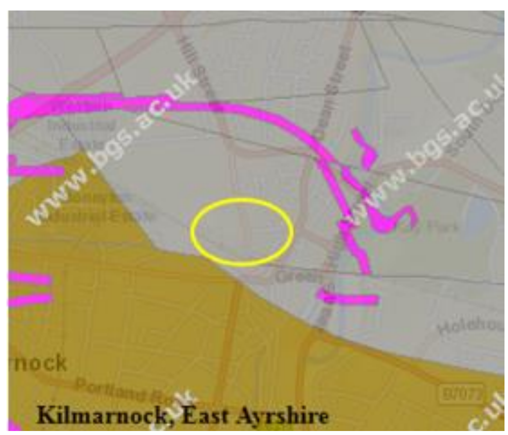


Figure 24 Bedrock below HALO project site in Kilmarnock [74]

Kilmarnock is part of the Midland Valley of Scotland. In order to get a first idea about the geological formation below Kilmarnock, the Geology of Britain viewer [74] was used (see screen shot in Figure 24). One can see that the bedrock below Kilmarnock consists of Scottish upper coal measures formation (brown area) and middle coal measures formation (grey area) that are both a sandstone, siltstone and mudstone mix with slightly different properties [75]. The pink parts are so-called "unknown igneous intrusions of unknown age – microgabbro". Under the project site (yellow circle in Figure 24) the bedrock is only classified as Scottish middle coal measures formation. In Table 12 some further information on this bedrock can be seen (black frame).

Table 12 Excerpt from the seven bedrock categories in Scotland [76].

Geological category	Main geological units	Main areas of outcrop	Principal lithologies	Overall rock character	Typical permeability	Thermal conductivity *
Non-metamorphosed sedimentary rocks	Stewartry Group; Hopeman Sandstone Formation; Stornoway Formation	Morayshire; Ayrshire; Dumfries and Galloway	sandstone; conglomerate	granular	high and very high	high
	Inverclyde Group; Strathclyde Group; Clackmannan Group; Scottish Coal Measures Group	Midland Valley	sandstone; mudstone	granular	moderate	low to high
	Old Red Sandstone Supergroup	Orkney Islands; Caithness and mainland fringes of Moray Firth Basin; Midland Valley; Scottish Borders	conglomerate; sandstone	granular	low to high	high

*where low is <2.0 W/mK, moderate is 2.5-3.0 W/mK and high is 3.0-3.5 W/mK

As seen in Table 12, the bedrock has a moderate permeability and can have a high heat conductivity. Therefore, it was assumed that the bedrock below Kilmarnock is suitable for geothermal exploration. More detailed information about thickness of these layers and underground conditions are not within the scope of an initial assessment.

Geothermal heat resources below Scotland can appear in form of hot sedimentary aquifers (HSA), abandoned mines and hot dry rocks. In the Midland Valley abandoned mines and hot sedimentary aquifers are present. Currently, in the east of Glasgow in Shettleston a GSHP that makes use of mine water is already in place. Collapsed and abandoned mines contain large amounts of groundwater that can be extracted for heating purposes. Depending on the depth mine water can have temperatures between 20 – 40 °C. A study that was conducted in 2004 even estimated the heat potential from mine waters up to 1,708 GWh per year that was 3% of the Scottish yearly heat demand at that time. To fully make use of those reservoirs more studies about potential, technical feasibility and permeability with detailed 3D models need to be conducted. However, a potential for mine water is seen in the Glasgow area and some 3D data is already available through the British Geological Survey. The Midland Valley is underlined by sedimentary strata that has good HSA prospects. However, this area is geologically complex and needs to be investigated more in terms of HSA potential [76].

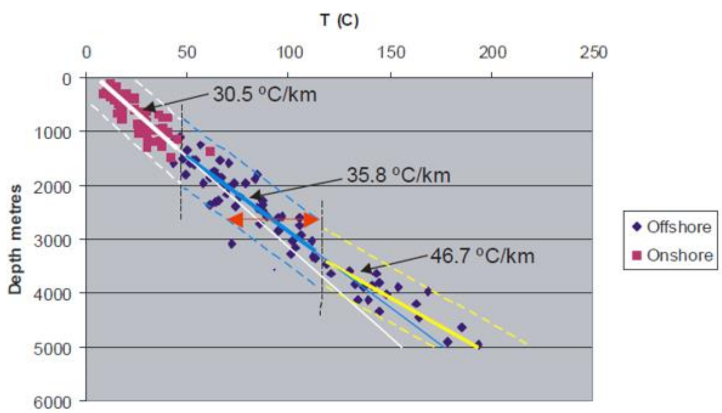


Figure 25 Geothermal temperature gradients in Scotland [76]

For boreholes beyond 100 m the temperature gradient is displayed in Figure 25. One can observe that the gradient slightly increases with depth. For the first 1.5 km the gradient is about 30.5 °C and raises in the following 2 km to 35.8 °C. At a depth between 3.5 km and 5 km the gradient is 46.7 °C. With regard to Figure 25 the planned geothermal well of a depth of 2,000 m is supposed to extract water at a temperature of 65-75 °C which would be advantageous for a geothermal source. However, the input data of the graphs in Figure 25 are mainly coming from offshore boreholes and have to be used with caution [76].

In summary, there is no possibility to assess a potential geothermal heat source below the HALO Kilmarnock project site in detail at the moment. As said before more reliable data can only be gathered through expert consultancies and with test wells. However, the results of the initial assessment were promising and therefore a deep geothermal well in connection to a GSHP or a heat exchanger was considered for the energy system.

Surface water source heat pump (SWSHP) uses heat from lakes, rivers and seas. In the following paragraph different constraints for the usage of a SWSHP were investigated.

An open loop installation with heat exchanger and heat pump was assumed. The first potential constraint was the location of the water source (Figure 26).

Figure 26 Water bodies close to project site in Kilmarnock [28]

Kilmarnock is situated around 16 km away from the coast and has two water bodies, the river Irvine (blue line) that runs in a distance of 1.5 km and Kilmarnock Water (orange line) that runs in a distance of 0.5 km from the project site (yellow circle). Since heat losses can occur in transportation pipes and extended pumping work increases costs the distance can play a critical role. In this case, Kilmarnock Water is in an adequate distance to the project site while Irvine River is slightly away. The second possible constraint is the water availability. The Irvine River comprises a volume of around 218 km^2 while Kilmarnock Water encompasses 74 km^2 [77]. Larger volumes mean more stability in flowrates and water temperatures that is an advantage for the Irvine River.

Another constraint can come from the quality of the thermal resource. In order to assess if the water body is suitable for a SWSHP, the heat capacity has to be calculated. The formula for this is:

$$\dot{Q} = \dot{m} * c_p * \Delta T \quad \text{(Equation 3)}$$

Where

$\dot{m}$ = mass flow of the water body (kg/s)

c_p = specific heat capacity of water (4.18 kJ/kgK)

ΔT = temperature change in °C

First of all, the water temperature was needed. This is a critical value since it needs to be ensured that the minimum operation temperature of the heat exchanger is not underrun due to ice crystal formations. For fresh river water this value is 3 °C with a 1 °C gradient [78]. Temperatures of the river Irvine and for Kilmarnock Water were not available.

Table 13 Average parameters and heat capacity in 2015 for Irvine River [own demonstration]

Time period	Average temperature in °C	Average flow rate in m3/s	Average mass flow rate in kg/s	Average thermal resource in kW
All year	9.40	7.53	7,527	264,281
Winter	4.63	14.15	14,150	214,897
Spring	8.30	5.41	5,406	164,945
Summer	14.48	2.80	2,803	157,977
Fall	10.08	7.90	7,897	299,834

For an estimation of the water temperature average ambient air temperatures of Kilmarnock were considered [30]. The mass flow can be calculated by multiplying the volume flow with the water density (1,000 kg/m^3). Volume flow rates were obtained for the river Irvine from the National River Flow Archive [77]. For Kilmarnock Water no data was available. For the initial assessment the average flow rates of the last fully reported year (2015) were taken. With these values and an assumed temperature drop of 1 °C the potential heat capacity for the Irvine River was calculated. Table 13 displays the average heat capacity calculated with average temperature and flow rate figures while Table 14 shows the minimum heat capacity to display the worst-case scenario. The geothermal well planned by HALO is expected to supply 750 kW [79] that was highly exceeded by the calculated heat capacities in Table 13 and Table 14.

Table 14 Minimum parameters and heat capacity in 2015 for Irvine River [own demonstration]

Time period	Minimum temperature in °C	Minimum flow rate in m3/s	Minimum mass flow rate in kg/s	Minimum thermal resource in kW
All year	6.20	0.45	450	9,781
Winter	1.83	1.77	1,768	6,159
Spring	4.70	0.77	765	11,831
Summer	11.00	0.49	491	20,524
Fall	7.10	0.45	450	11,474

In summary, most investigated potential constraints delivered satisfactory results. The Irvine River has a sufficient volume, only the distance can be a problem when it comes to transportation infrastructure and heat losses. Since the planned geothermal well of the HALO project is expected to provide 750 kW [79], the thermal resource of the Irvine River was considered as sufficient enough in this initial investigation. Nevertheless, this result has to be considered with caution as ambient temperature instead of water temperatures and flow rates of only 1 year were taken for the thermal resource analysis. Therefore, it would be advantageous to have a deeper look into this heating supply technology to ensure that climate fluctuations and transportation losses would not be too high. For Kilmarnock Water fewer information were available and an initial assessment for this water body was not possible. For the scope of this thesis a water source heat pump connected to the river Irvine was further considered.

Air source heat pumps extract heat from the ambient air in order to increase temperatures in a dwelling. They work best when the distance to the dwelling does not exceed 4 m. These single-packaged ASHP are installed at every dwelling to reduce heat losses. There is also a split-system available that can work within distances of 50 m by using refrigerant pipework [80]. In order to examine if an ASHP is suitable for a building there are some minor things to consider like location, insulation of home, heating system and if the ASHP is a part of a new development. The heat pump needs space, preferably at a sunny wall to get enough air flow. It operates best while producing heat at low temperatures and therefore a good insulation makes the heat pump more efficient. In comparison to e.g. a radiator-based heating system under-floor heating or warm air heating should be preferred since they require lower temperatures provided by the heat pump [81]. Since all dwellings and other buildings of the HALO initiative still need to be designed and built, these requirements can be considered from the beginning.

Table 15 Power outputs of ASHP at various temperatures [82]

Outdoor temp	Units	5kW	7kW	12kW	14kW
35° Flow					
-5	kW	3.1	4.55	7.40	8.31
	COP	2.45	2.71	2.75	2.62
2	kW	4	5.41	8.72	10.2
	COP	3.1	2.99	3.11	3.2
7	kW	4.8	7.2	11.82	14.5
	COP	3.8	3.9	3.9	4.06
45° Flow					
-5	kW	2.6	4.45	6.96	7.9
	COP	1.8	2.28	2.24	2.1
2	kW	3.9	5.38	8.45	10.2
	COP	2.6	2.55	2.61	2.6
7	kW	4.5	7.4	11.38	14
	COP	3.1	3.16	3.03	3.21
55° Flow					
-5	kW	2.02	4.24	7.06	7.6
	COP	1.38	2.02	1.92	1.8
2	kW	3.7	5.14	8.47	10.2
	COP	2.15	2.34	2.2	2.6
7	kW	4.35	6.71	11.04	13.9
	COP	2.5	2.68	2.5	2.82

The diverging power outputs of different sizes of ASHP can be extracted from Table 15. One can see that the system becomes more efficient within lower flow temperature and higher ambient temperature. This can also be seen in the diagram in Figure 27. In the UK the usage of air source heat pumps is increasing [80] that suggests that the UK climate suits this technology. A first-hand calculation should confirm that the climate in Kilmarnock is suitable for ASHP. Hence, the ideal coefficient of performance (COP) was calculated. As said in chapter 2.3 the average ambient temperature in

Kilmarnock is 9 °C and over the year temperatures range between 1.8 and 18.5 °C. To calculate the ideal COP it was assumed that the inside temperature of the dwelling is 21 °C with an average temperature of 9 °C on the outside.

$$T_{hot} = 21\text{ °C} + 273 = 294\text{ K}$$

$$T_{cold} = 9\text{ °C} + 273 = 282\text{ K}$$

$$COP_{mean} = \left(\frac{T_{hot}}{T_{hot} - T_{cold}}\right) = \left(\frac{294}{294 - 282}\right) = 24.5$$

The example displays that for every watt of input power 24.5 W heat is delivered into the dwelling by the ideal air source heat pump. These ideal conditions hardly ever appear in reality and normally real COP between 2 and 6 are reached [83] (see also Figure 27). To show that the heat pump efficiency decreases on cold days, as mentioned above, the ideal COP for the minimum temperature was calculated as well:

$$COP_{min} = \left(\frac{294}{294 - 274.8}\right) = 15.31$$

These first-hand calculations show that ASHP efficiency is highly dependent on climate. Nevertheless, since Scotland has a moderate climate (see chapter 2.3) the usage of an ASHP can be a feasible solution to supply renewable heat to the HALO Kilmarnock buildings. COP variation over the year in the Kilmarnock area should be investigated to ensure a constant and adequate ASHP performance.

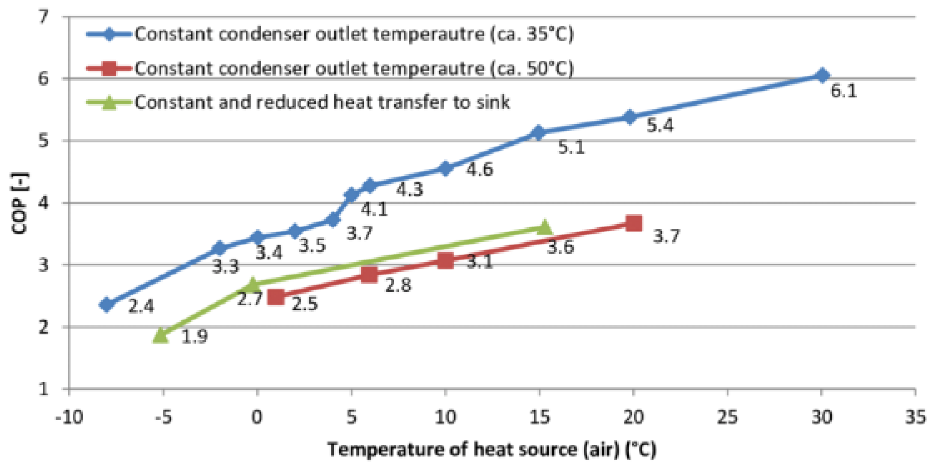


Figure 27 COP of ASHP at condenser outlet temperatures dependent on different ambient air temperatures [84]

3.1.4 Result of the initial assessment

Through first-hand calculations and an initial assessment of on-site conditions as well as technical and public restrictions the final decision on potential technologies for the sustainable district was made. Besides the already set cooling and storage options, all heat pump types (GSHP, ASHP and SWSHP) were considered in the following modelling process. The potential of solar installations like PV or solar thermal panels was found eligible as well. Wind power was identified to be unfeasible on the actual project site. However, this energy source was considered in one upcoming model in form of community ownership or wind power purchase.

3.2 Modelling of demand profiles

As mentioned in chapter 1.3.3 energy demand profiles were created in order to represent possible future demands of the Kilmarnock town quarter. The future site will have electric demand for buildings, lighting and 30 EV's as well as heating and cooling demand. The next paragraphs explain in detail how energy data was obtained and modified in order to create adequate demand profiles.

3.2.1 Electricity

Generic electricity demand profiles were obtained from Elexon [85] and Strathclyde University [86]. These profiles were used as a starting point in order to create exemplary demand profiles for the residential buildings and the non-domestic facilities of Phase I and Phase II. The demand profiles for the Urban and Lorry Park were self-developed with regard to seasonal sunrise and sunset times [6]. The generic demand profiles were inserted in an ESRU software called Merit. Merit has an incorporated profile designer with which generic demand profiles can be modified. To shape the profiles, two figures are needed that are peak load and annual consumption. The predicted peak load in kW of each facility was provided by the project team [87]. The overall annual consumption in kWh could not be provided since the facilities and their demand are not existent. For that reason, benchmark figures for energy consumption per square metre for different types of buildings and facilities were obtained from CIBSE [88] [89]. These benchmark numbers were multiplied by the predicted floor areas [79] of the facilities in order to receive a value for the annual energy consumption. All these data can be seen in Table 16. The orange cells show the data used to shape the profiles in Merit for each building type. When more units of a building type were planned, e.g. the domestic buildings, the unit peak load was used to create a single demand profile to be more flexible in scaling it.

Table 16 Phase I electrical load data and annual consumption [own demonstration]

Phase 1	Quantity	Area (m2)	Diversified load (kW)	Unit load (kW)	Benchmark energy consumption per m2 (kWh/m2)	Annual energy consumption (kWh) per unit
Innovation Hub	1	5,279	518.99	-	55	290,328.50
Duplex	44	84	62.7	1.425	30	2,520
2-Bedroom Terrace	26	89	37.05	1.425	30	2,670
Phase 1 Total	71	5,452	618.74			295,519

To start the modelling process in Merit the generic profiles were displayed in the profile designer and the annual consumption was inserted. As a result, the generic profile was scaled automatically with regard to the inserted consumption. Afterwards, the variability of the profile was added in order to achieve a peak load close to the given value in Table 16. Depending on input data in combination to the data from the generic profile, a higher or lower variability factor was used to size the demand profile properly. As soon as an adequate peak load was achieved, the demand profile was exported from Merit. In Figure 28 the complete electricity demand profile for the buildings of Phase I and in Figure 29 and Figure 30 the demand for a winter and summer day can be seen.

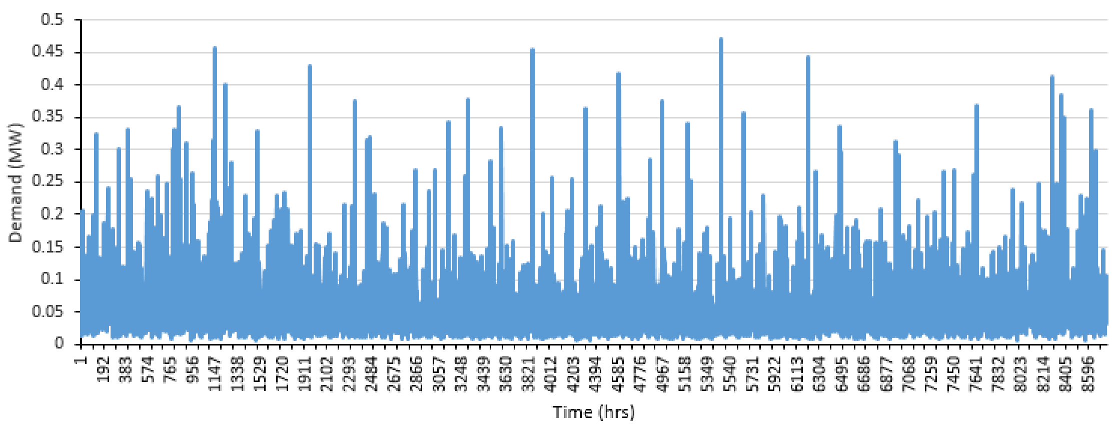


Figure 28 Electricity demand Phase I [own demonstration]

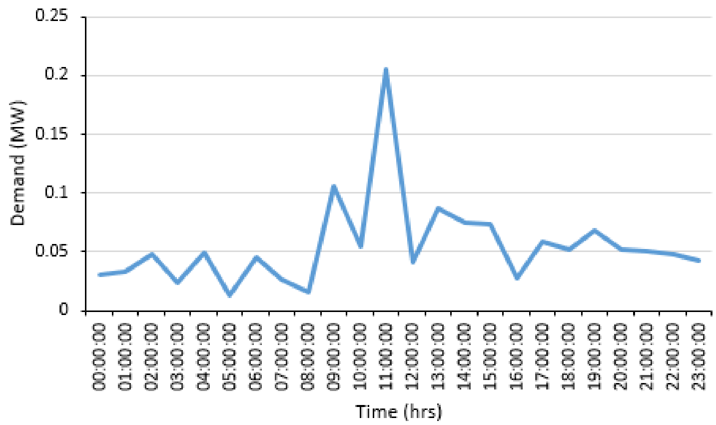


Figure 29 Electricity demand winter day Phase I (01/01/17) [own demonstration]

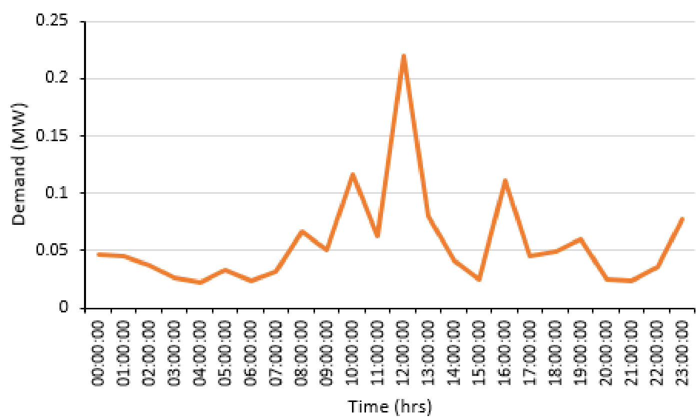


Figure 30 Electricity demand summer day Phase I (12/07/17) [own demonstration]

The same procedure was applied to create electricity demands for the buildings and parks of Phase II. The used data for shaping the profiles can be seen in Table 17.

Table 17 Phase II electrical load data and annual consumption [own demonstration]

Phase 2	Quantity	Area (m2)	Diversified load (kW)	Unit load (kW)	Benchmark energy consumption per m2 (kWh/m2)	Annual energy consumption (kWh)
Leisure Centre	1	9,300	469.25	-	95	883,500
Energy Centre	1	300	245.09	-	160	48,000
Live/Work	13	88	12.35	0.95	55	4,840
Live/Work (North)	9	88	8.55	0.95	55	4,840
Live/Work (South)	4	88	3.8	0.95	55	4,840
Speculative Office	-	5,160	271.8	-	55	283,800
Duplex houses	46	84	65.55	1.425	30	2,520
2-Bedroom Terrace	46	89	65.55	1.425	30	2,670
Flats	46	58	65.55	1.425	30	1,740
Religious Facility	1	300	10.5	-	20	6,000
Urban Park	1	4,300	21.5	-	20	86,000
Lorry Park	1	1,700	8.5	-	20	34,000
Phase 2 Total	**169**	**21,555**	**1,248**			**1,362,750**

In the end, only the overall adaptability of the developed energy system with regard to increased Phase II consumption was analysed. Therefore, only the yearly electricity demand profile for Phase I and II was displayed (Figure 31).

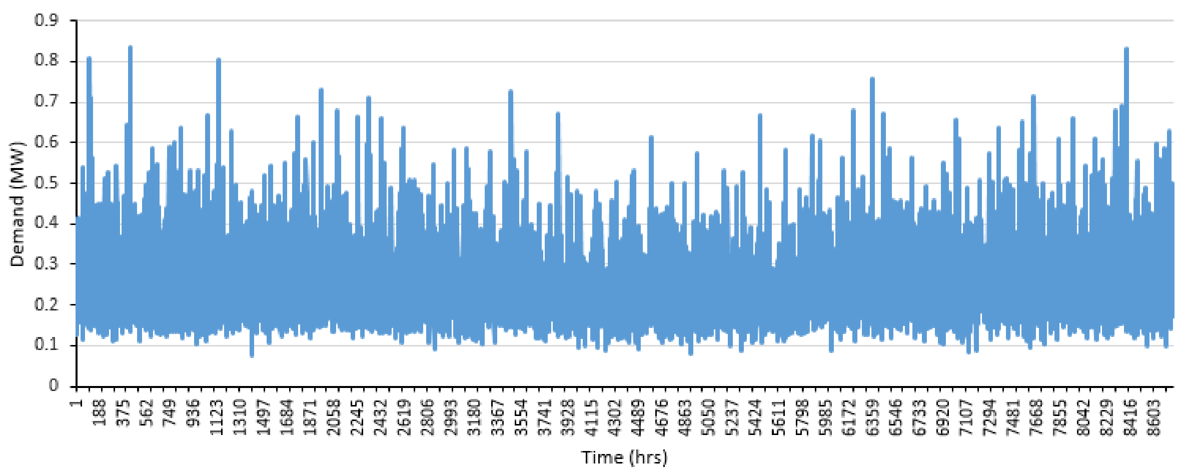


Figure 31 Electricity demand of Phase I and II [own demonstration]

EV demand

For the development of the EV demand profile the consumption in kilowatt hours per kilometre of common EV models [90] was calculated by using their battery capacity and range (Table 18). The average consumption of all models was then multiplied with the average annual mileage covered in UK, that is 7,800 miles per car [91], in order to calculate the annual electrical energy consumption per year. This number was then used to calculate the consumption for a single day and transferred to a power demand for each car per day (Table 19).

Table 18 Typical EV models and their specifications [90]

EV make	Battery capacity (kWh)	Range (km)	Consumption (kWh/km)
BMW i3	22	135	0.1630
GM Spark	21	120	0.1750
Fiat 500e	24	135	0.1778
Honda Fit	20	112	0.1786
Nissan Leaf	30	160	0.1875
Mitsubishi MiEV	16	85	0.1882
Ford Focus	23	110	0.2091
Smart ED	16.5	90	0.1833
Mercedes B	28	136	0.2059
Tesla S 60	60	275	0.2182
Tesla S 85	90	360	0.2500
Average			**0.1942**

Table 19 Energy and power demand of an EV [demonstration: [7]]

Annual mileage/car	7800.00	mil/car
Annual mileage/car	12480.00	km/car
Annual electrical energy consumption/car	2424.00	kWh/car
Daily electrical energy consumption/car	6.64	kWh/car
Electrical power demand/car	0.2767	kW/car

As said in chapter 1.3.3 a 12-hour overnight charging period was assumed. Distributing the demand equally over the charging time results in a power demand of 0.5534 kW each hour for 1 EV and respectively 16.602 kW for 30 EV's between 19:00 – 07:00 (Figure 32).

A growing technology is rapid charging that can recharge a battery in 30 min – 1 hour [92]. However, rapid charging draws high amounts of power from the grid that can result in voltage fluctuations, high power losses or overloading [93]. For that reason, the standard charging rate was considered.

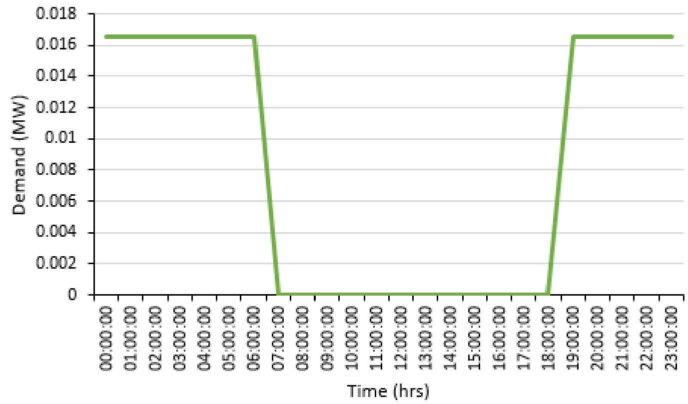


Figure 32 Daily electricity demand for 30 EVs [own demonstration]

In the software modelling procedure this electricity consumption was added in some models next to the building electricity demand in order to analyse if the grid limitation of 2,000 kVA would not be exceeded.

3.2.2 Heating / Cooling

Heating demand

Heating demand profiles were created in the same way as described in chapter 3.2.1. with peak loads and floor areas provided by the project team [79] and annual consumption calculated with CIBSE energy consumption benchmark figures [88]. The heating demand consists of space heating and heat for domestic hot water. The profiles were created by a colleague who worked on the same project [8]. The heating demand profile for Phase I as well as daily profiles for winter and summer can be seen in Figure 33, Figure 34 and Figure 35. For Phase I and II the yearly profile can be seen in Figure 36.

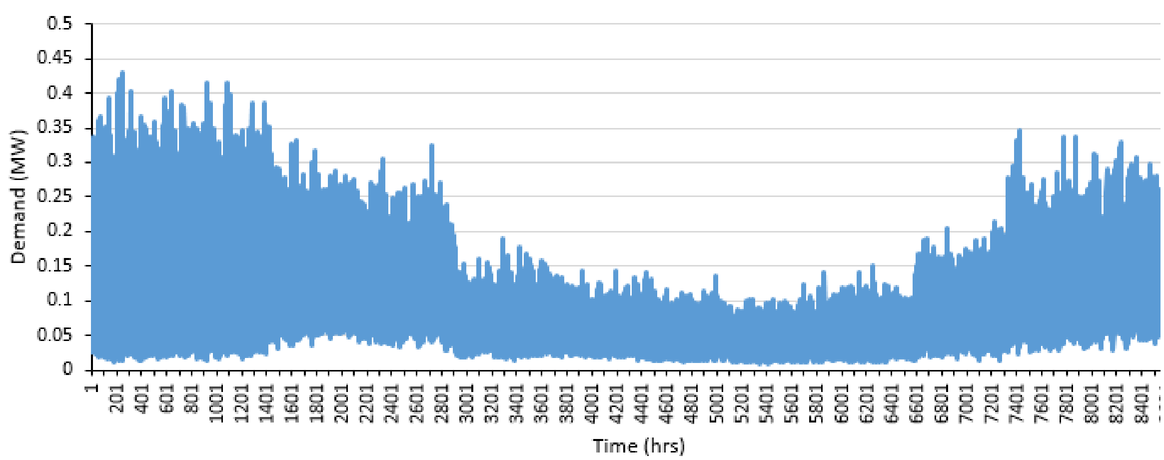


Figure 33 Heating demand Phase I [own demonstration]

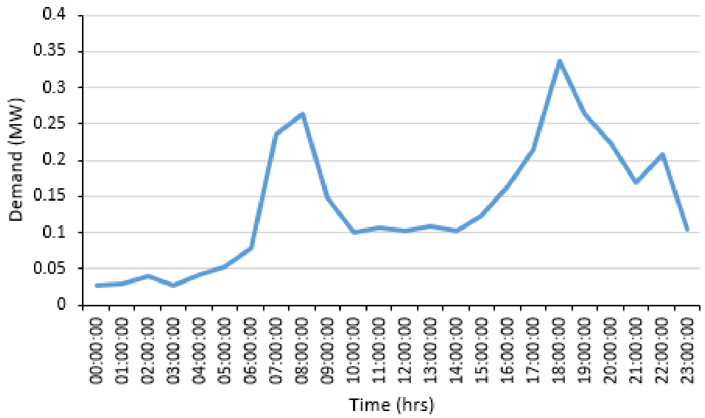


Figure 34 Heating demand winter day Phase I (01/01/17) [own demonstration]

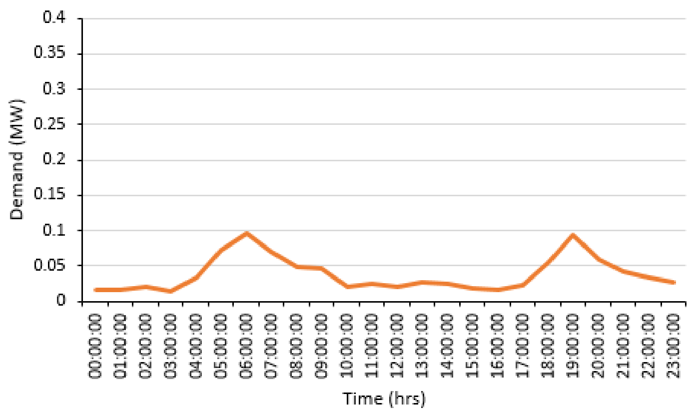


Figure 35 Heating demand summer day Phase I (12/07/1) [own demonstration]

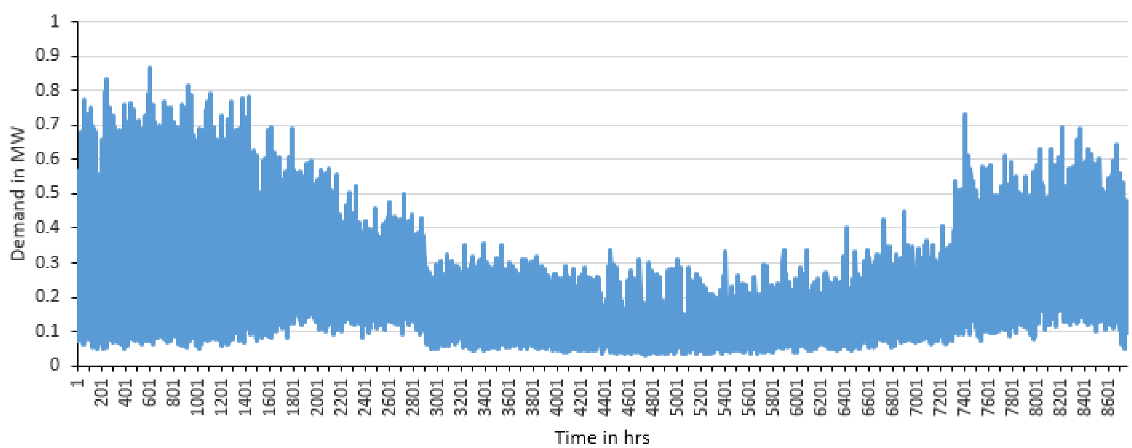


Figure 36 Heating demand Phase I and II [own demonstration]

Cooling demand

Cooling demand was assumed to arise only in non-domestic buildings. Cooling is highly dependent on building features, like glazed areas. To this stage the building design was not existent as well as cooling peak loads for the non-domestic buildings except for the Innovation and Enterprise Hub that can be seen in Table 20. It was assumed that these peak loads contained several safety factors and were too high. A generic cooling demand was taken from the Technology and Innovation Centre (TIC) building at Strathclyde University [86] since there was no source available stating generic cooling demand profiles. This demand profile is probably too high since the TIC building has a high HVAC and a specific cooling demand due to the design and operation of the building. Due to the fact that no feasible data was available the cooling modelling was limited in this master thesis. Two modelling scenarios assume passive cooling and only one investigates active cooling with the imprecise cooling demand profile developed in this chapter. Component sizes and real-life interpretations cannot be obtained from that scenario and therefore a feasible active cooling simulation was recommended for future work.

Table 20 Phase I cooling load data and annual consumption [own demonstration]

Phase 1	Area (m2)	Diversified load (kW)	Benchmark energy consumption per m2 (kWh/m2)	Annual energy consumption (kWh)
Innovation Hub	5,279	251	20	105,574

The cooling demand profile was created by modifying the potentially oversized generic demand profile taken from the TIC building. It was shaped with the given peak load and calculated annual consumption (see Table 20) in the same way as the electricity demand profiles using the software Merit. The energy consumption benchmark figure for cooling was obtained from AuditAC, an European Commission Initiative for field benchmarking for audit methods in air conditioning [94]. The resulting cooling demand profile can be seen in Figure 37.

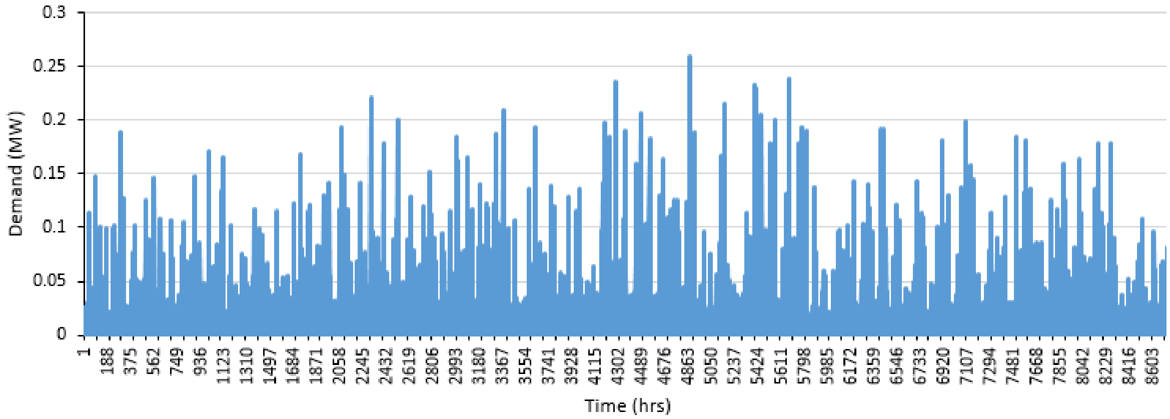


Figure 37 Cooling demand Phase I [own demonstration]

Since for Phase II no cooling figures were available, the investigation of active cooling of Phase II buildings was scoped out from the thesis.

Demand profiles for all energy streams were developed to ensure a modelling process that can focus on matching future energy demands with sustainable supply technologies. The demand profiles vary in their reliability since data and generic profiles were obtained from sources with different levels of credibility. Therefore, the upcoming results and sizes of components were interpreted with caution. However, the explained way of creating demand profiles was feasible enough for the high-level scoping study in this thesis.

3.3 Energy systems analysis and modelling results

In this chapter scenarios were identified that consist of different energy system configurations to meet the future electricity, heating and cooling demand of the Phase I buildings of the HALO sustainable district. Afterwards, the adaptability of the chosen system for Phase II and an increased energy demand was assessed, too. To analyse different energy systems the energy modelling software energyPRO was used.

As explained in chapter 1.3.3 the energy system modelling procedure was based on a scenario approach. Three scenarios were identified that incorporate different system configurations. The main aim was to meet the critical value that was the demand and supply match rate with each of these configurations. If the critical value was fulfilled different other KPI's were analysed to compare the configurations. Each scenario with its configurations was assessed individually with a summary in the end of each subchapter. In the end a summary in table form of all feasible configurations (independent of the scenario) was displayed and a recommendation for a system was made. Throughout the modelling process only the technical rather than the economic feasibility was assessed. The final conclusion was discussed in chapter 4.

It is important to consider that losses in energy production units or in piping networks were neglected throughout the whole investigation process. The modelled configurations are ideal systems. Only the heat pumps and storage options were specified with efficiencies that represent real conditions. In terms of specifications and sizing this is important to consider when modelled energy systems should be implemented in reality.

Due to the fact that in the upcoming analysis not only yearly trends but also a winter and summer day were displayed, Figure 38 to Figure 41 show the wind and solar profile of those days that perform as a reference point to the investigations in the next subchapters. In the modelling analysis three winter and summer days were assessed for each configuration. However, it was decided to display only one representative winter and summer day when necessary next to the yearly trends. The reason for that is that the observations made for three representative days were the same as for one and therefore the clearness of the analysis was preserved. Since the graphical outputs not always show precisely when demand and supply matched data from energyPRO reports were used to gather information about assessed KPI's. For demonstration purposes only the graphs and not the reports were displayed in this thesis. However, the reports were submitted within the energyPRO models in addition to this thesis.

All input data used for the setup of the energy units in energyPRO and their references can be seen in the tables in the Appendix.

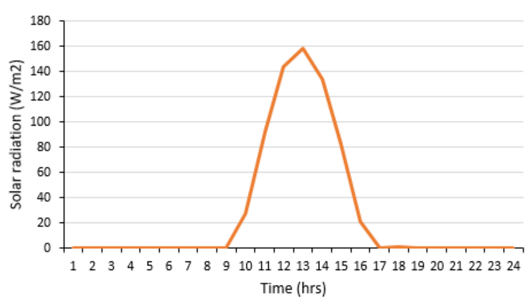


Figure 38 Solar profile on winter day (01/01/2017) [own demonstration]

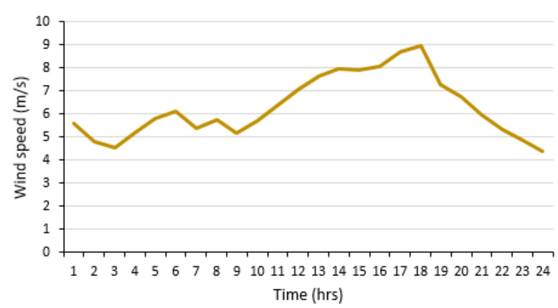


Figure 39 Wind profile on winter day (01/01/2017) [own demonstration]

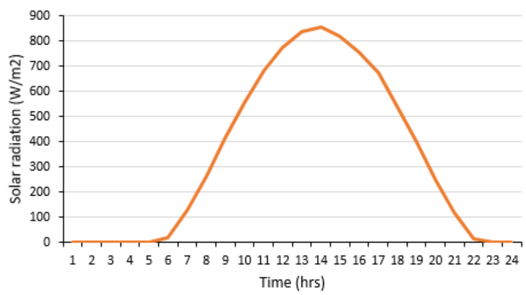


Figure 40 Solar profile on summer day (12/07/2017) [own demonstration]

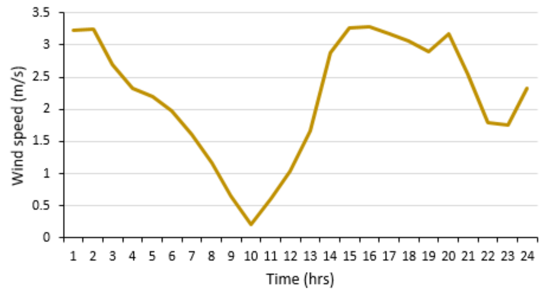


Figure 41 Wind profile on summer day (12/07/2017) [own demonstration]

3.3.1 Scenario 1 – Investigation of electricity supply technologies

First of all, the electricity side was investigated. In Scenario 1 different combinations of renewable energy sources with battery or grid were investigated to meet the demand of Phase I and afterwards with additional EV energy consumption. It is assumed that a district heating system consisting of the planned geothermal well in combination with a heat exchanger provided heating energy while the cooling was done passively. For that reason, the heating and cooling side were not displayed in the Scenario 1 models. Table 21 shows the assessed system configurations. In the following paragraphs each configuration was analysed as described in chapter 1.3.3.2.

Table 21 Scenario 1 and its configurations [own demonstration]

		Scenario 1 Renewable penetration District heating: Geothermal well with heat exchanger Passive cooling	
Configuration			**Demands**
C1	**PV**	**x**	Electricity Demand Phase I
C2	**PV + BAT**	**x**	Electricity Demand Phase I
C3	**PV + BAT + GRID**	**x**	Electricity Demand Phase I
C3+	**PV + BAT + GRID**	**x**	Electricity Demand Phase I + EV Demand
C4	**PV + WIND + BAT**	**x**	Electricity Demand Phase I + EV Demand

Configuration C1

The first configuration C1 consists of PV panels that should meet the electricity demand of the Phase I buildings (Figure 42).

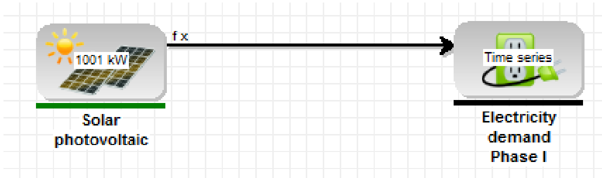


Figure 42 Configuration 1 [demonstration: energyPRO]

The installed PV peak capacity of 1001 kW was obtained from the solar assessment provided by Wood. It was assumed that PV panels with an area size of 1.94 m^2 cover 80% of the roof area of the Phase I building and the belonging parking space [95]. The specifications for the PV panels were obtained from a manufacturer sheet provided by Wood [96]. The solar radiation in the Kilmarnock area was obtained from energyPRO and is displayed in Figure 15 in chapter 2.3. The solar profile for the winter and summer day can be seen in the introduction to this chapter 3.3. The electricity demand for Phase I can be seen in Figure 28 (annual), Figure 29 (winter day) and Figure 30 (summer day) in chapter 3.2.1 and encompasses 470.6 MWh overall.

The modelling results for yearly and daily electricity consumption in comparison to the PV output can be seen in Figure 43 to Figure 45. The electricity consumption almost constantly exceeds the PV output. The demand and supply match rate only achieves 47.5 %.

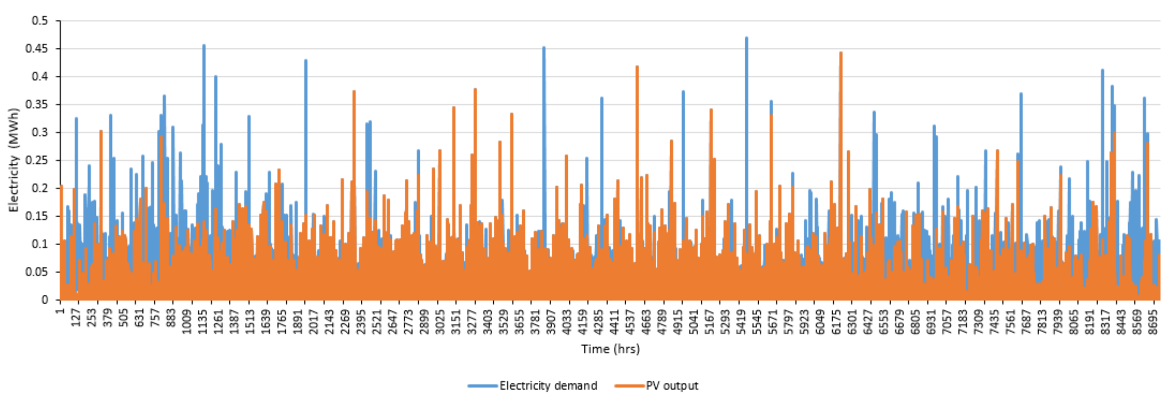


Figure 43 Yearly electricity consumption and solar PV output in C [own demonstration]

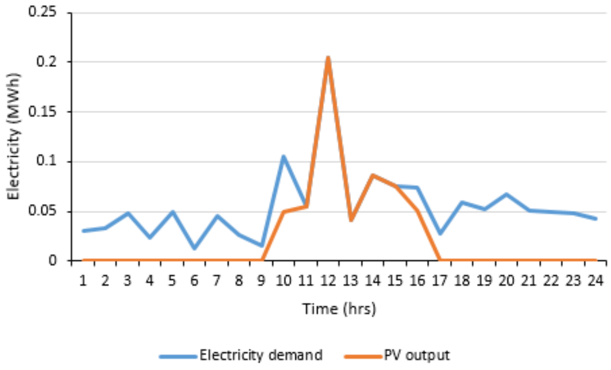


Figure 44 Daily electricity consumption and solar PV output in C1 (01/01/17) [own demonstration]

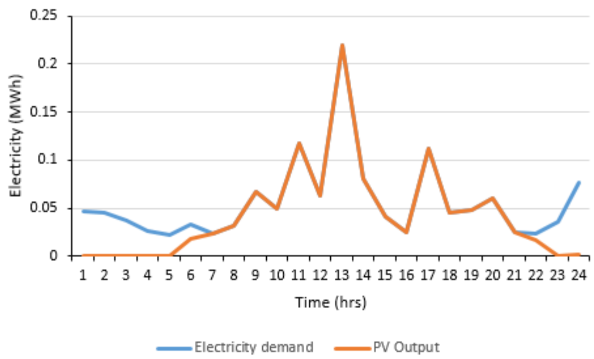


Figure 45 Daily electricity consumption and solar PV output in C1 (12/07/17) [own demonstration]

Since no storage or a grid connection was available, this system configuration even limits the PV output to 223.6 MWh per year because the surplus electricity could not be consumed. Due to the fact that the critical value (demand and supply match rate) is not 100% or higher a battery was incorporated in the next configuration.

Configuration C2

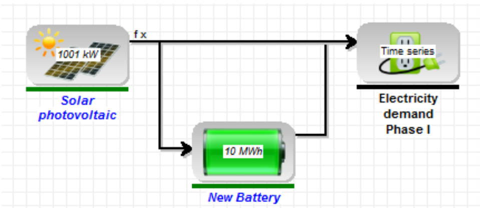


Figure 46 Configuration 2 [demonstration: energyPRO]

A battery storage of 10 MWh and 85% charging efficiency was added to C1 (Figure 46).

This time the PV output meets the electricity demand between March and September but not for the rest of the year. The demand and supply match rate rose to 95.7%. Hence, it was considered to increase the battery storage but that did not result in a higher match rate, which is why the optimum storage size was found. In Figure 47, Figure 48 and Figure 50 the yearly demand and supply match as well as a representative winter and summer day are shown. When a surplus or deficit evolved, the battery was used as a buffer (Figure 49 and Figure 51).

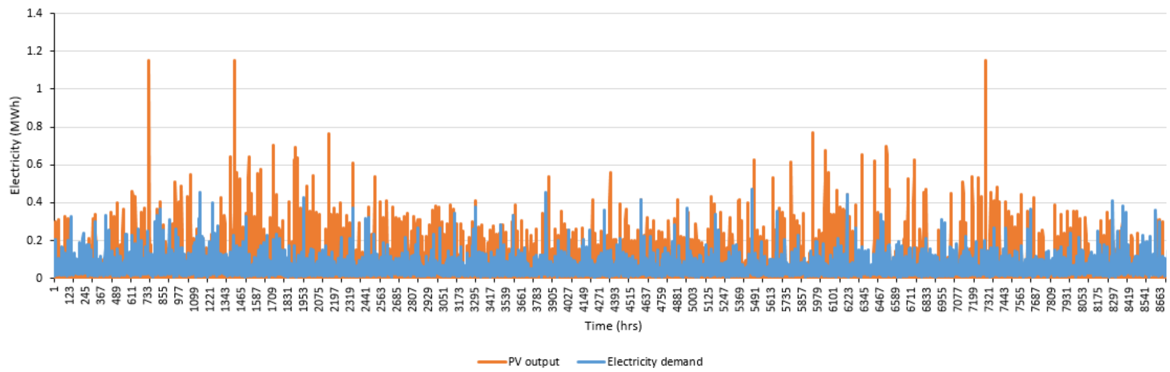


Figure 47 Yearly electricity consumption and solar PV output in C2 [own demonstration]

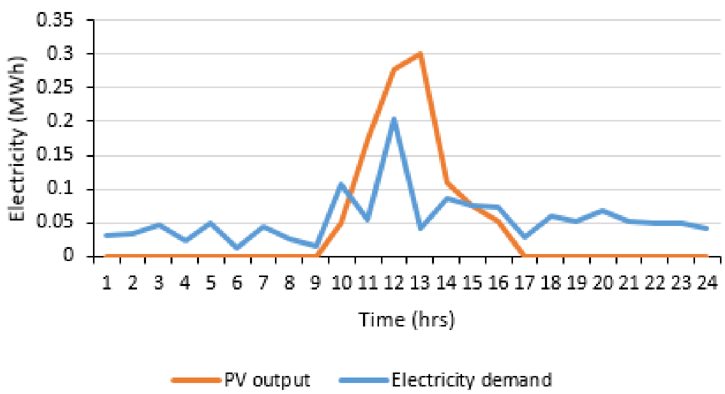


Figure 48 Daily electricity consumption and solar PV output in C2 (01/01/17) [own demonstration]

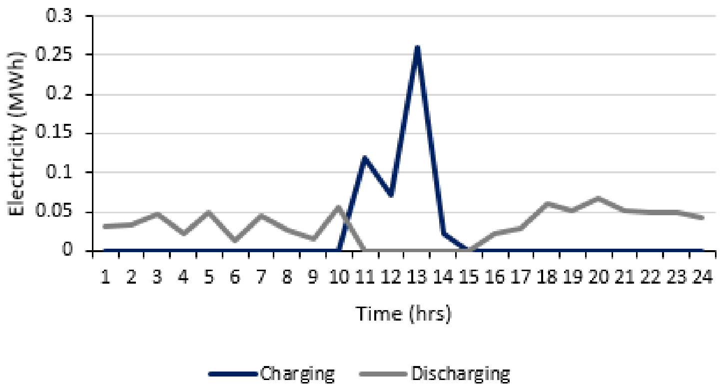


Figure 49 Charging and discharging rate of battery storage in C2 (01/01/17) [own demonstration]

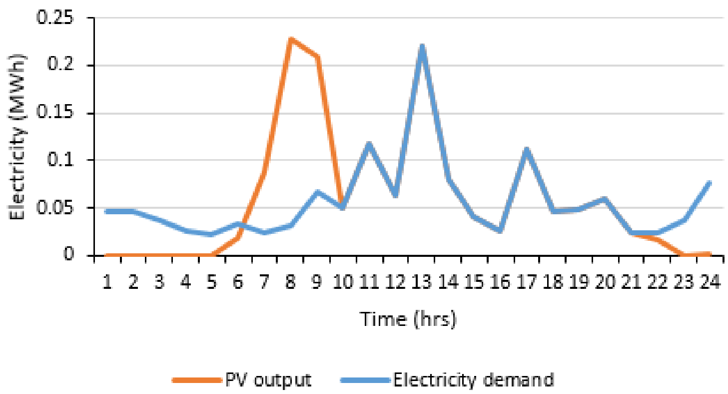


Figure 50 Daily electricity consumption and solar PV output in C2 (12/07/17) [own demonstration]

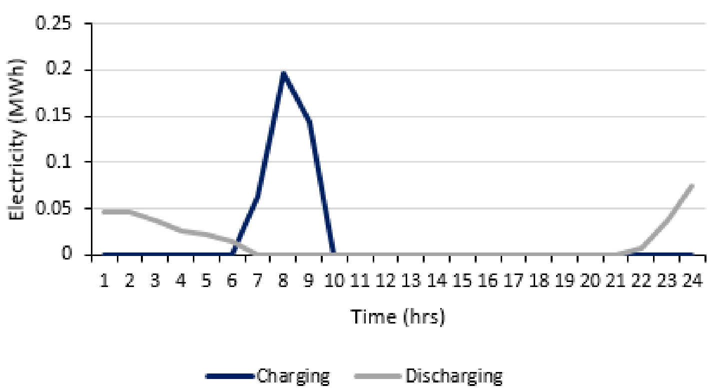


Figure 51 Charging and discharging rate of battery storage in C2 (12/07/17) [own demonstration]

The electricity produced by PV increased to 450.4 MWh in comparison to the limited 223.6 MWh in Configuration 1. The reason for that was the incorporated battery that can consume surplus energy and balance out deficits. However, as said before, there were still times in winter where the sun radiation respectively the PV output is too low to satisfy the demand. This information was obtained from the energy conversion report energyPRO provided. Due to the fact that the critical value was not met again a grid connection was incorporated in the next configuration.

Configuration C3

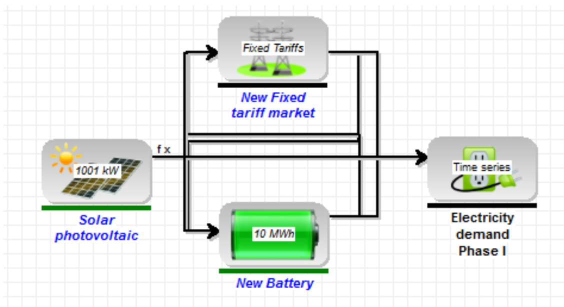


Figure 52 Configuration 3 [demonstration: energyPRO]

A grid connection was added to the model in order to ensure a supply and demand match over the full year and to maximise the renewable energy output of the PV panels (Figure 52). The grid was inserted with a time-of-use tariff. However, since this master thesis did only focus on technical and not economic feasibility the tariffs were not further discussed.

With the grid connection, the PV output rose to 992.6 MWh per year. The impact can be seen in Figure 54 that shows a summer day in 2017. For the same day the PV output was smaller when no grid connection was available (Figure 50). For winter days these changes are minimal since only little sun is available. The winter profile (Figure 53) does only slightly change in comparison to Figure 48.

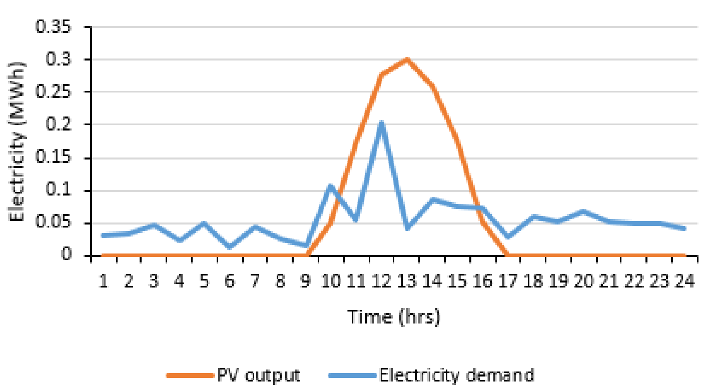


Figure 53 Daily electricity consumption and solar PV output in C3 (01/01/17) [own demonstration]

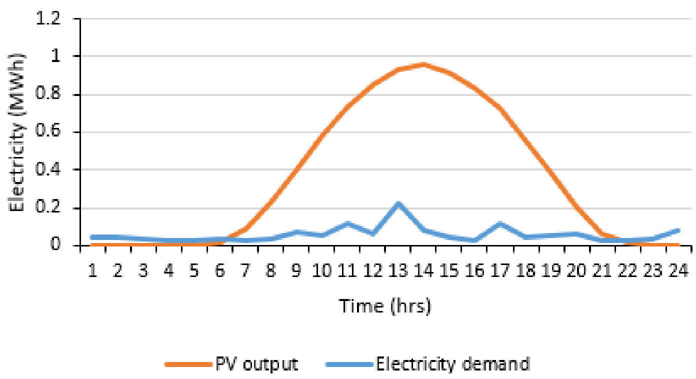


Figure 54 Daily electricity consumption and solar PV output in C3 (12/07/17) [own demonstration]

With the maximum PV output the electricity demand between March and September was met and high amounts of surplus energy was produced (Figure 55). For the rest of the year the grid provided sufficient electricity so that the match rate rose over 100%. A total of 83.2 MWh of electricity was imported for that. Additionally, 542.2 MWh were exported to the grid. The renewable penetration factor of this electricity system was 92.3 %.

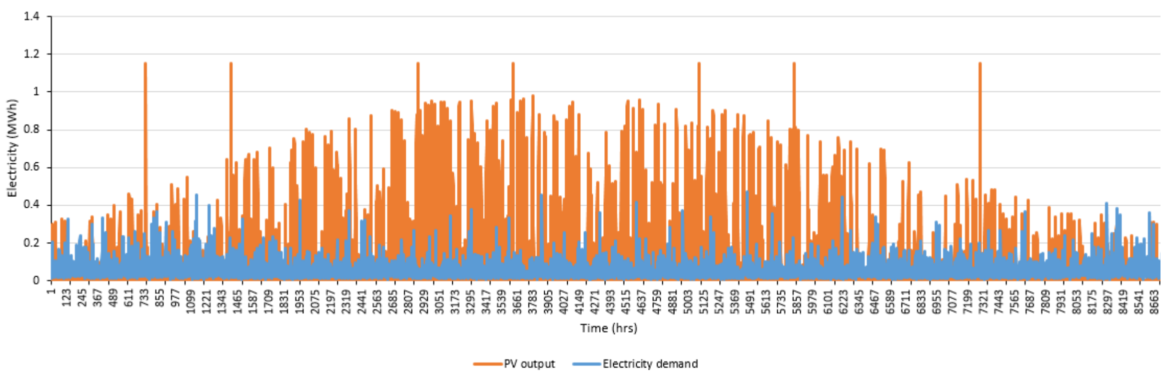


Figure 55 Yearly electricity consumption and solar PV output in C3 [own demonstration]

With those large amounts of produced renewable energy the town quarter can be an exporter of energy into the local grid. Since the surplus electricity produced over the whole year is twice the amount of the annually consumed electricity it would be advantageous to install a seasonal storage. With a seasonal storage the town quarter would be, at least for Phase I, self-sustained and does not need a grid connection. However, since this is a high-level scoping study the values need to be justified again with real life demand profiles to ensure a permanent oversupply by the PV panels for most of the year.

All in all, this configuration fulfilled the critical value by achieving over a 100% demand and supply match rate. Therefore, the consumption of the planned 30 electric vehicles is added to the next configuration that can be seen in Figure 56.

Configuration C3+

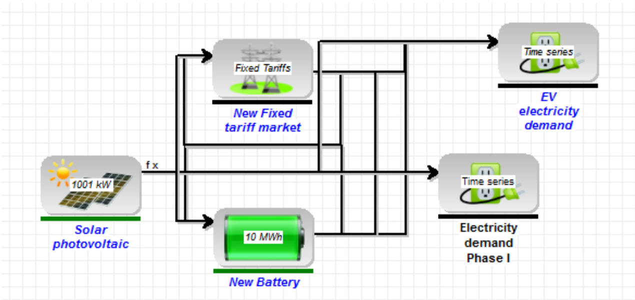


Figure 56 Configuration 3 plus EV electricity demand [demonstration: energyPRO]

With the incorporated EV consumption the overall electricity demand rose to 543.3 MWh (see chapter 3.2.1). Again, an overproduction in summer arose that kept the match rate above 100%. In total, 29.1 MWh more electricity per year was imported and 59.1 MWh less exported to the grid. The renewable penetration factor dropped to 89.8 %. Changes in the graphs are minimal and therefore the graphs in Figure 54 (summer day), Figure 53 (winter day) and Figure 55 (annual) of Configuration 3 still show adequate trends for configuration C3+.

All in all, Configuration 3 provides sufficient energy for the daily electricity demand of Phase I as well as for 30 EV's. This configuration is a feasible solution for the future energy system. Before moving on to the next scenario, the renewable penetration on-site was increased by incorporating wind power.

Configuration C4

Apart from installing a seasonal storage that could support a 100% renewable energy supply over the years, wind power can be used to balance out the deficits that occur in winter periods from the PV panels. For demonstration purposes a wind turbine was inserted although this would be highly unlikely in reality (see chapter 3.1.1). In reality, instead of installing a turbine, there are also the possibilities of a community ownership or the purchase of wind power from a wind park.

In order to display how much capacity was needed to supply 100% renewable electricity on the site a wind farm was modelled in combination with PV (Figure 57).

The power provided from the wind farm had a capacity of 265.6 kW with each turbine having a measure height of 100 m and a hub height of 23 m. This data and the wind power curve were obtained from an available energyPRO model for Findhorn ecovillage.

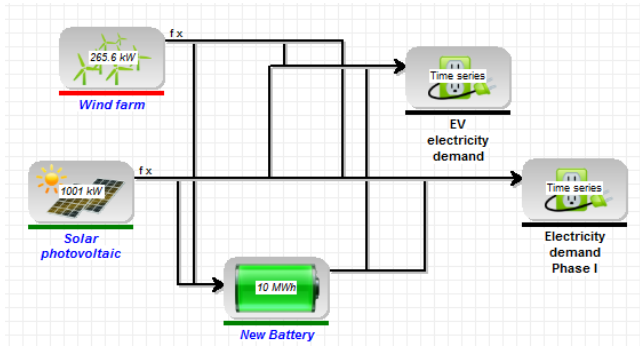


Figure 57 Configuration 4 [demonstration: energyPRO]

Figure 58 to Figure 62 show the electricity consumption and renewable energy outputs during the year and on a winter and summer day as well as battery charging rates. Wind power is represented stronger in the winter month (Figure 59) and solar in summer (Figure 61). Surplus energy is stored in the incorporated battery (Figure 60 and Figure 62). Overall, the renewable electricity production is 601 MWh/year with a renewable penetration factor of 100% and 0 MWh imported electricity from the grid.

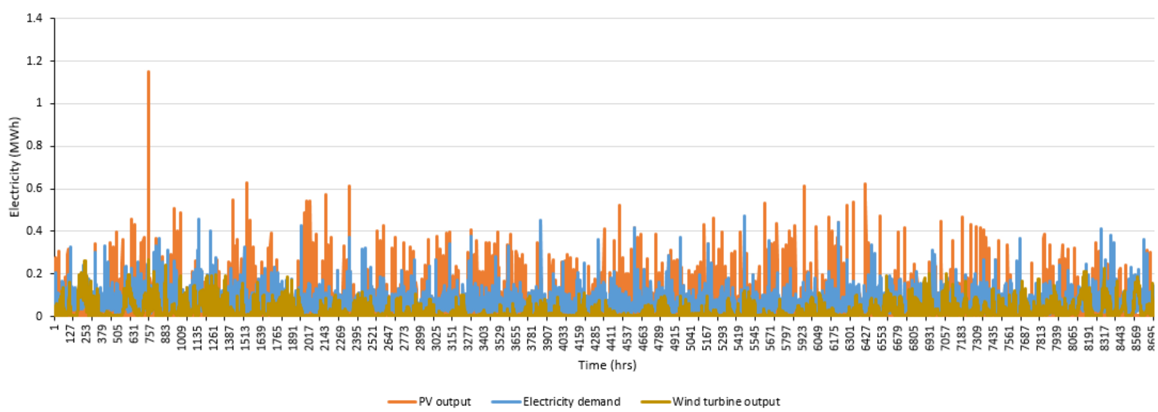


Figure 58 Yearly electricity consumption and solar PV as well as wind output in C4 [own demonstration]

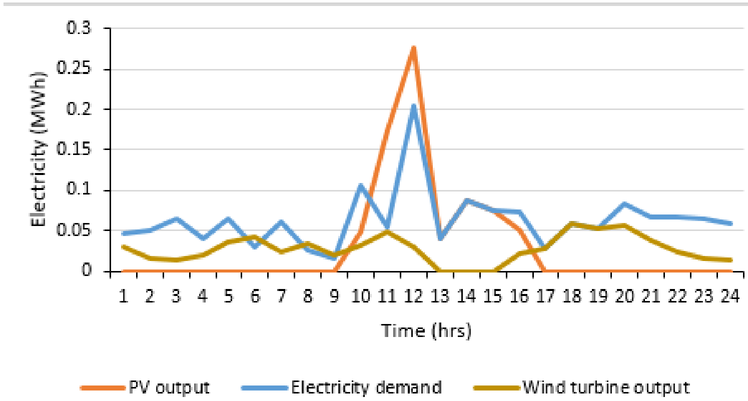


Figure 59 Daily electricity consumption and PV as well as wind output in C4 (01/01/2017) [own demonstration]

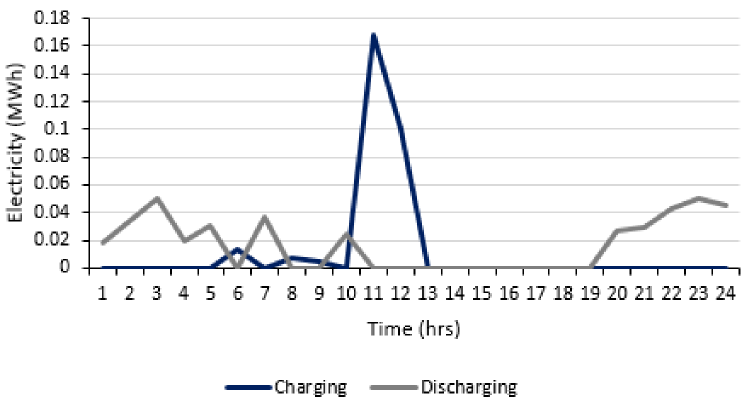


Figure 60 Charging and discharging rate of battery storage in C4 (01/01/17) [own demonstration]

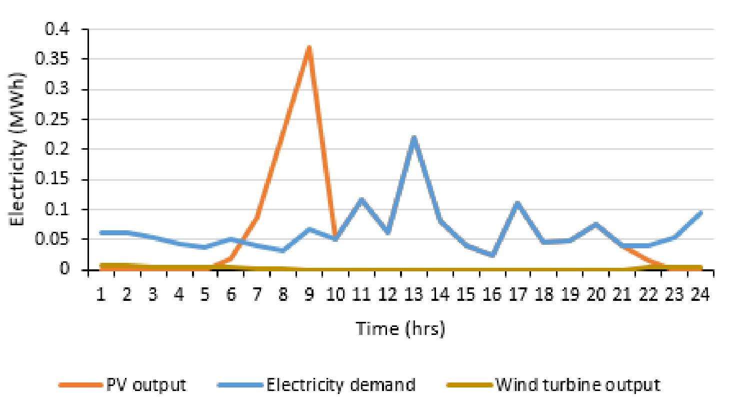


Figure 61 Daily electricity consumption and PV as well as wind output in C4 (12/07/2017) [own demonstration]

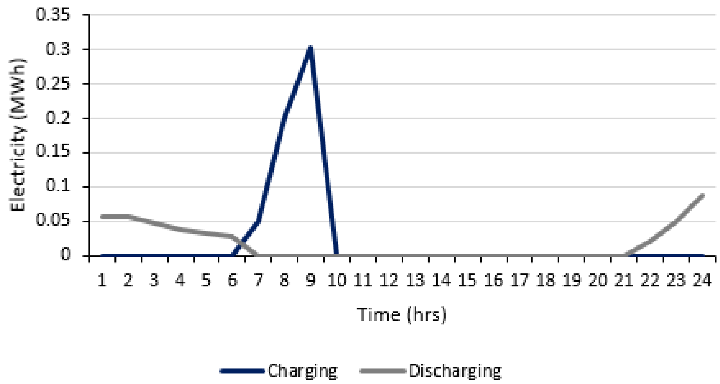


Figure 62 Charging and discharging rate of battery storage in C4 (12/07/2017) [own demonstration]

The solar PV output was limited again to 372.9 MWh. With additional seasonal storage or a grid connection the PV output can be increased. Both options should be considered since an energy system that is only dependent on intermittent renewable energy production is probably not feasible in the future. Production rates can vary during the year or even over decades and then a reliable electricity supply is not ensured.

Summary

In Scenario 1 four different configurations were assessed with regard to a supply and demand match rate of at least 100%. Table 22 shows the two configurations that fulfilled the critical value. These configurations were assessed towards other KPI that were the renewable electricity production, the amount of imported electricity and the resulting renewable penetration factor. The electricity peak was observed in order to verify if the electricity consumption stayed under the grid limit of 2,000 kVA. From Scenario 1 two possible energy systems were developed that are feasible for a future implementation in the HALO Kilmarnock town quarter. The first one is a combination of PV, battery and grid and the second one of PV, battery and wind power while assuming that heating demand was met by a geothermal well with heat exchanger and cooling is done passively. Instead of installing a wind turbine on-site options like community ownership or wind power purchase could be considered. A detailed investigation of these possibilities was not part of this thesis.

Table 22 Summary of Scenario 1 [own demonstration]

Configuration		Key Performance Indicators: Renewable Electricity Production (MWh/year)	Imported Electricity from Grid (MWh/year)	Renewable Penetration Factor (%)	Electricity Peak (MW)	Under Grid Limit of 2,000 kVA	Demands
C3	PV + BAT + GRID	992.6	83.2	92.27	0.431	yes	Electricity Demand Phase I
C3+	PV + BAT + GRID	992.6	112.3	89.84	0.431	yes	Electricity Demand Phase I + EV Demand
C4	PV + WIND + BAT	601.0	0	100.00	-	yes	Electricity Demand Phase I + EV Demand

3.3.2 Scenario 2 – Investigation of heating supply technologies

In Scenario 2 the heating side was investigated. Table 23 shows the assessed system configurations. It was assumed that electricity demand was supplied by the grid that was not displayed in the models as long as no grid connection was used to power technology for the district heating system. PV panels were incorporated to supply power for the heat pumps. Wind power was disregarded since an installation on-site was highly unlikely and the feasibility of other possibilities (e.g. community ownership) were not investigated in this thesis. Cooling was assumed to be passive and was not displayed in the models as well.

Table 23 Scenario 2 and its configurations [own demonstration]

Configuration		Scenario 2 Grid connection (+PV) District heating: Heat pump or Solar thermal Passive cooling	Demands
C5	PV + ASHP + TS	x	Heating Demand Phase I
C6	PV + BAT + ASHP + TS	x	Heating Demand Phase I
C7	PV + BAT + GRID +ASHP + TS	x	Electricity + Heating Demand Phase I
C7+	PV + BAT + GRID +ASHP + TS	x	Electricity + Heating + EV Demand Phase I
C8	PV + BAT + GRID +WSHP + TS	x	Electricity + Heating Demand Phase I
C8+	PV + BAT + GRID +WSHP + TS	x	Electricity + Heating + EV Demand Phase I
C9	PV + BAT + GRID +GSHP + TS	x	Electricity + Heating Demand Phase I
C9+	PV + BAT + GRID +GSHP + TS	x	Electricity + Heating + EV Demand Phase I
C10	ST + TS	x	Heating Demand Phase I

Configurations 5 to 9 consist of different heat pump types. First of all, ASHP were investigated to evaluate if the PV panels (plus battery) could supply sufficient energy to meet the demand of the heat pumps. Since this was not the case (see upcoming subchapters) a grid connection was incorporated as well as the electricity demand of Phase I to see if the consumption stayed below the limit of 2,000 kVA. This configuration was then modelled with different heat pump types and with EV demand to show the different outcomes. The last configuration in Scenario 2 displays the heat production of solar thermal panels.

The used heat pump specifications (COP, flow temperatures) were average seasonal performance parameters for typical user demand conditions and UK climate. The parameters were integrated based on the detailed performance in heating and hot water mode over the whole range of conditions across the year. Within the limits of the thesis, this approach is adequate. However, for future work, a more detailed performance characteristic of specific heat pump types dependent on climate should be considered. This is important for a detailed designing of the system.

Configuration C5

Configuration 5 consists of PV panels that should meet the electricity demand of the air source heat pump with an additional thermal storage (Figure 63).

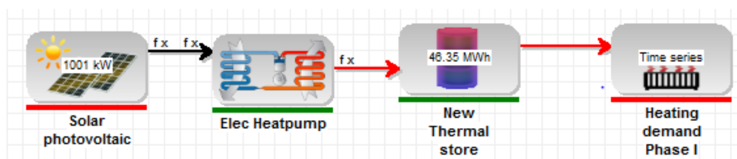


Figure 63 Configuration 5 [demonstration: energyPRO]

The installed peak capacity was again 1001 kW and the ASHP was sized to meet the peak demand of Phase I that is 430 kW. The COP was chosen to be 2.5 [97] and therefore the resulting electricity consumption was 172 kW. The hot side flow/return temperatures were 35/60 °C and the source side temperatures were 10/5 °C [98]. The thermal store had a capacity of 1,000 m^3. The annual heating demand can be seen in Figure 33 in chapter 3.2.2 and encompasses 761.7 MWh. The exemplary winter and summer day heating demand profile can be seen in the same chapter in Figure 34 and Figure 35.

The yearly heating consumption and heat pump output can be seen in Figure 64 while the usage of the thermal storage is displayed in Figure 65. Both indicate that the heating demand was not met the whole year and the heat pump is highly oversized since the storage was rarely used. Since some data is hidden in the winter month in Figure 64 the energy conversion reports of energyPRO were reviewed. These also displayed that the PV output was too small in some periods to meet the heating demand constantly. The heat demand and supply match rate accounted for 77.4%.

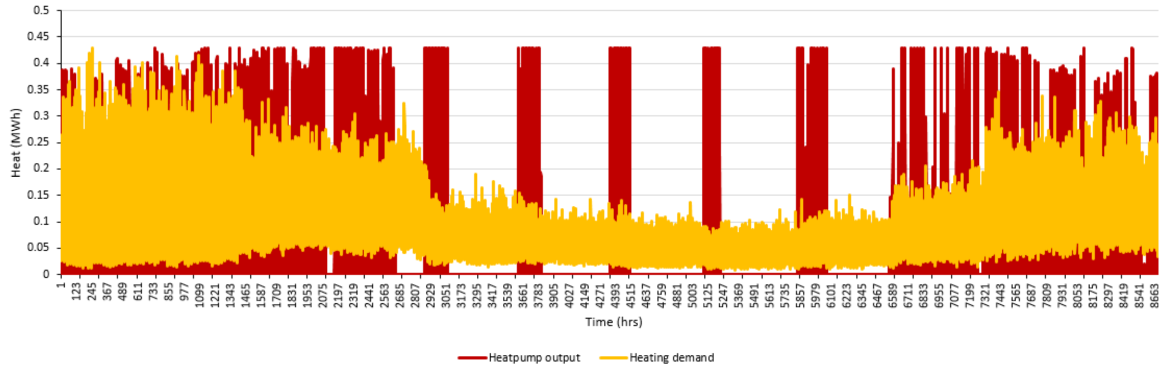


Figure 64 Yearly heat consumption and heat pump output in C5 [own demonstration]

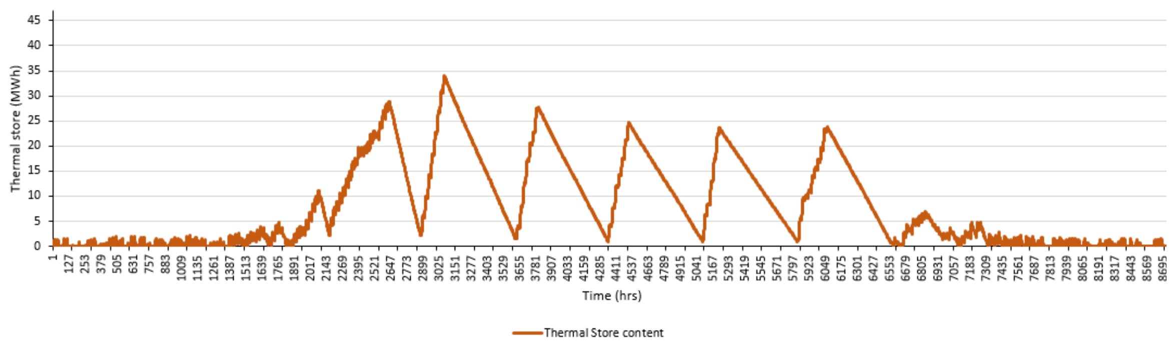


Figure 65 Yearly thermal storage content in C5 [own demonstration]

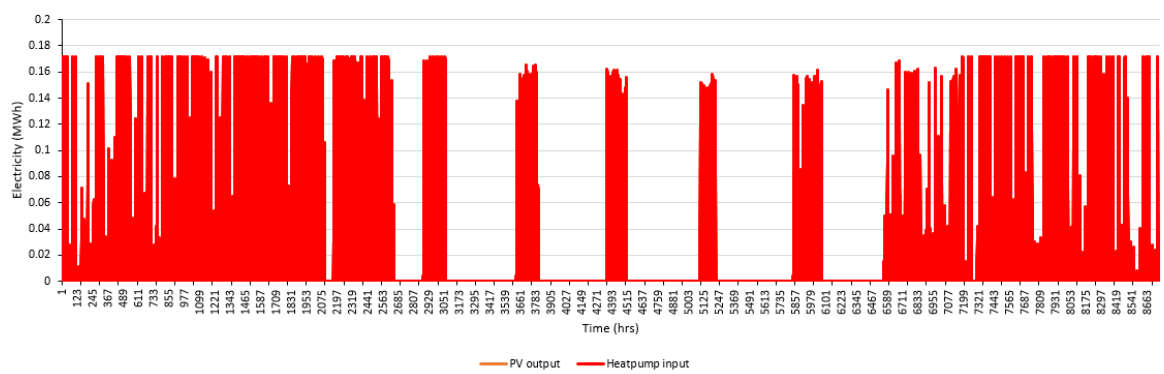


Figure 66 Yearly electricity consumption and solar PV output in C5 [own demonstration]

Figure 66 to Figure 70 show that all the available electricity produced by PV was used by the heat pump. Therefore, the PV output data is hidden behind the heat pump input data in Figure 66, Figure 68 and Figure 70. It is striking that in summer, although the solar radiation is higher, there were some days where no PV output was available (Figure 70). A reason for this PV limitation was the usage of the thermal storage. The heat stored was used to meet the small heating demand in these summer days (Figure 71) until the tank was almost empty (Figure 65). Since no other consumer was available at that time, the PV output was limited (e.g. Figure 69). In times when the storage was empty the heat pump consumed electricity again to produce new heat. Throughout the whole year the produced renewable electricity amounts for 234.8 MWh instead of the possible 992.6 MWh as seen in chapter 3.3.1.

All in all, this configuration showed that only the installed PV panels do not provide enough electricity for the heat pump to meet the heat demand of the whole year. Moreover, the heat pump and the thermal store were oversized. For those reasons two alternative configurations were taken into consideration. In the next step a battery is incorporated. After that the heat pump and thermal store were downsized.

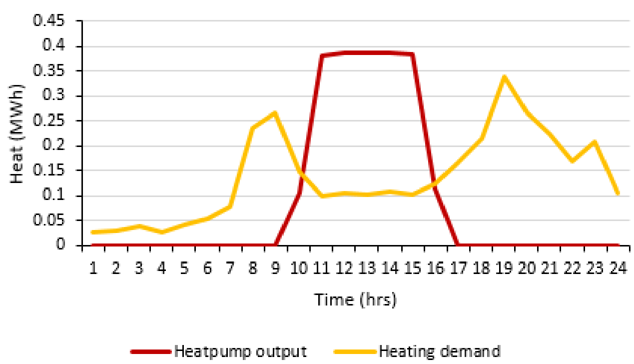


Figure 67 Daily heat consumption and heat pump output in C5 (01/01/2017) [own demonstration]

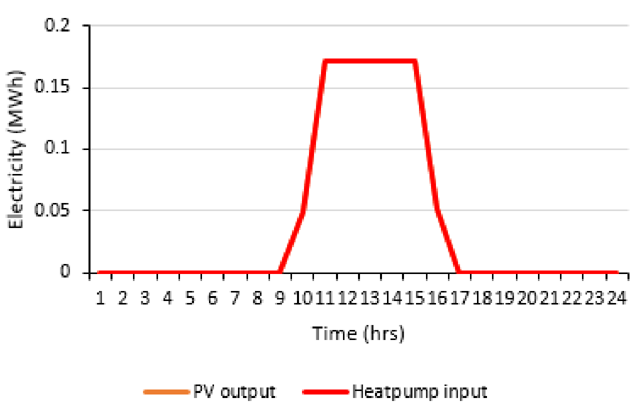


Figure 68 Daily electricity consumption and PV output in C5 (01/01/2017) [own demonstration]

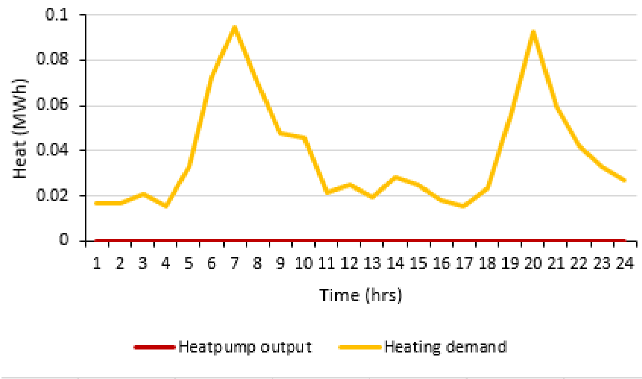


Figure 69 Daily heat consumption and heat pump output in C5 (12/07/2017) [own demonstration]

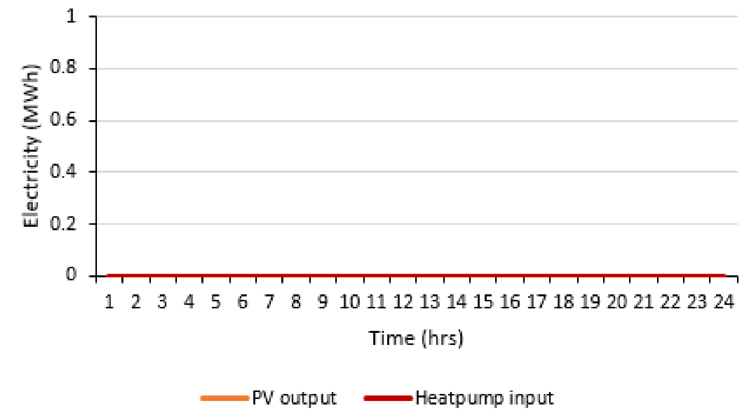


Figure 70 Daily electricity consumption and PV output in C5 (12/07/2017) [own demonstration]

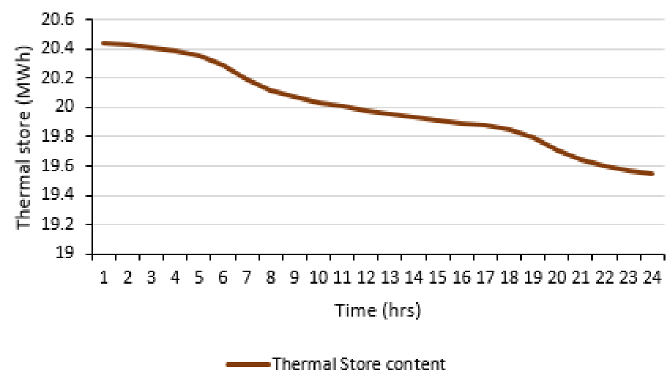


Figure 71 Daily thermal storage content in C5 (12/07/17) [own demonstration]

Configuration C6

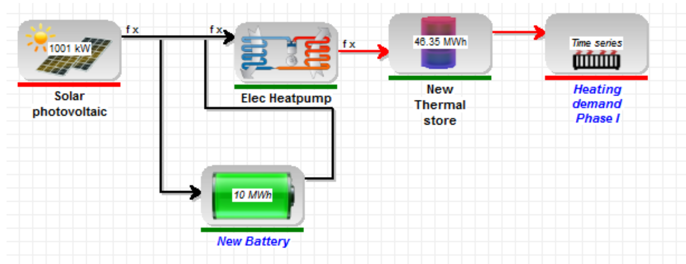


Figure 72 Configuration 6 [demonstration: energyPRO]

Different sizes of batteries were incorporated in Configuration 6 (Figure 72) in order to maximise the PV output. With a 10 MWh battery the electricity production was increased to a maximum of approx. 292.4 MWh. The resulting heat consumption and production graph can be seen in Figure 73. The graph already indicated a better supply and demand match. However, the more detailed data in the energyPRO reports showed that in most periods of the year the demand cannot be met constantly.

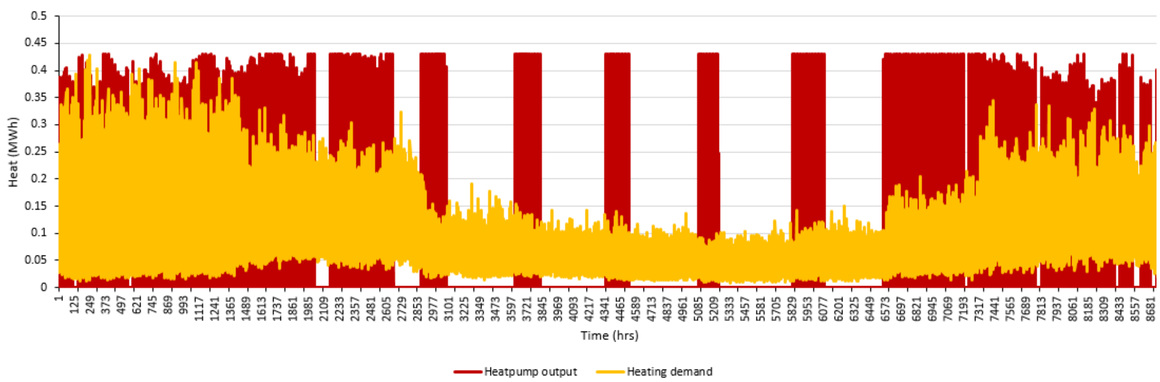


Figure 73 Yearly heat consumption and heat pump output in C6 [own demonstration]

The usage of the thermal storage did not change with regard to Figure 65 and the electricity production of the PV panel was still limited in summer (Figure 74). This limitation decreased due to the available battery storage. Nevertheless, in summer the PV output was still intermittent since in that time the thermal store was used to meet the small heat demand and the battery storage was full (Figure 75).

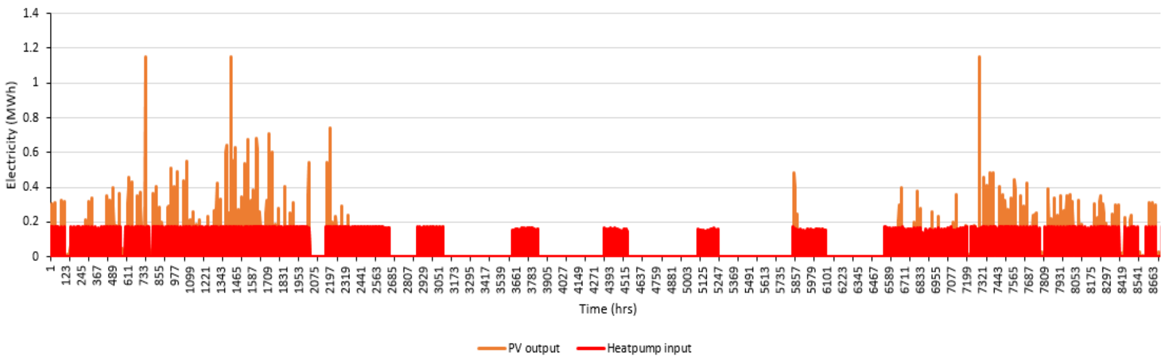


Figure 74 Yearly electricity consumption and solar PV output in C6 [own demonstration]

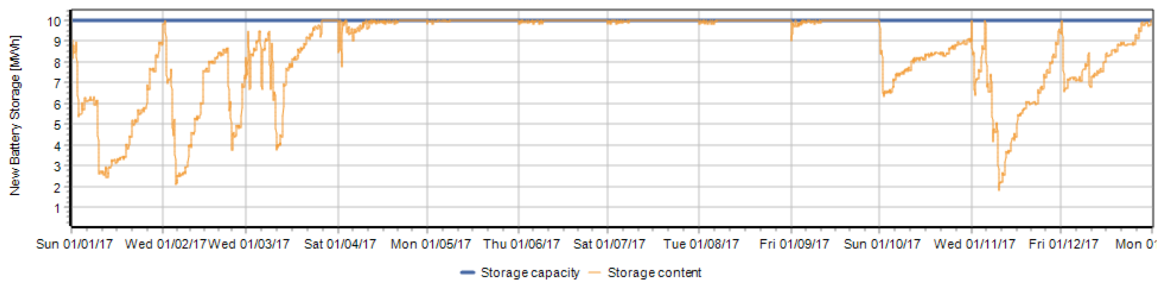


Figure 75 Yearly battery storage content in C6 [demonstration: energyPRO]

The winter day profile in Figure 76 shows that the battery was fully charged in the beginning and provided electricity for the heat pump to produce more heat than needed at that time.

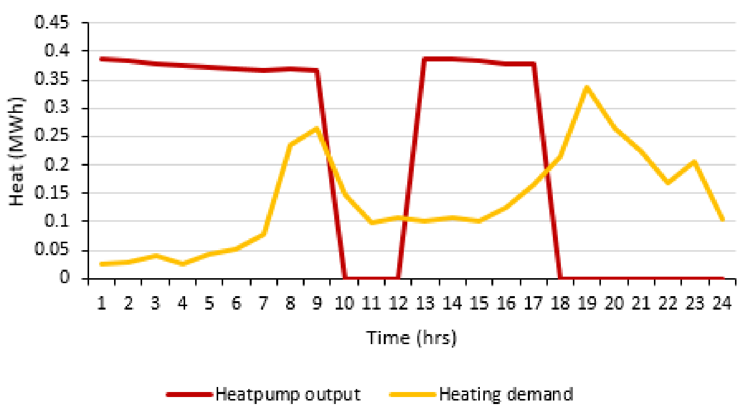


Figure 76 Daily heat consumption and heat pump output in C6 (01/01/2017) [own demonstration]

As said before, in summer the PV output was still limited since the battery was fully charged and no other consumer was available. The low heating demand was met with the stored heat (see Figure 77 and Figure 78).

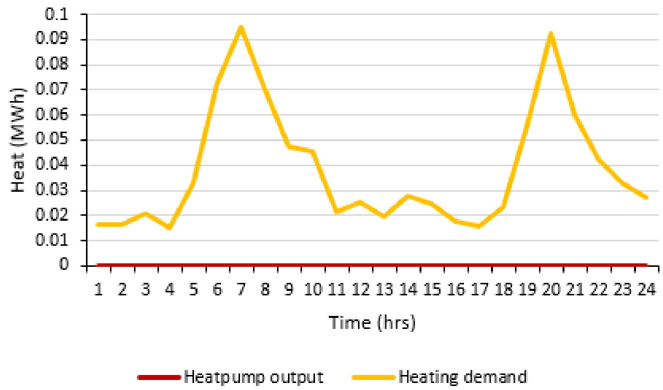


Figure 77 Daily heat consumption and heat pump output in C6 (12/07/2017) [own demonstration]

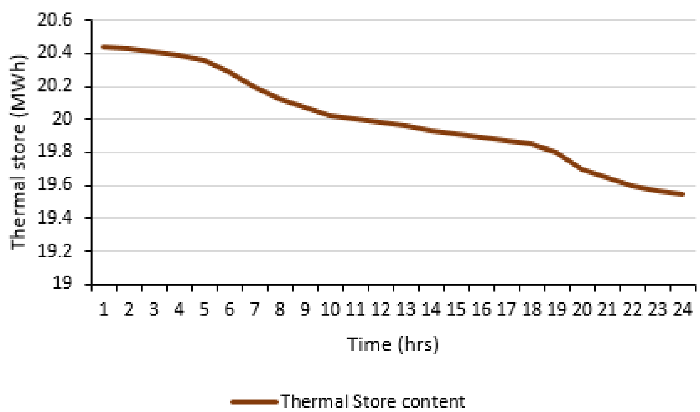


Figure 78 Daily thermal storage content in C6 (12/07/2017) [own demonstration]

All in all, more heat was produced than before with a new heat match rate of 84.0 %. That indicates also that the battery storage supports periods where less sun is available in order to increase the PV output that was used to power the heat pump. Nevertheless, even with other battery sizes, the results were not improved significantly. Therefore, it can be stated that the available amount of solar radiation is not sufficient to meet the heat pump's electricity demand in order to deliver the desired energy output for the whole year.

In order to fulfil the critical value a grid connection was incorporated that was assumed to produce enough electricity for the heat pump to supply sufficient heat during the whole year.

Configuration C7

To be able to meet the heating demand constantly and increase the renewable electricity output a grid connection was incorporated. Configuration 7 can be seen in Figure 79. Besides the heating demand the electricity demand of the Phase I buildings was inserted. The reason is that this demand was assumed to be met by the grid and it was important to ensure that the grid limitation was not exceeded. The EV demand was first neglected and added afterwards.

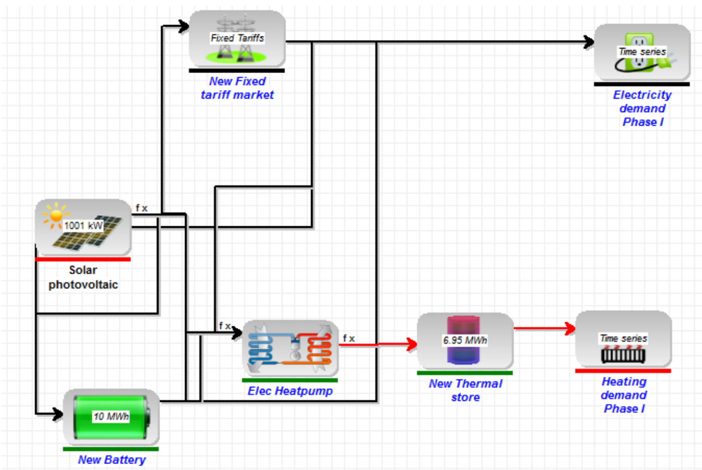


Figure 79 Configuration 7 [demonstration: energyPRO]

The system components were downsized at the same time in order to prevent an oversizing of the whole system. The component sizes were reduced as much as possible while still meeting the demand. That resulted in a heat pump output capacity of 155 kW (input: 62 kW) and a thermal storage of 150 m^3. The sizes were only optimised with regard to the match rate and with no focus on economics and space restrictions in the buildings since no information on this were available. Therefore, the approach was to minimise the heating supply technology as much as possible while having a bigger storage.

In Figure 80 and Figure 81 the yearly heat consumption and production as well as the usage of the thermal storage can be seen. Heat pump and storage are used in an optimal way to ensure a constant match rate that is 100%. For demonstration purposes the y-axis of both figures has different maximum values to ensure that both graphs are readable. However, ones should recognise that the heating peak demand is around 0.43 MWh while the storage was still holding 1.4 MWh energy at the same time. Therefore, the demand can be met. With regard to the grid connection the PV panel output was not limited anymore since the surplus electricity of 405.2 MWh could be stored and exported now (Figure 82). Due to winter times with less solar radiation a total of 259.5 MWh electricity was imported. The renewable penetration factor was 79.3 %.

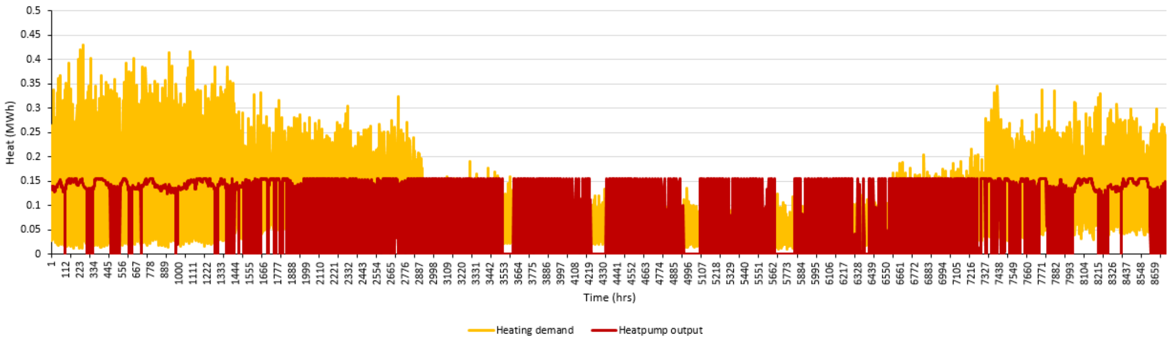


Figure 80 Yearly heat consumption and heat pump output in C7 [own demonstration]

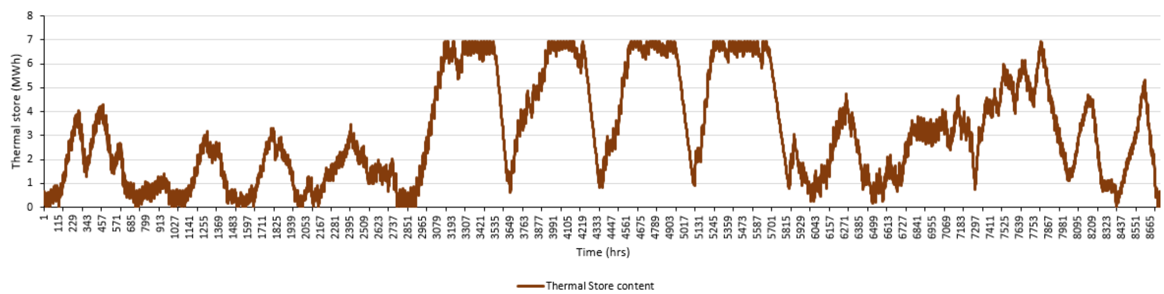


Figure 81 Yearly thermal storage content in C7 [own demonstration]

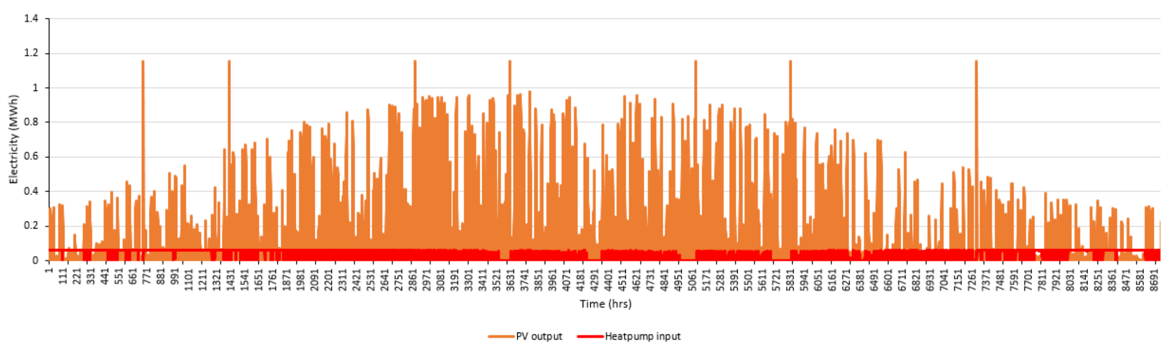


Figure 82 Yearly electricity consumption and solar PV output in C7 [own demonstration]

The winter day profile on the 1st of January shows a constant heat supply (Figure 83) that was ensured by the constant electricity supply through the grid for the heat pump. The PV production was not able to supply an equivalent amount of electricity (Figure 84). The thermal store supported the heat supply and demand match (Figure 85).

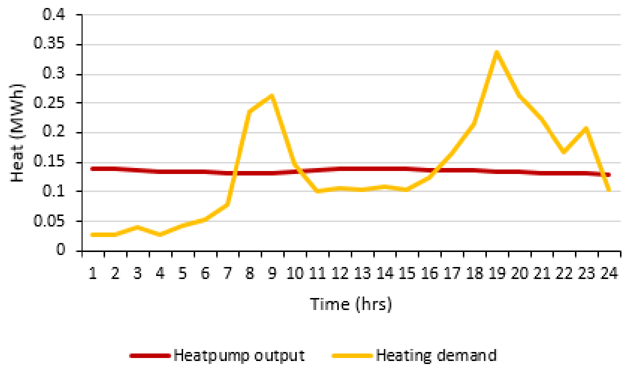


Figure 83 Daily heat consumption and heat pump output in C7 (01/01/2017) [own demonstration]

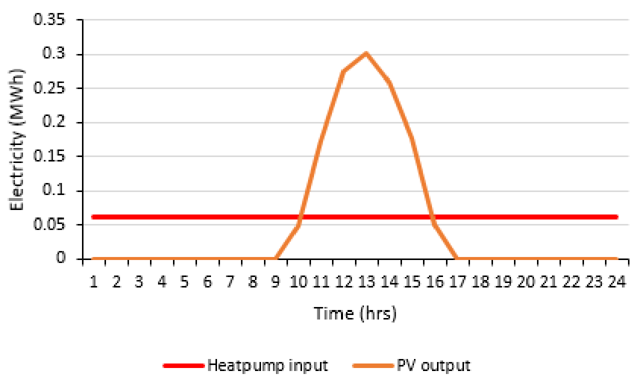


Figure 84 Daily electricity consumption and solar PV output in C7 (01/01/2017) [own demonstration]

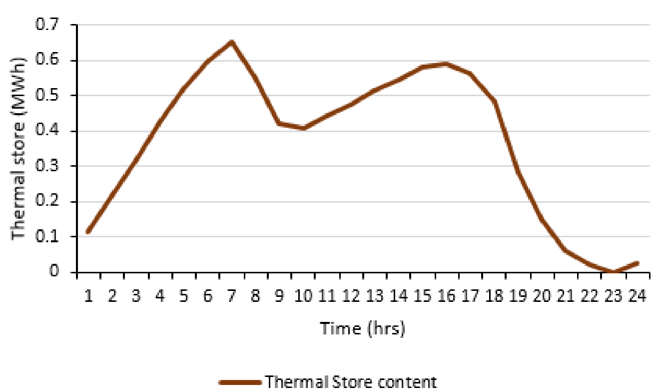


Figure 85 Daily thermal storage content (01/01/2017) [own demonstration]

The profile of the summer day in July show that less imported electricity is needed since the PV panels provide even a surplus that was first used to charge the battery and then exported to the grid (Figure 86 to Figure 88).

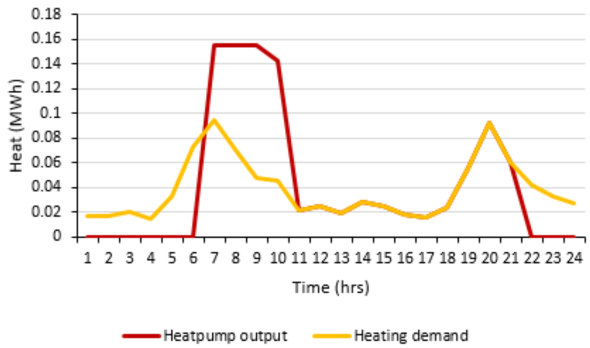


Figure 86 Daily heat consumption and heat pump output in C7 (12/07/2017) [own demonstration]

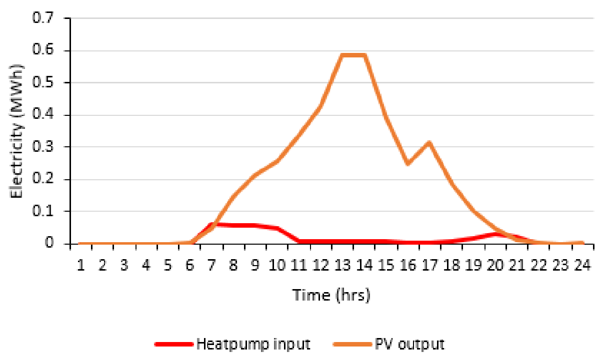


Figure 87 Daily electricity consumption and solar PV output in C7 (12/07/2017) [own demonstration]

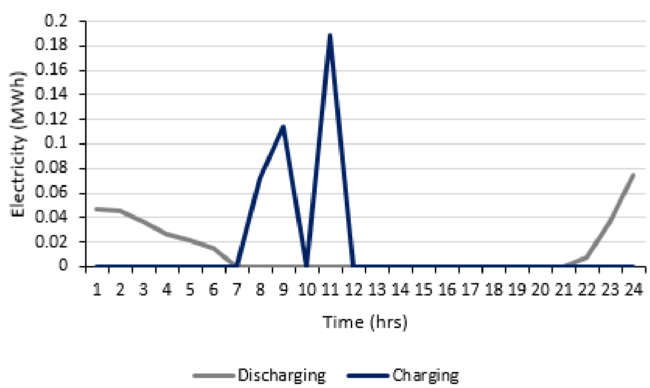


Figure 88 Charging and discharging of battery in C7 (12/07/2017) [own demonstration]

With this configuration a demand and supply match for heating as well as for electricity was achieved. Therefore, some more KPI's were assessed and can be seen in the summary table in the end of this scenario investigation. Afterwards the EV demand was inserted and therefore the heat pump capacity rose slightly to 155 kW (input: 62 kW) to meet the additional electricity. Some more electricity was imported (295.6 MWh in total) and a slight drop of the renewable penetration factor to 77.1 % occurred. This feasible configuration was then analysed for a WSHP (Configuration 8) and GSHP (Configuration 9) installation with and without EV demand respectively.

Configuration C8

Configuration 8 consists of the same components as Configuration 7 except of the installed WSHP. The maximal output heat capacity was 150 kW and the input electricity capacity was 47 kW. The COP was 3.2, the hot side flow/return temperatures were 55/75 °C and the source side temperatures 8/5 °C [99]. The thermal store had a capacity of 150 m^3.

Since the specifications of the heat pump types display only slight differences, there were only marginal changes in the resulting graph. Figure 80 and Figure 81 represent also for this configuration the yearly heat consumption and production as well as the usage of the thermal storage. The heat match rate is 100% and the renewable penetration factor was 82.7 % with 207.4 MWh imported electricity while 424.1 MWh can be exported. Also, the daily profiles do not differ from the ones before and were therefore not inserted again. With additional EV demand the imported electricity raised to 243 MWh and the renewable penetration factor dropped to 80.3 %. An overview of the assessed KPI's and the interpretation can be seen in the summary of this scenario investigation.

Configuration C9

In Configuration 9 a GSHP was installed. The maximum output heat capacity was 150 kW and the input electricity capacity was 52 kW with a COP of 2.9 [97]. The hot side flow/return temperatures were 35/65 °C and the source side temperatures were 12/0 °C [100]. The thermal store had a capacity of 150 m^3.

Changes in trend lines in the graphs were not visible again due to the slightly increased electricity demand. Therefore, the graphs were not inserted again. The match rate for heat is 100% and the renewable penetration factor is 81.7 % with 222.0 MWh imported electricity and 414.1 MWh exported electricity. Including EV demand the imported electricity rose to 258 MWh and the renewable penetration factor dropped to 79.4 %. The KPI's can be seen, as said before, in the end of this subchapter.

Configuration C10

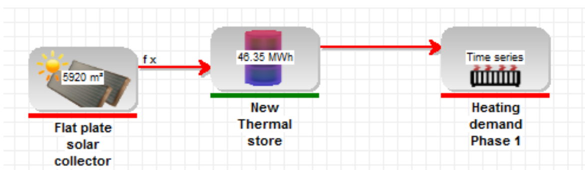


Figure 89 Configuration 10 [demonstration: energyPRO]

The last configuration in this scenario was a solar thermal heating system including flat plate solar collectors and a thermal store. For this configuration (Figure 89) 5,920 m^2 flat plate solar collectors were installed that accounted for 80% of the rooftop area of Phase I buildings and belonging parking space. The thermal store was increased to 1,000 m^3 again.

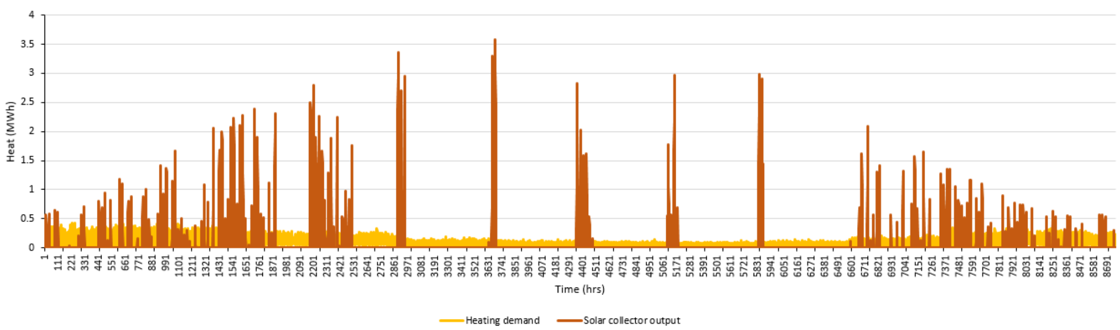


Figure 90 Yearly heat consumption and solar collector output in C10 [own demonstration]

A district heating system simply using solar thermal panels met 71.7 % of the heating demand of the buildings (Figure 90). In the winter month when the solar radiation is low only some heat demand can be met (Figure 92). In summer the solar radiation is higher and sufficient heat was produced and stored so that at some days no production was necessary (Figure 93 and Figure 91). However, as it can be seen in Figure 90, this surplus heat was not sufficient enough to provide energy for all the low sun radiation days.

Figure 91 Yearly thermal storage content in C10 [own demonstration]

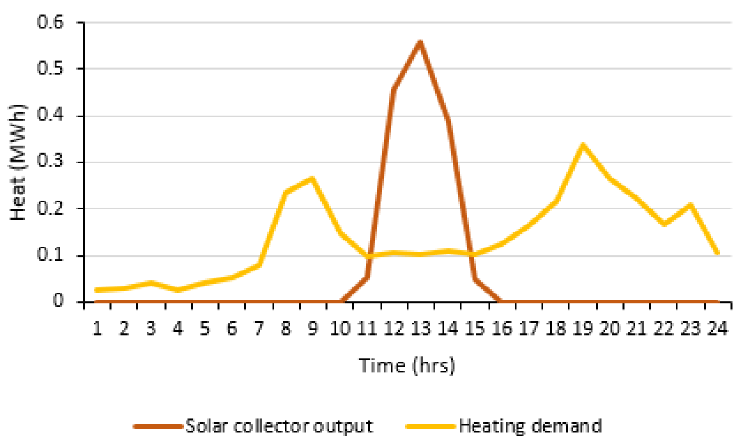


Figure 92 Daily heat consumption and solar collector output in C10 (01/01/2017) [own demonstration]

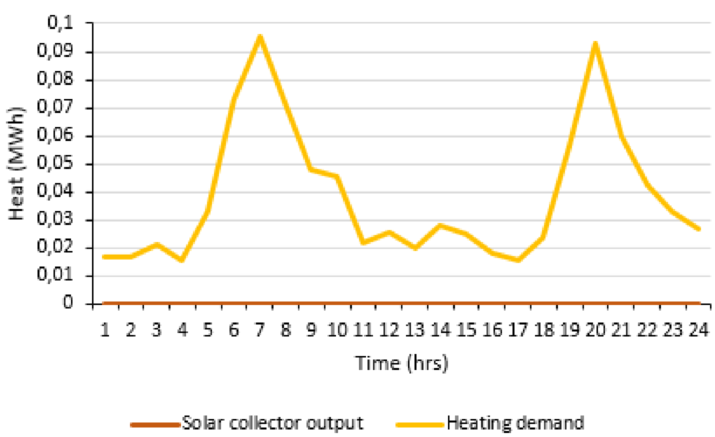


Figure 93 Daily heat consumption and solar collector output in C10 (12/07/2017) [own demonstration]

For that reason, a solar thermal system for heating supply was scoped out. The reason was the lack of solar radiation in the Kilmarnock area.

Summary Scenario 2

The configurations that met the critical value are shown in Table 24. The renewable electricity production was for all configurations the maximum amount of 992.6 MWh that highly exceeds the yearly consumption. Depending on the heat pump type, the imported electricity amount varies. Water source heat pumps have a COP of around 3.2 and therefore provide more heat capacity with less electricity consumption than the other heat pumps. Therefore, the renewable penetration factor for the WSHP configuration was the highest one with 82.72 %. The electricity peak demand in these configurations varied between 0.434 and 0.449 MW and did not exceed the 2,000 kVA limit of the grid. For all configurations a demand extension with additional EV consumption was also modelled in order to show that the implementation has no negative effect except of a slightly lower renewable penetration factor and slightly higher grid imports. In summary, all three configurations are feasible options for the HALO Kilmarnock sustainable district.

Table 24 Summary of Scenario 2 [own demonstration]

Configuration		Key Performance Indicators					
		Renewable Electricity Production (MWh/year)	Imported Electricity from Grid (MWh/year)	Renewable Penetration Factor (%)	Electricity Peak (MW)	Under Grid Limit of 2,000 kVA	Demands
C7	PV + BAT + GRID +ASHP + TS	992.6	259.5	79.27	0.449	yes	Electricity Demand Phase I + Heating Demand Phase I
C7+	PV + BAT + GRID +ASHP + TS	992.6	295.6	77.05	0.449	yes	Electricity Demand Phase I + Heating Demand Phase I + EV Demand
C8	PV + BAT + GRID +WSHP + TS	992.6	207.4	82.72	0.434	yes	Electricity Demand Phase I + Heating Demand Phase I
C8+	PV + BAT + GRID +WSHP + TS	992.6	243.0	80.33	0.434	yes	Electricity Demand Phase I + Heating Demand Phase I + EV Demand
C9	PV + BAT + GRID +GSHP + TS	992.6	222.0	81.72	0.439	yes	Electricity Demand Phase I + Heating Demand Phase I
C9+	PV + BAT + GRID +GSHP + TS	992.6	258.0	79.37	0.439	yes	Electricity Demand Phase I + Heating Demand Phase I + EV Demand

3.3.3 Scenario 3 – Investigation of cooling supply technologies

In Phase I only the Enterprise and Innovation Hub centre was assumed to be equipped with cooling technology since the climate in Scotland normally does not require cooling for domestic buildings. EnergyPRO does not offer the opportunity to cool with the already installed electric heat pumps. Therefore, absorption and electric chiller with cold storage were investigated as an active cooling system (see Table 25).

Table 25 Scenario 3 and its configurations [own demonstration]

		Scenario 3 Grid connection + PV	
		District heating: Heat Pump	
Configuration		Active cooling	**Demands**
C11	**PV + GRID + HP + TS + EC + CS**	**x**	Electricity + Heating + Cooling + EV Demand Phase I
C12	**PV + GRID + HP + TS + AC + CS**	**x**	Electricity + Heating + Cooling + EV Demand Phase I

In Scenario 3 the electricity demand was assumed to be met with the grid and additional PV panels while wind power was disregarded again due to the already mentioned reasons. The heating demand was met with an electric heat pump. Scenario 2 already showed the heating results of the different heat pump types. An ASHP is used in this combination for heating supply since this technology had the lowest efficiency and therefore the most conservative option could be analysed.

As said in this chapter 3.2.2 the cooling demand had many uncertainties and the profile was only developed for demonstration purposes. The following investigation was supposed to show which cooling technology would be the favourable one without giving any recommendations for component sizes in reality.

<u>Configuration 11 and Configuration 12</u>

The cooling technologies were investigated parallel (see Figure 94 and Figure 95). The sizes of the components for each configuration can be seen in Table 26. The COP of the electric chiller was 1.2 [101] and the COP of the absorption chiller was 0.7 [102]. For both configurations, the component sizes were optimised for the given demands to ensure a demand and supply match and prevent an oversizing of the system. This procedure was different to the investigations above but chosen to identify the better active cooling technology rather than finding the perfect energy supply to match an imprecise demand. The cooling demand for Phase I can be seen in Figure 37 in chapter 3.2.2 and encompass 633.4 MWh.

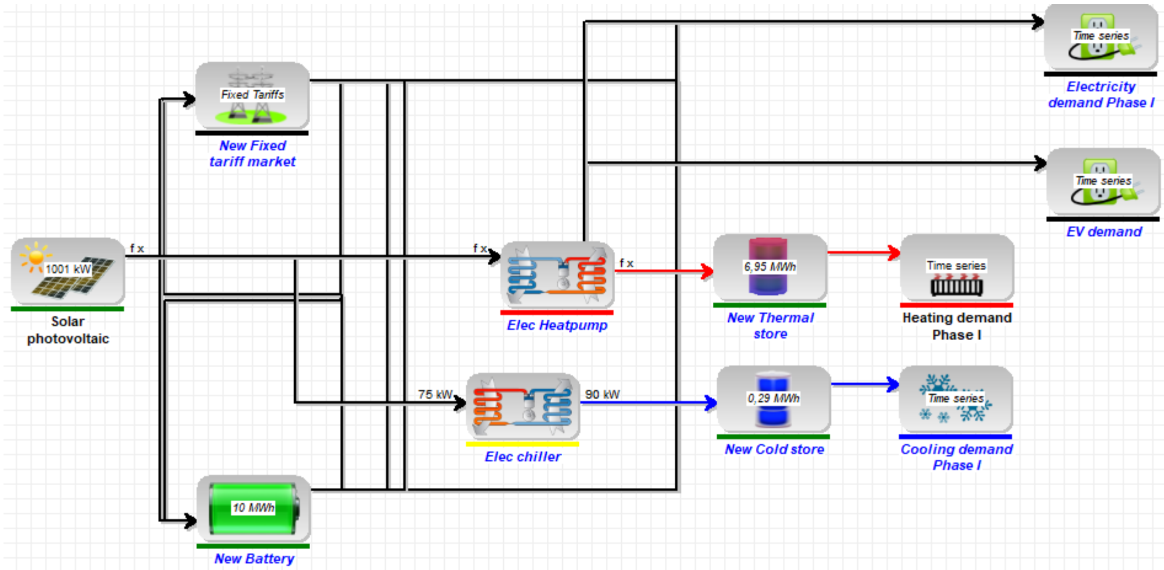


Figure 94 Configuration 11 [demonstration: energyPRO]

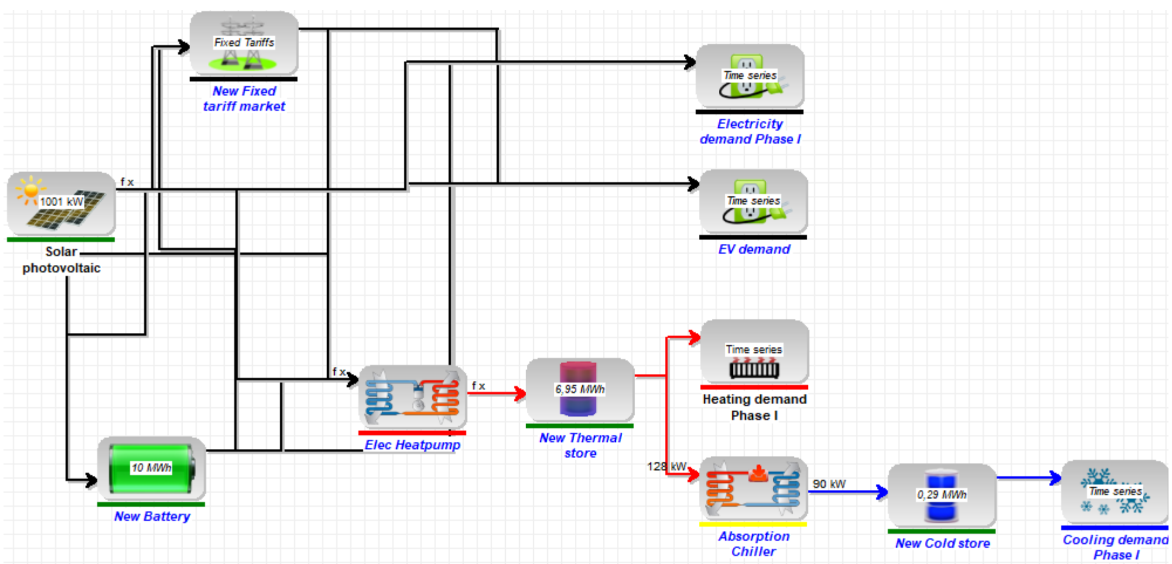


Figure 95 Configuration 12 [demonstration: energyPRO]

Table 26 Component sizes of cooling configurations [own demonstration]

	Electric Chiller Configuration	**Absorption Chiller Configuration**
Electricity consumption heat pump (kW)	64	104
Heating supply heat pump (kW)	160	260
Thermal storage volume (m3)	150	150
Electricity consumption electric chiller (kW)	75	
Heat consumption absorption chiller (kW)		128
Cooling supply electric/absorption chiller (kW)	90	90
Cold storage volume (m3)	50	50
Electricity usage total (kW)	139	104

Figure 96 shows that the constant cooling supply by the electric chiller met the cooling demand over the whole year. Demand fluctuations were met with the cold store (Figure 97). However, this supply and demand match was not the focus in this analysis. More important was the electricity usage and the renewable penetration factor that were obtained from the energy conversion report of energyPRO and not graphically displayed since the differences cannot be identified in the graphs due to the minor changes.

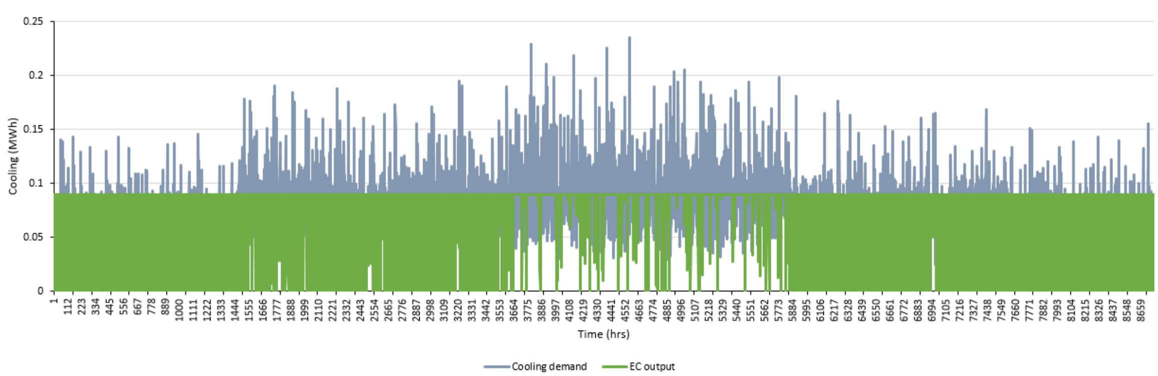


Figure 96 Yearly cooling consumption and electric chiller output in C11 [own demonstration]

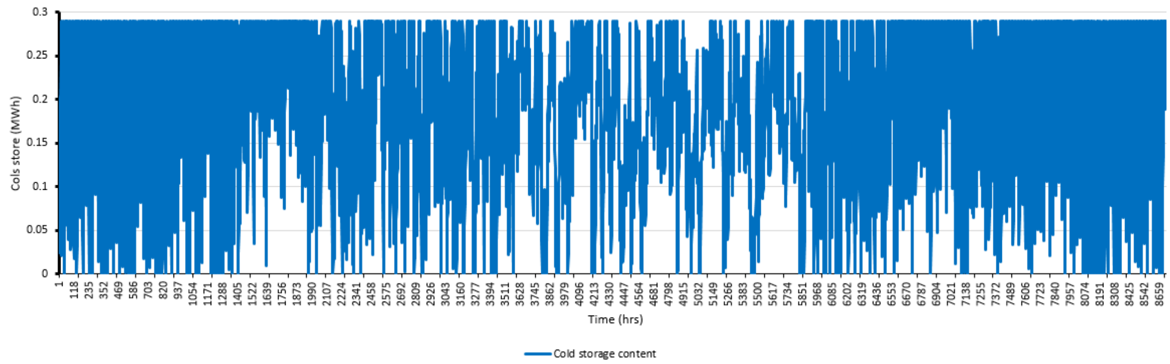


Figure 97 Yearly cold storage content in C11 [own demonstration]

In total the PV panels produced 992.6 MWh again. In total 836.5 MWh electricity was consumed that resulted in grid exports of 74.7 MWh. The electric chiller consumes 527.5 MWh and the electric heat pump 309 MWh. To match demand and supply over the whole year additional 577 MWh were imported that result in a renewable penetration factor of 63.2%.

For the sake of completeness, the matching of demand and supply for the absorption chiller configuration was shown as well (Figure 98 and Figure 99).

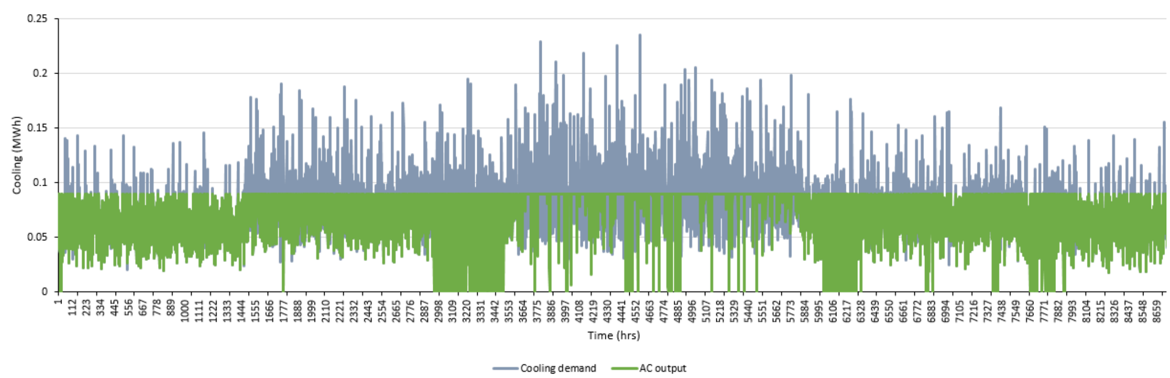


Figure 98 Yearly cooling consumption and absorption chiller output in C12 [own demonstration]

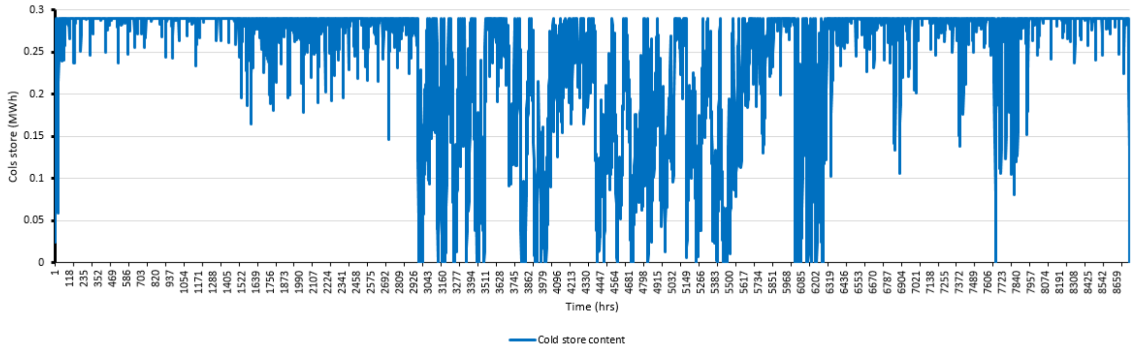


Figure 99 Yearly cold storage content in C12 [own demonstration]

In Configuration 12 the renewable energy share that is consumed by the ASHP was 664.1 MWh while the rest of 193 MWh can be exported. An amount of 523.7 MWh imported electricity is necessary to match demand and supply the whole year that result in a renewable penetration factor of 65.5 %.

Summary

Table 27 shows an overview of the configurations and their results for the KPI's. It can be seen that the electricity consumption of the configuration with absorption chiller was less than the one with an electric chiller that is an advantage when only a certain amount of electricity is available. However, since surplus energy was available almost the whole year from the PV panels, this argument is not deciding. Furthermore, the imported peak electricity was not even close to the grid limitation. The absorption chiller option needs less electricity imports that kept the renewable penetration factor at a higher level, though the difference to Configuration 11 was not crucial. No waste heat was available for an absorption chiller and therefore a bigger heat pump needed to be installed to provide enough heat. The installation of a bigger heat pump and the purchase of an absorption chiller that is more expensive than an electric chiller would result in higher cost. Due to the available surplus electricity and smaller capital costs, Configuration 11 with the electric chiller was identified as the most favourable active cooling technology.

Table 27 Summary of Scenario 3 [own demonstration]

Configuration		Renewable Electricity Production (MWh/year)	Imported Electricity from Grid (MWh/year)	Renewable Penetration Factor (%)	Electricity Peak (MW)	Under Grid Limit of 2,000 kVA	Demands
		Key Performance Indicators					
C11	PV + GRID + HP + TS + EC + CS	992.6	577.0	63.24	0.506	yes	Electricity + Heating + Cooling + EV Demand Phase I
C12	PV + GRID + HP + TS + AC + CS	992.6	523.7	65.46	0.490	yes	Electricity + Heating + Cooling + EV Demand Phase I

3.3.4 Result of modelling process

In Table 28 all feasible energy systems (the versions that include EV demand) are shown. Seeing a high renewable penetration factor as crucial premise with regard to sustainable and clean energy supply the most favourable options were C3+ and C4. Configuration 3+ consists of a combination of PV, battery and grid for electricity supply as well as a geothermal well with heat exchanger for heating supply and passive cooling methods. For Configuration 4 the same assumptions were made in terms of heating and cooling but here only PV and wind turbines supplied electricity. For that reason, the renewable penetration factors were 89.84% and 100% for these configurations. Although, Configuration C4 consists only of renewable energy sources it produced approx. 390 MWh less renewable electricity than C3+. The reason is that the production from the PV panels was limited due to the fact that no consumer (e.g. storage or a grid) was available.

Table 28 Comparison of all feasible energy system configurations [own demonstration]

Configuration		Renewable Electricity Production (MWh/year)	Imported Electricity from Grid (MWh/year)	Renewable Penetration Factor (%)	Electricity Peak (MW)	Under Grid Limit of 2,000 kVA	Demands
		Key Performance Indicators					
C3+	PV + BAT + GRID	992.6	112.3	89.84	0.431	yes	Electricity Demand Phase I + EV Demand
C4	PV + WIND + BAT	601.0	0	100.00	-	yes	Electricity Demand Phase I + EV Demand
C7+	PV + BAT + GRID +ASHP + TS	992.6	295.6	77.05	0.449	yes	Electricity Demand Phase I + Heating Demand Phase I + EV Demand
C8+	PV + BAT + GRID +WSHP + TS	992.6	243.0	80.33	0.434	yes	Electricity Demand Phase I + Heating Demand Phase I + EV Demand
C9+	PV + BAT + GRID +GSHP + TS	992.6	258.0	79.37	0.439	yes	Electricity Demand Phase I + Heating Demand Phase I + EV Demand
C11	PV + GRID + HP + TS + EC + CS	992.6	577.0	63.24	0.506	yes	Electricity + Heating + Cooling + EV Demand Phase I

However, both configurations were only investigated from the electricity side rather than from the heating side. The investigation if a geothermal well with heat exchanger can provide sufficient heat was not part of the analysis in this master thesis. Same applies to the purchase of wind power instead of using the available grid connection. Due to these uncertainties those configurations were not analysed towards an extension for Phase II. Configuration 8+ consists of a WSHP. The thermal resource of the Irvine River was initially assessed. Though, the assessment also includes many uncertainties. The temperature used was the ambient temperature and flow rates were obtained only from one year. The River is located 1.5 km away from the site which result in increased infrastructure costs that also need public permissions. In the end transportation losses can be high as well. Although, this heat pump type showed the best efficiency, this configuration was not chosen for the Phase II extension analysis. Configuration 11 and 12 represented active cooling technology for the non-domestic buildings. Due to the fact that the sustainable district is still in its design phase the recommended cooling strategy would be passive cooling due to higher energy efficiency and less costs (see also chapter 2.4.2). Both Configurations 7+ and 9+ have its advantages and disadvantages. Ground source heat pumps have, in average, a higher COP and the initial assessment showed that shallow and deep GSHP have an adequate potential when it comes to ground temperatures. Nevertheless, the exact ground conditions below the project site are completely unknown and experts need to be consulted to investigate potential aquifer occurrences and rock layers. The COP of air source heat pumps can vary heavily, depending on the climate, and was assumed to have the lowest level with 2.5. Nevertheless, the usage of air source heat pumps in the UK is increasing and many house owners in Scotland report that the technology is working well [103]. Due to the fact that performances of ASHP are mainly dependent on climate and the used temperatures in the initial assessment had the least uncertainties Configuration 7+ is chosen to be the most feasible one. In the following chapter this energy system was analysed towards its adaptability for a Phase II extension.

In summary, in this final evaluation an energy system was chosen that consists of PV panels and a grid connection for electricity supply, an air source heat pump for heating supply and passive cooling for cooling supply. The configuration was chosen due to the strong potential of a successful implementation and due to major uncertainties resulting from the other options. It is still possible that another option is the more efficient or inexpensive one. For that reason, some more detailed analyses have to be carried out. Recommendation can be found in chapter 6 Future work.

3.4 Phase II extension

Different scenarios consisting of a variety of configurations were investigated in the previous chapter. As the most feasible option of this high-level scoping analysis Configuration 7+ was chosen (Figure 100). The adaptability of the energy system for a Phase II extension was carried out and explained in this chapter.

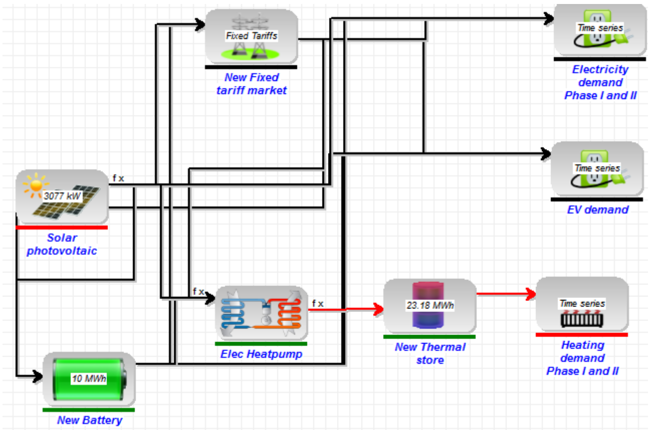


Figure 100 Phase II extension for Configuration 7+ [demonstration: energyPRO]

The energy system that was extended with Phase II conditions consists of the following elements:

- Electricity production through PV panels and a grid connection with a limit of 2,000 kVA
- Heat supply by a district heating system with an air source heat pump
- Passive cooling

Electricity and heating demand were increased and displayed for all buildings of Phase I and II plus the additional EV demand in order to ensure that the grid limit of 2,000 kVA was not exceeded. The yearly electricity demand trend for both phases can be seen in Figure 31, for heating in Figure 36 and the EV demand in Figure 32 of chapter 3.2. In total, the heating demand accounted for 1,927 MWh and the electricity demand for 2,329.3 MWh.

For Phase II no installed PV capacity or roof areas were given. It was assumed that the capacity rose to 3,077 kW that represented a coverage of 80% of an assumed roof area of 22,608 m^2 for all buildings. The heat pumps capacity rose to 168 kW electricity input and 420 kW heat output. The thermal store accommodated 150 m^2.

The following figures show yearly trends and no daily graphs since it was only important to identify if the grid limit was not exceeded. The heat consumption and air source heat pump supply can be seen in Figure 101 and the thermal storage capacity over the year in Figure 102. The heat demand was met the whole year and the components were sized in an optimum way.

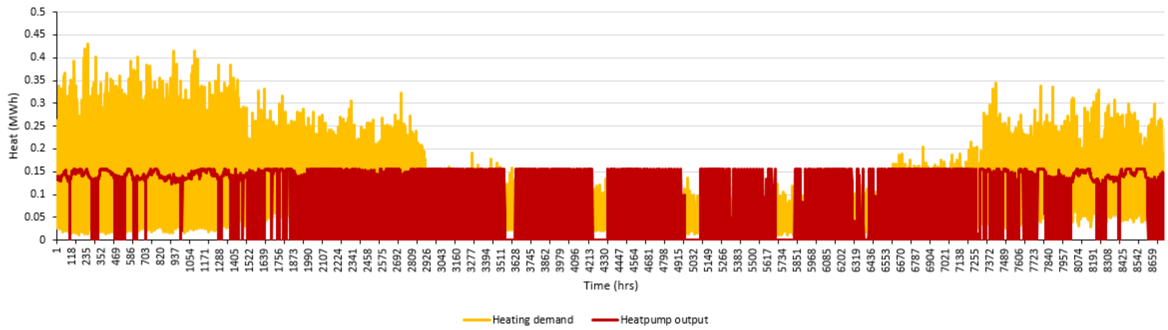


Figure 101 Yearly heating consumption and ASHP output for Phase II extension [own demonstration]

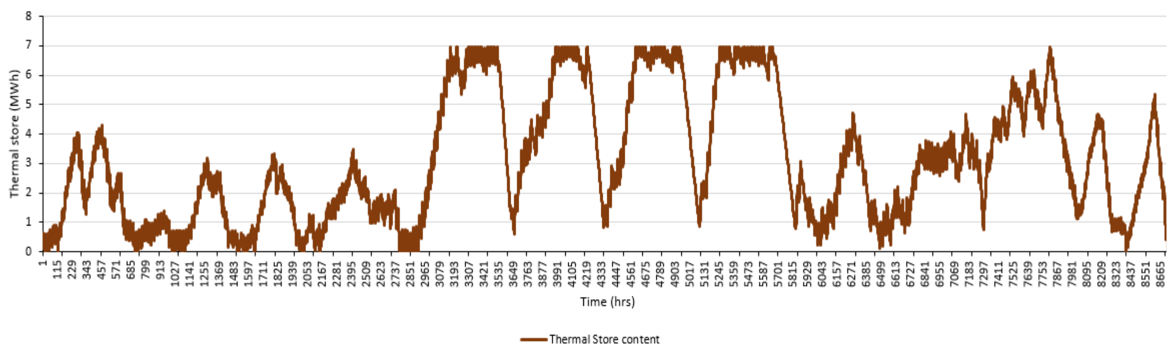


Figure 102 Yearly thermal storage content for Phase II extension [own demonstration]

Figure 103 shows the electricity consumption of the heat pump and the high PV output electricity of 3,051.3 MWh over the whole year. This electricity met the demand between March and September. In the other month minor amounts of electricity needed to be imported from the grid in order to match the heat demand. This information cannot be seen in Figure 103 but was obtained from the energyPRO reports. In total 858.4 MWh electricity could be exported and in total 1,181.7 MWh were imported from the grid to meet not only the electricity demand of the heat pump but also the electricity consumption of the whole district including EV's.

Table 29 displays the assessed KPI for the Phase II extension. The renewable penetration factor dropped to 72.08 % and the peak electricity demand rose to 0.878 MW.

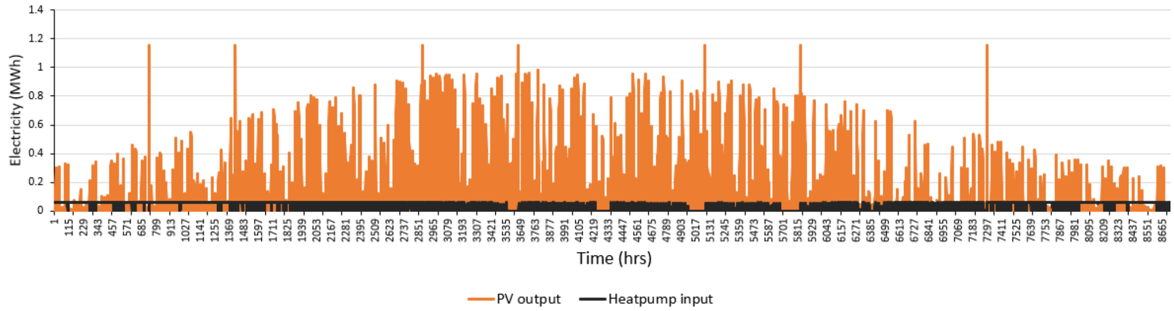


Figure 103 Yearly electricity consumption and PV output for Phase II extension [own demonstration]

This amount of electricity was still below the grid limitation and therefore the analysis verified that the chosen energy system is adaptable for the plans for Phase II. It still has to be considered that an assumption was made for the installed PV capacity for Phase II that has an impact on imported electricity and the peak demand. Nevertheless, the electricity is far below the limit and for that reason it can be assumed that the energy system is a feasible future option for the sustainable district. It is also important to know that the chosen Configuration 7+ had the lowest results when it comes to efficiency and since this configuration stayed below the limitation also all other systems with different heat pumps will be feasible as well.

Table 29 Assessed KPI's for Phase II extension [own demonstration]

		Key Performance Indicators					
Configuration		Renewable Electricity Production (MWh/year)	Imported Electricity from Grid (MWh/year)	Renewable Penetration Factor (%)	Electricity Peak (MW)	Under Grid Limit of 2,000 kVA	Demands
Phase II extension	PV + BAT + GRID +ASHP + TS	3,051.8	1,181.6	72.09	0.878	yes	Electricity and Heating Demand Phase I and II + EV Demand

Overall, it was proved that the selected energy system for the HALO sustainable district in Kilmarnock is adaptable to not only supply sufficient energy for Phase I of the project but also enough energy to meet the demand of Phase I and II. For that only a bigger heat pump was needed with a heat capacity of 420 kW instead of 155 kW. Therefore, it is important to discuss if an oversized heat pump for Phase I or an additional heat pump in Phase II should be installed in the sustainable district. In this investigation an increased amount of PV panels on the additional buildings were installed as well. A quick sensitivity check showed that this would not be necessary in order to stay below the grid limit. However, the renewable penetration factor would decrease to 31.4 % when the installed PV capacity stays at 1,001 kW.

4 Discussion

The aim of this master thesis was the design of an energy system for the HALO Kilmarnock project in order to utilise renewable technologies for a future sustainable district. For the HALO district a grid connection with a limit of 2,000 kVA and a geothermal well with a depth of 2,000 m were planned to this stage. In order to evaluate those options for a future energy system as well as other renewable energy technologies a high-level scoping study was carried out. In the end the research question "What would a future on-site energy system for the HALO sustainable district look like" was answered. After a brief technology screening in the context of the project site a more detailed site-specific initial assessment was conducted. Wind and solar power as well as different heat pump types were assessed with regard to the on-site conditions. As a result, solar energy, GSHP, ASHP and WSHP were found eligible. Wind power in form of an on-site wind turbine is highly unlikely and was only considered as a community ownership or purchase option. Cooling and storage technology were not assessed since the literature review already showed a detailed comparison. Afterwards, three different scenarios with several energy system configurations consisting of the assessed and chosen technologies were analysed in terms of supply and demand match rate, renewable penetration factor and electricity peak demand. In this chapter the results for each energy stream and the final energy system were discussed. Additionally, the validation of results and limitations of this thesis were displayed.

4.1 Electricity supply

For the electricity supply the initial assessment indicated that PV would be a feasible solution rather than wind energy. The installation of a wind turbine would result in an extensive permitting process and the initially assessed wind parameters seemed not favourable. In contrast PV panels could produce a reasonable amount of electricity while being installed on rooftops. The result of the scoping study was that the electricity demand of the Phase I and II buildings as well as demand for 30 EV's cannot be met by only PV panels but in combination to a grid connection. In summer much surplus electricity was produced by PV and only in the winter months electricity had to be imported that was favourable for the renewable penetration factor as well for staying far below the grid limitation. The penetration factor could even be raised through wind power from an owned turbine share or purchased power from a wind farm which is located in the outskirts of Kilmarnock rather than from an installed on-site turbine. The analysis of the practicability of these wind options were out of the scope of this thesis and therefore a combination of PV panels and grid were chosen for the future Kilmarnock district. With additional smart control schemes like the one tested in the ORIGIN project in Findhorn energy efficiency can be increased and costs can be decreased. Making use of load shifting through smart control can also be a major benefit with regard to the development of the future grid and its high renewable penetration. Another advantage is that increasing the renewable energy supply goes directly along with the innovative vision of the HALO initiative and can improve living standards in this sustainable district.

4.2 Heating supply

For the heating side the focus of this study was on the electrification of heat through heat pump technology. Combined heat and power schemes were not investigated since the rationale of this thesis was to supply reliable energy in the cleanest way. In the initial assessment different heat pumps were analysed with regard to on-site conditions and their potential for the Kilmarnock sustainable district. Ground source, water source and air source heat pumps all showed potential in that area although one has to consider that the investigations were afflicted with uncertainties. In order to evaluate the real thermal sources more detailed analyses have to be carried out while experts need to be involved. After modelling all system configurations a decision was made on a district heating system including an ASHP although the efficiency of this heat pump type is the lowest one. Due to the findings in the initial assessment to this stage an ASHP shows the highest potential without requiring many additional and extensive studies to rule out uncertainties. Air source heat pumps are already installed in Scottish climate and show a good performance. With a moderate climate in Kilmarnock this will not change. To know if the planned geothermal well including a GSHP or a heat exchanger is viable and to gather information of subsurface conditions, aquifer existence and geothermal temperature gradients, test wells need to be drilled and geologists need to be consulted. The WSHP option is the most efficient one. However, the extensive piping network that would have to be build, potential transportation losses and a detailed study of the heat capacity of the Irvine River are reasons for abandoning this option.

An exclusive installation of solar thermal panels was investigated as an additional option to supply clean heating energy. Such an energy system was found not to be feasible since the solar radiation in Kilmarnock is not high enough during the year.

4.3 Cooling supply

Concerning cooling, passive cooling methods are the most viable option due to energy efficiency and electricity usage. Passive cooling has minimal mechanical interaction and does not require any electricity. In Scottish climate ventilation is a viable passive cooling method since adequate wind speeds are available that can ensure high indoor air quality. In combination with building walls that have a low reflectivity and good thermal conductivity, this could ensure sufficient cooling in summer in the non-domestic buildings. These principles have to be considered in the detailed building design phase. Since high amounts of PV surplus electricity were predicted for the time between March and September the installation of electric chillers could also be considered. Active cooling could support server rooms or open-plan offices where temperatures are high due to occupation. Depending on the building design, e.g. large glazed areas, the installation of electric chillers could be necessary.

4.4 Summary

For the future sustainable district in Kilmarnock the installation of PV panels on 80% of the roof areas of the buildings as well as above the car park was recommended. Additionally, a district heating system consisting of a 155 kW air source heat pump and a 150 m^3 thermal storage was found to be feasible for the Phase I implementation. For Phase II supplementary 265 kW heat capacity are needed and therefore an additional heat pump in Phase II or an oversized heat pump for Phase I have to be installed. Those component sizes have to be evaluated again to ensure an adequate implementation in reality. Cooling should be carried out as passive cooling through a sustainable building design rather than installing additional active cooling technologies. If passive cooling cannot provide sufficient energy for the non-domestic buildings an electric chiller is a viable option since much surplus electricity was found to be produced during the year.

Sustainable building design with a high renewable penetration and smart control schemes can result in certifications after BREEAM or LEED. Having an innovative district equipped with a sustainable certification like this can easily result in a higher reputation and potentially in higher tenant's attraction and better dwelling sales. A sustainable district with a reliable and clean energy system plus additional control schemes and certification does not only go along with the vision of the HALO initiative but can also serve as an innovative role model for future building projects.

4.5 Validation and Limitations

In order to match future demands with supply from different technologies the energy system modelling software energyPRO was chosen. As stated in the chapter 1.3.3 energyPRO is a reasonable modelling tool to investigate different energy situations. Due to the high score achieved in Lyden et al. (2018) [10] this software was chosen to investigate potential energy systems. One limitation of this master thesis is that only one software was used and modelling results could not be validated with results from a second tool. For that reason, a qualitative input and output data validation was carried out throughout the thesis. The approach for that was the critical discussion of all results presented. Input data were measured data obtained from manuals and technical reports and often represented by average figures on an annual basis (e.g. heat pump COP). The limitations of the used data were always stated and considered when interpreting and discussing results.

Another limitation is the usage of simplified and mostly ideal models that, to some extent, did not take losses into account. This high-level scoping study can be used for an overall strategic assessment of different technologies but not in order to size components and to specify heat capacity and thermal resources. Since the town district was still in its design phase demand profiles had to be produced out of generic profiles from different sources. This also limits the viability of the results and was considered as well as critically discussed during the investigation and analysis process. Additionally, all demand profiles and energyPRO projects were provided to ensure an easy customisation and investigation in case more reliable data is available. All in all, the technical feasibility of energy technologies was assessed rather than economic benefits. This has to be considered and related to personal requirements when designing a future town district.

5 Conclusion

This master thesis was an accompanying study to the planning process of an energy system for the HALO Kilmarnock project done by the engineering company Wood. The HALO initiative plans to build a new innovative residential and working district in the town centre of Kilmarnock in order to revitalise urban and depleted old industry areas and support the local economy. Besides, HALO's incentive is to attract young people to live and work while stimulating entrepreneurial businesses in this innovation centre. The innovative character of the HALO town quarter is related to the worldwide trend of establishing ecovillages to ensure sustainable living. Sustainability is always connected to clean and reliable energy supply and therefore an energy system that consists of renewable and CO_2-free technology would be of interest for this project site. So far electricity supply through a limited grid connection of 2,000 kVA and a geothermal well with a depth of 2,000 m was planned.

The aim of this master thesis was the assessment of energy supply technologies for a future energy system for the HALO Kilmarnock project. Supply technologies from areas for electricity production, electrification of heat, passive and active cooling as well as the electrification of transport and storage were assessed to harness renewable energy integration in a future ecovillage.

In order to achieve this aim an extensive technology assessment was carried out. For the energy system only the most sustainable and cleanest technologies were considered and therefore many technologies were scoped out in the first screening that took notice of the availability and usability of the technologies with regard to the project site. Afterwards, an initial assessment of electricity and heating supply sources towards their suitability for the specific Kilmarnock location followed. On the electricity side solar and wind power were initially assessed while on the heating side the potential of different heat pump technologies was evaluated. Most cooling and storage options are not dependent on site-specific locations and were already chosen in the screening process and not initially assessed. The result of the initial assessment was that solar power and all heat pump types had an on-site potential and were set for the modelling procedure. For the installation of a wind turbine technical and public restrictions were identified and therefore only community ownership or purchase of wind power was considered. These technologies were then combined in energy system configurations. The modelling approach was done in two steps. Firstly, creating demand profiles for the Kilmarnock quarter to display sufficient energy consumption and secondly using a scenario-based approach to evaluate energy system configurations with an energy modelling software. The technical feasibility to align the demand and supply match and stick within the grid limitation was assessed. The software modelling displayed that PV panels in combination to a grid connection could meet the electricity demand of Phase I and II as well as of 30 EV's. Between March and September even high electricity surpluses could be achieved. The electrification of heat with heat pumps was found a feasible option. The highest potential was identified with a district heating system consisting of an air source heat pump and a thermal storage rather than with the planned geothermal well. The reason for that were the insufficient knowledge about ground conditions and temperatures. In order to safe extra energy, passive cooling with an adequate thermal mass and ventilation rate was considered as the most feasible option for a cooling strategy for non-domestic buildings. However, due to the surplus energy that was produced most of the year an electric chiller installation would be another solution. All demand profiles and energyPRO projects were provided within this thesis to ensure that the investigations can be carried out again with customised data. Additionally, smart control schemes and sustainable building certification processes were recommended since these benefit not only the energy efficiency but also the reputation of the district.

In summary, the future energy system for the sustainable district in Kilmarnock was selected and therefore the research questions, what a system would look like, answered. The desired sustainable and innovative design of a reliable energy system was considered to be possible. Implementing a carbon-free and clean energy system as recommended will support the vision of the HALO initiative and enhance the prestige of the planned sustainable district.

6 Future Work

For future work some studies that deepen or expand the high-level scoping investigation presented in this master thesis should be conducted.

In order to increase the renewable penetration factor it would be favourable to consider alternative or additional electricity sources like the already mentioned community ownerships or wind power purchases from the Whitelee wind farm. One should investigate the availability and economics of the incorporated wind power and the needed infrastructure in comparison to the imported electricity from the grid. Furthermore, a more detailed analysis of the surrounding area to re-define wind parameters and planning permissions for an on-site wind turbine should be carried out.

Heating supply technologies like heat pumps were initially investigated. As a follow-up it is important to re-evaluate the thermal resources with more detailed analyses, on-site investigations and technical experts. With that real performances, thermal gradients and heat capacities can be found. For modelling purposes average COP on an annual basis were chosen for each heat pump type. Due to climate COPs and consequently the heat pump's efficiency can vary over the year. A more detailed performance characteristic of specific heat pumps should be considered in detail in the design stage of the project. Additionally, it has to be analysed if one big or two smaller heat pumps are economically and technically more practical to be installed to meet the Phase I as well as the Phase II demand.

Likewise, in the building design stage the future cooling strategy needs to be taken into account. Within the building design and dependent on glazing, walls and ventilation rates passive cooling can be incorporated rather than active cooling technologies. For the adequate implementation of an electric chiller cooling demands need to be redefined since the ones used in this thesis contain many uncertainties and therefore component sizes and real-life interpretations cannot be obtained from that modelling scenario. Similarly, before deciding on component sizes, the electricity and heating demand profiles need to be reviewed again.

Finally, economic parameters can be added to this technical investigation process to find the overall best solution for an energy system. Smart control schemes should be considered and economically and technically assessed as well.

References

[1] Global Ecovillage Network, “Dimensions of Sustainability,” (n.d.). [Online]. Available: https://ecovillage.org/projects/dimensions-of-sustainability/. [Accessed 26 06 2018].

[2] Global Ecovillage Network Europe, “Ecovillages,” (n.d.). [Online]. Available: https://gen-europe.org/about-us/ecovillages/index.htm. [Accessed 15 06 2018].

[3] HALO Urban Regeneration, “HALO Urban Regeneration - Live, Work, Learn and Play,” [Online]. Available: https://halo-projects.com/. [Accessed 09 06 2018].

[4] M. Sameti and F. Haghighat, “Optimization approaches in district heating and cooling thermal network,” *Energy and Buildings,* vol. 140, pp. 121-130, (2017).

[5] R. Pepper, Interviewee, *Ph.D student.* [Interview]. 18 06 2018.

[6] Scotland Info Guide, “Daylight Hours - Sunrise and Sunset Times,” (n.d.). [Online]. Available: https://www.scotlandinfo.eu/daylight-hours-sunrise-and-sunset-times/. [Accessed 02 07 2018].

[7] ELECTRIC VEHICLE PARADIGM SHIFT - Group Project 2018 (RESE), “ELECTRIC VEHICLE PARADIGM SHIFT,” (2018). [Online]. Available: http://www.esru.strath.ac.uk/EandE/Web_sites/17-18/paradigmev/index.html. [Accessed 05 07 2018].

[8] G. Lavery, Interviewee, *Master student.* [Interview]. 02 07 2018.

[9] EMD International A/S, “Order energyPRO,” (n.d.). [Online]. Available: https://www.emd.dk/energypro/order-energypro/. [Accessed 28 06 2018].

[10] A. Lyden, R. Pepper and P. G. Tuohy, “A modelling tool selection process for planning of community scale energy systems including storage and demand side management,” *Sustainable Cities and Society,* vol. 39, pp. 647-688, (2018).

[11] Global Ecovillage Nework, “Ecovillages,” (n.d.). [Online]. Available: https://ecovillage.org/projects/. [Accessed 29 06 2018].

[12] Global Ecovillage Network, “Vision, Mission, Goals,” (n.d.). [Online]. Available: https://ecovillage.org/global-ecovillage-network/vision-mission-goals/. [Accessed 29 06 2018].

[13] Bioregional, “One Planet Living,” (n.d.). [Online]. Available: https://www.bioregional.com/oneplanetliving/. [Accessed 12 06 2018].

[14] BREEAM, “BREEAM Communities - International Technical Standard,” (2012). [Online]. Available: http://www.breeam.com/communitiesmanual/. [Accessed 28 06 2018].

[15] GreenBuild Consult, “The benefits of BREEAM,” (2017). [Online]. Available: https://greenbuildconsult.co.uk/the-benefits-of-breeam/. [Accessed 09 07 2018].

[16] LEED, “LEED is green building,” (n.d.). [Online]. Available: https://new.usgbc.org/leed. [Accessed 09 07 2018].

[17] R. Burger, “What are the benefits of LEED certification?,” (2018). [Online]. Available: https://www.thebalancesmb.com/what-are-the-benefits-of-leed-certification-845365. [Accessed 09 07 2018].

[18] Findhorn Ecovillage, “Key Dates,” (n.d.). [Online]. Available: https://www.ecovillagefindhorn.com/index.php/ecovillage-findhorn/key-dates. [Accessed 12 06 2018].

[19] Findhorn Ecovillage, “Ecological Building,” (n.d.). [Online]. Available: https://www.ecovillagefindhorn.com/index.php/building. [Accessed 12 06 2018].

[20] Findhorn Ecovillage, “Renewable Energy Systems,” [Online]. Available: https://www.ecovillagefindhorn.com/index.php/renewable. [Accessed 12 06 2018].

[21] K. Andrews, “BEDZED: Beddington Zero Energy Development in London,” (2008). [Online]. Available: https://inhabitat.com/bedzed-beddington-zero-energy-development-london/. [Accessed 12 06 2018].

[22] Bioregional, “BedZED,” (n.d.). [Online]. Available: https://www.bioregional.com/bedzed/. [Accessed 12 06 2018].

[23] D. Thorpe, “The world's most successful model for sustainable urban development?,” (n.d.). [Online]. Available: https://www.smartcitiesdive.com/ex/sustainablecitiescollective/words-most-successful-model-sustainable-urban-development/229316/. [Accessed 15 06 2018].

[24] Y. Xiaopeng, “Preliminary Exploration of the Appropriate Technologies of Ecovillage in Germany - Taking Bramwich Ecovillage in Hamburg as an Example,” *Advanced Materials Research*, vol. 224, pp. 109-117, (2011).

[25] K. Rumming, “Sustainable Development - The Ecologically Exemplary New Settlement of Hannover-Kronsberg,” (n.d.). [Online]. Available: https://www.unil.ch/files/live/sites/ouvdd/files/shared/Colloque%202006/Communications/Eco-urbanisme/Bonnes%20pratiques/K.%20Rumming.pdf. [Accessed 16 06 2018].

[26] City to City, “Creation of the new Kronsberg District,” (2011). [Online]. Available: http://fad.cat/citytocity/2/eng/?cat=17. [Accessed 16 06 2018].

[27] Landeshauptstadt Hannover, “Modell Kronsberg - Sustainable Building for the future,” (2013). [Online]. Available: https://www.hannover.de/Leben-in-der-Region-Hannover/Umwelt-Nachhaltigkeit/Umweltinformation/%C3%96kologisches-Bauen/Modell-Kronsberg/Kronsberg-Model-Ecological-Building-for-the-Future. [Accessed 12 06 2018].

[28] Goolge, “Google Earth,” (2018). [Online]. Available: https://www.google.co.uk/intl/en_uk/earth/.. [Accessed 18 06 2018].

[29] J. Byers, Interviewee, *Graduate Engineer*. [Interview]. 04 07 2018.

[30] Met Office, “Kilmarnock climate,” (n.d.). [Online]. Available: https://www.metoffice.gov.uk/public/weather/climate/gcuu3sm50. [Accessed 15 06 2018].

[31] UK Government, “Solar photovoltaics deployment,” (2018). [Online]. Available: https://www.gov.uk/government/statistics/solar-photovoltaics-deployment. [Accessed 04 06 2018].

[32] N. J. Kelly and J. A. Clarke, *Solar Energy - lecture notes Energy Sources and Policy (ME927),* Glasgow: University of Strathclyde, (2017).

[33] G. Destouni and H. Frank, “Renewable Energy,” *AMBIO,* vol. 39, no. 1, pp. 18-21, (2010).

[34] IRENA, “Renewable Power Generation Costs in 2017,” International Renewable Energy Agency, Abu Dhabi, (2018).

[35] DTU Wind Energy, “The wind atlas methodology,” (n.d.). [Online]. Available: https://www.wasp.dk/dataandtools#wind-atlas__european-wind-atlas. [Accessed 04 06 2018].

[36] J. A. Clarke and N. J. Kelly, *Wind Energy - lecture notes Energy Sources and Policy (ME927),* Glasgow: University of Strathclyde, (2017).

[37] J. A. Clarke and N. J. Kelly, *Hydro Power - lecture notes Energy Sources and Policy (ME927),* Glasgow: University of Strathclyde, (2017).

[38] H. Alverfalk et al., “Large heat pumps in Swedish district heating systems,” *Renewable and Sustainable Energy Reviews,* vol. 79, pp. 1275-1284, (2017).

[39] The Renewable Energy Hub UK, “How a heat pump works,” (n.d.). [Online]. Available: https://www.renewableenergyhub.co.uk/heat-pumps-information/how-does-a-heat-pump-work.html. [Accessed 05 06 2018].

[40] Star Renewable Energy, “Norwegian city proves COP21 carbon reduction targets are achievable with Water Source Heat Pumps,” (n.d.). [Online]. Available: http://www.neatpumps.com/news/norwegian-city-proves-cop21-carbon-reduction-targets-are-achievable-with-water-source-heat-pumps.aspx. [Accessed 08 08 2018].

[41] Star Renewable Energy, “UK's Largest Air-Source Heat Pump for Residential Use to Showcase at All-Energy Event,” (n.d.). [Online]. Available: http://www.neatpumps.com/news/uks-largest-air-source-heat-pump-for-residential-use-to-showcase-at-all-energy-event.aspx. [Accessed 08 08 2018].

[42] The Greenage, “Electric Boilers,” (n.d.). [Online]. Available: https://www.thegreenage.co.uk/tech/electric-boilers/. [Accessed 05 06 2018].

[43] N. A. Al-Azri, “Development of a typical meteorological year based on dry bulb temperature and dew point for passive cooling applications,” *Energy for Sustainable Development*, vol. 33, pp. 61-74, (2016).

[44] S. Werner, “International review of district heating and cooling,” *Energy*, vol. 137, pp. 617-631, (2017).

[45] D. Connolly, “A review of energy storage technologies,” University of Limerick, Limerick, (2009).

[46] I. Sarbu and C. Sebarchievici, “A Comprehensive Review of Thermal Energy Storage,” *Sustainability*, vol. 10, no. 191, pp. 1-32, (2018).

[47] P. Eames et al., “The Future Role of Thermal Energy Storage in the UK Energy System: An Assessment of the Technical Feasibility and Factors Influencing Adoption,” UKERC, London, (2014).

[48] D. Pudjianto et al., “Smart control for minimizing distribution network reinforcement cost due to electrification,” *Energy Policy,* vol. 52, pp. 76-84, (2013).

[49] P. G. Tuohy et al., “Orchestration of Renewable Generation in Low Energy Buildings and Districts using Energy Storage and Load Shaping,” *Energy Procedia,* (2015).

[50] Energy Saving Trust, “Wind turbine measuring wind speed,” (n.d.). [Online]. Available: http://www.energysavingtrust.org.uk/sites/default/files/reports/wind%20turbine_measuring%20wind%20speed.pdf. [Accessed 09 07 2018].

[51] Energy Saving Trust, “Wind Speed Prediction Tool,” (n.d.). [Online]. Available: http://www.windspeed.energysavingtrust.org.uk/. [Accessed 18 06 2018].

[52] RenSMART, “NOABL Wind Speed Database,” (n.d.). [Online]. Available: http://www.rensmart.com/Weather/BERR. [Accessed 19 06 2018].

[53] DTU, “DTU Global Wind Atlas,” (n.d.). [Online]. Available: https://irena.masdar.ac.ae/gallery/#map/103. [Accessed 18 06 2018].

[54] International Electrotechnical Commission, “IEC 61400-1 Wind turbines -Part 1: Design requirements, 3. ed.,” International Electrotechnical Commission, Geneva, (2005).

[55] Scottish Government, “Scotland's Protected Nature Sites,” (n.d.). [Online]. Available: https://www.environment.gov.scot/data-analysis-applications/protected-nature-sites/. [Accessed 18 06 2018].

[56] Scottish Government, “Habitat Map of Scotland,” (n.d.). [Online]. Available: https://www.environment.gov.scot/our-environment/habitats-and-species/habitat-map-of-scotland/. [Accessed 18 06 2018].

[57] Scottish Natural Heritage, “Carbon and peatland 2016 map,” (2018). [Online]. Available: http://soils.environment.gov.scot/maps/carbon-and-peatland-2016-map/. [Accessed 18 06 2018].

[58] RSPB, “Mapping and locational guidance,” (2018). [Online]. Available: https://www.rspb.org.uk/our-work/our-positions-and-casework/our-positions/climate-change/action-to-tackle-climate-change/uk-energy-policy/wind-farms/mapping-and-locational-guidance/. [Accessed 18 06 2018].

[59] Historic Environment Scotland, “Listed buildings,” (n.d.). [Online]. Available: https://www.historicenvironment.scot/advice-and-support/listing-scheduling-and-designations/listed-buildings/search-for-a-listed-building/. [Accessed 18 06 2018].

[60] Local Government Boundary Commission for Scotland, “Local Government Boundary Commission for Scotland,” (2018). [Online]. Available: http://www.lgbc-scotland.gov.uk/maps/. [Accessed 18 06 2018].

[61] Ordnance Survey, “Ordnance Survey Election Maps,” (2018). [Online]. Available: https://www.ordnancesurvey.co.uk/election-maps/gb/. [Accessed 18 06 2018].

[62] Historic Environment Scotland, “HLAMap,” (n.d.). [Online]. Available: http://map.hlamap.org.uk. [Accessed 18 06 2018].

[63] East Ayrshire Local, “Development Plan,” (n.d.). [Online]. Available: https://www.east-ayrshire.gov.uk/Resources/PDF/E/EALDP-Kilmarnock-Map.pdf. [Accessed 18 06 2018].

[64] C. R. Warren and M. McFayden, “Does community ownership affect public attitudes to wind energy? A case study from south-west Scotland,” *Land Use Policy,* vol. 27, pp. 204-213, (2010).

[65] Scottish Power, “Whitelee Windfarm,” (2018). [Online]. Available: https://www.scottishpower.co.uk/whitelee/. [Accessed 2018 08].

[66] Valentin Software, “PV*Sol,” (n.d.). [Online]. Available: https://www.valentin-software.com/en/products/photovoltaics/55/pvsol. [Accessed 18 06 2018].

[67] Ricardo-AEA and Local Energy Scotland, “Community and Renewable Energy Scheme Project Development Toolkit Heat Pump Module,” (2017). [Online]. Available: https://www.localenergy.scot/media/107007/cares-toolkit-heat-pumps-module-v4.pdf. [Accessed 05 07 2018].

[68] T. Kusuda and P. R. Achenbach, “Earth Temperatures and Thermal Diffusivity at Selected Stations in the United States,” (1965). [Online]. Available: https://nvlpubs.nist.gov/nistpubs/Legacy/RPT/nbsreport8972.pdf. [Accessed 28 06 2018].

[69] D. Bertermann et al., “Thermomap Map Viewer,” (n.d.). [Online]. Available: http://geoweb2.sbg.ac.at/thermomap/. [Accessed 20 06 2018].

[70] British Geological Survey, “Example report, BGS Keyworth. Ground Source Heat Pump Temperature and Thermal Properties (Detailed),” (2011). [Online]. Available: https://shop.bgs.ac.uk/GeoReports/examples/S005.pdf. [Accessed 20 06 2018].

[71] B. Sanner, “Shallow Geothermal Systems,” (n.d.). [Online]. Available: http://geothermalcommunities.eu/assets/elearning/6.11.Shallow%20Geothermal%20Systems.pdf. [Accessed 24 07 2018].

[72] GreenMatch, “What is a Ground Source Heat Pump?,” (n.d.). [Online]. Available: https://www.greenmatch.co.uk/heat-pump/ground-source-heat-pump/ground-source-heat-pump-borehole. [Accessed 24 07 2018].

[73] J. Busby, A. Kingdon and J. Williams, “The measured shallow temperature field in Britain,” *Q. J. Eng. Geol. Hydrogeol.*, vol. 44, no. 3, pp. 373-387, (2011).

[74] British Geological Survey, “Geology of Britain viewer,” (2018). [Online]. Available: http://mapapps.bgs.ac.uk/geologyofbritain/home.html. [Accessed 09 07 2018].

[75] British Geological Survey, “The BGS Lexicon of Named Rock Units - Result Details,” (n.d.). [Online]. Available: http://www.bgs.ac.uk/lexicon/lexicon.cfm?pub=PUCM. [Accessed 2018 07 24].

[76] M. R. Gillespie, E. J. Crane and H. F. Barron, “Deep geothermal energy potential in Scotland,” British Geological Survey, Nottingham, (2013).

[77] National River Flow Archive, “83013 - Irvine at Glenfield,” (n.d.). [Online]. Available: https://nrfa.ceh.ac.uk/data/station/info/83013. [Accessed 09 07 2018].

[78] Department of Energy and Climate Change, “National Heat Map: Water source heat map layer,” (2015). [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/416660/water_source_heat_map.PDF. [Accessed 24 07 2018].

[79] Vital Energi Utilities Limited, *HALO Enterprise and Innovation Centre - Stage 3 report*, (2017).

[80] W. Pan and M. Cooper, “Decision Criteria for selecting air source heat pump technology in UK low carbon housing,” *Technology Analysis & Strategic Management*, vol. 23, no. 6, pp. 623-637, (2011).

[81] Energy Saving Trust, “Air source heat pumps,” (n.d.). [Online]. Available: http://www.energysavingtrust.org.uk/renewable-energy/heat/air-source-heat-pumps. [Accessed 27 06 2018].

[82] Glow-worm, “Basic guide to heat pump system sizing,” (n.d.). [Online]. Available: https://www.glow-worm.co.uk/renew-ability/heat-pump-system-sizing-a4-lr-244921.pdf. [Accessed 09 07 2018].

[83] S. Pisupati, “Air-source heat pump or air to air heat pump examples,” (n.d.). [Online]. Available: https://www.e-education.psu.edu/egee102/node/2112. [Accessed 24 07 2018].

[84] M. Haller et al., “SOL-HEAP. Solar and Heat Pump Combisystems,” Swiss Federal Office of Energy, Ittingen, (2014).

[85] Elexon, “Profiling,” (n.d.). [Online]. Available: https://www.elexon.co.uk/operations-settlement/profiling/. [Accessed 02 07 2018].

[86] D. Charles, Interviewee, *Energy Engineer.* [Interview]. 12 07 2018.

[87] Ramboll, *Electrical Load Assessment - Project Report, Rev. 1,* (2017).

[88] CIBSE TM 46, “Energy Benchmarks,” The Chartered Institution of Building Service Engineers, London, (2008).

[89] CIBSE, “Energy use in offices,” (2000). [Online]. Available: http://www.cibse.org/getmedia/7fb5616f-1ed7-4854-bf72-2dae1d8bde62/ECG19-Energy-Use-in-Offices-(formerly-ECON19. [Accessed 25 07 2018].

[90] Battery University, “BU-1003: Electric Vehicle (EV),” (2018). [Online]. Available: http://batteryuniversity.com/learn/article/electric_vehicle_ev. [Accessed 04 07 2018].

[91] Department for Transport, “Road Use Statistics Great Britain 2016,” (2016). [Online]. Available: https://www.licencebureau.co.uk/wp-content/uploads/road-use-statistics.pdf. [Accessed 04 07 2018].

[92] UK EVSE, “Charge Points,” (n.d.). [Online]. Available: http://ukevse.org.uk/charge-points-chargers/. [Accessed 05 07 2018].

[93] M. Islam, H. Shareef and A. Mohamed, “Optimal sizing of rapid charging station for electric vehicles considering Bangi city road network in Malaysia,” *Turkish Journal of Electrical Engineering & Computer Science,* vol. 24, pp. 3933-3948, (2016).

[94] J. Adnot et al., “A benchmarking guide adapted to air conditioning based on electricity bills,” Association pour la Recherche et le Développement des Méthodes et Processus Industriels, Paris, (2018).

[95] Wood Group UK Limited, *Halo - Solar Assessment,* Glasgow: Wood Group, (2018).

[96] Canadian Solar, *MAXPOWER2 CS6XA-325 I 330 I 335M,* Ontario: Canadian Solar Inc., (2016).

[97] Energy Saving Trust, “The heat is on - heat pump field trials phase 2,” Energy Saving Trust, London, (2013).

[98] CIBSE Journal, “Module 13: Design of air source heat pump systems for heating and hot water,” (2010). [Online]. Available: https://www.cibsejournal.com/cpd/modules/2010-02/. [Accessed 12 07 2018].

[99] N. Cowan, “Heat Pumps & Energy Efficiency Influencers - Making the right choice,” (n.d.). [Online]. Available: http://www.star-ref.co.uk/smart-thinking/how-to-choose-an-efficient-heat-pump-large-scale-heat-pumps-and-district-heating-making-the-right-choice.aspx. [Accessed 12 07 2018].

[100] Forkers Renewable Energy, “A Guide to Ground Source Heating,” (n.d.). [Online]. Available: http://www.forkers.com/filestore/pdf/a%20guide%20to%20ground%20source%20heating.pdf. [Accessed 12 07 2018].

[101] Ref Wiki, “HVAC Absorption Chillers vs. Electric Chillers,” (n.d.). [Online]. Available: http://www.ref-wiki.com/technical-information/162-chillers/32888-hvac-absorption-chillers-vs-electric-chillers.html. [Accessed 12 07 2018].

[102] Hitachi Ltd., “Advanced heat driven cooling cycles for low-temperature waste heat recovery,” (2018). [Online]. Available: http://www.nedo.go.jp/content/100874854.pdf. [Accessed 12 07 2018].

[103] Energy Saving Trust, “Green Homes Network,” (n.d.). [Online]. Available: http://greenhomesnetwork.energysavingtrust.org.uk/Default.aspx?search=G40PS&radius=25&esm=&tech=2,4,1&prtyp=&prage=&scheme=&awards=&vutyp=&vtyp=&vowntyp=&sys=1&sysx=2,3,4. [Accessed 07 08 2018].

Appendix

1. Input data for energyPRO

The data were also submitted in a separate document within this thesis.

PV Panel

district	Phase I	Phase II	Source
Installed capacity (kW)	1,001	3,077	Solar Assessment by Wood plus own assumption
Inclination of PV (°)	15		Solar Assessment by Wood
Orientation of PV	South		Solar Assessment by Wood
Ambient temperature	Online Database connected through energyPRO		
Solar radiation	Online Database connected through energyPRO		
Maximum power (kW)	0.33		Solar Assessment by Wood
Temperature coefficient of power (%/°C)	-0.041		Canadian Solar
NOCT (°C)	45		Canadian Solar

Wind turbine

		Source
Wind speed	Online Database connected through energyPRO	
Measure Height (m)	100	obtained from Findhorn example from ESRU Library (source: Andrew Lyden)
Hub Height (m)	23	
Hellmann exponent	0	

Wind speed [m/s]	Power [kW]	Power Modified [kW]	Source
0.00	0.00	0.00	obtained from Findhorn example from ESRU Library (source: Andrew Lyden)
3.00	2.00	6.40	
3.00	2.00	6.40	
4.00	2.50	8.00	
5.00	5.00	16.00	
6.00	15.00	48.00	
7.00	20.00	64.00	
8.00	30.00	96.00	
9.00	37.00	118.40	
10.00	45.00	144.00	
11.00	52.50	168.32	
12.00	60.00	192.00	
13.00	67.00	214.40	
14.00	72.00	230.40	
15.00	75.00	240.00	
16.00	80.00	256.00	
17.00	82.00	262.40	
18.00	83.00	265.60	
19.00	83.00	265.60	
20.00	83.00	265.60	
55.00	83.00	265.60	

Heat Pumps

district	ASHP		WSHP		GSHP	
	Phase 1	Source	Phase 1	Source	Phase 1	Source
Electr. Capacity (kW)	172	calculated with COP	134	calculated with COP	148	calculated with COP
Max. Heat capacity (kW)	430	Peak demand from heating profile (before downsizing)	430	Peak demand from profile (before downsizing)	430	Peak demand from heating profile (before downsizing)
COP	2.5	Energy Saving Trust (2013). The heat is on: heat pump field trials phase 2	3.2	Star Refrigeration http://www.starref.co.uk/smart-thinking/how-to-choose-an-efficient-heat-pump-large-scale-heat-pumps-and-district-heating-making-the-right-choice.aspx	2.9	Energy Saving Trust (2013). The heat is on: heat pump field trials phase 2
Heated from (°C)	35	Cibse journal https://www.cibsejournal.com/cpd/modules/2010-02/	55		35	Forkers, http://www.forkers.com/filestore/pdf/a%20guide%20to%20ground%20source%20heating.pdf
Heated to (°C)	60		75		65	
Heat source cooled from (°C)	10	own assumption	8		12	
Cooled to (°C)	5		5		0	
Actual temperatures: Heat source cooled from (°C)	T0	own assumption, ASHP are dependent from ambient temperature (cools down around 2 degrees)	8		12	
Actual temperatures: Cooled to (°C)	T0-2		5		0	

Solar thermal

	Phase 1	
Parameter	**Base**	**Source**
Total area of collectors (m2)	5,920	Solar Assessment by Wood + own assumption
Inclination of solar collector (°)	15	Solar Assessment by Wood + own assumption
Orientation of solar collector	South	Solar Assessment by Wood
Ambient temperature	Online Database connected through energyPRO	
Solar radiation	Online Database connected through energyPRO	
Start efficiency	0.717	Apricus, https://www.energymatters.com.au/images/apricus/Brochure.pdf + own assumption
Loss coefficient (W/m2 °C)	1.600	
Loss coefficient (W/m2 °C)	0.0085	
Incidence angle modifier – coefficient	4	

Absorption Chiller

		Source
Heating Consumption (kW)	128	calculated with COP
Cooling Supply (kW)	90	Peak demand from profile
COP	0.7	Hitachi Ltd, http://www.nedo.go.jp/content/100874854.pdf

Electric Chiller

		Source
Electric Consumption (kW)	75	calculated with COP
Cooling Supply (kW)	90	Peak demand from profile
COP	1.2	Ref-wiki, http://www.ref-wiki.com/technical information/162-chillers/32888-hvac-absorption-chillers-vs-electric-chillers.html

Battery

	District	Source
Parameter	**Base**	**own assumption**
Max. capacity (MWh)	10	
Efficiency	85%	

Thermal Store

	District	Source
Parameter	**Base**	**own assumption**
Volume (m3)	10	
Temperature in top (°C)	90	
Temperature in bottom (°C)	50	

Cold Store

Parameter	Innovation Hub	Source
Volume (m3)	50	**own assumption**
Temperature in top (°C)	10	
Temperature in bottom (°C)	5	

2. Additional Investigations

For Wood additional investigations of individual heating systems as well as of a district sewage network heat recovery system were carried out. Since both analyses were not in the scope of this thesis, the high-level results were presented here in the Appendix. The energyPRO models for both investigations were submitted as well.

Individual systems

For the individual heating supply systems, a combination of PV panels, grid, air source or ground source heat pump as well as thermal store was investigated for each building type of Phase I. Additionally, a configuration with electric boiler instead of a heat pump was analysed. The installed PV capacity per building unit can be seen below and was obtained from the solar assessment of Wood:

- Duplex dwelling: 5 kW
- Terrace dwelling: 6.2 kW
- Enterprise and Innovation Hub: 228 kW

For the heat pumps the same COP and flow temperatures where used as before only the heat capacity of the heat pumps as well as the electricity input was smaller for each building unit. The values can be seen in the following table and were submitted in a separate document within this thesis as well:

individual	ASHP			Source	GSHP			Source
	Duplex	Terrace	Innovation Hub		Duplex	Terrace	Innovation Hub	
Electr. capacity (kW)	0.24	0.24	68	calculated with COP	0.17	0.21	59	calculated with COP
Heat capacity (kW)	0.6	0.6	170	Heat needed to meet demand	0.5	0.6	170	Heat needed to meet demand

For the electric boiler configurations a 100% efficiency rate was assumed. Since the Enterprise and Innovation Hub building was already equipped with cooling technology in Scenario 3 of this thesis, this investigation was not carried out again. Nevertheless, the individual system for the Enterprise and Innovation Hub building including an electric boiler was extended with cooling technology. Since the individual systems investigation was a high-level study, only the KPI results were displayed in the following table rather than the graphical outputs:

Configuration	House type	Renewable Electricity Production (MWh/year)	Imported Electricity from Grid (MWh/year)	Renewable Penetration Factor (%)	Electricity Peak (MW)	Under Grid Limit of 2,000 kVA	Demands
		Key Performance Indicators					
PV + GRID + ASHP + TS	duplex	5.00	1.00	83.33	0.000	yes	Heating Demand Phase I
PV + GRID + ASHP + TS	terrace	6.10	1.00	85.92	0.000	yes	Heating Demand Phase I
PV + GRID + ASHP + TS	innov.	226.10	156.20	59.14	0.068	yes	Heating Demand Phase I
PV + GRID + GSHP + TS	duplex	5.00	0.80	86.21	0.000	yes	Heating Demand Phase I
PV + GRID + GSHP + TS	terrace	6.10	0.80	88.41	0.000	yes	Heating Demand Phase I
PV + GRID + GSHP + TS	innov.	226.10	127.00	64.03	0.059	yes	Heating Demand Phase I
PV + GRID + EB + TS	duplex	5.00	2.40	67.57	0.001	yes	Heating Demand Phase I
PV + GRID + EB + TS	terrace	6.10	2.20	73.49	0.001	yes	Heating Demand Phase I
PV + GRID + EB + TS	innov.	226.00	415.10	35.25	0.160	yes	Heating Demand Phase I
PV + GRID + EB + TS + AC + CS	innov.	226.00	1207.30	15.77	0.200	yes	Heating Demand and Cooling Demand Phase I
PV + GRID + EB + TS + EC + CS	innov.	226.00	874.80	20.53	0.175	yes	Heating Demand and Cooling Demand Phase I

This information can be used in order to decide if a district or individual systems should be installed in the HALO sustainable district. The individual systems have to be installed per building unit that makes an expansion of the heating system more flexible and means less piping installation and transportation losses. However, a district system has a higher convenience factor and is economical beneficial. Since the investigation of the feasibility of individual systems was not in the scope of this thesis, the results above were not further discussed.

Sewage Network Heat Recovery

Besides the individual systems, also a Sewage Network Heat Recovery System (SNHR) was investigated. The three configurations below were briefly assessed in order to find out if they could meet the heat demand of Phase I:

- SNHR + TS
- PV + ASHP + SNHR + TS
- PV + GSHP + SNHR + TS

The constant heat supply by the SNHR, that was 41.7 kW, was obtained from a colleague who worked on the same project and focused the heating side in more detail.

The energyPRO models for this investigation were submitted as well. As a result, all three configurations could not meet the heat demand since the PV panels did not supply enough electricity for the heat pump. The heat supply through the SNHR was also not sufficient enough. Therefore, a grid connection was inserted to review the results with this additional electricity supply. With the incorporated grid the heating demand could be met easily. As said before, the detailed results can be seen in the submitted energyPRO models and were not further displayed and discussed here since they were not part of this master thesis.