Carl von Ossietzky Universität Oldenburg

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Master's Thesis

Title:

Exergy as assessment criterion for multimodal supply concepts in a model residential area for future energy supply

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Contents

Abstract

With the increasing thrive on cutting off Greenhouse Gas (GHG), it has become a necessity of our times to implement energy-saving options that focus on rational and efficient energy use in the building sector, as this sector is responsible for around 40% of final energy use. Exergy analysis is a proven methodology to analyze and reduce the energy gap between the energy supply and actual energy use for a growing complex energy demand scenario. The best configuration between the supply options and demand is obtained through the demonstration of thermodynamic efficiency.

In the thesis, different technologies utilizing various quality energy sources are made available in order to fulfill the electric and thermal demands of a community. Quasi- steady energy and exergy flows with hourly timesteps are generated based on two optimization criteria: price minimization and constant weight. These two optimization criteria selects the technology from a pool of different options to generate energy and exergy flow. The energy and exergy flows thus generated, are analyzed based on preferences and share of each technology, quality factor, duration of operation of individual technology, and use of storage.

The network with a high-quality supply mix did not produce a difference in both energy and exergy scenarios. However, with the addition of low exergy sources like SC and heat pump (HP), a significant difference in the preference of technology is observed. Among different configuration of technologies, examined in the study, the network with HP and SC optimized for exergy minimization proved to be the most exergy efficient network with the minimum gap between supply and demand. In the exergy scenario with around 2 mega watt hour (MWh) of space heating (SH) and domestic hot water (DHW) demand, the configuration generated based on exergy minimization uses 40 MWh of supply options, which is almost half of the consumption of a configuration, optimized based on energy, and 4 to 5 times less than for a configuration price based on price.

Dedication

I dedicate my thesis to my family and friends. I am always grateful to my parents, Tulasa and Narayan, for their words of encouragement to push my limits. My two sisters, Bandana and Sambriddhi have never failed me with their humor to cheer me up. I also dedicate this work to all my friends who consistently supported me throughout the journey. Without you all, the process would not have been joyful.

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Acronym

BMU Bundesministerium für Unwelt, Naturschutz und nukleare Sicherheit

CHP Combined heat and power

CO_2 carbon-dioxide

COP coefficient of performance

cpf carnot performance factor

DH district heating

DwD Deutscher Wetterdienst

DLR Deutsche Zentrum für Luft and Raumfahrt

DHW domestic hot water

ENaQ Energetisches Nachbarschaftsquartier

EST Energy System Technology

EU European Union

GHG Greenhouse Gas

HP heat pump

kW kilowatt

kWh kilo-watt hour

MWh mega watt hour

oemof open energy system modelling framework

RE renewable neergy

SC solar collector

SH space heating

TESPy Thermal engineering system in python

Chapter 1

Introduction

1.1 Background and motivation

In the European Union (EU), the building sector is a significant contributor to GHG emissions, with 36% of carbon-dioxide (CO_2) emissions and 40% of total energy consumption [1]. Nevertheless, the building sector also has the highest emission reduction potential [2]. The study conducted by the Bundesministerium für Unwelt, Naturschutz und nukleare Sicherheit (BMU) presents the reduction target of 67% by 2018 compared to the year 1990 [2]. This action shows the country's urge to move towards complete decarbonization. BMU also presents three ways of curbing the reduction target within its Climate Action Plan 2050: establishing new building standards, phasing out the fuel-based heating systems, and increasing the share of renewable neergy (RE). Typically, a heating system within the building exhausts 90% of energy consumption. As a result, more than one-third of the final energy consumption worldwide is consumed just for heating and cooling of building infrastructures [3]. The preferred way is still the combustion of fossil fuels and natural gas. This explains the reason behind the higher share in emissions. However, with time, the share of RE in the electrical system has been increased to mitigate the effect of emissions. But still, larger potential areas in the heating sector of building clusters are yet to be tapped.

A community is a neighborhood of a larger group of buildings with different energy demands, for instance, heating, lighting, and electricity. There are also many possible ways to fulfill these energy demands by utilizing different energy sources. With today's national and international agreements like the Paris Agreement, to limit global warming to a maximum rise in temperature of 1.5°C compared to the pre-industrial level [4], it is probable that RE share will increase. The volatile nature of RE will lead to periods of excess energy besides deficient production. In this context, sector coupling strategies can be an efficient management tool. Sector coupling in a local community supply system allows integration of distributed generation and consumption, which in turn helps to minimize energy losses and also reduces the stress on the energy supply infrastructure [5]. However, several interactions between supply and demand make future energy supply options a challenge [6]. The common way of dealing with this complexity is energy system analysis, where each system is designed with proper sizing, and losses are identified through energy balance. The maximum exploitation of a thermodynamic potential of energy flow, however, cannot be addressed on the mere ground of energy assessment. Energy demands on the heat, electricity, and mobility sectors are of very different thermodynamic quality. Exergy analysis assesses the quality of energy besides the quantity of energy flow. It represents that part of the energy, which can actually be transformed into other forms of energy [7]. Thereby, a deeper insight can be obtained regarding the path for meaningful and efficient energy use, which leads to optimum use of the different available resources for the existing demands [5]. In the sector coupling contexts, where different qualities in the demand and supply exist, exergy analysis can better describe the performance of low-temperature technologies such as district heat, low temperature solar thermal systems, heat pumps, and different boilers [7].

1.2 Problem statement

In every form of energy use, the measures for increasing efficiency have become a fundamental obligation as it is one of the drivers for the reduction in GHG emissions [8]. With the conventional method of an energy assessment, which focuses on reducing primary energy demand, the difference in efficiency improvement is marginal as compared to exergy assessment [9]. The quality of energy, termed as exergy, is obtained by combining the first and second laws of thermodynamics. Different studies have presented the areas and quantity of exergy losses during each step, from generation to consumption, inside the buildings. However, the optimization of supply options for communities, based on different energy demands, has not been widespread.

Communities are considered as a prime area for energy savings because there is a huge mismatch between demand and supply, especially when high exergy sources are used to fulfill low exergy requirements. Let us consider a building cluster where the energy demand comprises heating and cooling, operation of household electric appliances, and lightings. Heating requirements are generally for SH and the purpose of DHW. The temperature ranges from 25°C - 30°C to 50 °C - 55 °C for SH and DHW, respectively. The lower the temperature for thermal supply, lower is its potential to obtain a portion of work from its energy conversion, known as quality factor[10]. Therefore, the quality levels at the demand side for heating requirements are relatively low (q = 0.07), whereas electric appliances and lightings require high energy qualities(q = 1) [7]. Now, it is quite evident that energy demands are at different temperature levels. But the existing supply options are still primitive. The supply options are either electricity or fossil fuels for both high and low exergy applications.

For instance, the combustion of fossil fuel generates a flame to heat up to 1500°C. The exergy obtained from this fuel is almost completely wasted if these fuels are used for space heating or domestic hot water requirement [8, 7]. Due to this reason, gas boilers, which are highly energy-efficient, will have very low exergetic efficiency as a huge part of the exergy supply will be destroyed due to the inherent irreversibility of energy conversion. The gap has been identified for a long time, but the issue has not been addressed properly, particularly in the community infrastructure. Therefore, this thesis work is driven to encourage efficient quality and quantity use of resources highlighting the importance of moving towards low-exergy technologies, the use of renewable and low-temperature heat sources in accordance with the actual exergy requirements for supply mode.

1.3 Objective and driving questions

The main goal of the master thesis is to develop and implement a method of analysis based on exergy performance, that could be used for energy system of Energetisches Nachbarschaftsquartier (ENaQ) neighbourhood. For this, an existing algorithm for steady-state assessment of the exergy flows within the energy system is used as a starting point. The algorithm is further developed to include dynamic analysis of all relevant exergy flows in a suitable level of accuracy.

In the process of achieving the main goal of the master thesis, the following questions shall be answered:

- What are meaningful, simplified approaches for dynamic exergy assessment to achieve reasonable accuracy and minimize the required input data?
- What are the differences between energy and exergy optimized system configurations? What variables lead to such different conclusions?
- Which technology combinations lead to minimizing exergy losses in the whole energy system? How are they influenced by the share of thermal energy demands in the system?

The result from exergy assessment shall be well represented for visualizing the main insight from dynamic exergy analysis.

1.4 Organization of thesis

The current chapter introduction starts with an overview of the context of the thesis topic and leads to a section explaining the need and motivation for this analysis. The main goal of the thesis is explained in a later section with some guiding questions which shall be answered during the process of finding the optimum configuration of supply options.

The second chapter is basically a combination of theory and literature review which explains the fundamentals of exergy, description of exergy analysis and its link to the community energy system and ends with the approaches followed for the present study.

Methodology is the third chapter, which has three main sections. In the first section, the layout based on which the design of the modeling is based is explained. It is followed by the section with mathematical equations representing different energy and exergy flow. The last section deals with descriptions of two simulation environments, TESPy and oemof, where parameterization of individual supply options and its networks are explained.

The developed models with the afore-mentioned methodologies are tested in the validation chapter, and some verified results are depicted in basic charts.

The outcomes of tested simulation environments are presented in the results sections. Some peculiar and some indistinguishable trends are discussed later in the discussion section. The optimum configuration based on exergy is then presented in a visual way.

The last two chapters are conclusions and outlook of the present study. Based on the results of simulations, conclusions are derived, and the future perspective of the conducted research is presented briefly in the outlook section.

Chapter 2

Fundamentals of exergy analysis

2.1 Fundamentals of thermodynamics

According to the first law of thermodynamics, energy can be converted from one form to another in both reversible directions with the interaction of heat, work, and internal energy. However, it cannot be created or destroyed. It can be represented mathematically as

$$\Delta U = q + w \tag{2.1}$$

Where ΔU is the total change in internal energy of a system, q is the heat exchanged between the system and its surroundings and w is the work done by or on the system [11].

Let us consider a reversible process of heating a room by an electric heater. According to the first law of thermodynamics, the amount of electric energy supplied by an electric heater is equal to the amount of heat transferred into the room. However, if we reverse the process, it is by no means possible that the heat supplied to a heater would generate an equivalent amount of electric energy. However, this action does not violate the first law of thermodynamics. More information is needed to explain the direction of a process and to predict its possibility of occurrence in a process.

With the application of second law of thermodynamics, a better understanding of a process can be extracted. It states that for every thermodynamic system in equilibrium there is an extensive scalar property called entropy S. The change in entropy dS is equal to heat transfer dQ by the absolute temperature T [12],

$$dS \geq dQ/T \tag{2.2}$$

For an irreversible physical process, the combined entropy of a system and the environment will always increase over time, and the change in entropy in the universe can never be negative [11]. In the same example above, after the energy transformation into heat, it can never wholly be brought back to electricity as this would reduce the entropy of the system in defiance of the second law of thermodynamics. Therefore, it can be inferred that there is a natural tendency of an isolated system to degenerate into a more disordered state [13]. After every energy conversion, the quantity of energy remains the same, just the quality or it's potential for work decreases.

2.1.1 Definition of exergy

When a system and it's surroundings are not in equilibrium with each other, the pressure and temperature gradient between them can be utilized to perform mechanical work. In that perspective, exergy is the available energy. In the words of Szargut, "Exergy is the amount of work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings through reversible processes, involving interaction only with the above-mentioned components of nature." However, with every single irreversible process, its usefulness is reduced. The reduction is termed as 'exergy destruction' which is the primary cause of increased energy consumption of any process involved [14]. Therefore, exergy is a thermodynamic property that is a function of both physical properties of a resource and its surroundings [15].

In the real scenario, due to irreversible processes, the energy content remains the same, and what changes is the amount of exergy i.e,.it decreases as the quality of energy decreases with the further transformation of energy [16]. Therefore, it is also termed as a measure of usefulness or quality of an energy flow [17]. This is the main difference between the energy and exergy as the former one is always conserved, whereas the latter one is consumed during the ideal process [18].

2.1.2 Definition of the reference environment

In the section above, the term 'exergy' is perceived as a dependent variable. Hence, the definition of a reference environment significantly impacts the results for an exergy analysis. In principle, the thermodynamic reference environment should be the large compressible system capable of absorbing all the generated entropy generated during energy conversion[19]. This idealized reference environment should be characterized by a perfect state of equilibrium,i.e., intensive properties must not change as a result of the energy and mass transfer [20].

Several definitions of reference environment are found in the literature for exergy analysis. Most authors take outdoor air as their reference environment [3, 7] and for the exergy analysis involving thermal energy flows inside the buildings, the indoor condition is taken as a reference environment [21]. For the studies presented here, the outdoor environment of Oldenburg is taken as reference as the ambient air does carry heat and is readily available in abundance. The measured values of ambient temperature and the total horizontal irradiance from Deutscher Wetterdienst (DwD) weather station form the base of undertaken exergy analysis calculations.

2.1.3 Relevant exergy flows for the thesis

Exergy is fundamentally divided into exergy associated with the transfer of energy, mass transfer, and exergy associated with the closed system [22]. However, the undertaken study is based solely on energy and mass transfer. Exergy due to mass transfer is further divided into kinetic exergy, potential exergy, chemical exergy, and physical exergy. Kinetic and potential exergy can be defined by its kinetic and potential energies in relation to the environment, while chemical exergy is the maximum work that can be obtained from the substance by taking it to chemical equilibrium with the reference environment at constant temperature and pressure [23, 15]. Physical exergy is defined as the amount of work required to bring a substance from its generic state to a state of thermal and mechanical equilibrium with the environment [24]. That signifies physical exergy is subdivided into mechanical exergy. which is associated with the system pressure, and thermal exergy associated with the system temperature [14]. Nevertheless, the overall analysis of this study is based only on thermal exergy.

Thermal exergy

Thermal energy is a function of the difference in temperature between the flow under consideration between the reference environment and the system. Under steady-state conditions, the exergy of a heat transfer between temperature levels T and T_o, is the maximum work that can be achieved from a Carnot cycle, which is depicted in Fig. 1.

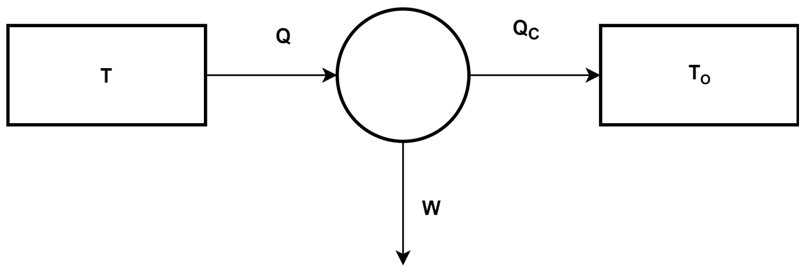


Figure 1: Carnot engine diagram where Q flows from the high temperature T to cold sink T_O

$$X_Q = Q \times \underbrace{\left(1 - \frac{T_o}{T}\right)}_{\text{Carnot factor}} \tag{2.3}$$

Where T_o is an ambient temperature, T is the temperature of heat source, and Q is the amount of heat.

The Carnot factor often termed as a *quality factor* is only valid for analyzing exergy transfer for an isothermal heat transfer both below and above the reference temperature T_o[3]. In a case where the temperature of system varies throughout heat transfer, the exergy is termed as 'exergy of matter' [22]. The quality factor then will be expressed, as shown in the equation.

$$F_q = 1 - \frac{T_o}{T_i - T_f} \cdot \ln \frac{T_i}{T_f} \tag{2.4}$$

Where T_i is an initial temperature, and T_f is a final temperature.

2.1.4 Sign conventions and notation

The 'Positive in' sign convention is used throughout the undertaken study. In this sign convention, the exergy input, heat transfer into the system, and any work input is considered as positive.

$$X_W = W \tag{2.5}$$

Let us observe Fig. 2 recalling the Equation 2.3.

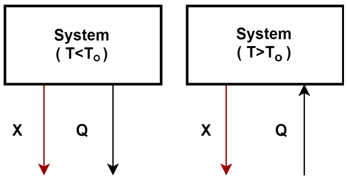


Figure 2: Direction of heat flow and exergy flow

When the system temperature T > T_o the reference temperature , value of the Carnot factor becomes positive. However, the heat flows from a system towards the environment resulting in its negative value. So, the exergy flow becomes negative. Similarly, when T < T_o, value of the carnot factor becomes negative while the heat flows from the environment towards the system. Hence ,it has a positive value. As a result, the exergy value is negative.

2.2 Exergy analysis

The process occurring in everyday life are irreversible due to friction, mixing of matters at different composition, heat transfer through a finite temperature difference. and chemical reactions to mention a few [25]. In this context, exergy analysis is an effective method for the assessment of an energy conversion system based on exergy concepts, balances, and efficiency [20]. It identifies the locations, causes, and sources of deviation from the theoretical limit of a system. It has been widely used for optimization of power plants as it evaluates the thermodynamic values of the products in a complex system like trigeneration plants with multiple products [17]. Also, the benefits of exergy analysis in residential areas, building, and district heating optimization have been acknowledged widely as it opens up room for further insight and improvement within this field [26].

Exergy analysis for better utilization of resources

The exergy concept for residential area aims to improve the quality match between the supply and demand [27]. In most cases, high quality energy sources are used to satisfy low temperature demands with low exergy needs.

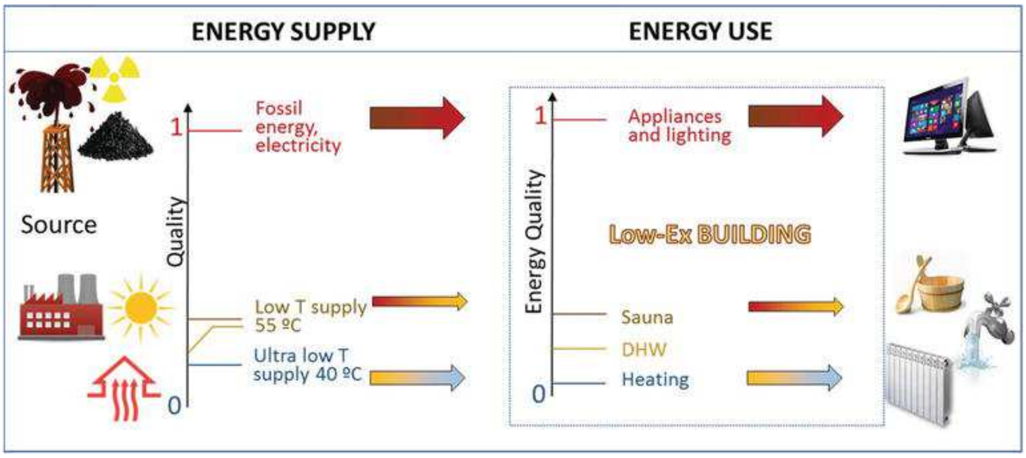


Figure 3: Left: Energy supply through the high quality energy source Right: Fulfilment of same energy demand through different energy quality sources [28]

Fig. 3 shows the contrast between the use of energy sources with varying qualities. With a low-temperature heating system and renewable energy sources, the efficient utilization of energy sources could be visualized, resulting in the substantial reduction of both fossil and renewable primary energy demand of residential complex [29, 8]. There are varieties of solutions available now to provide low-temperature levels for heating, which is termed as 'low-exergy' technologies. Thus, it is possible to examine the suitability of different energy systems for the supply of demand through exergy analysis [30].

Exergy analysis for optimization of cost and CO_2 emissions

Exergy based performance indicators give meaningful representation in terms of resource use and guide towards process improvement [31]. But there are other criteria such as costs, emissions, and environmental implications that can be linked with exergy analysis but are not inherently connected [32]. The utilization of waste heat from industry to supply heating demand in the vicinity is an example of eliminating CO_2 emissions through boilers from every buildings [33]. However, we must admit the fact that the waste heat source is not an aspect of exergy analysis itself. Instead it explains how supply integrates with district heating, and detailed examination requires expansion of reference boundaries [32]. Similarly, exergy analysis can be utilized to compare different approaches if the cost constraints are considered. For example, exergy analysis can give a comparison between using thicker insulation in operating a passive house to using an efficient heat pump connected to a lower temperature radiant heating system, which may also result in the same primary energy input[32]. Therefore, exergy analysis can be utilized for different objectives. Thus, it is necessary to fix the system boundary and approaches for each undertaken study.

2.2.1 Approach for exergy analysis

Steady-state

Any system or process is said to be in a steady state when the variables defining that system or process do not change with time. If we consider $\vec{p}$ as system properties, the partial derivative with respect to time is zero.

$$\frac{\partial \vec{p}}{\partial t} = 0 \tag{2.6}$$

for all values of t [34].

In other words, it is a circumstance in which there is no accumulation of mass or energy within a control volume. Therefore, the steady state approach for exergy analysis would consider the difference between the exergy input and and exergy output as the summation of exergy consumed and exergy stored as depicted in Equation 2.7.

$$X_{consumed,steady} = X_{in} - X_{out} \tag{2.7}$$

Dynamic state

In a dynamic state, the state variables are changing with time. In converse to a steady-state, dynamic state takes into account accumulation of energy and mass within the system. In total, a time-dependent X_{stored} is added in the equation 2.7 for a dynamic state, as shown in Equation 2.8.

$$X_{consumed,dynamic} = X_{in} - X_{out} - X_{stored} \tag{2.8}$$

Quasi steady-state

Quasi steady-state is a hybrid between dynamic and fully steady-state calculation methods. In this approach, the change of state variables is considered over short time steps. However, the storage phenomena are disregarded, assuming that all the input exergy will be exiting in the overall time.

2.3 Exergetic analysis for community energy systems

2.3.1 State of the art

Energy systems are very diverse in a community system as different energy supply chains are interconnected. Further, it requires a large amount of data to predict the typical supply and consumption patterns [30]. Therefore, most of the works are done taking smaller energy systems within the complex network of the community energy system. The study done by [8] presents an exergy assessment for the fulfillment of SH and DHW demand of a small neighborhood in Germany. This low-temperature heat is supplied from waste heat and distributed in houses through a centralized heat exchanger. The exergy analysis is done with both dynamic and steady-state approaches. The exergy efficiency of 40% of the system was achieved with a marginal difference of 2% between the steady and dynamic approach. Similarly, work from [30] aims at usage of exergy analysis for acCO_2 neutrality for municipalities. The study presents the results of exergy analysis of decentralized energy supply if the thermal demand of space heating has to be made. It depicts values of primary exergy if alternative supply options such as district heating (DH) from Combined heat and power (CHP), geothermal, waste heat recovery, and HPs are used. The comparison reveals waste heat from industrial sources as the best-case scenario with primary exergy efficiency of 35%. The least favored option proved to be the district heating from old CHP plants. Furthermore, the study also highlights that the primary exergy utilization is higher when the electricity supply is considered due to its higher energy contents. In addition, the paper [35] presents the exergy scenario for a community if central CHP or boiler in cascade with heat pump is utilized to fulfill the thermal demand i.e., SH and DHW. It contains mainly three cases; first case is represented by separate electricity and heat generation. The second one is using a power plant to cover the thermal demand, and the last one is use of CHP integrating with a boiler. Among all cases, the first case of using heat from power plant though HP for space heating and running boiler to fulfill the DHW is the most exergy efficient from a building point of view. However, the use of CHP with HP shows better exergy performance in the community level. It offers better utilization of excess heat along with the generation of electricity. The paper [36] followed a similar methodology adopted for the thesis. It presented the exergy inputs and outputs through four different technologies, namely SC, geothermal, gas boiler, and a small volume of thermal storage to fulfill annual heat demand. The results shows higher energy input for geothermal and solar collector in comparison to a gas boiler. However, both technologies have lower fossil input and lower exergy input, making it suitable for covering low-temperature heat demand for buildings clusters.

2.3.2 Approach for the thesis

For the undertaken study, following assumptions, simplifications and boundaries were considered:

- ENaQ is a targeted residential area featuring an integrated energy system. However, mobility demand is not considered. Demands series consist of thermal demands for space heating and domestic hot water and hourly electricity demand.
- The outdoor temperature of Oldenburg is taken as a reference environment for exergy measurement.
- Emphasis is given for the fulfillment of thermal demands with different technologies. The utilization of each technology is done through linear power flow optimizer oemof.
- Both steady and quasi-steady approach are used for the assessment.
- Exergy flows are evaluated for a time step of 1 hour.

Chapter 3

Methodology

3.1 Layout of exergy flow

The exergy flow between the supply and demand is modeled, as depicted in Fig. 4. The three rectangular blocks i.e., red, black, and grey represent heat, gas, and electricity buses. Electricity and gas buses get their input from consecutive markets, whereas all the heat-generating units eject their heat output into the heat bus. Among all the heat- generating units, HP works differently. The demand for heat is at 32°C and 40°C, however, we have SC and HP operating at 15°C. This is because HPs are in cascade with each other. Therefore, HP32 takes input from the output of HP15, and HP40 takes its input from HP32. Both HPs deliver their output to their corresponding heat buses. From this heat buses and the electricity bus, the demand of the households is fulfilled. All the technologies used for the transformation are modeled individually with their particular operating parameters based on mathematical models explained in section 3.3. In order to get maximum out of fluctuating heat generated from SCs an idealized buffer is utilized. Unlike other transformers, a buffer has bi-directional flows.
The estimated thermal and electrical demands are the starting point of the configuration. Thermal demands can further be divided into several temperature levels based on applications. In the present study, there are thermal demands at 32°C and 40°C for SH and DHW, respectively. Therefore, all individual technologies are able to produce heat demand at at least two temperature levels. Based on the hourly demand, some technologies are operated. An optimizer decides the share and the operating hour of each technology using different linear cost functions. In the present study, the market price of gas and electricity is used as the first cost function. The other optimization is based on energy and exergy. In this scenario, all the technologies are considered to have the same weight and the utilization of each technology is done for minimizing energy and exergy consumption.

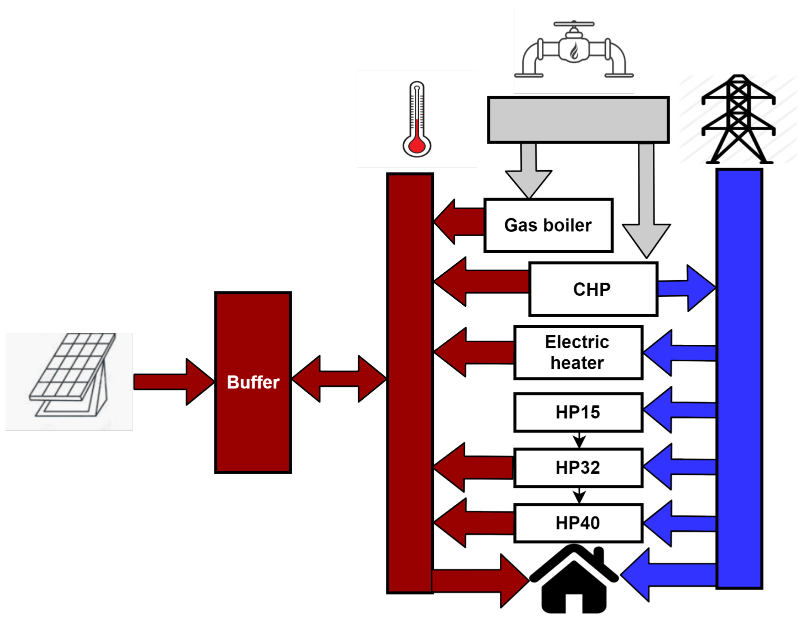


Figure 4: Layout of exergy flow adopted from oemof

3.2 Input-output approach

Exergy analysis on a system level is carried in the input-output approach as depicted in Fig.5 in different studies [37, 3] in order to visualize several subsystems in the supply chain. Though the thesis aims to find the optimum configuration of different supply options for the residential load as a whole, this approach is utilized as a simplification. The distribution component between demand and generation is neglected. However, each supply option is exergetically optimized, and the difference between the input and demand is termed as exergy loss.

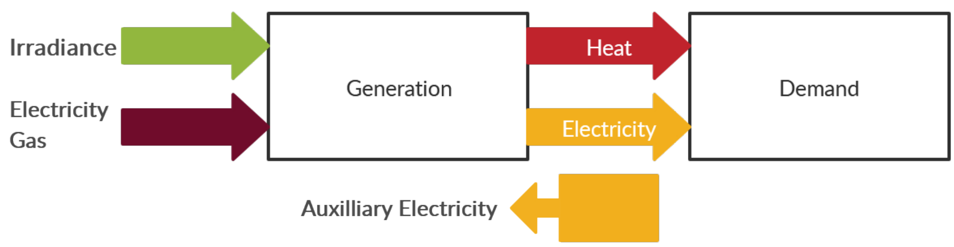


Figure 5: Exergy supply chain for SH, DHW, and electricity from electricity and gas [Design adapted from [3, 8]]

3.3 Mathematical models representing the exergy flow

With an approach for the thesis mentioned in section 3.2, the thermal exergy comprising of SH and DHW demand is represented by mathematical equations in the demand section. Similarly, technologies fulfilling these thermal demands are also expressed in terms of exergy in the supply options in the following subsections. The equations presented are based on [3] for quasi-steady exergy analysis and follow the sign convention mentioned in section 2.1.4.

3.3.1 Demand-side exergy

Exergy demand for DHW Supply

The exergy demand for DHW supply $X_{\text{dem,DHW}}$ shown in equation 3.1 is the function of cumulative DHW demand Q_{DHW}, ambient temperature T_{a}, required supply temperature $T_{\text{sup,DHW}}$ for a time step of t_k which is 1 hour in the undertaken study.

$$X_{\text{dem,DHW}}(t_k) = Q_{\text{DHW}} \times \underbrace{\left[1 - \frac{T_{\text{a}}(t_k)}{T_{\text{sup,DHW}}(t_k)}\right]}_{\text{Fq, DHW}} \tag{3.1}$$

For the present study, T_{a} is hourly values measured for Oldenburg whose trend is presented in the section 3.4.1 and $T_{\text{sup,DHW}}$ is considered as 40°C.

Exergy demand for space heating

With the cumulative heating demand Q_{SH}, the temperature of water entering the radiator as T_{in}, the temperature of water exiting the radiator as T_{out} along with the ambient temperature T_{a} at a time step of t_k, the exergy demand for SH is calculated as shown in the equation 3.2.

$$X_{\text{dem,SH}}(t_k) = Q_{\text{SH}} \times \underbrace{\left[1 - \frac{T_{\text{a}}(t_k)}{(T_{\text{in}}(t_k) - T_{\text{out}}(t_k))} \ln \frac{T_{\text{in}}(t_k)}{T_{\text{out,DHW}}(t_k)}\right]}_{\text{Fq, SH}} \tag{3.2}$$

For the study presented here, the space heating network is assumed to have a return water temperature of 20°C, which is represented as T_{in} and outlet temperature T_{out} of 32°C.

3.3.2 Exergy for supply options

In order to fulfill SH and DHW demand, different supply options are available. On the basis of fuel type, there are technologies operating with electricity, gas, and solar irradiance. For each technology, the later section presents mathematical equations representing the exergy flows.

Electric heater

An electric heater is the other technology that operates with electrical energy. The exergy output ($X_{\text{b,out}}$) is determined by the product of electricity input, which is also an exergy input ($X_{\text{b,in}}$), electric efficiency, and quality factor.

$$X_{\text{b,out}} = El_{\text{in,heater}} \times \eta_{heater} \times F_q \tag{3.3}$$

Quality factor follows the expression shown in Equation. 3.1 and Equation. 3.2 for SH and DHW applications.

Heat Pump

HP is one of the technologies utilizing electricity as input. With the approach adopted for the present study, HP has exergy coming in as input and exergy going out as an output. The input side of HP is an electricity consumption $El_{\mathrm{in,HP}}$, whose quality factor is considered 1. This implies that the value of electricity corresponds to the amount of input exergy ($X_{\mathrm{in,HP}}$). The output from HP denoted by $X_{\mathrm{out,HP}}$, is the function of electricity input $El_{in,HP}$, coefficient of performance (COP), and quality factor(F_q) as shown in Equation. 3.4.

$$X_{\mathrm{out,HP}} = El_{\mathrm{in,HP}} \times COP \times F_q \tag{3.4}$$

The expression of a quality factor depends on the application. HP operating for DHW follows the equation depicted in Equation.3.1, whereas HP running to fulfill SH demand takes Fq as in Equation.3.2. In SH application, the inlet temperature $T_{\mathrm{in,HP}}$ is represented by T_{a} as the heat from the environment is neglected, and ambient air is considered as a source. In the present study, apart from HP for fulfilling SH and DHW demand, there is HP operating at temperature level of 15°C. Nevertheless, it also follows the Equation 3.1 with output temperature of 15°C. COP, which is an essential operating parameter of HP, is a function of temperature at higher and lower ends as shown in the Equation. 3.5. The value obtained from the equation is an ideal COP. Therefore, the value is further divided by a constant factor called carnot performance factor (cpf).

$$COP_{ideal} = \frac{T_{\mathrm{out,HP}}}{T_{\mathrm{out,HP}} - T_{\mathrm{in,HP}}} \tag{3.5}$$

$$COP = \frac{COP_{ideal}}{cpf} \tag{3.6}$$

COP for HP at a temperature level 15°C is the function of ($T_{\mathrm{in,HP}}= T_a$) and ($T_{\mathrm{out,HP}}=$ 15°C). Similarly, COP for HP at 32°C has 32°C and 15°C as its $T_{\mathrm{out,HP}}$ and $T_{\mathrm{in,HP}}$. Lastly, COP for HP at 40°C is a function of 40°C and 32°C as its outlet and inlet temperatures.

Solar collector

SC directly use the energy obtained through incident solar radiation. In many energy sources where efficiency of conversion from solar irradiation into kinetic energy, chemical or heat at the surface is disregarded, the thermal energy output from a collector field at its corresponding temperature is considered as a primary energy source, prevalent and ready to use [3].

The exergy output for meeting its thermal demand mentioned in section 3.3.1 and 3.3.1 depends on the heat generated through the collector and the quality factor for that temperature level, as shown in the Equation.3.7.

$$X_{\mathrm{SC,out}} = Q_{\mathrm{SC}} \times F_q \tag{3.7}$$

Gas boiler

As the name signifies, the input in a boiler is gas. The exergy output ($X_{\mathrm{g,out}}$) is the product of energy content of the fuel, thermal efficiency(η_{boiler}),and quality factor for thermal applications.

$$X_{g,out}(t_k) = Q_g(t_k) \times \eta_{boiler} \times F_q \tag{3.8}$$

Combined heat and power

CHP is an only supply option that contributes to both electrical and thermal exergy demand. The exergy out of CHP is the product of a sum of electrical efficiency $\eta_{\text{el}}$and thermal efficiency η_{th}, an energy content of the fuel, quality factor of an energy carrier, and the quality factor for thermal applications.

$$X_{\text{CHP,out}} = Q_g \times [\eta_{\text{el}} + \eta_{\text{th}} \times F_q] \tag{3.9}$$

3.4 Description of models for simulations

3.4.1 TESPy simulation environment for SC

TESPy is a simulation package for thermal processes. It is an external extension module of oemof, which can also be used independently [38]. It allows designing a plant with essential components such as turbines, pumps, compressors, heat exchangers, pipes, mixers, and splitters [38]. Each component is connected to form a network and each network variables such as temperature, enthalpy, fluid, etc can be explicitly modeled to replicate the original plant behavior assuming the system reached its equilibrium. The SC is one of the components of TESPy which predicts the heat generated through the collector on the basis of irradiance, ambient temperature, mass flow, inlet, and outlet temperatures. The source code is available in Appendix.

Inputs for SC

In order to develop a network to replicate the SC system, some fixed parameters presented in table 1 were used. However, for dynamic simulation, hourly values of ambient temperature and irradiance for a year are used.

Table 1: Fixed input parameters for SC model

Parameters	Values	Units
Temperature of feed water	10	^{0}C
	25	
	30	
Temperature of water out of collector	15	^{0}C
	32	
	40	
Fluid	H_2O	-
lfk line (α_1)	1.17	$\frac{W}{K.m^2}$
lfk quad (α_2)	0.0082	$\frac{W}{K^2.m^2}$
Collector surface area (A)	200	m^2

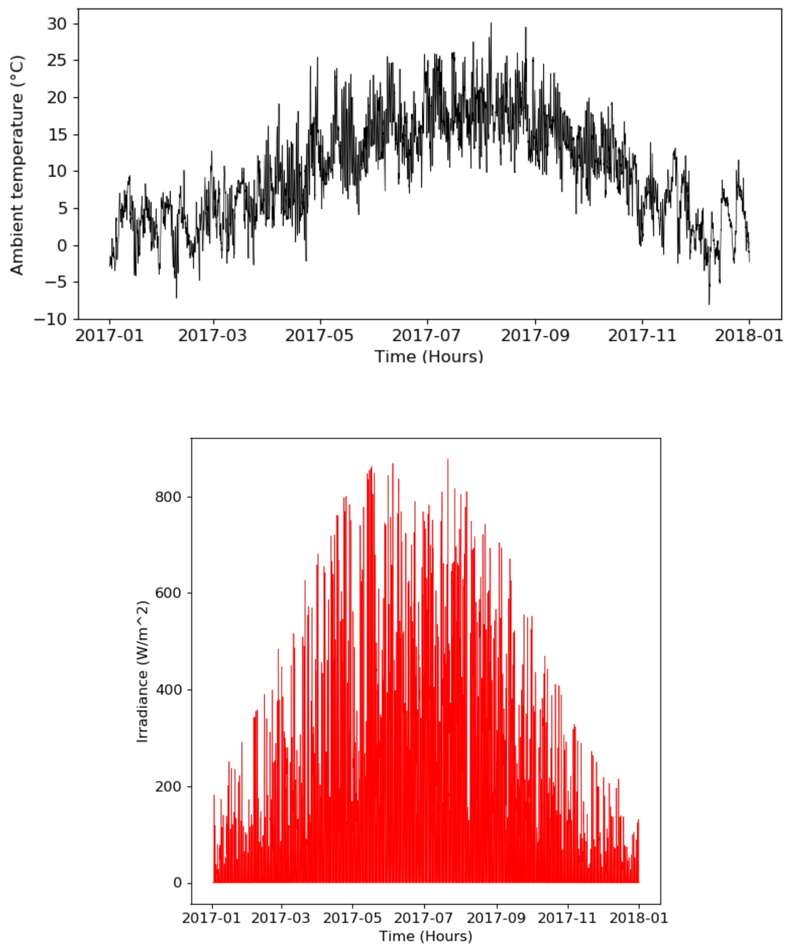


Figure 6: Trend of ambient temperature and irradiance for Oldenburg for the year 2017

3.4.2 Oemof simulation environment

Oemof is an open-source framework that provides a toolbox to construct comprehensive energy system models for high temporal and spatial resolution for energy system modeling, representation, and analysis [39]. Fig 7 is a graphical representation of how an arbitrary energy system is created using the network system [40]. The network consists of nodes and edges. Nodes are subdivided into buses and components. Components are a representation of producers, consumers or processes and buses are the connection in between them. Based on function, components are classified as transformers, sinks, and sources. As shown in Fig. 7, transformers have inputs and outputs, sinks have only inputs and sources have only outputs.

For the study presented here, electric and thermal demands are sinks, whereas electricity, gas, and heat from the environment are sources. Since the thermal demands have different temperature level, two buses for thermal demands b_{th32} and b_{th40} and one bus b_{th15} to accommodate output from SC is created. Above mentioned buses are utilized by several transformers, namely electric heater, gas boiler, SC, HP, and CHP to fulfill the demand at its sink. The source code for final network is attached in the Appendix. The operational parameters for each transformer are described in the section below.

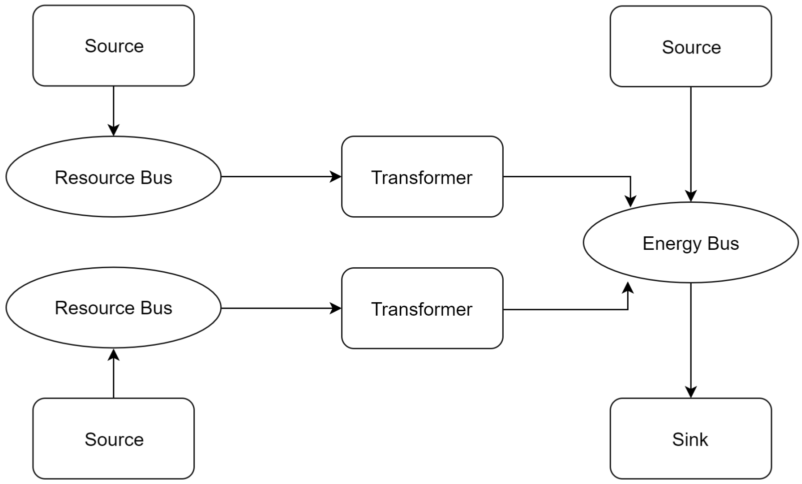


Figure 7: Schematic diagram of an energy system in an oemof network

Simplification in oemof environment

- The trend of ambient temperature from Fig. 6 shows that the value of temperature varies from -5°C to almost 30°C in summer. At the same time, it is also known from the Eq. 2.3 that the quality factor is the function of ambient temperature and the final output temperature for thermal applications. During the summer days, the temperature of ambient is higher than the output temperature for the temperature level of 15°C. This results in the negative values of exergy flows. This result could not be accommodated with the present methodology used to create an energy system within oemof as flows in oemof have to be in positive [40]. Therefore, the optimization was simulated for winter and autumn months.
- The generic buffer used as one of the components in the energy system is an idealized case of storage. No parameters to represent the thermal losses are included. Hence, the preference of utilization of buffer throughout the simulation is highly possible.
- The heat energy generated through the SC for a reference environment Oldenburg is scaled to a hundred times as the main aim of the study is to observe the preference of technologies from a pool in various optimization schemes. Therefore, the vast area of SC resulted due to upscaling of heat generated is considered as a realistic option.

Parameterization of individual components

All the components are modeled to fulfill SH demand which corresponds to 80% of aggregate thermal demand at 32°C and remaining DHW demand at 40°C. Besides, community energy supply also has electric demand which most of the time is fulfilled either by direct electricity purchase from the market or some percentage through electricity from CHP. The flows between the inputs and outputs are expressed both in terms of energy and exergy. The conversion from energy flow to exergy flow is done by using a quality factor explained in section 3.3 for both supply and demand options is used.

Electric heater

To create a network with electric heater as a transformer, the electricity market(m_{el}) is taken as a source which provides the required electricity for transformers into the electric bus(b_{el}) as output. Quantity of electricity brought from the market to the electric bus is governed by 'cost-function' and the demand of electricity. In the undertaken study, three cost functions are being used. For example: if we consider price as one of the cost functions, a summation of electricity price from the day ahead market with consumer fees for utilizing electricity defines the quantity of electricity purchase. The quantity of heat generated by heater is then in accordance with the heat demand for two temperature levels for SH and DHW. For the present study, the electric heater is considered 100% efficient, and quality factor is introduced for its thermal output in order to generate an exergy flow.

Gas boiler

The setup for a gas boiler is similar to the electric heater. However, the significant difference is the use of gas as input. The gas is purchased from a gas market(m_{gas}) and fed into the gas bus(b_{gas}). Likewise for electricity, the unit cost of gas with consumer fees for gas utilization is used as one of the cost function defining the gas input into the gas bus. For the study, the higher heating value of gas, which corresponds to 1.11 is taken according to EnEV/ DIN V 18599 standards. This corresponds to a boiler efficiency of 0.9 and the quality factor for temperature levels 40°C and 32°C are considered for energy and exergy flows.

Solar collector

The employment of SC is different from other transformation technologies. It is a heat source without any inputs. The time series of generated heat from the collectors at three temperature levels 15°C, 32°C, and 40°C obtained from the TESPy environment is utilized for hourly contribution to fulfill SH and DHW demand. For an optimization based on the price of fuel utilized, the heat generated from SC is considered abundantly prevalent and free to use.

HP

Heat generation from HP is influenced by COP and cpf. As mentioned in section 3.5, COP is the function of inlet and outlet temperature. Therefore, three COP values for each of the
acHPs operating at 15°C, 32°C, and 40°C are considered. But this COP is calculated based on maximum theoretical efficiency. Therefore, a constant value of Carnot performance factor(cpf = 0.23) is introduced for each temperature levels. Since HP15 is function of ambient temperature, the values of COP vary from 4 to 12 whereas HP32 and HP40 have a constant COP of 4.13 and 9, respectively. For the thermal exergy component, quality factor according to the application is used.

CHP

Gas-fired CHP takes its input from b_{gas} earlier like gas boiler. Since the main aim is to cover the thermal demand, higher thermal efficiency of 0.55, and an electrical efficiency of 0.32 is considered. The outputs are delivered to b_{el} and b_{th} buses as electricity and heat respectively.

Buffer

The simplest form of storage with ample capacity is incorporated while establishing a network. Three individual buffers buf_{15}, buf_{32}, and buf_{40}) are idealized storage without thermal losses and have bidirectional flow. Therefore, they take input from corresponding thermal buses b_{th15} ,b_{th32},

b_{th40} and return its output in each respective buses. Each of the buffers have a storage capacity of 1 MWh for energy flows whereas, in terms of exergy, the capacity is the product of 1 MWh with its corresponding quality factors.

Parameterization for imports and exports

For the operation of transformers, two main markets, namely market for gas and market for electricity are established as sources of imports. Similarly, a sink for electricity export is also introduced in order to sell electricity generated out of CHP during its operation. For both nodes, the value of variable cost is an essential parameter for the purchase of either gas or electricity. For the optimization in terms of price, a fixed price of 35 euros per MWh of gas and the day ahead price of electricity for a year is considered for both import and export. However, all the fuels are considered of same weight while optimizing in terms of energy and exergy minimization.

Networks with different combinations of technologies

To achieve the final configuration of technologies based on exergy performance, three different networks are created. The first network is the most straightforward simplest energy system with two transformers, namely electric heater and gas boiler, both operating with high-quality fuel. The second network is a use of SC, HP and a buffer system. The last configuration includes all the technologies mentioned in the section 3.4.2. The detail layout and connections are explained in the coming sections. All the networks are simulated with two optimization scheme i.e., optimization in terms of price of fuel, optimization based on equal weight for all kinds of fuel input. The first two networks give the contrast between the use of high-quality fuel to low-temperature technologies. However, primary analysis and discussions are based on the last configuration with a combination of all the technologies.

Electric heater and gas boiler network

The most straightforward network with two transformers, electric heater and gas boilers utilizes high-quality fuel(Fq=1). Electric heater extracts power through the electric bus b_{el}, and the gas boiler takes its input through gas bus b_{gas}. Both of the transformers feed their output to thermal bus b_{th}, which is then connected to demand d_{th}.

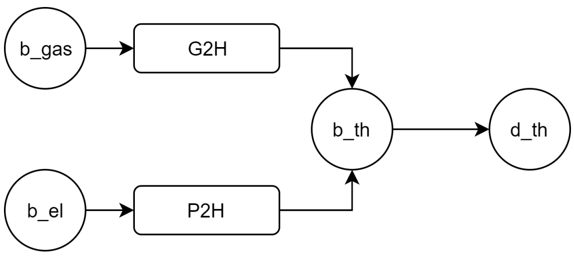


Figure 8: Oemof network with electric heater and gas boiler

SH with buffer and HP network

It is a network created from all low-temperature transformers, as shown in Fig. 9. There are three thermal buses b_{th15}, b_{th32}, and b_{th40} for three temperature levels. Each bus is connected with three technologies i.e., SC, HP, and buffer. HP operating at all three temperature levels are connected in cascade while SC contributes to its respective thermal buses individually. However, buffers are able to contribute and consume from their respective thermal buses. Demand for heat at 32°C for SH is fulfilled through d_{th32}. For higher temperature demand for DHW is met through d_{th40} after one more operation through HP40.In a case of a higher availability of 40°C heat, cooling with mixing can be done to fulfill the demand of 32°C. In the present study, the majority of demand is at 32°C temperature level.

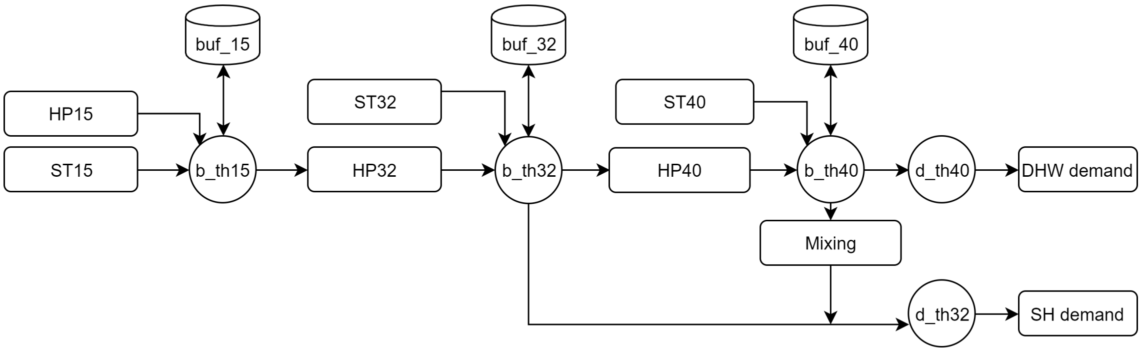


Figure 9: Oemof network with collector, buffer and HP

Combination of a SC with buffer, HP, CHP, electric heater, and gas boilers

The complete network consists of an electric heater, gas boiler, HP, CHP and SC with buffers as supply options. Electric boilers and HPs draw electricity from the electric bus b_{el} coming from the electricity market m_{el}. Similarly, gas boiler and CHP draw gas from gas bus b_{gas} originating from the gas market m_{gas} whereas SC is the only source with an output flow. All the transformers generate heat demand at two temperature levels 32°C and 40°C for SH and DHW. As mentioned in section 3.4.2, HPs are in cascade with three temperature levels. Similarly, three temperature level SCs are also connected with their respective thermal buses. CHP injects thermal output in two temperature levels thermal bus, and electric output is fed to the electric bus. The network topology is presented in the Fig.10

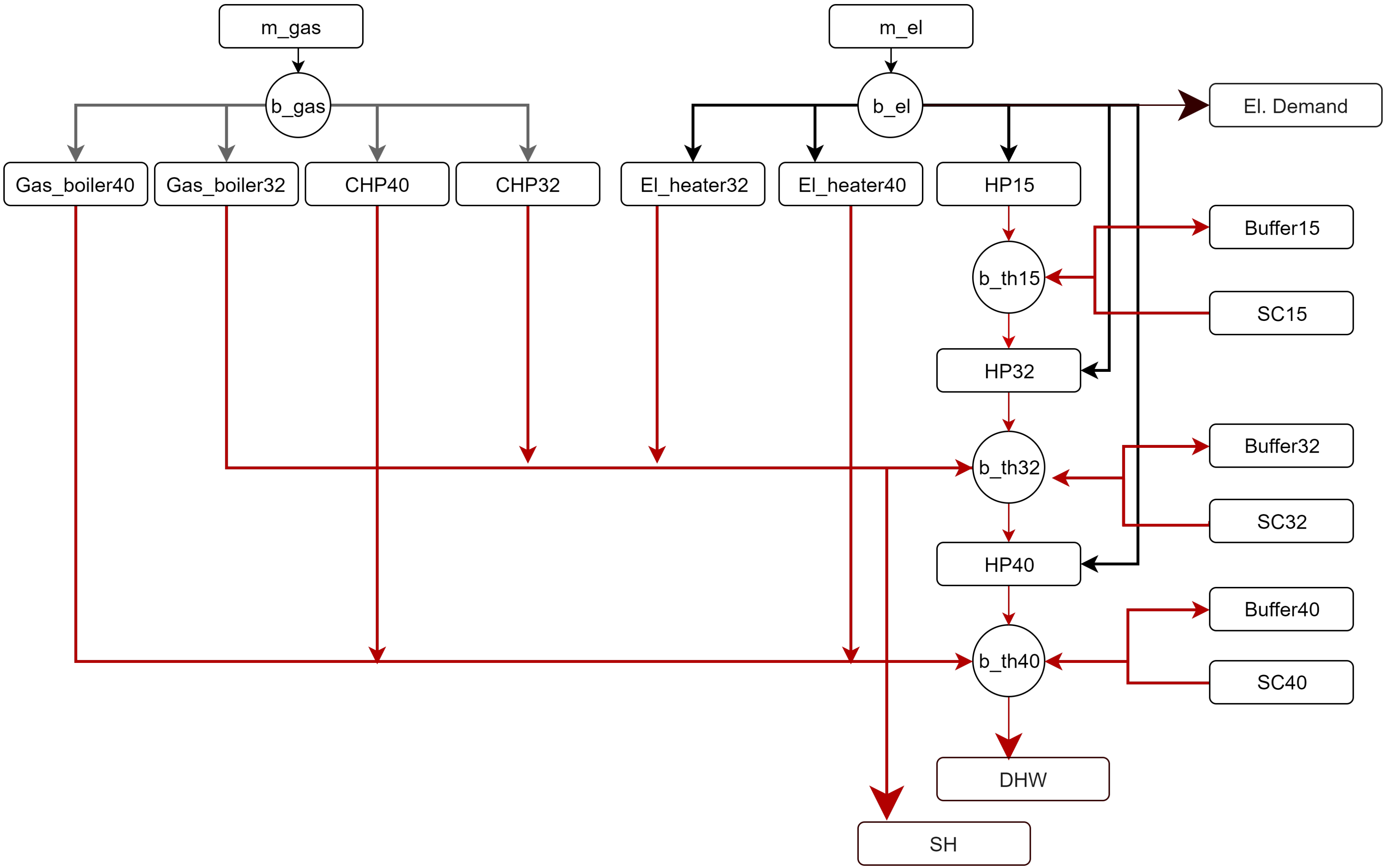


Figure 10: Network with different supply options

Chapter 4

Validation of model

Before discussing the implication of results, the model shall be verified. The use of different transformers for the establishment of a network with different parameterization mentioned in section 3.4.2 needs to be realistic and should depict the usual trend. Therefore, as a first step, a network with electric heater and CHP is analysed within a short duration of a week for both energy and exergy flow. First, both the technologies are represented by energy and exergy flow as supply options and secondly exergy and energy flow for fulfilling its thermal demand. After the evaluation of dynamic flows for a short period, the final network is analyzed. For the purpose, a Sankey diagram is created, representing the overall energy balance for the whole duration of a simulation. Then three of the main transformers which was operated are cross-checked for its operating parameters. As mentioned in section 3.4.2, electricity and gas are high exergy sources. The quality factors for both the sources are almost 1. If we simulate an exergy flow generated from fuel input to the transformers, it has to match the energy flow. Fig. 11 presents the same pattern. The indices (el, in) and (gas, in) represents the electricity and gas sent into the electric heater and CHP, respectively. The methodology adopted to generate exergy flow based on a quality conversion from energy function is accurate.

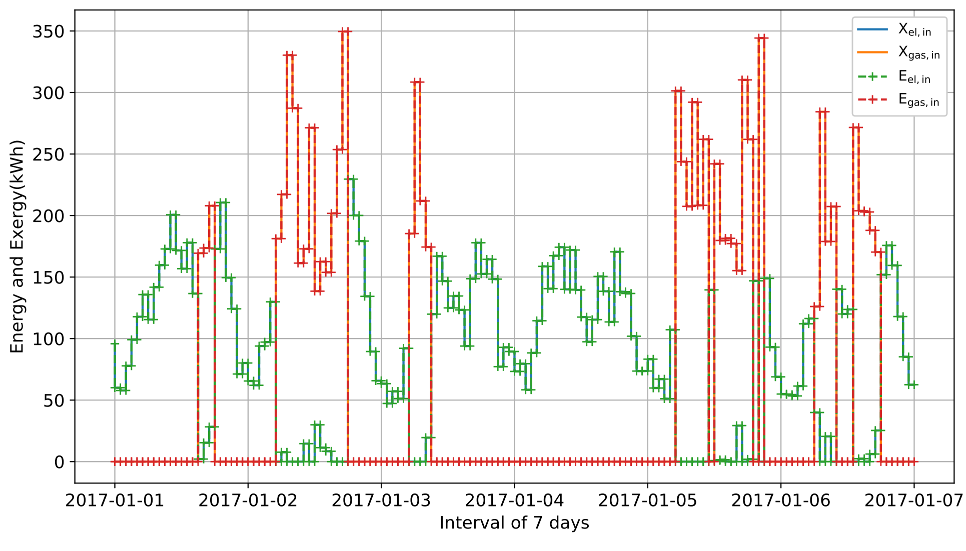


Figure 11: Input energy and exergy flows from two supply options

Furthermore, the same network is analyzed from the demand perspective. The transformers are utilized to provide the heating demand of an ENaQ community. Unlike fossil fuel and electricity, heat at a temperature of 40°C has a lower quality factor. Therefore, the expected energy and exergy flows should follow the a similar trend, but values should be different with some weight factor that depends on the ambient temperature. While observing Fig.12, it is quite evident that the exergy values represent approximate 10% - 12% of energy flows. This weight factor is relevant considering the ambient temperature range in this interval of 7 days.

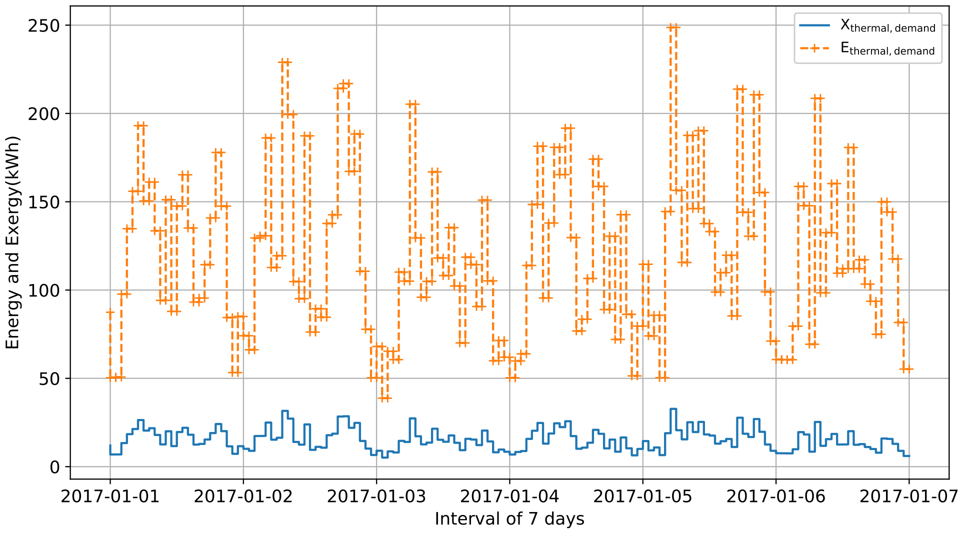


Figure 12: Output heat flows in terms of energy and exergy from two supply options

With the above-mentioned trends, it points out to the proper functioning of transformers in a short interval of one week. However, to observe the energy balance of the whole scenario, a Sankey diagram, as shown in Fig. 13, is created. The figure indicates a well balanced energy network. Out of this network, two main energy transformers, namely HP and CHP for all temperature levels, are crossed checked for its operating parameter based on of its input and output flows. HP15 is the only transformer that is directly influenced by the ambient temperature. Therefore, the measured values of COP is compared against the generated values of COP from the energy flows. Fig. 14 shows a match of 98% . Similarly, COPs for HP32 and HP40 generated through the results of energy flow matches with the input value of 4.13 and 9, respectively. Likewise, the values of thermal and electrical efficiency are very close to the input values of 55% and 32%. All the positive values of cross verification validate the accuracy of the model.

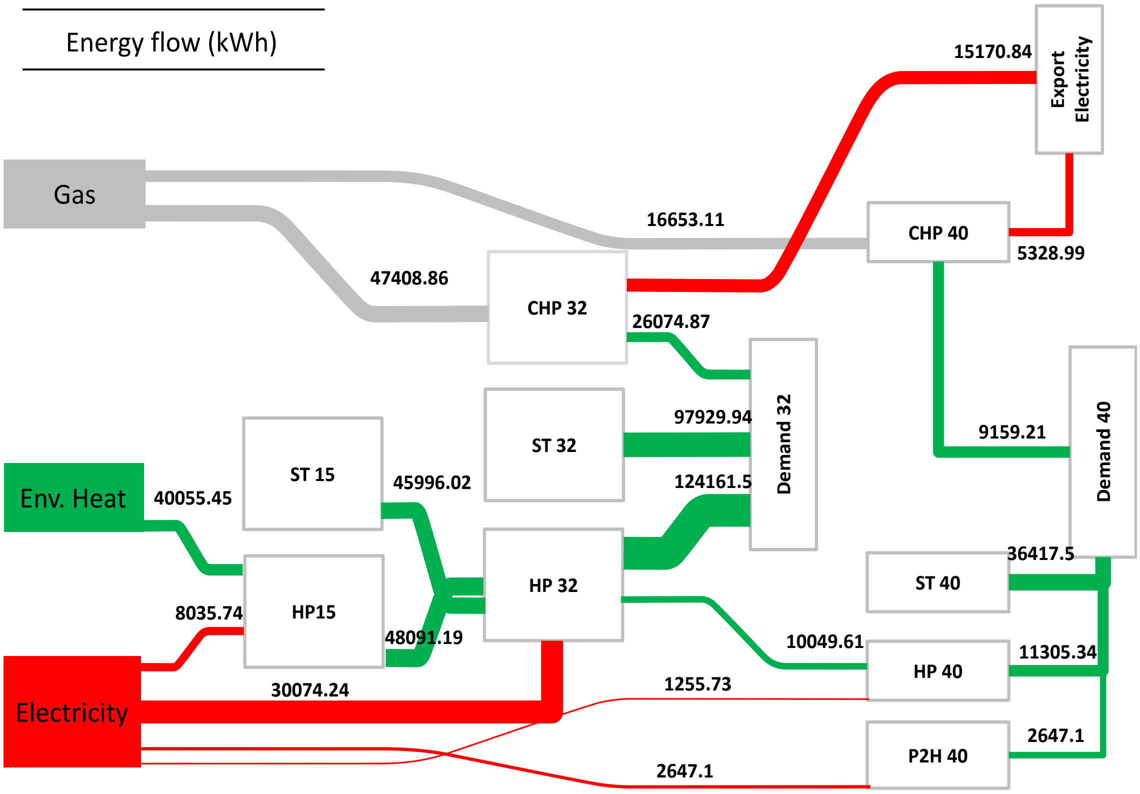


Figure 13: Energy flow

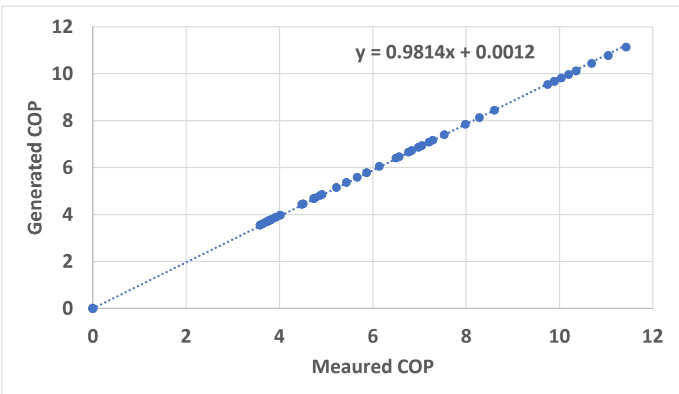


Figure 14: Verification of COP for HP15 with measured and generated values

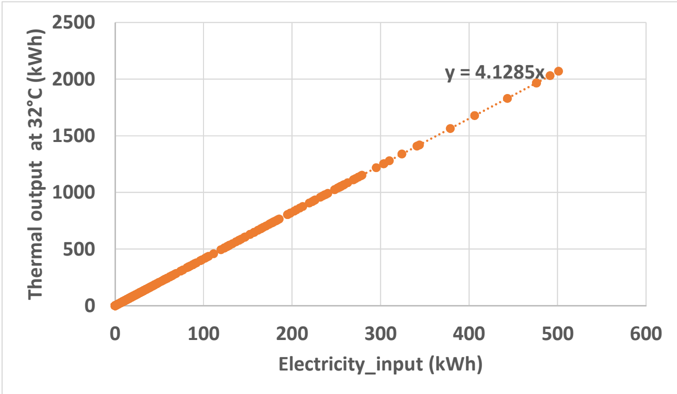


Figure 15: Generated values of COP for HP32

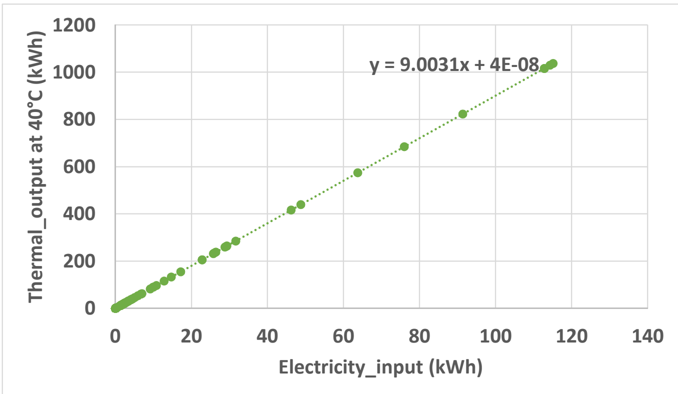


Figure 16: Generated values of COP for HP40

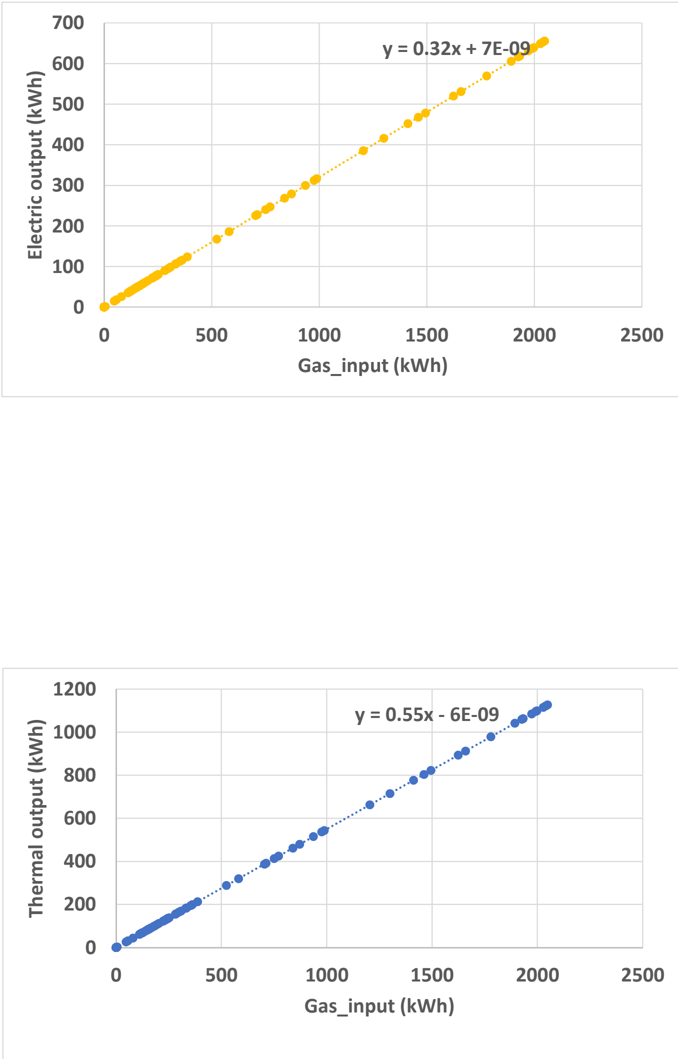


Figure 17: Generated electric and thermal efficiency

Chapter 5

Results

5.1 Heat generation through SC utilizing TESPy Model

The parameters mentioned in Table.1 are passed into the SC model in TESPy, and the time series values of heat generation for desired temperature levels are generated by varying the mass flow. It can be observed from Fig. 19 that with the irradiance available at the chosen location, the quantity of heat generation is significantly lower. While observing the trend of the whole year, a maximum of 8 kilo-watt hour (kWh) at peak sunshine can be achieved. If we zoom into the graph as shown in fig 19a and Fig. 19b, the intermittent supply is visible. In Fig. 19a, during January, hardly 2.5 kilowatt (kW) of peak power can be harvested. While in the months of July-August, the quantity i.e., energy is increased, and at the same time, the peak power is increased to more than 8 kW.

Since, the whole idea in the optimization is to see the influence of different technologies which can supply some percentage of heat demand, especially working with lower temperature, the heat generated through the SC is scaled up. It can be observed from Fig. 20a, the frequency when SC is able to generate heat remains the same; however, the quantity of heat generation is increased. Furthermore, the volatile outputs of SC is presented with a load duration curve in Fig. 20b. The area under the curve represents the total quantity of heat that is generated from SC and is available in order to fulfill SH and DHW demand.

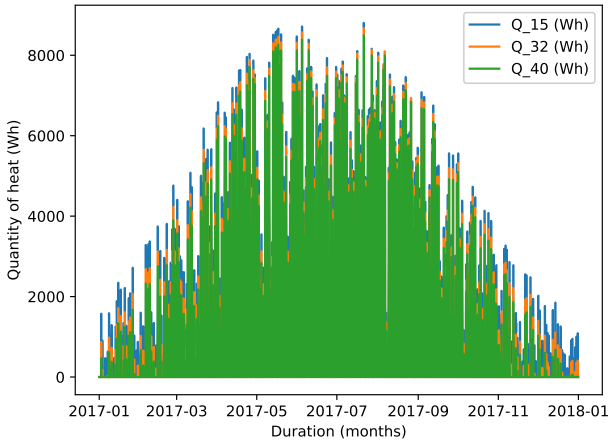
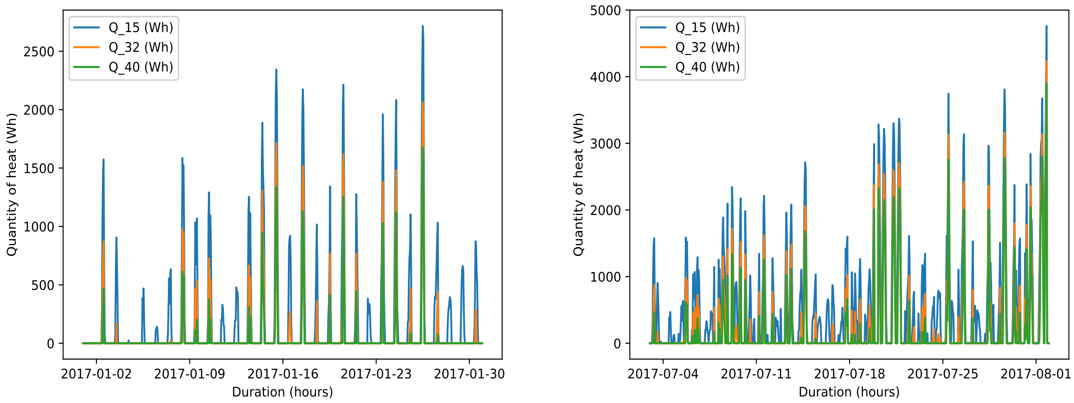
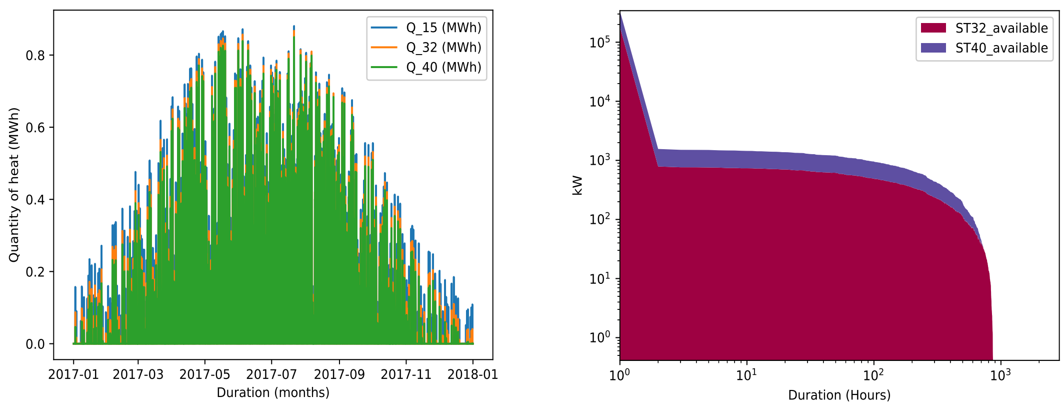


Figure 18: Heat generated from a collector throughout a year



(a) (b)

Figure 19: a. Heat generated in January b. Heat generated in July



(a) (b)

Figure 20: a. Heat generated from a collector after up-scaling b. Duration curve for the available heat from SC

5.2 Flow optimization with two cost functions for different networks

The section presents exergy and energy flows with two optimization schemes for a day. The first configuration generates energy and exergy flow utilizing cost variables for different fuels. The optimizer chooses the share of each technology based on cost minimization function. For the second configuration, all the technologies are given the same weight. Therefore, in the exergy scenario, a flow is created based on exergy minimization and likewise, energy flow is generated based on energy minimization.These two optimization schemes are adopted for different networks with a combination of supply options. The charts in the following sections have abbreviated terms for technologies used. Power to heat (P2H) is named for electric heater, supply out of buffer for each temperature level are represented as bufout and heat from SC in each temperature levels are termed as ST15, ST32, and ST40 respectively.

5.2.1 Price based optimization

Electric heater and gas boiler network

Fig. 21 depicts the variation of preference of technology due to the price of gas and electricity. It is quite visible that with different times of day, either boiler or heater is selected. From 1:00 am till 2:00 pm, the electric heater provides the total heat demand for both the temperature levels. Afterward the gas heater is switched on for 8 hours which is a typical duration of electricity demand peak. Starting from 10:00 pm to 5:00 am , the electric heater again comes into action. This signifies that the price of varying electricity on the day ahead market governs time and running hours of transformers. The preference of technology in both scenarios for energy and exergy is the same. The only difference in terms of exergy is that the demand for heat does not coincide with the exergy supplied either through gas or electricity. It is due to the fact that the quality factor for both gas and electricity is high ($F_q = 1$ and $F_q = 0.9$) respectively. On contrary, the heat demand at a temperature of 40°C has a relatively lower quality factor ($F_q \approx 0.11$).

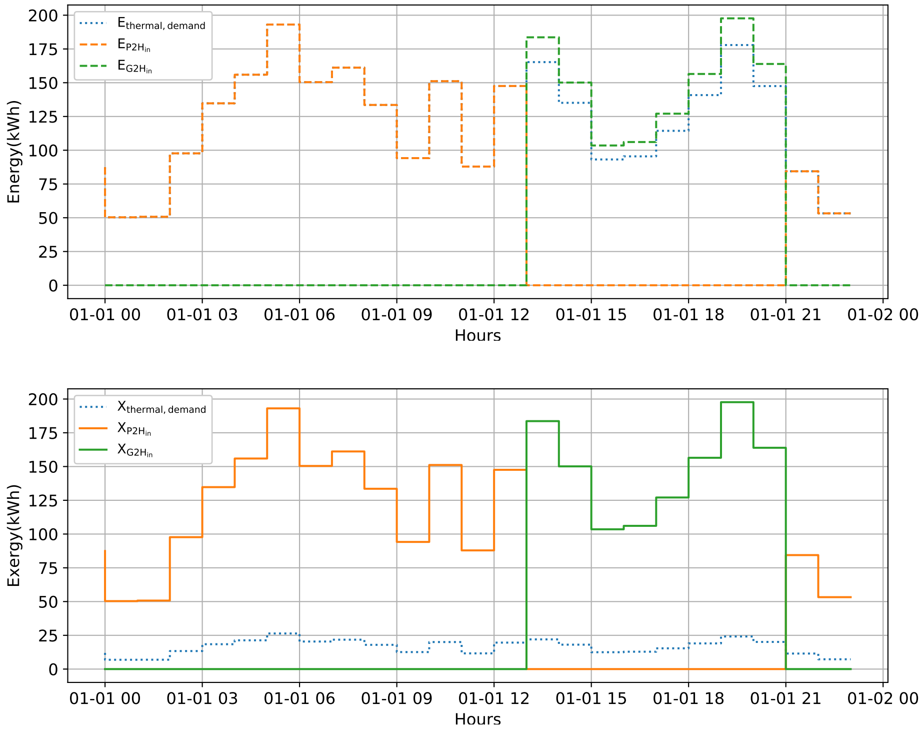


Figure 21: Preference of technology on the basis of energy and exergy due to price

SC with buffer and HP network

In the network with SC, HP, and buffer, HP is the only technology driven by the price. The heat generated through SC is considered free, and the rest is storage. In both the cases in Fig. 22, SC can supply heat in all temperature levels for an interval of four hours. The remaining demand is fulfilled through HPs. In both scenarios, HP frequently operates during the time of lower electricity prices. At the time of operation, it fulfills the demand of that hour and also supplies energy into the buffer till its maximum capacity. Hence, the rest of the demand is covered by a buffer, which is indicated by the cross marks in the chart.

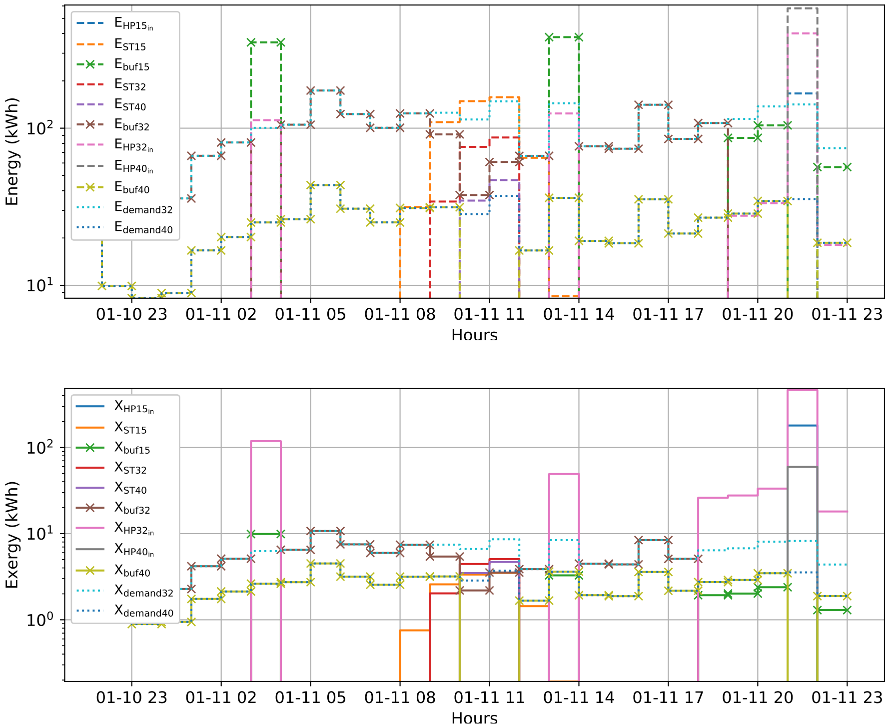


Figure 22: Choice of technology

Combination of all technology network

The combination of all the technologies gives this network. Due to the price being the cost function, only particular technologies are operated in that period. Referring to the optimisation for energy in Fig. 23, three distinct technologies, namely CHP, HP and, SC are operated in different periods. At the period of 10:00 am - 12:00 pm, SC for 15°C and 32°C, along with HP32, is employed. As mentioned in section 3.4.2, HP32 is in cascade with a temperature level of 15°C. Therefore, SC15 provides the necessary environment heat during the operation of HP32 at 10 am-11 am. It is visible from the chart that the supply at the time of generation is higher than the demand represented by the dotted line. The excess heat beyond the demand at the time of generation is fed into the buffer, which operates between 12:00 pm - 9:00 pm when there is no single technology in the running. Furthermore, at 10:00 am -11:00 am, CHP32 gets started along with SCs covering the thermal as well as electrical demand at that hour. The picture is similar when the optimization is carried in an exergy scenario with the price. Only the operation of HPs for 32°C and 15°C becomes prominent.

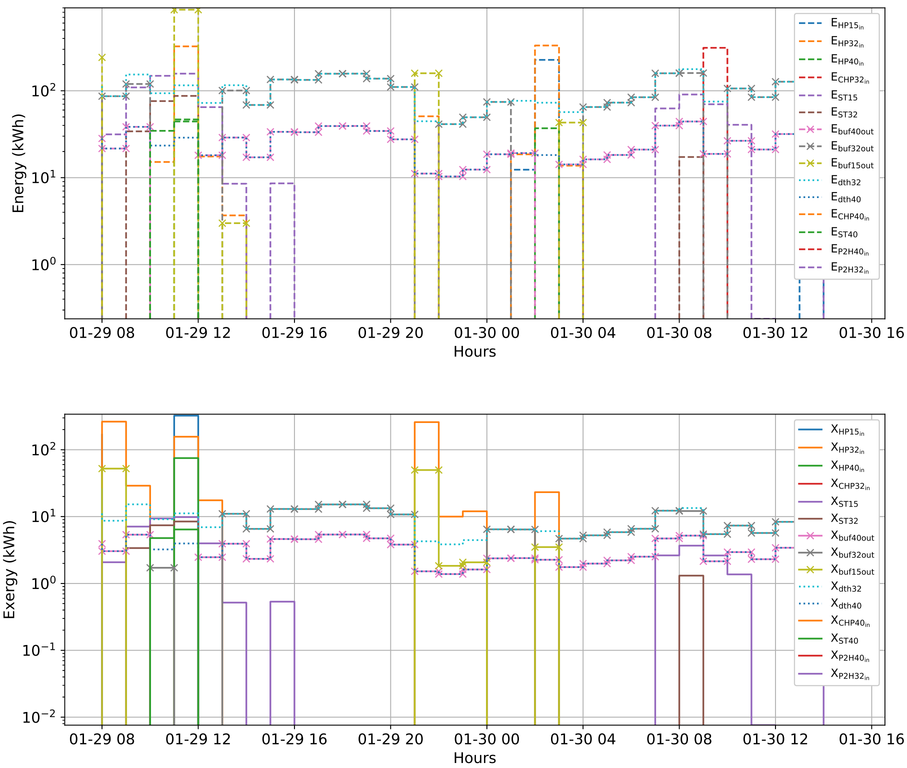


Figure 23: Configuration in terms of energy and exergy utilizing price as the cost function

5.2.2 Optimization based on constant weight

Electric heater and gas boiler network

When both the technologies are given the same weight, in both the scenarios of energy and exergy minimization, the operation of an electric boiler is preferred. Although gas and electricity have the same quality factor, the efficiency of electric boiler is assumed higher than the gas boiler. Therefore, in Fig. 24 only electric boiler is operated throughout the day in comparison to Fig. 21, where both technologies were employed according to different times of the day.

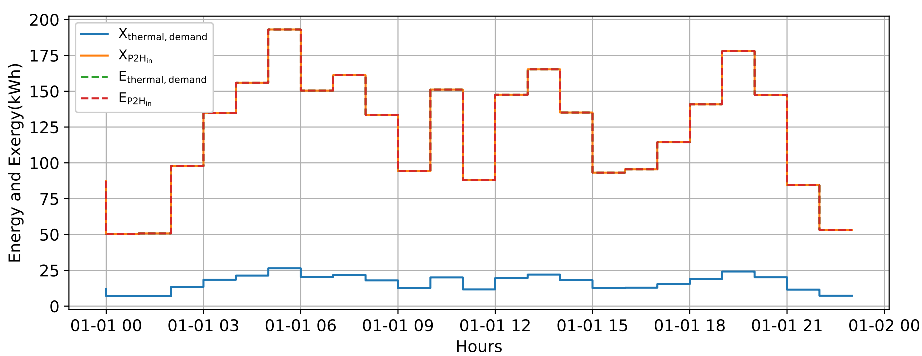


Figure 24: Preferred technology when electric heater and gas boiler are given the same weight

Solar collector with buffer and HP network

In the energy scenario, when HP and SC are given an equal weight, the operation of SC is ceased. For the whole duration of a day, the HP covers the hourly demand by operating three hours for a temperature level of 15°C while it runs continuously for both the temperature level of 32°C and 40°. It is due to the cascade connection between the HPs at different temperature levels. HP15 is the function of ambient temperature. Therefore, it operates from 1:00 pm - 2:00 pm when it has the highest COP and at 9:00 pm to 10:00 pm to fulfill buffer completely at its maximum capacity. However, HPs at 32°C and 40°C run at constant COP as it is independent of ambient temperature. Therefore, HP32 runs continuously from 5:00 am -11:00 pm and utilizes buffer from 11:00 pm- 3:00 am. However, in the case of HP40, it operates through without utilizing the buffer. The network works similarly for exergy except for the fact that it allows penetration from SC. Therefore, at the time where there is available irradiance, SC, for all temperature levels are functional. It covers the hourly demand and also contributes to the buffer. HP40 and HP15 operate for a short interval, whereas HP32 operates multiple times a day. Only in between 8:00 pm to 12:00 am, buffer for 32°C becomes functional.

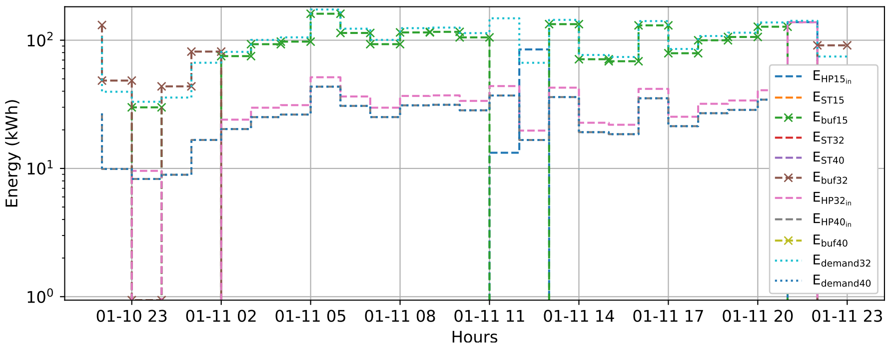


Figure 25: Preference in energy minimized network of SC and HP

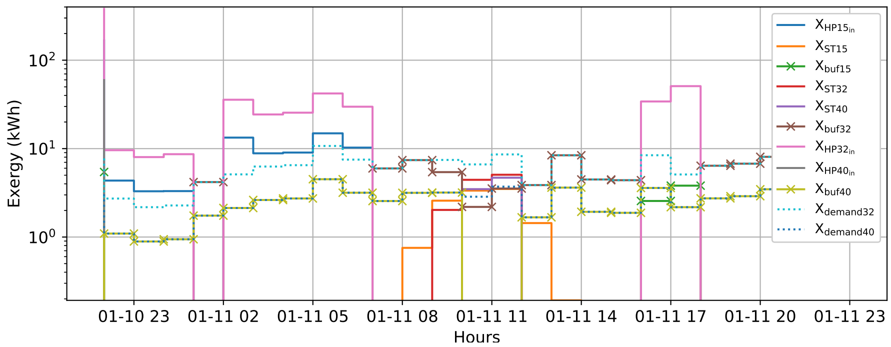


Figure 26: Preference in exergy minimized network of SC and HP

Combination of all technology network

The energy picture of the final configuration is similar to the previous network with SC and HP. Cascaded heat pump surpasses the functionality of all the other technologies as it is the most energy-efficient among the pool. The capacity of buffer completely governs the operation frequency of the HP. HP15 starts running between 8:00- 15:00 pm as it is a duration required to fill cover the hourly demand and fill the buffer of 1 MWh. Similar is the case of HP40 which operates once at 2:00 pm as the demand of 40°C is lower in comparison to 32°C. Therefore,one-time operation can

generate approximately 814 kWh. This amount is sufficient to fulfill the hourly DHW demand for the next day. Due to the higher demand for SH at 32°C, one-time operation exceeds the maximum storage capacity of the buffer. Therefore, it operates nearly every 24 hours for this typical day under consideration.
The exergy scenario is also relatable. In this exergy minimized network, the use of technologies like CHP and even electricity-driven heaters are discouraged. The heat from SC is completely absorbed, and it reduces the load for HP32. HP32 operates three hours between 8:00 am - 11:00 am and till 9:00 pm, buffer and heat from SC fulfill the demand. After 9:00 pm it continuously runs till the next day 6:00 am. Similarly, HP15 also operates continuously from 9:00 pm to 6:00 am. Later on a day, it operates once at 9:00 am, and SC fulls the rest. But in comparison, HP40 operates just 3 hours at different times a day. The use of that period of HP and SC fulfill the demand.

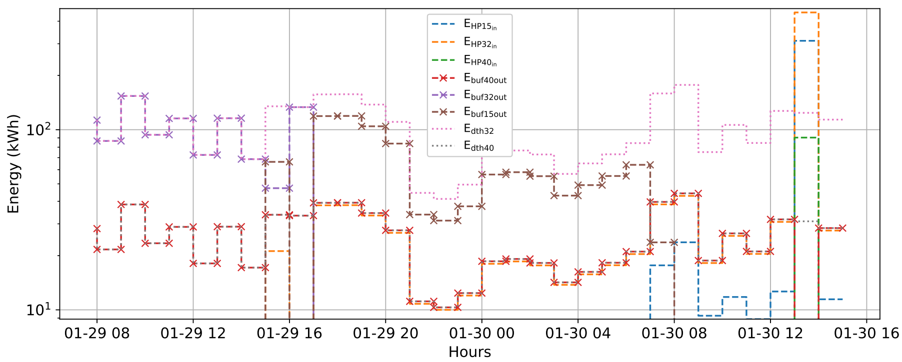


Figure 27: Final configuration of technologies in energy minimized network

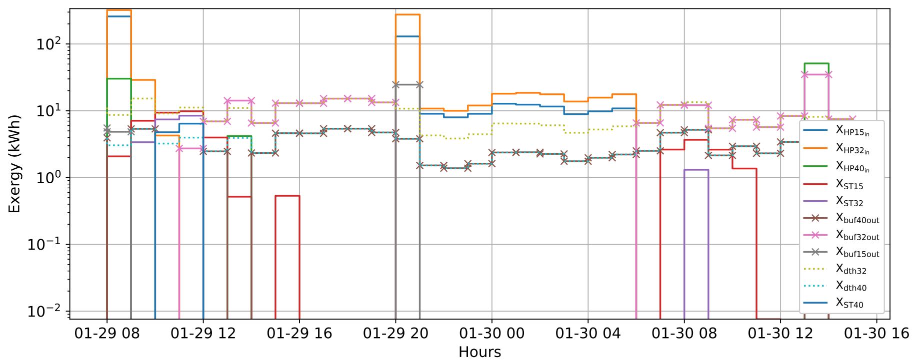


Figure 28: Final configuration of technologies in exergy minimized network

Chapter 6

Discussions

The figures presented in section 5.2 are based on the values a day. The operation and duration of the technologies in a network vary when simulated for a extended period. In this chapter, the results from a network with all the combinations of technologies simulated for the entire period which is four months as mentioned in section 3.4.2. The simulation is carried out by using two optimization functions that are analyzed in different subheadings.

6.1 Share of supply options

As indicated in the sections 5.2.2 and 5.2.1, with different optimization functions, the structure for energy and exergy flows, utilizes more than one technology. It is, therefore, essential to summarize the shares of technologies for each optimization criteria.

6.1.1 Share for price based optimization

When the network is optimized in terms of price, the energy and exergy flows generated utilize all the resources of fuel supplied i.e., gas, electricity and, solar energy as illustrated in Fig. 29. In this optimization scheme, the energy from SC is considered as free. Furthermore, the network also has a facility to export the excess electricity back to the market. Considering the energy scenario represented by the name supply energy and demand energy, the share of heat from a SC is the highest. Gas is the second-highest utilized fuel in order to operate a CHP. As mentioned in the methodology, electric boiler are considered 100% efficient. Nevertheless, the preference is given to CHP. It is due to the fact that during its operation for the fulfillment of thermal demand, 32% of electricity is also produced, which have a higher value in the electricity market in terms of price. To mention one of the time when CHP is functional, the price of gas is 32 €/MWh while the export price of electricity is 104 €/MWh. The last fraction is the share of electricity, where both HPs and electric boilers are functional.

When comparing the exergy scenario with the energy, the influence of price becomes significant. With the height of the demand block, it is clear that the demand in terms of exergy is minimal. However, if we analyze the supply option share, we find slight increase with the share of gas. As mentioned in the previous paragraph, the network facilitates the export of electricity. Therefore, approximately 65 MWh of gas is purchased which is, 5 MWh more than the energy flow. The effect is reflected in the increased height in the export bar of exergy. In the context, the operation of CHP is proved to be exergy efficient and economically robust. While comparing the other supply options, electricity has a marginal decrease in the supply for SH and an increase in DHW demand. However, SC is a low energy technology that demonstrates a considerable difference in terms of exergy due to its lower quality factor. Therefore, it is responsible for the decrease in the quantity of supply as the other two supply options share the same quality factor in both scenarios.

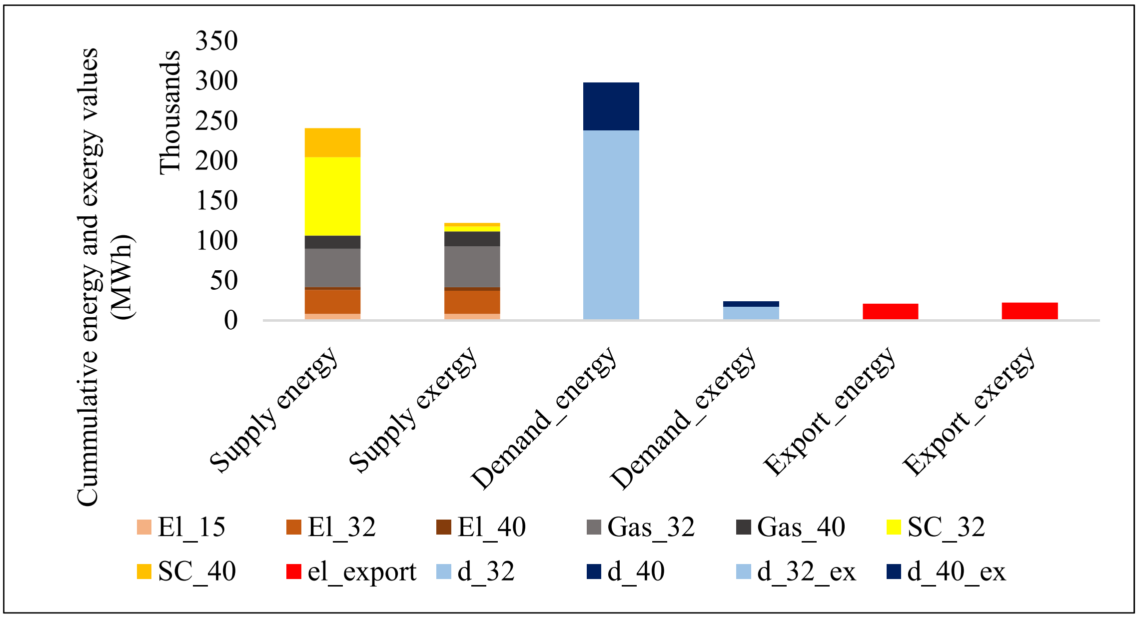


Figure 29: Share of technology for energy and exergy flows in terms of price minimization

6.1.2 Share for optimization based on constant weight

When all the technologies are given the same weight, energy and exergy flows are generated in terms of energy and exergy minimization. The supply options that are opted out are very different compared to those explained in section 6.1.1, and the export of electricity is not preferred. From the pool of technologies, only two i.e., HP and SC, are operated. Before analyzing each scenario, it is necessary to point out that the quantity of energy consumed is reduced by three-folds in both the flows. As the optimization is performed in terms of energy minimization, the energy network is created with the single operation of HP for meeting the whole thermal demand. If we study the performance parameter for all the technology, the cascade HP is the most energy-efficient technology, and therefore, it validates the preference for its operation. The network is also different in terms of exergy within the same optimization criteria. The network for exergy flow has heat supply through HP and SC, as shown in Fig. 30. It is visible that with exergy minimization as a cost function reduces the gap between the supply and energy use. Furthermore, it is observed that the quantity of heat utilized from SC is higher than in the scenario for price minimization even though the heat from SC is considered free. It points out that in terms of exergy minimization, the use of solar heat is maximized. However, if we compare the available heat from the SC depicted in Fig. 20b, only 57% and 28% of the heat for SH and DHW respectively is utilized as demonstrated in Fig. 31.

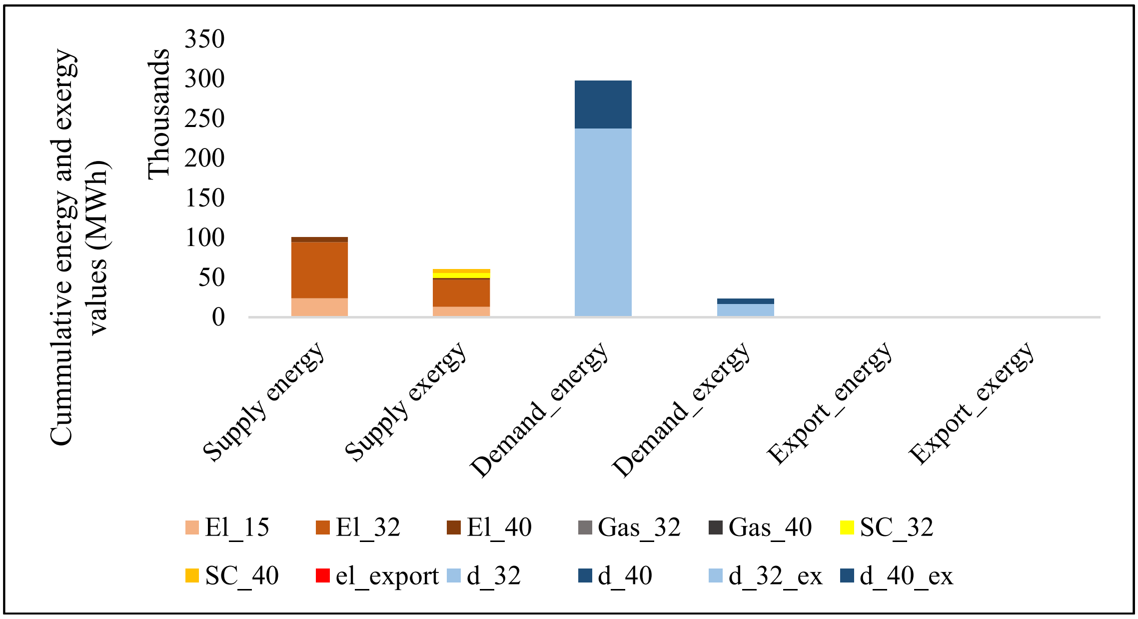


Figure 30: Share of technology for energy and exergy minimization

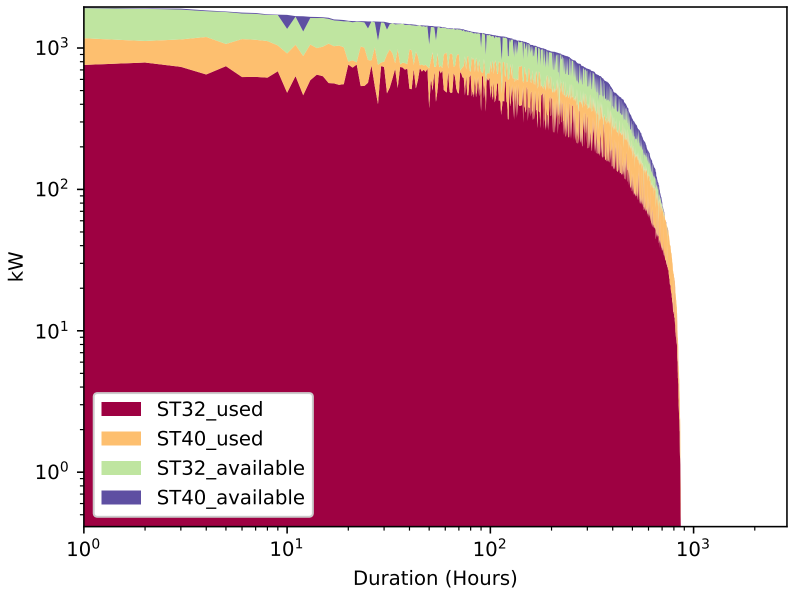


Figure 31: Quantity of heat utilized from SC in exergy minimization

6.2 Scenarios of quality factor

The share of each technology is known from the previous section. At the same time, it is also interesting to observe the quality of the energy used for the hourly operation. Therefore, the section below presents the quality of energy used for meeting the SH and DHW demand and also the quality of supply itself for both of the optimization scenario.

6.2.1 Quality factor for price based optimization in terms of energy

Fig.32 represents the quality factor of the fuel utilized by the network in order to fulfill the demand of SH and DHW. Electricity gives the highest quality, therefore, no difference is witnessed as depicted by blue dots passing through the origin. Similarly, gas employed in the study has marginal difference with the quality factor of electricity as higher heating value of gas is considered as mentioned in section 3.4.2. However, green dots representing energy from collectors lie in a zone of lower energy and exergy, representing lower quality factors.

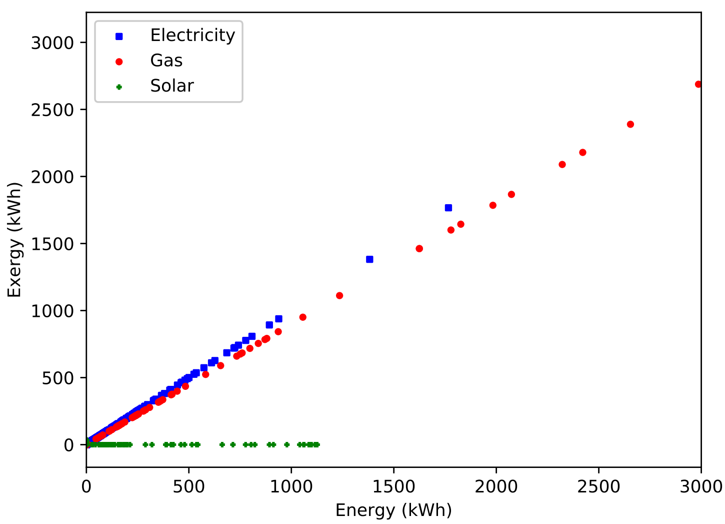
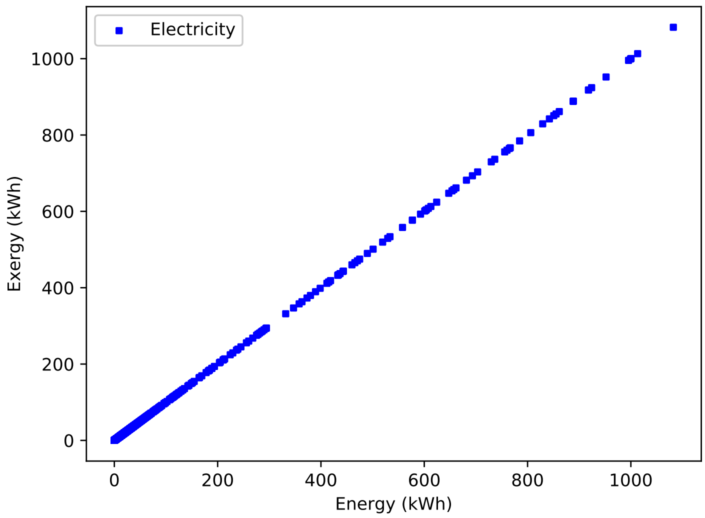


Figure 32: Quality factor of network optimised by price

6.2.2 Quality factor for network with same weight

The quality factor of the network optimized for energy is solely governed by the quality factor of electricity, as it is the only supply option being utilized. However, the same network stimulated for exergy allows penetration of heat through SC represented by the second scatterplot in Fig. 33. This decreases the overall quality factor of the network.



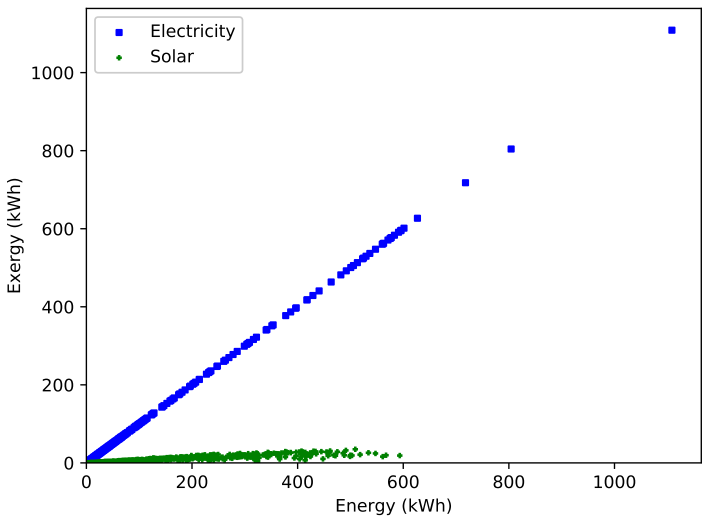


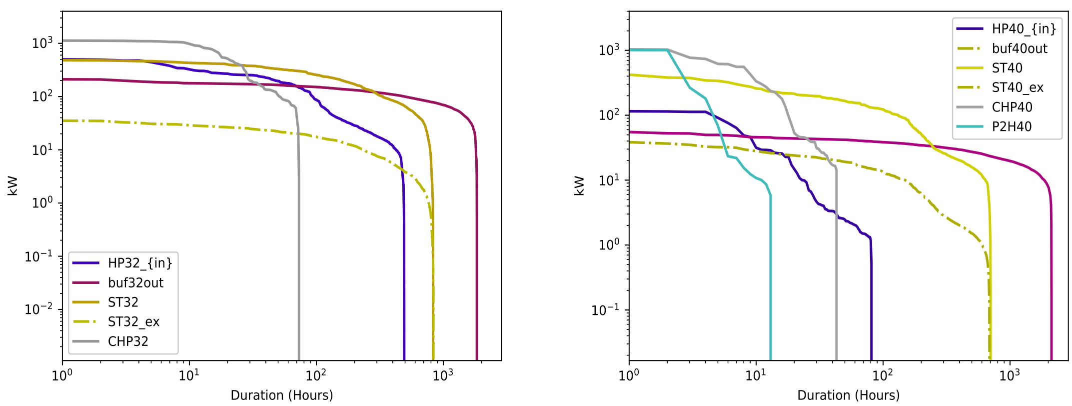
Figure 33: Quality factor of network optimised by weight

6.3 Duration of supply options

The final configuration of supply options also includes a generic storage between the supply and demand at all temperature levels. Due to the employment of storage, with different optimization criteria, the frequency and duration of operation of technologies are varied. This section explains how much of each of the technology mentioned in section 6.1 is operated through the simulation period and presents the coverage of storage. The load curve generated are in logarithmic scale in order to properly visualize the trend. As a result, trend have rather smooth lines compared to the fact that, each technologies are time series of 1 hour interval. The on and off state of technologies which makes the curve rough is eliminated. Furthermore, the curves present the values of technologies which are abbreviated as ST for SC and buffer for bufout. In addition, the scale of y-axis at the beginning is different in some scenarios. The difference is due to the use of small fraction of either of technologies.

6.3.1 Load duration curve for price based optimization

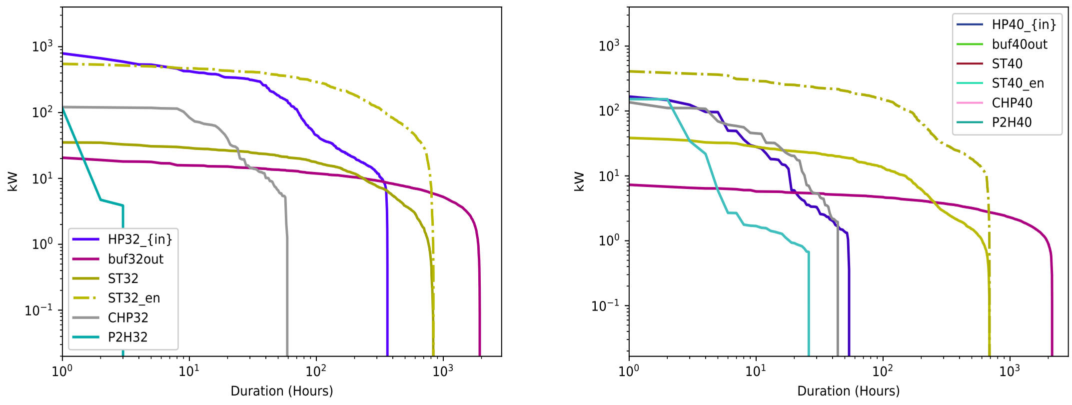
Fig 34a is the only network where all the technologies, including buffer, operate with a higher load and longer duration of time. In Fig. 34b, the demand is comparatively lower; therefore, the longer operating hours of HP are reduced significantly, and electric heater(P2H) is operated for approximately 11 hours to cover the load. SC operates with the same trend whereas due to reduced load buffer operates at a maximum of 60kW. Among all the technologies, SC is the only technology which has significant differences between energy and exergy. Therefore, dotted lines are created in order to visualize the exergy values at that energy points.



(a) (b)

Figure 34: a. Logarithmic load duration curve for energy flow for SH b. Logarithmic load duration curve for energy flow for DHW

The preferences of technologies remain the same with exergy flows, as shown in Fig. 35a and 35b, but it is interesting to observe even with reduced demand; there is not a significant drop in the capacity of load and its operational hours. It is because technologies are operating at similar scale as energy, and the residual energy is exported to the grid. HP operates at a higher load of around 800 kW at peak and operates for 380 hours, whereas CHP operates at 3000 kW for 60 hours. The buffer now operates longer with a lower load. The dotted line for SC here represents the energy values for the exergy values utilized in the configuration.

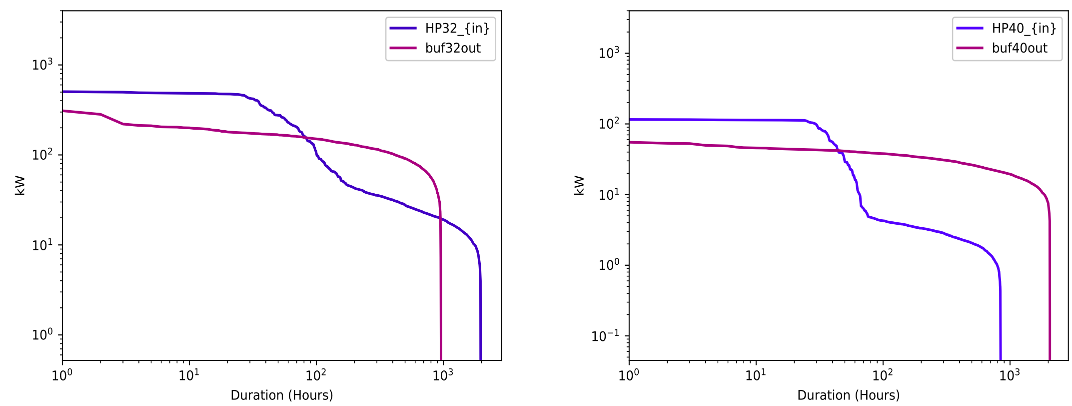


(a) (b)

Figure 35: a. Logarithmic load duration curve for exergy flow for SH b. Logarithmic load duration curve for exergy flow for DHW

6.3.2 Load duration curve for optimization based on constant weight

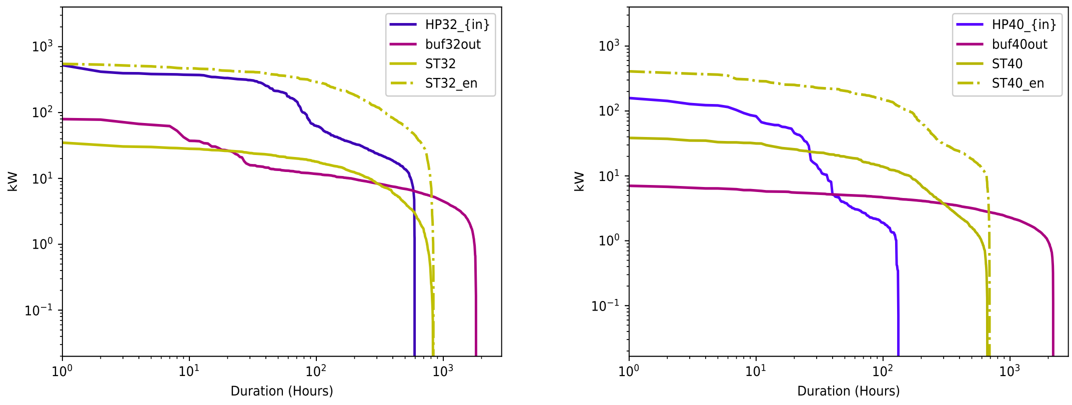
The curves in Fig. 36a and 36b represent energy minimization where HP is only utilized, which was never given the first priority in any other network. Different scales in the y-axis is visible for SH and DHW due to the weight of demand. Demand for DHW is four times smaller than the demand of SH. As a result variation in power is seen in the range 10 kW -100kW in SH whereas it is evident for the range of 6 kW - 20kW.



(a) (b)

Figure 36: a. Load duration curve for energy minimized network for SH and b. Load duration curve for energy minimized network for DHW

The exergy efficient network operating with the SC, HP, and, buffer also carry the similar trend of buffer utilization. In this scenario, SC contributes to 40% of SH demand. The majority of demand is covered by HP, therefore, the trend follows the load curve of HP. Whereas, the case reverses for DHW, majority of the demand is covered by SC following its smooth trend. Because of this reason buffer for SH operates at high load in comparison to the DHW. Nevertheless, the mix of SC at a lower load for higher duration and a higher load HP with the comparatively shorter duration with buffer is the most exergy efficient configuration, as shown in Fig. 37b .



(a)

(b)

Figure 37: a. Load duration curve for exergy minimized network for SH and b. Load duration curve for exergy minimized network for DHW

6.4 Scenario of exergy flow due to buffer size

As mentioned in section3.4.2, the size of buffer in case of energy and exergy are different. The buffer for energy flows has capacity of 1 MWh and the capacity is function of quality factor in the case of exergy flows. From the section above it is evident that, the frequency of operation of technologies is dependent on buffer size. Therefore, the exergy minimized scenario is simulated with oversized buffer i.e., buffer for energy and exergy flows are considered the same, 1 MWh. It can be observed that with the use of oversized buffer, SC is utilized more in all temperature levels, whereas when the buffer is exergetically sized, utilization of HP for all temperature is preferred than SC.

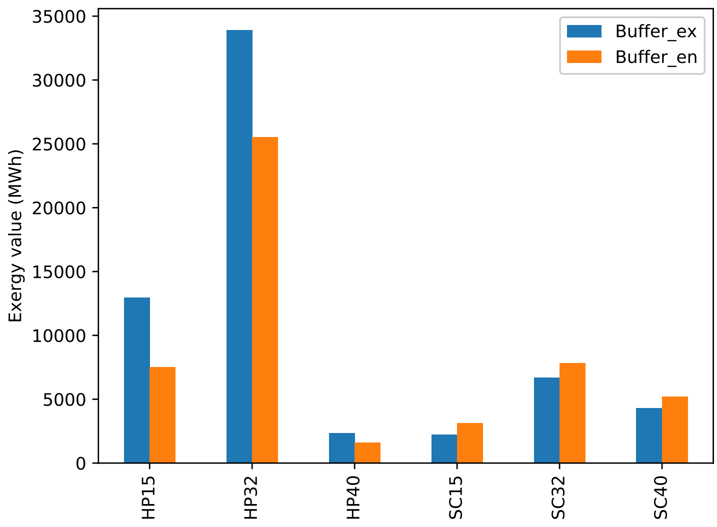


Figure 38: Share of HP and SC for different temperature levels for different sized buffer

Chapter 7

Conclusions

The undertaken study of exergy analysis has proven to be a correct approach for analyzing an energy system consisting of different energy supply sources with a common ground of temperature. Nevertheless, the study involves various simplifications. The assumption of given ambient temperature as a reference environment depicted the performance of the technology in a real environment. The varying COP for the operation of HP and the intermittent heat generated from the SCs support the statement. Similarly, the method of dynamic simulation based on the quasi-steady approach worked well for the study as the focus was on the flows in a generation level rather than a distribution level. Due to this constraint, the calculation for thermal demand could be done with constant temperature levels.

With regards to the differences observed in exergy analysis, it can be concluded that for the general scenario with high-quality fuel input mix, there is no difference. It is depicted by the linear trend of quality factor without intercepts. However, with the addition of low exergy sources like a solar collector, differences can be pictured. The differences can be scaled on the basis of different control strategies and optimization criteria. The price, which was one of the optimization criteria did not yield a significant difference. Simply due to the reduced load in terms of exergy, the frequency of operation is changed not the preference of technology. However, in the following optimization, where every technology is given similar weight, differences in terms of preferences of technology are witnessed. In both the scenarios the operation of storage remained the same. Due to the assumption of ideal storage with fixed capacity, buffers are utilized more than any of the other technologies. Due to this factor, the storage capacity of buffer worked as one of the control strategy.

The other finding is the fulfillment of electric demand. The configuration of the network involved CHP, which is capable of producing electricity. However, throughout the optimization, the electric demand was fulfilled straight away from a purchase in a market. Therefore, it is concluded that there is no influence of electrical demand in the exergy analysis if a direct purchase option is available.

After analyzing the results, it can be concluded that a network with HPs cascaded for different thermal levels with the provision of heat from the solar collector gives the most exergy efficient network. The exergy can be further minimized if the share from the collector is increased. This leads to the final conclusion that with only a higher share of low-temperature technologies with the provision of different temperature levels heat utilization, the potential benefits from the use of exergy as an assessment criteria can be witnessed. Nevertheless, the use of exergy instead of energy as an assessment base can point out further potential for an optimization of the energy supply and demand configuration.

Chapter 8

Outlook

The configuration with the supply options taken for the study in terms of exergy analysis seems to be a beneficial tool for optimizing a community energy system. Nevertheless, the assumption of three temperature levels due to the dynamic limitation of oemof has significantly narrowed the potential use of exergy analysis in many ways.

The development of a feature to incorporate dynamic temperature behavior as a future work can facilitate research for cascade thermal behavior. This, in turn, makes a model feasible for different supply environments ranging from residential complex to service facilities. Also the simplest assumption made for the use of generic storage has a significant influence on the results achieved. The storage in practical environment is associated with more than half of the thermal losses in relation to its temperature levels. Therefore, it is essential to simulate the model with the constraints of thermal losses as a function of temperature. It would then give an idea whether the preference and duration of technology from the pool of supply options would remain the same as obtained in this study.

Furthermore, the dynamic use of ambient temperature as a reference environment resulted in a negative flow for the period with higher temperatures for low-temperature demands. This constraint has limited the current model to be simulated for winter optimized scenario. The addition of a small methodology to counter back the flow as a future work would make the model valid for all temperature ranges. Eventually, it widens the scope of the model.

In the scenario where the future work could incorporate different temperature levels, it opens a scope to optimize an energy system based on price of heat. This might be interesting to analyze as it is already being discussed as a parameter for the development and monitoring of the low-temperature heat networks.

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Appendix A

Source code for TESPy

```
from tespy import con, cmp, nwk
import numpy as np
import pandas as pd

# reading the input files
df = pd.ExcelFile('weather_dwd_2017.xlsx').parse('Sheet1')
T_rad= df[(df[['temp_air(K)','irradiation']] != 0).all(axis=1)]
T_amb = T_rad.loc[:,'temp_air(K)']
E_glob = T_rad.loc[:,'irradiation']

# network
fluid_list = ['H2O']
nw = nwk.network(fluids=fluid_list, p_unit='bar', T_unit='K', h_unit ='J / kg')

# sinks & sources
back = cmp.source('to collector')
feed = cmp.sink('from collector')

# components and connections
coll = cmp.solar_collector(label='solar thermal collector')
b_c = con.connection(back, 'out1', coll, 'in1')
c_f = con.connection(coll, 'out1', feed, 'in1')
nw.add_conns(b_c, c_f)

# component and connection parameters
coll.set_attr(pr=0.99, Q= 4e3, lkf_lin=1.17, lkf_quad=0.0082, A=200, Tamb=288)
b_c.set_attr(p=5,T=303, fluid={'H2O': 1})
c_f.set_attr(T=313,p0=2, m=0.417)

# solving
mode = 'design'
coll.set_attr(Q=np.nan, E=np.nan)
nw.solve(mode=mode)
nw.save('SC')

#making a loop based on change in ambient temperature and irradiance
def q_var_ambT(E_glob,T_amb):
```

```
    nw.set_printoptions(print_level='none')
    mode = 'offdesign'
    c_f.set_attr(m=np.nan)
    coll.set_attr(Q=np.nan)
    coll.set_attr(E=E)
    coll.set_attr(Tamb=T)
    nw.solve(mode=mode, design_path='SC')
    return coll.Q.val

Q =[]
for E,T in zip(E_glob,T_amb):
    Q.append(q_var_ambT(E_glob,T_amb))
```

Appendix B

Source code for final oemof network

```
import numpy as np
import pandas as pd
import networkx as nx

from oemof.graph import create_nx_graph
from oemof.solph import (Bus, constraints, EnergySystem, Flow, Model,
                         NonConvex, Sink, Source, Transformer)
from oemof.solph.components import GenericStorage
import oemof.outputlib
import matplotlib.pyplot as plt

from common.constants import HS_PER_HI
from common.datapreprocessing import prepare_dataframe

N_THREADS = 4
SOLVER_ACCURACY = 0.01
SOLVER_VERBOSE = False

def carnot_efficiency(t_in, t_out):
    """
    :param t_out: temperature
    :param t_in: reference temperature
    :return: relative exergy (E_x/E_th)
    """
    return 1-t_in/t_out

def quality_factorSH(t_in, t_out, t_a):
     """
    :param t_out: supply temperature
    :param t_in: return temperature
    :param t_a: reference temperature
    :return: quality factor
    """
     return 1-t_a/(t_in-t_out)*np.log(t_in/t_out)
```

```
# import
first_step= 0
number_of_steps = 2880

data = prepare_dataframe(first_step, number_of_steps)

# width of time steps (in h)
dt = data.index.freq / pd.Timedelta('1h')

pd.plotting.register_matplotlib_converters()

T_b = 20 + 273.15
Tl =  15 + 273.15
Tm =  32 + 273.15
Th =  40 + 273.15

Tr = data["Temperature (K)"]

for exergy in [True, False]:

    energy_system = EnergySystem(timeindex=data.index)
    periods = len(data.index)

    b_el   = Bus(label="b_el")
    b_gas  = Bus(label="b_gas")
    b_th15 = Bus(label="b_th15")
    b_th32 = Bus(label="b_th32")
    b_th40 = Bus(label="b_th40")

    energy_system.add(b_el, b_gas, b_th15, b_th32, b_th40)

    if exergy:
            weight_th15 = carnot_efficiency(t_out=Tl, t_in=Tr)
            weight_th32 = quality_factorSH(t_in=T_b, t_out=Tm, t_a =Tr)
            weight_th40 = carnot_efficiency(t_out=Th, t_in=Tr)
    else:
            weight_th15 = 1
            weight_th32 = 1
            weight_th40 = 1

        # demands

    demands40 = weight_th40 * data["th. Demand (MW)"] * 0.20
    demands32 = weight_th32 * data["th. Demand (MW)"] * 0.80

    energy_system.add(Sink(label='d_th40', inputs={b_th40: Flow(
            actual_value=demands40,
            fixed=True,
            nominal_value=1)}))
    energy_system.add(Sink(label='d_th32', inputs={b_th32: Flow(
            actual_value=demands32,
            fixed=True,
```

```
        nominal_value=1)}))

   # external ("market") source
el_consumer_fees = 0
el_market_price = data["el. Price (EUR/MWh)"]
el_market_price[el_market_price<0] = 0
el_price = 1
energy_system.add(Source(label='m_el',
                         outputs={b_el: Flow(
                             variable_costs = el_consumer_fees
                             + data["el. Price (EUR/MWh)"])}))

gas_consumer_fees = 0
gas_price = 1
energy_system.add(Source(label='m_gas',outputs={b_gas: Flow(
        variable_costs = gas_consumer_fees + 35 / HS_PER_HI)}))

energy_system.add(Sink(label='d_el', inputs={b_el: Flow(
    actual_value=(data["el. Demand (MW)"]),
    fixed=True,
    nominal_value=1)}))

el_export_proceeds =data["el. Price (EUR/MWh)"]

energy_system.add(Sink(label='x_el',
                       nominal_value=100,
                       inputs={b_el: Flow(
                               nominal_value=1,
                               grid_connection=1,
                               nonconvex=NonConvex(),
                               variable_costs= -el_price)}))#el_export_proceeds)}))
# collector
st_price = 1
energy_system.add(Source(label='st_15', outputs={b_th15: Flow(
    max=weight_th15 * data["Q_15 (MW)"]*100,
    variable_costs=st_price,
    nominal_value=1)}))

energy_system.add(Source(label='st_32', outputs={b_th32: Flow(
    max=weight_th32 * data["Q_32 (MW)"]*100,
    variable_costs=st_price,
    nominal_value=1)}))

energy_system.add(Source(label='st_40', outputs={b_th40: Flow(
    max=weight_th40 * data["Q_40 (MW)"]*100,
    variable_costs=st_price,
    nominal_value=1)}))

#idealised buffers
energy_system.add(GenericStorage(label='buf_15',
                                     nominal_storage_capacity=1,
                                     inputs={b_th15: Flow()},
                                     outputs={b_th15: Flow()}))
```

```
energy_system.add(GenericStorage(label='buf_32',
                                     nominal_storage_capacity=1,
                                     inputs={b_th32: Flow()},
                                     outputs={b_th32: Flow()}))
energy_system.add(GenericStorage(label='buf_40',
                                     nominal_storage_capacity=1,
                                     inputs={b_th40: Flow()},
                                     outputs={b_th40: Flow()}))

# power to heat
energy_system.add(Transformer(label='P2H32',
                              inputs={b_el: Flow()},
                              outputs={b_th32: Flow()},
                              conversion_factors={
                                  b_th32: weight_th32}))

energy_system.add(Transformer(label='P2H40',
                              inputs={b_el: Flow()},
                              outputs={b_th40: Flow()},
                              conversion_factors={
                                 b_th40: weight_th40}))

#boilers
boiler_efficiency = 0.9
energy_system.add(Transformer(label='G2H32',
                              inputs={b_gas: Flow()},
                              outputs={b_th32: Flow()},
                              conversion_factors={
                                  b_gas: 1 / boiler_efficiency,
                                  b_th32: weight_th32}))

energy_system.add(Transformer(label='G2H40',
                              inputs={b_gas: Flow()},
                              outputs={b_th40: Flow()},
                              conversion_factors={
                                  b_gas: 1 / boiler_efficiency,
                                  b_th40: weight_th40}))

 #CHP
CHP_th_efficiency = 0.55
CHP_el_efficiency = 0.32

energy_system.add(Transformer(label='CHP32',
                              inputs={b_gas: Flow()},
                              outputs={b_th32: Flow(),
                                       b_el: Flow()},
                              conversion_factors={
                                  b_el: CHP_el_efficiency,
                                  b_th32: CHP_th_efficiency * weight_th32}))

energy_system.add(Transformer(label='CHP40',
                              inputs={b_gas: Flow()},
                              outputs={b_th40: Flow(),
```

```
                                          b_el: Flow()},
                                 conversion_factors={
                                     b_el: CHP_el_efficiency,
                                     b_th40: CHP_th_efficiency * weight_th40}))
 # Heat pumps

cpf= 0.23

ceff15 = carnot_efficiency(t_in=Tr, t_out=Tl) / cpf
ceff32 = carnot_efficiency(t_in=Tl, t_out=Tm) / cpf
ceff40 = carnot_efficiency(t_in=Tm, t_out=Th) / cpf

energy_system.add(Transformer(label='HP15',
                          inputs={b_el: Flow()},
                          outputs={b_th15: Flow()},
                          conversion_factors={
                                  b_el: ceff15,
                                  b_th15: weight_th15}))

energy_system.add(Transformer(label='HP32',
                          inputs={b_el: Flow(),
                                  b_th15: Flow()},
                          outputs={b_th32: Flow()},
                          conversion_factors={
                                  b_el: ceff32,
                                  b_th15: weight_th15*(1-ceff32),
                                  b_th32: weight_th32}))

energy_system.add(Transformer(label='HP40',
                                  inputs={b_th32: Flow(),
                                          b_el: Flow()},
                                  outputs={b_th40: Flow()},
                                  conversion_factors={
                                    b_el: ceff40,
                                    b_th32: weight_th32*(1-ceff40),
                                    b_th40: weight_th40}))
model = Model(energy_system)

model.solve(solver="cbc",
            solve_kwargs={'tee': SOLVER_VERBOSE},
            cmdline_options={'threads': N_THREADS,
                             'ratio': SOLVER_ACCURACY})

results = oemof.outputlib.processing.results(model)

result_sequences15 = oemof.outputlib.views.node(results,
                                                'b_th15')['sequences']
result_sequences15.rename(columns={(('st_15', 'b_th15'), 'flow'):
                                      "ST15",
                                      (('HP15', 'b_th15'), 'flow'):
                                          "HP15",
                                          (('b_th15', 'buf_15'), 'flow'):
                                           "buf15in",
```

```
                                         (('buf_15', 'b_th15'), 'flow'):
                                             "buf15out"}, inplace=True)

result_sequences32 = oemof.outputlib.views.node(results,
                                              'b_th32')['sequences']
result_sequences32.rename(columns={(('st_32', 'b_th32'), 'flow'):
                                   "ST32",
                                   (('HP32', 'b_th32'), 'flow'):
                                   "HP32",
                                   (('P2H32', 'b_th32'), 'flow'):
                                   "P2H32",
                                   (('G2H32', 'b_th32'), 'flow'):
                                   "G2H32",
                                   (('CHP32', 'b_th32'), 'flow'):
                                    "CHP32",
                                    (('b_th32', 'd_th32'), 'flow'):
                                    "d_th32",
                                    (('b_th32', 'buf_32'), 'flow'):
                                    "buf32in",
                                   (('buf_32', 'b_th32'), 'flow'):
                                    "buf32out"},
                          inplace=True)

result_sequences40 = oemof.outputlib.views.node(results,
                                              'b_th40')['sequences']
result_sequences40.rename(columns={(('st_40', 'b_th40'), 'flow'):
                                   "ST40",
                                   (('HP40', 'b_th40'), 'flow'):
                                   "HP40",
                                   (('P2H40', 'b_th40'), 'flow'):
                                   "P2H40",
                                   (('G2H40', 'b_th40'), 'flow'):
                                   "G2H40",
                                   (('CHP40', 'b_th40'), 'flow'):
                                    "CHP40",
                                   (('b_th40', 'd_th40'), 'flow'):
                                    "d_th40",
                                    (('b_th40', 'buf_40'), 'flow'):
                                    "buf40in",
                                   (('buf_40', 'b_th40'), 'flow'):
                                    "buf40out"},
                          inplace=True)

result_sequences_el = oemof.outputlib.views.node(results,
                                               'b_el')['sequences']
result_sequences_el.rename(columns={(('m_el', 'b_el'), 'flow'):
                                    "E_{el,in}",
                                    (('b_el', 'd_el'), 'flow'):
                                        "E_{demand}",
                                    (('b_el', 'x_el'), 'flow'):
                                    "E_{el,out}",
                                    (('b_el','P2H32'), 'flow'):
                                    "P2H32_{in}",
```

```
                                    (('b_el','P2H40'), 'flow'):
                                    "P2H40_{in}",
                                    (('b_el', 'HP15'), 'flow'):
                                    "HP15_{in}",
                                    (('b_el','HP32'), 'flow'):
                                    "HP32_{in}",
                                    (('b_el', 'HP40'), 'flow'):
                                    "HP40_{in}",
                                    (('CHP32', 'b_el'), 'flow'):
                                    "CHP32_{el}",
                                    (('CHP40', 'b_el'), 'flow'):
                                    "CHP40_{el}"},
                                   inplace=True)
result_sequences_gas = oemof.outputlib.views.node(results,
                                             'b_gas')['sequences']

result_sequences_gas.rename(columns={(('m_gas', 'b_gas'), 'flow'):
                                     "Gas,in",
                                     (('b_gas', 'CHP32'), 'flow'):
                                     "CHP32_{in}",
                                     (('b_gas', 'CHP40'), 'flow'):
                                     "CHP40_{in}",
                                      (('b_gas', 'G2H32'), 'flow'):
                                     "G2H32_{in}",
                                     (('b_gas', 'G2H40'), 'flow'):
                                     "G2H40_{in}"},
                                    inplace=True)
result_sequences = pd. concat([result_sequences_el["E_{el,in}"],
                               result_sequences_el["E_{el,out}"],
                               result_sequences_el["E_{demand}"],
                               result_sequences_el["HP15_{in}"],
                               result_sequences_el["HP32_{in}"],
                               result_sequences_el["HP40_{in}"],
                               result_sequences_el["P2H40_{in}"],
                               result_sequences_el["P2H32_{in}"],
                               result_sequences_gas["Gas,in"],
                               result_sequences_gas["G2H32_{in}"],
                               result_sequences_gas["G2H40_{in}"],
                               result_sequences_gas["CHP40_{in}"],
                               result_sequences_gas["CHP32_{in}"],
                               result_sequences15["ST15"],
                               result_sequences15["buf15out"],
                               result_sequences15["buf15in"],
                               result_sequences15["HP15"],
                               result_sequences32["ST32"],
                               result_sequences32["HP32"],
                               result_sequences32["CHP32"],
                               result_sequences32["buf32out"],
                               result_sequences32["buf32in"],
                               result_sequences32["d_th32"],
                               result_sequences32["P2H32"],
                               result_sequences32["G2H32"],
                               result_sequences40["ST40"],
```

```
                                result_sequences40["HP40"],
                                result_sequences40["P2H40"],
                                result_sequences40["G2H40"],
                                result_sequences40["CHP40"],
                                result_sequences40["buf40out"],
                                result_sequences40["buf40in"],
                                result_sequences40["d_th40"],
                                result_sequences_el["CHP40_{el}"],
                                result_sequences_el["CHP32_{el}"]],
                                 axis=1, sort=False)

result_sequences *= 1000

if exergy:
        symbol = "X"
        basename = "exergy"
        linestyle='solid'
else:
        symbol = "E"
        basename = "energy"
        linestyle='dashed'

if result_sequences.index.tzinfo is not "UTC":
        date_format = "%Y-%m-%dT%H:%M:%SZ"
else:
        date_format = "%Y-%m-%dT%H:%M:%S%z"


result_sequences.to_csv(basename+"filetouse_wt_26.csv",
                             sep=',',
                             encoding='utf-8',
                             date_format=date_format)

plt.rc('figure', figsize = (13,5))

plt.step(result_sequences.index,
             result_sequences["HP15_{in}"],
             label=symbol+r"$_\mathrm{HP15_{in}}$",
             linestyle=linestyle)
plt.step(result_sequences.index,
             result_sequences["HP32_{in}"],
             label=symbol+r"$_\mathrm{HP32_{in}}$",
             linestyle=linestyle)
plt.step(result_sequences.index,
             result_sequences["HP40_{in}"],
             label=symbol+r"$_\mathrm{HP40_{in}}$",
             linestyle=linestyle)
plt.step(result_sequences.index,
             result_sequences["CHP32_{in}"],
             label=symbol+r"$_\mathrm{CHP32_{in}}$",
             linestyle=linestyle)
plt.step(result_sequences.index,
             result_sequences["ST15"],
```

```
                 label=symbol+r"$_\mathrm{ST15}$",
                 linestyle=linestyle)
    plt.step(result_sequences.index,
                 result_sequences["ST32"],
                 label=symbol+r"$_\mathrm{ST32}$",
                 linestyle=linestyle)
    plt.step(result_sequences.index,
                 result_sequences["buf40out"],
                 label=symbol+r"$_\mathrm{buf40out}$",
                 linestyle=linestyle,
                 marker='x')
    plt.step(result_sequences.index,
                 result_sequences["buf32out"],
                 label=symbol+r"$_\mathrm{buf32out}$",
                 linestyle=linestyle,
                 marker='x')
    plt.step(result_sequences.index,
                 result_sequences["buf15out"],
                 label=symbol+r"$_\mathrm{buf15out}$",
                 linestyle=linestyle,
                 marker='x')
    plt.step(result_sequences.index,
                 result_sequences["d_th32"],
                 label=symbol+r"$_\mathrm{dth32}$",
                 linestyle='dotted')
    plt.step(result_sequences.index,
                 result_sequences["d_th40"],
                 label=symbol+r"$_\mathrm{dth40}$",
                 linestyle='dotted')
    plt.step(result_sequences.index,
                 result_sequences["CHP40_{in}"],
                 label=symbol+r"$_\mathrm{CHP40_{in}}$",
                 linestyle=linestyle)
    plt.step(result_sequences.index,
                 result_sequences["ST40"],
                 label=symbol+r"$_\mathrm{ST40}$",
                 linestyle=linestyle)
    plt.step(result_sequences.index,
                 result_sequences["P2H40_{in}"],
                 label=symbol+r"$_\mathrm{P2H40_{in}}$",
                 linestyle=linestyle)
    plt.step(result_sequences.index,
                 result_sequences["P2H32_{in}"],
                 label=symbol+r"$_\mathrm{P2H32_{in}}$",
                 linestyle=linestyle)

plt.grid()
plt.legend()
plt.rc('xtick', labelsize=13)
plt.rc('ytick', labelsize=13)
plt.xlabel('Hours', fontsize=13)
plt.ylabel('Energy (kWh)', fontsize=13)
plt.show()
```

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Declaration

I state and declare that this thesis was prepared by me and that no means or sources have been used, except those, which I cited and listed in the references section. The thesis is in compliance with the rules of good practise in scientific research of Carl von Ossietzky Universität Oldenburg.

Oldenburg, 29 November 2019