Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

Åshild Ryen Vespestad

Assessing energy flexible operation of a residential Zero Emission Building (casaZero)

Master's thesis in Energy and Environmental Engineering
Supervisor: Vojislav Novakovic
Co-supervisor: Karen Byskov Lindberg
June 2022

NTNU
Kunnskap for en bedre verden

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EPT-M-2022

PROJECT WORK

for

student Åshild Ryen Vespestad

Spring 2022

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Vurdering av energifleksibel drift av et nullutslippshus (casaZero)

Background and objective

Moving towards zero emission buildings, energy can be managed in a flexible way, to achieve e.g., reduced power peaks, reduced energy use, reduced CO_2-emissions, increased self-consumption of locally produced energy, or provide flexibility services to distribution system operators (DSOs).

The aim of this assignment is to investigate the impact of intelligent energy management in households, using data gathered from a real zero emission building situated in Oslo (casaZero). casaZero has roof-mounted PV, a ground-source heat pump, waterborne floor heating and a ventilation system. The goal is to establish a model that can simulate the house, and use this model to investigate different operational strategies and how these will affect the performance of the building regarding e.g. peak load, energy costs and self-consumption of PV, as well as thermal comfort of the residents and other indoor environmental parameters.

The following tasks are to be considered:

1. Review previous work on optimal and/or flexible operation of Zero Emission Buildings / Zero Energy Buildings.
2. Propose and develop a suitable simulation model of casaZero (using e.g. Modelica or IDA-ICE) that could be used for assessing the energy flexibility potential of the case building (casaZero). Preferably utilising some of the energy measurements gathered in the project thesis.
3. Investigate how different operational strategies of the ground source heat pump may impact the performance of the building.
4. Make a draft proposal (6-8 pages) for a scientific paper based on the main results of the work performed in the master thesis.
5. Make proposal for further work on the same topic.

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The master work comprises 30 ECTS credits.

Address
N-7034 Trondheim
Norway

Location
K. Hejes vei 1b

Tel. +47 73 59 38 60
Fax +47 73 59 35 80
Org. no. NO 974 767 880

The work shall be edited as a scientific report, including a table of contents, a summary in Norwegian, conclusion, an index of literature etc. When writing the report, the candidate must emphasise a clearly arranged and well-written text. To facilitate the reading of the report, it is important that references for corresponding text, tables and figures are clearly stated both places.
By the evaluation of the work the following will be greatly emphasised: The results should be thoroughly treated, presented in clearly arranged tables and/or graphics and discussed in detail.

The candidate is responsible for keeping contact with the subject teacher and teaching supervisors.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

According to “Utfyllende regler til studieforskriften for teknologistudiet/sivilingeniørstudiet ved NTNU” § 20, the Department of Energy and Process Engineering reserves all rights to use the results and data for lectures, research and future publications.

Submission deadline: June 15th, 2022

☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department for Energy and Process Engineering, *January 2022*

Vojislav Novakovic

Vojislav Novakovic
Supervisor

Co-Supervisor(s):
Senior Research Scientist Karen Byskov Lindberg, SINTEF Community, e-mail: karen.lindberg@sintef.no

Preface

This Master´s thesis was written at the Department of Energy and Process Engineering at the Norwegian University of Science and Technology, NTNU, in Trondheim. The work was conducted during the spring of 2022. The supervisor for this project was Vojislav Novakovic, and Karen Byskov Lindberg was the co-suprevisor.

The author would like to express gratitude for all the help and guidance provided by the supervisor Vojislav Novakovic. Furthermore, acknowledgement should be given to the co-supervisor Karen Byskov Lindberg for her great help and patience during the work of this thesis as well as her willingness to share data from casaZero. Natasa Nord should also be thanked for her help in providing licence and guidance for the work performed in IDA ICE. Last the author would like to thank NTNU for providing the opportunity to complete this master´s degree.

Trondheim, June 2022.

Åshild Ryen Vespestad

Abstract

With an increasing amount of new and retrofitted buildings qualifying as ZEBs, the interaction between buildings and the grid has increased. Buildings that both produces and consumes electricity, prosumers, are likely to both import and export electricity to the grid. Hence, the need to utilized smart controlling of the electricity consumption in buildings is reinforced, as an attempt to reduce the stress on the grid. This study is a contribution to increasing the knowledge on flexible operation of ZEBs. The case building in this research was a residential ZEB located in Norway. The building was equipped with a GSHP, a balanced ventilation system, PV panels and water borne floor heating. A simulation model of the case building was established in IDA ICE. By implementing 65 different operational schedules to the GSHP the impact on the performance of the building was analysed, regarding self-consumption, peak load and cost. It was found that the self-consumption could be increased by 13.7%. The summer season was found to be the most influential season considering further increasing of the self-consumption. By introducing an additional load simulating the battery of an EV, the self-consumption was further increased by 53.3%, compared to the case without a GSHP schedule. The maximum reduction for peak load and cost found in this research were 50% and 9.7%, respectively. When equally weighting the three KPIs, the results showed that a GSHP schedule with a constant value of 0.5 gave the best overall result. A relation between the different KPIs were discovered, making it challenging to decrease the cost while increasing the self-consumption.

Sammendrag

Med en økende andel nyoppsatte og oppussede bygg som tilfredsstiller dagens krav for nullutslippshus har også interaksjonen mellom bygninger og kraftnettet økt. Bygg som både produserer og konsumerer elektrisitet, prosumers, er ofte både importører og eksportører av elektrisitet til nettet. Av den grunn har behovet for smart styring av laster i bygg økt i et forsøk på å senke belastningen på nettet. Dette studiet er et bidrag til å øke kunnskapen om fleksibel drift av nullutslippshus. Bygget som ble studert i denne masteroppgaven er et nullutslipps bolighus i Norge. Bygget var utrustet med en bergvarmepumpe, balansert ventilasjon, solcellepaneler på taket og vannbåren gulvvarme. En simuleringsmodell av bygget ble laget i IDA ICE. Ved å implementere 65 ulike timeplaner for driften av varmepumpen i bolighuset ble påvirkningen på byggets energiprestasjon studert, med tanke på selv-konsumering, topplast og kostnad. Fra resultatene i oppgaven ble det funnet at selv-konsumeringen kunne økes med 13.7%. Sommeren var den årstiden som hadde størst potensialet for videre økning av selv-konsumeringen. Ved å implementere en last som representerte batteriet til en elbil ble selv-konsumeringen økt med 53.3% sammenlignet med modellen uten timeplan for styring av varmepumpa. Den største reduksjonen i topplast og kostnad var henholdsvis 50% og 9.7%. Når hver av de tre indikatorene for nøkkelytelse ble vektlagt likt viste resultatene at varmepumpetimeplanen med konstant verdi på 0.5 ga de beste resultatene sammenlagt. Det ble oppdaget en sammenheng mellom de ulike indikatorne for nøkkelytelse, noe som gjorde det vanskelig å redusere kostnadene samtidig som selv-konsumeringen skulle økes.

Abbreviations

AHU Air Handling Unit

BIM Building Information Modeling

BPS Building Performance Simulation

CHP Combined Heat and Power

DHW Domestic Hot Water

DSM Demand Side Management

EV Electric Vehicle

GHG Green House Gas

$GSHP$ Ground Source Heat Pump

$HEMS$ Home Energy Management System

HP Heat Pump

$HVAC$ Heating, Ventilation and Air Conditioning

$IDA\ ICE$ IDA Indoor Climate and Energy

IFC Industry Foundation Classes

KPI Key Performance Indicator

$nZEB$ nearly Zero Emission Building

PPD Percentage of People Dissatisfied

PV Photo voltaic

TES Thermal Energy Storage

ZEB Zero Emission Building

ZEN Zero Emission Neighborhood

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1 Introduction

This section introduces the motivation and the scope of this thesis as well as some limitations. Last, an overview of the content of this thesis is given.

1.1 Motivation

About one third of the global energy use and 40% of the total CO2 emission world wide today is caused by the building sector, during the constructional and operational phase [1]. To lower the CO2 emission in Europe the European Union has decided to reduce the CO2 emission associated with the building sector by 80-95%, compared to the 1990 level by 2050 [2]. To reach this goal Zero Emission Buildings (ZEBs) are an important part of the strategy. In 2010 the European Union stated that by the end of 2020 all new buildings should be nearly Zero Emission Buildings (nZEBs) [3].

As all buildings require a minimum amount of electricity, ZEBs depend on on-site renewable electricity production to fulfill the ZEB requirement. The renewable electricity sources available are often fluctuating, leaving the building dependent on electricity from the grid in the hours when the local electricity sources are not supplying sufficient amount of electricity to the building [4]. When the local electricity sources produce more electricity than consumed by the building, excess electricity can be supplied to the grid. This way of buying and selling electricity to the grid characterizes the building as a prosumer [5]. With an increasing number of prosumers intermittently supplying electricity to the grid, the grid companies are facing challenges handling the unpredictability in the grid. Both considering hourly mismatch and seasonal mismatch [6].This calls for an increased utilization of energy flexibility measures in ZEBs to increase the self-consumption of electricity in the building.

The energy flexibility measures are divided into three categories, load shifting measures, peak shaving measures and valley filling measures. The first measure aims to shift the load from hours with high electricity consumption to hours with lower electricity consumption. The second measure reduces the peak load, and the third measure aims to increase the consumption in periods with low consumption to flatten the curve [7]. By combining these measures the operation of a ZEB can be managed in an optimal and flexible way. One way of optimizing the operation of a ZEB is by parametric study. In this method all parameters except one are fixed. The non-fixed parameter is varied to find the optimal solution to the problem [8]. The more complex the building is, the more time consuming the optimization process becomes. To optimize the load profile in a more time effective way simulation based methods are needed. These can be used, for instance, in optimization of the building design, concerning energy use or in cost- optimization of the operation of a building [9].

Since the term ZEB was introduced in 2006 [10], several research papers have been written focusing on optimizing ZEBs. New and improved technology has emerged, enabling communication between technical equipment in the building. This increases the possibility for operating buildings in an optimal way, considering cost, CO2 emission, indoor environment etc. Despite this, to the authors knowledge, the main research area on ZEB has been optimizing the design rather than the operation. Research like [6] and [11] are focusing on cost optimization of the design of a ZEB, while [12] is focusing on optimizing the design to minimize green house gas (GHG) emission. In a research done in a climate with cold winters and hot summers, an optimization of design indicated almost 35% reduction in electricity consumption of a residential building [13]. To find out how optimal operation of a ZEB can effect the energy use, cost, CO2 emission etc. more research on optimization of the operation of ZEBs is coveted.

1.2 Scope

To contribute to more research on optimal and flexible operation of ZEBs, this thesis aims to establish a model to simulate a ZEB in order to investigate the energy flexibility potential of the building. The main objective of this research is to assess energy flexible operation of a residential ZEB, named casaZero. The building is located in Norway and it is equipped with photo voltaic (PV) panels, a ground source heat pump (GSHP), a balanced ventilation system and a water borne heating system. By the use of simulation software, different operational strategies are to be investigated in regard to peak load, cost and self-consumption.

To perform this analysis the task is divided into five main parts:

- Perform a literature review on previous research on optimal or flexible operation of ZEBs.
- Establish a model of the case building to be used in assessment of the energy flexibility potential of casaZero.
- Apply different operational strategies to the GSHP to find the influence on the performance of the building.
- Make a proposal for further work on the same topic.
- Write a draft for a scientific paper based on an excerpt of the results found in this master thesis.

1.3 Limitation

Amongst the limitations found in this research are the many assumptions necessary to establish a simulation model in IDA ICE. Several schedules were implemented for cost, tapping of domestic hot water (DHW), occupants, temperature etc. To produce more accurate results real measured data should be used. The household possesses an electric vehicle (EV) that is considered a shiftable load. Only one simulation was run with a load corresponding to the battery of an EV. To find the energy flexibility potential of casaZero with the EV, more simulations should be done including the EV. Further, IDA ICE does not offer the possibility to establish schedules with seasonal differences. Applying different schedules for different seasons would provide better results, due to the large variation in electricity consumption for the different seasons.

1.4 Thesis overview

The content of this thesis is divided into 8 chapters. Chapter 2 includes background information and a literature review on optimal and flexible operation of ZEBs. Chapter 3 describes the utilized methodology, including the simulation software, a detailed description of the case building and the key performance indicators (KPIs) utilized to analyse the results. Chapter 4 describes the cases studied in this thesis. Chapter 5 includes the results. Chapter 6 discusses some limitations of this research. Chapter 7 is the conclusion of the work and Chapter 8 includes suggestions for further work on the topic.

2 Theory

This section describes the background information for this master thesis. It includes definitions of ZEBs, energy flexibility and demand side management (DSM). The last part of this chapter is a literature review of previous research on optimal and flexible operation of ZEBs.

2.1 ZEB definition

Before discussing the operation of a ZEB, a definition of the ZEB-concept must be established. A ZEB is usually referred to as an energy efficient building with on-site renewable energy generation sized to generate at least the amount of energy used by the building [10]. This can be achieved by designing a house with a minimum need of energy combined with utilization of local renewable energy sources [14]. The exact definition and requirement for a ZEB differs from country to country. One such difference is the minimum requirement for utilization of renewable energy. While the US does not have any requirements, the EU has a minimum number of 20% of the total energy use of the building [15]. The targeted energy use does also vary for these two regions. In addition to regulations differing from countries, the local climate condition is an important factor when deciding the design and technical solutions of a ZEB. Solutions to reduce the cooling demand is important in a hot climate [16], while in a cold climate, solutions to reduce the heating demand is vital to meet the local requirements for a ZEB [11].

The three important principles when designing and operating a ZEB is shown in Figure 1. The first principle is to avoid unnecessary energy use. This includes constructing the building envelope to avoid thermal bridges and to minimize heat loss through external surfaces. The second principle is to reduce energy use by, for instance, increasing the energy efficiency of technical installations in the building. The last, and most vital principle to qualify as a ZEB is replacing the energy used in the building by on-site renewable energy generation.

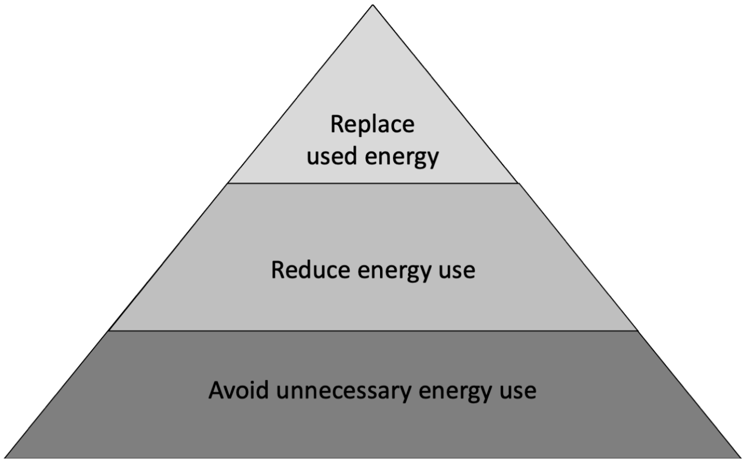

Figure 1: The three basic principles for ZEBs.

The ZEB research centre [17] has organized ZEBs into different sub categories depending on the ambition levels for the zero emission balance of the building.

- ZEB-O: The building generates as much renewable energy as required to compensate for GHG emission during operation of the building.
- ZEB-O÷EQ: The building generates as much renewable energy as required to compensate for GHG emission during operation of the building, minus the energy used by equipment.
- ZEB-OM: The building generates as much renewable energy as required to compensate for GHG emission during operation of the building and during production of the used materials.
- ZEB-COM: The building generates as much renewable energy as required to compensate for GHG emission during operation, during production of the used materials and during the construction of the building.
- ZEB-COMPLETE: The building generates as much renewable energy as required to compensate for GHG emission for the entire life cycle of the building.

Figure 2 shows the energy balance in a ZEB-COMPLETE with a renewable energy generation balancing the energy use for all four phases of the building life cycle.

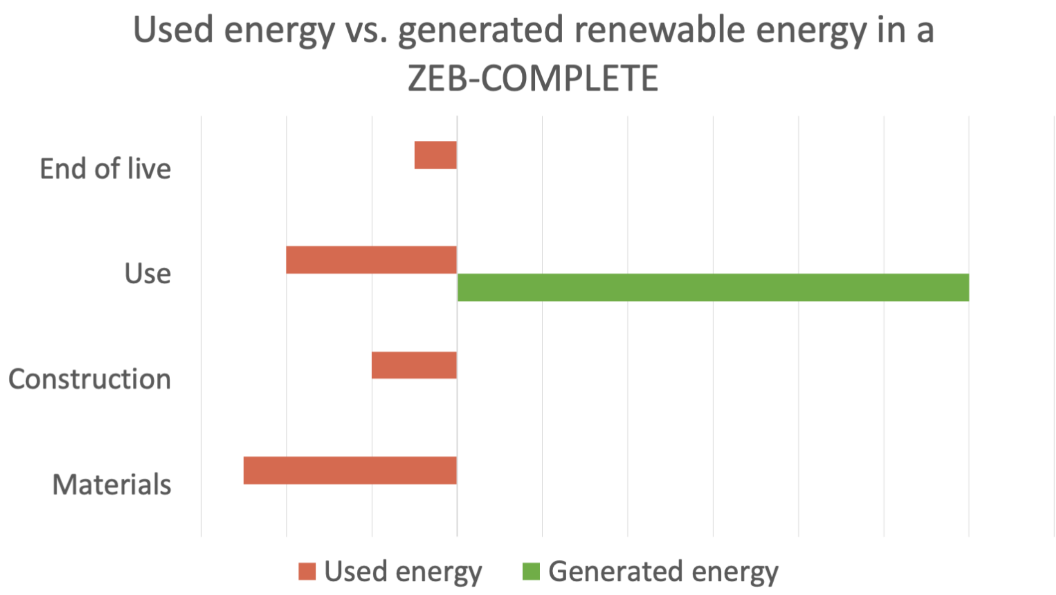

Figure 2: Energy balance for a ZEB-COMPLETE.

2.2 Defining energy flexibility of buildings

With increased focus on ZEBs, the utilization of on-site fluctuating renewable energy sources is rising. This has led to a growing interest in utilization of the energy flexibility potential of buildings. However, it is not easy to define the energy flexibility that a building can provide [18]. This is due to the large amount of factors effecting the energy flexibility. The Cambridge dictionary definition of flexibility is "the ability to change or be changed easily according to the situation". Hence, the definition of energy flexibility of buildings would also include the ability to change according to the situation. The International Energy Agency defines energy flexibility in a building as "the capacity of a building to manage its demand and generation according to local climate conditions, user needs and grid requirements" [19].

Figure 3 shows an overview of typical factors contributing to the potential of energy flexibility in a building. Building mass, thermal storage and batteries are all offering energy flexibility potential by storing energy, so that energy peaks can be shifted. Generation provides a potential of self-consumption to the building that might ease the pressure on the grid. Fuel shifting is based on the concept of utilizing several fuels to be able to switch the energy source in the building depending on, for instance, the price of the different fuels. A combination of a heat pump (HP) and a gas boiler to satisfy the heating demand, is an example of increasing the potential of energy flexibility in a building by fuel shifting. The last category is the flexibility provided by connecting the building to a grid.

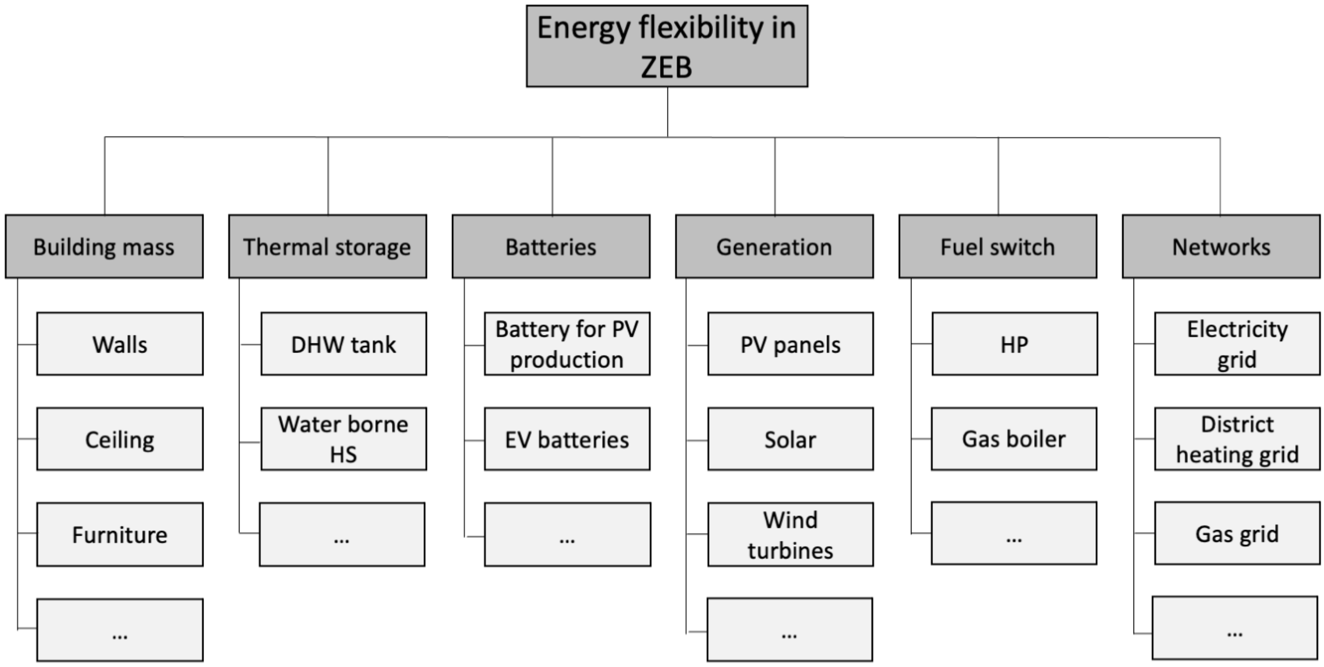

Figure 3: Categorized ways to achieve energy flexibility in a building.

Though the building might include several of the components displayed in Figure 3, the ability to utilize the energy flexibility depends on implementation of control strategies [18]. Such strategies might vary in complexity from a simple schedule controlling on and off of a ventilation system, to complicated model based controlling strategies where load forecasting, price estimation and occupancy behaviour are some of the factors influencing the system.

2.3 Demand Side Management

An example of utilization of energy flexibility in a building by implementing control strategies is the demand side management (DSM). DSM aims to balance the demand and supply in a smart energy system. To optimize building operation with respect to GHG emission, minimizing the gap between energy generation and energy use is of importance according to Farrokhi et al. [20]. To enable DSM in a building a communication infrastructure between the equipment of the building is important. Through communication, the different equipment and technical installations in the building can interact towards optimal operation. DSM can be utilized to enable energy flexibility measures in a buildings, such as valley filling and peak shaving. All three measures are displayed in Figure 4. DSM can perform instantaneously optimization of building operation by being an integrated part of the system in a building. This requires a load prediction model to estimate the future load for the building.

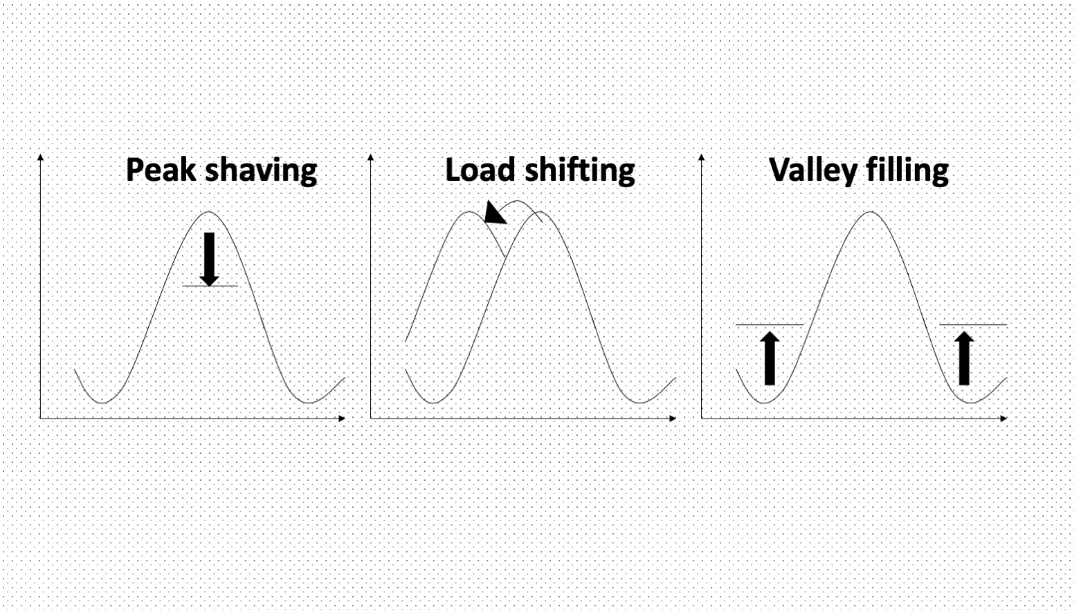

Figure 4: Demonstration of peak shaving, load shifting and valley filling.

Night time heating is an example of peak shaving implemented in some office buildings [21]. This allows heating to be performed during the night or early in the morning, before employees arrive. The office can be provided with comfortable temperatures and at the same time reduce the peak load during the day by utilization of thermal energy storage (TES) in the building. This example shows how technical installations of the building can be controlled to contribute to a more optimal operation of a building.

2.4 Optimal and flexible operation of ZEB

There are several reasons for utilizing the energy flexibility of a building through optimization of the building operation. Researchers have pointed out reduction of stress on the electricity grid [22], cost reduction and CO2 emission reduction [23] as some important factors. In this subsection, previous literature on the topic is used to conclude how energy flexibility of buildings can be evaluated.

Optimization of a process can be both single objective optimization and multi objective optimization, depending on the amount of objectives for the optimization process [24]. The goal for both single and multi objective optimization of building operation is to find the solution that optimizes the objective function based on a set of given constraints. In building operation the objective function can be minimization of cost, energy demand, GHG emission, peak load etc. Examples of constraints are the energy balance, indoor air temperature, air quality and other factors influencing the comfort of the occupants of the building. It has been shown that optimizing one parameter might degrade the results of other parameters [25]. When performing optimization of building operation, multi objective optimization is more convenient as it considers multiple objectives and constraints.

Handling multi objective optimization problems requires a large amount of various parameter combinations. To optimize such problems in a time efficient way, optimization tools can be utilized. One such tool is the optimization software GenOpt. This software is developed to minimize a cost function. By iterative calling of building energy modeling (BEM) softwares like IDA ICE, TRNSYS or EnergyPlus, GenOpt evaluates the objective function. GenOpt has been used in research like [9] and [26]. Another software used for optimization is FICO Xpress Mosel. This optimization language can be used to develop models to solve comprehensive optimization problems. In a research done by Lindberg et al. [6] this optimization language was utilized to evaluate the cost-optimal solution for an energy system as well as the hourly operation of a ZEB.

Another example of combining a dynamic energy simulation tool and an optimization tool like GenOpt can be found in a research performed by Ferrara et al. [23], in 2019. The method was used to cost optimize the energy efficient measures of a nearly zero emission multi-family building, located in northern Italy. In the research, the energy simulation program TRNSYS was used to establish the objective function, and a suitable optimization algorithm was chosen in GenOpt. This software can be used to evaluate, not only the optimal solution, but also neighbouring values. Hence, alternative solutions to the optimal value can be considered. In the mentioned research this resulted in findings that showed the possibility of decreasing the energy demand per square meter by slightly increase the total cost.

The review of previous research on flexible and optimal operation of ZEBs found that the most common objectives are minimizing the cost and maximizing self-consumption. Furthermore, it was found that most research uses multi objective optimization, focusing on several objectives at a time. The following sections describes the most common optimization objectives in ZEB operation.

2.4.1 Optimizing cost

An important factor when designing and operating a ZEB is the cost. Since economics is a governing factor in a lot of decisions made both in private life and on a national level, reducing the cost of building operation will always be of interest.

When minimizing the operational cost of a ZEB, it is important to include the thermal comfort of the occupants as a restriction. This is in addition to the restrictions given by the definition of a ZEB. This was done in a research performed by Zhang et al. [27]. The aim of their research was to find the optimal operation, considering both minimizing electricity cost and maximizing comfort for the occupants. By making use of a home energy management system (HEMS) the imported, exported and consumed electricity by the different installations were monitored. The HEMS was equipped with a controller that communicated with the components through a home area network. The HEMS also accessed weather prediction, that enabled it to make estimations for both PV production and heat load for the building. During the process of establishing the optimization algorithm the research team utilized weighting methods to merge the two optimization objects into a single optimization object. This resulted in an algorithm implemented to the HEMS that optimized the cost and comfort properties for the next 24 hours.

Lindberg et al. [6] investigated the energy systems in a ZEB. They found that the variety in ZEB definitions might influence the cost optimization of a building. In a cost optimization research utilizing three different grades of ZEB, "no"-ZEB, "nearly"-ZEB and "Strictly"-ZEB, the cost optimal energy system and hourly operation was studied. They differed regarding to their level of ZEB, hence, the level of gap between generation and use of energy. It was found that the optimal operation of the building, depended on the definition of ZEB. This indicate that optimal operation of a ZEB might differ from country to country due to different requirements regarding energy use and generation in ZEBs.

When considering cost of operation of a building, the concept of penalty cost due to emission should be mentioned. This was the focus in a research performed by Thorvaldsen et al. [28]. The aim was to cost-optimize the operation of a ZEB while considering costs due to emission compensation. It was found that with a low penalty cost for emission, the operation was regulated by the electricity price. This caused load shifting to hours of the day when the electricity price was low. With high penalty cost the operation of the building was changed, increasing the load during hours with low emission intensity. Cost optimal operation of a ZEB will therefore vary depending on penalty cost of CO2 emission.

2.4.2 Optimizing self-consumption

While self-sufficiency is the amount of the energy demand that is covered by the on-site generation, self-consumption is the share of the produced electricity that is consumed locally [29]. To ease the pressure on the grid, the self-consumption should be as high as possible.

Though a building might have a high rate of self-sufficiency, the self-consumption can still be low without proper energy storage or load control strategies. Figure 5 shows a fictive curve of the load profile and the electricity production in a residential building for a 24 hour period. The need for load matching is clearly vital when optimizing the self-consumption of a ZEB. Lopes et al. [30] divides the approaches found in research on load matching into three, energy storage, DSM and a combination of the two. Most of the researches including energy storage consider TES or electrical batteries, but some research analyzes the ability of hydro storage to improve the load matching [31]. The following sections confirms that by utilizing energy storage and control strategies, it is possible to improve the self-consumption of a ZEB.

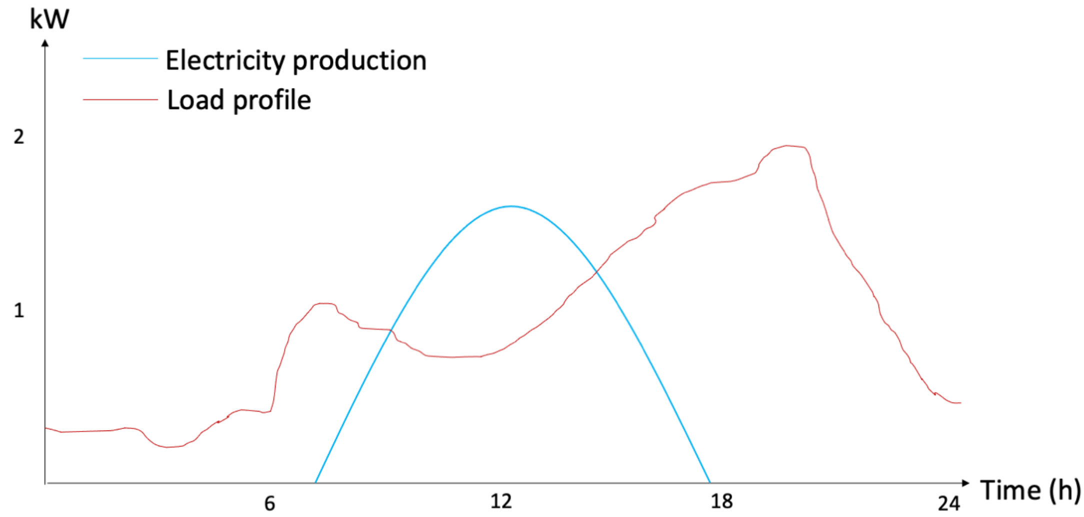

Figure 5: Example of how the load profile for a 24h period might not match the electricity production in a residential building.

Dar et al. [25] did a research on improving the energy flexibility of a ZEB based on HP control. The chosen energy storage for the research was the TES, and the research included investigation of three control strategies. It showed that the self-consumption could be increased by 40% with proper control of the HP. In the case of the research a seasonal storage could further improve the amount of self-consumed energy for the building.

Cillari et al. [32] found that only 40% of the produced electricity from the PV panels were consumed by the building without energy storage. By introducing energy storage this value increased to 97%. A study performed by Liu et al. [14] claimed that by adjusting the angle of the PV panels, the self-consumption in some of the analyzed buildings were increased to 100%. The mentioned thesis further implied that maximizing the self-consumption might provoke a reduction of produced electricity. It is therefore important to find appropriate weighting factors for the evaluated KPIs, as an optimization of one KPI might reduce another important KPI.

Kayo et al. [33] concluded that zero emission neighborhood (ZEN) is favorable compared to ZEBs in order to increase the self-consumption. The concept of a ZEN differs from a ZEB as it is not as limited in size, shape and availability of on-site energy generation as a single ZEB. Merging the energy generation systems for several buildings may also reduce the total investment cost, compared to investing in energy generation system for each ZEB in the neighborhood. The possibility of increased self-consumption for ZEN is caused by the possibility to transfer surplus electricity between buildings. An office building, a hospital, a hotel and a shopping centre in Japan was studied separately and in clusters. By applying three different control strategies for the combined heat and power (CHP) generator, the amount of annually primary energy use was studied. It was discovered that with any combination of buildings, the annually used energy decreased, compared to the energy used when the buildings were operating separately. Furthermore, a reduction in surplus electricity was found, hence an increasing in self-consumption.

Lopes et al. [30] performed a research on cooperative nZEBs, confirming that by connecting nZEBs the total self-consumption could be increased. They found an improvement of 18-20% in self-consumption in the community, compared to the respective values for each building separately. The authors assumed the increase to be caused by the difference in load profile for each building, as well as an increased amount of loads manageable by the DSM system in the community. Furthermore, the potential of increased amount of available generated energy is mentioned as one of the causes.

2.4.3 Optimizing peak load

A third optimization objective found in literature is the minimization of peak load. A new price regulation for grid costumers in Norway is to be implemented by the end of 2022 [34], encouraging reduction in peak load. Today Norwegian grid costumers pay a constant price for grid rent, in addition to the price for the amount of electricity imported from the grid. The new prices suggests that costumers also pay according to the peak load of the imported electricity. This makes minimization of peak load more valuable.

Comodi et al. [35] investigated a multi apartment ZEB in Italy. They found that the TES provided peak shaving potential, as heat energy could be stored and used during peak hours. The building was equipped with both a battery for the PV production and TES solutions. Though both the battery and the TES increased the energy flexibility potential of the building, only the TES was profitable at the current price conditions. The article expresses the need for energy storage solutions to increase the energy flexibility of a building, especially regarding the peak shaving potential. It further emphasise the importance of considering economy when analysing optimal operation of ZEBs.

2.4.4 Optimizing energy use

The last evaluation criteria to be discussed is the minimization of energy use. During the design phase, research on minimization of energy use is based on choices of technical installations and materials, while research during operational phase focus on how these components can work together in an optimal way. As ZEBs are considered one of the solutions to reducing the world wide energy use, more research on minimization of energy use based on optimal operation is to be expected in the coming years.

A problem that might occur in ZEBs is that the estimated self-sufficiency during design phase does not match the one during operational phase. This can be due to, for instance, mismatch between estimated and actual occupancy behaviour [36]. Mavrigiannaki et al. [37] performed a research to confirm the level of ZEN on a neighborhood in Italy. It showed that there was a difference in the gap between estimated and monitored electricity consumption. While the gap was significant during heating season, it was reduced during cooling season. The authors concluded that this was caused by individual preferences of the occupants controlling the HVAC system. However, the research also found that though there was a monthly mismatch between consumption and production, the yearly electricity consumption did not exceed the electricity production.

Zhou et al. [38] did a study on an existing ZEB in China. In contrast to Mavrigiannaki et al. they discovered that the gap between energy use and on-site generation of energy had increased compared to the estimated energy balance, to a level where the building no longer qualified as a ZEB. The main reasons found for the mismatch was variations in the weather file used for the simulation compared to the measured data, causing less produced electricity from the PV panel than predicted. The second reason was the lack of competence among the occupants to use the GSHP system in an optimal way. A slight difference in building function and equipment from the design phase to the operational phase led to further gap between predicted and measured energy use. This discovery shows the need for not only energy simulations during the design phase, but also monitoring during the operational phase as those values might differ significantly.

Though the main focus on reduction of energy use is during the design phase, the transition from design to operational phase is of importance to reach the ZEB requirements. Ferrara et al. [9] points out the importance of considering the relation between variables in a building to achieve optimal operation. The utilization of reliable energy models must therefore be stressed in attempts to reduce the gap in performance between the design phase and the operational phase.

3 Methodology

During the project work related to this master thesis, an attempt was done to gather measured data on electricity consumption and production from casaZero. Due to difficulties in accessing sufficient amount of data, it was decided to utilize a simulation based method to assess the energy flexibility potential of casaZero. The available data was used to calibrate the simulation model. This chapter includes description of the chosen simulation software. It describes the building utilized in this research as well as the three KPIs evaluated in this research. At last this chapter includes a section on the process of assessing the energy flexibility potential of casaZero.

To decide the simulation software utilized in this study, it was decided to emphasize the following characteristics:

- time efficient
- user friendly
- ability to simulate relevant outputs for energy flexibility analysis
- transparent

Based on these characteristics it was decided to utilize the simulation software IDA ICE.

3.1 IDA ICE

IDA ICE is a Building Performance Simulation (BPS) tool developed by the Swedish company EQUA Simulation AB. A mathematical model of a building can be made in IDA ICE by implementing physical parameters of building envelope and technical equipment in the building, such as ventilation system and heating mechanisms. The model is then used to simulate indoor climate and energy use. IDA ICE support import from Building Information Modeling (BIM) tools via Industry Foundation Classes (IFC) like AutoCAD, ArchiCAD and Autodesk Revit. Physical properties of a building can therefore be directly implemented from these softwares [39]. To find the influence of different operational strategies on the GSHP concerning three KPIs, calculations and experimental methods would be too time demanding. A one year simulation period of casaZero was performed in less than two hours, by utilization of IDA ICE. This enabled the possibility to try different operational strategies for the GSHP, without spending several years measuring data from the building.

The software is intuitive and user friendly. Hence, it is easy to use if the modeling skills in advance are limited. Furthermore, IDA ICE offers a wide range of output parameters such as temperatures, unmet heating hours, CO2 concentration etc. This makes it possible to analyse the indoor climate for each zone in detail. An energy report is given for each simulation, including the electricity consumption and production as well as import and export of electricity to the grid. Figure 6 shows an excerpt of the energy report from a simulation in IDA ICE. The electricity consumption is divided into different types of loads. This is of importance when assessing the energy flexibility potential of a building. Another advantage of utilizing IDA ICE is the transparency of the software, enabling the user to inspect every detail of the model.

	Total		Peak demand	
	kWh	kWh/m^2	kW	Time
Lighting, facility	1519.2	6.5	0.2538	18 Dec 07:47
Electric cooling	232.0	1.0	1.779	01 Aug 17:04
HVAC aux	1316.2	5.6	0.8144	15 Jul 17:57
Electric heating	1334.1	5.7	7.899	09 Feb 04:43
Total Facility	4401.5	18.8		
Equipment, tenant	1380.3	5.9	0.2263	18 Dec 07:48
Total Tenant	1380.3	5.9		
PV production	-10392.5	-44.5	-9.272	15 Jul 13:43
CHP electricity	0.0	0.0	0.0	
Total Produced	-10392.5	-44.5		
Electricity, balance	-4610.7	-19.7		

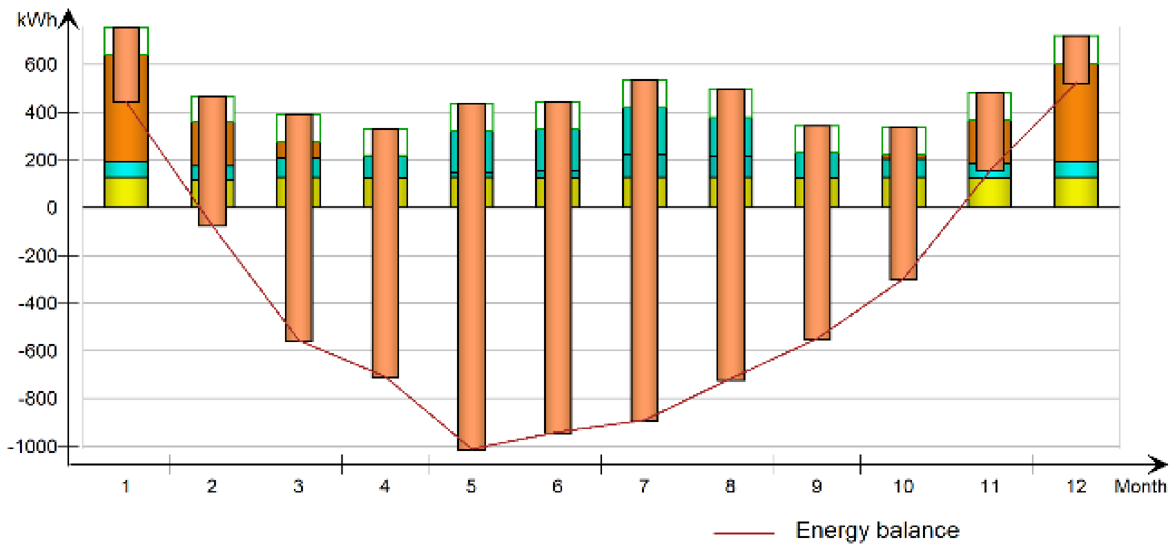

Figure 6: An excerpt of the delivered energy report given when running simulations in IDA ICE.

For evaluation of cost and income according to the delivered energy, IDA ICE provides settings for energy contracts. These contracts enables the user to implement prices for imported and exported energy, depending on the energy carrier. CO2 emission can also be added per volume of each energy carrier. This enables calculations on both the economical aspect and the environmental impact of the chosen solution. As cost was chosen as one of the KPIs analysed in this thesis, the potential of economical calculations was of importance when choosing the simulation software.

With the newest version of IDA ICE, IDA ICE 5, optimization tools are included in the software. In the newest version both GenOpt and AutoMOO can be initiated from IDA ICE. While GenOpt needs to be available as an external software on the computer, optimization utilizing AutoMOO can be done exclusively in IDA ICE. Figure 7 shows a chart flow of the optimization process utilizing AutoMOO. As described in the figure text, output data are given multiple times during an optimization. When the optimization process is done, the data is displayed in a diagram showing the results for every run during the optimization. The optimization function in IDA ICE enables optimization of several parameters at a time.

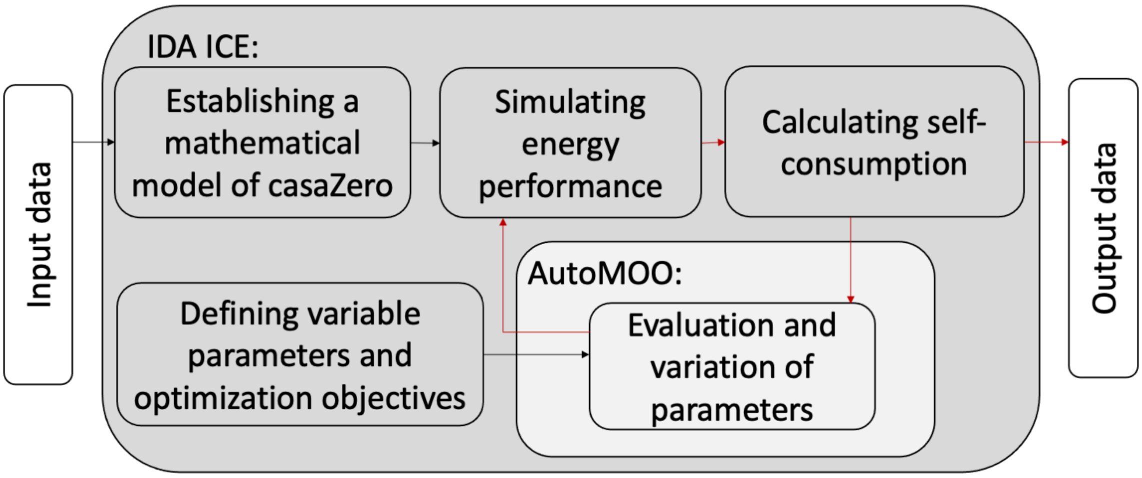

Figure 7: The chart flow for a process in IDA ICE, aiming to maximize the self-consumption. Black lines represent processes that are only done once, while the red lines represent repetitive processes that are done several times during an optimization.

During the work of this thesis, the development of IDA ICE 5 was still ongoing. Therefore, a beta version of the software was used. The optimization function was not capable of performing the planned optimization simulation due to a bug in the utilized version of IDA ICE. As a result of this, a manually implementation of different schedules for operation of the GSHP was implemented to evaluate its influence on the chosen KPIs. The procedure is described in the following sections.

3.2 CasaZero

The ZEB analysed in this thesis is a renovated residential building from the 1960s located in Kolsås, close to Oslo. The building consists of 3 levels, with two floors above and one below the ground level. The total heated area of the building is 233.6 m^2.

The building was divided into 21 zones, representing the rooms of casaZero. In the actual building, the living room area and the hall/entrance area on the 1. floor is open as shown in Figure 8. To reduce the size of the zones and increase control, the IDA ICE model was made with separate zones for the hall and the living room. The floor plan made in IDA ICE for each level is displayed in Figure 9. In casaZero there is an open solution between the entrance hall and the living room on the second floor. To simulate this in IDA ICE, zones where chosen differing from the actual zones of the building. The hall on the 1. floor was divided into three zones due to difference in room height. One zone representing the part of the hall covering the 2. floor. Another zone representing the hall in the 1. floor, and the last zone representing the entrance area. To simulate the actual circumstances, the hall zone on the 2. floor was equipped with a large opening in the floor, for heat to circulate as if there were no construction between the two zones. For the separated zones, openings were located on the walls between the zones to simulate the actual open area. Furthermore, the stairs to the basement represents an opening between the 1.floor and the basement in the actual building, this however, was not considered in the model. The exterior doors and the remaining interior doors were kept close during the simulation.

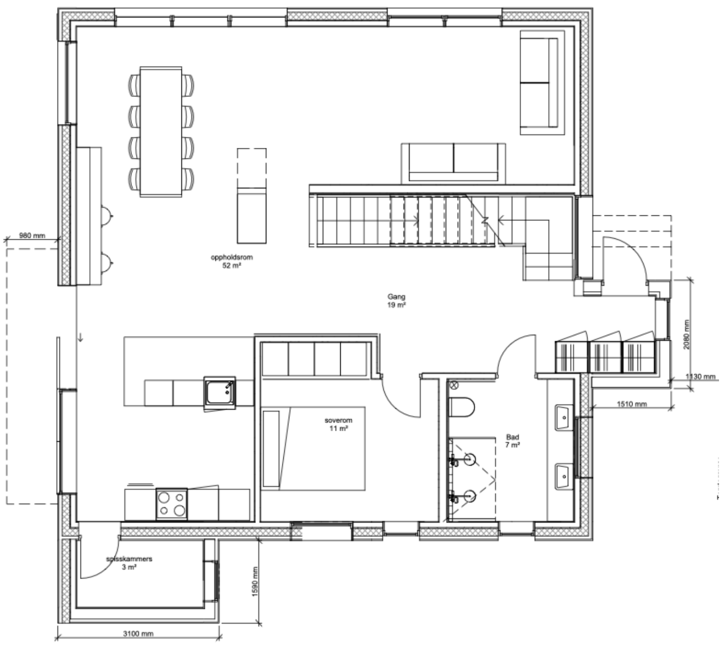

Figure 8: The actual floor plan for the 1.floor in casaZero drawn by Snøhetta.

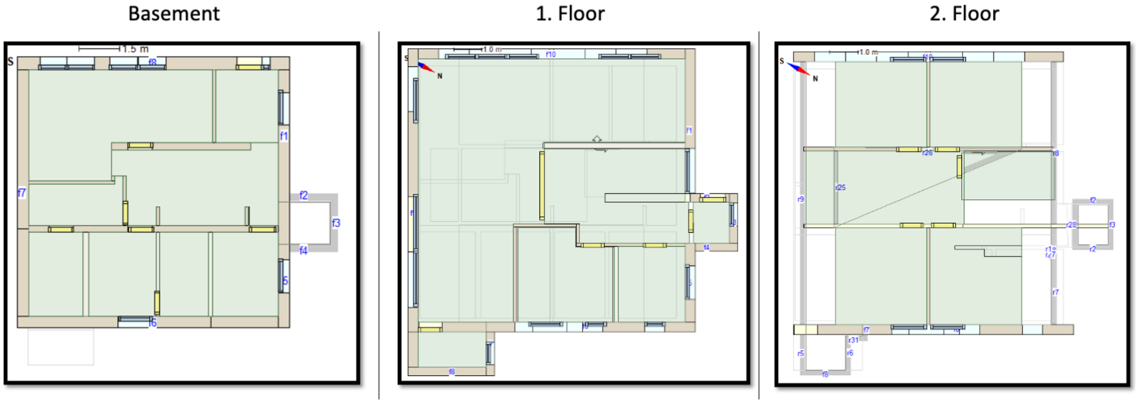

Figure 9: The floor plan for all three levels in casaZero made in IDA ICE.

The orientation of casaZero is shown in Figure 10. No shading objects, such as threes or neighbouring buildings, were considered in the model.

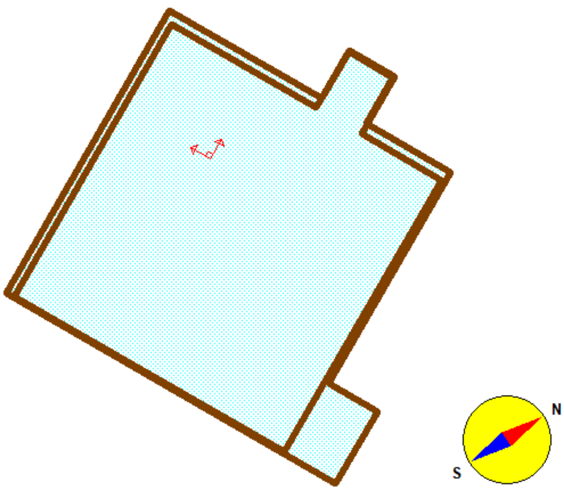

Figure 10: The orientation of casaZero.

The south side of the roof of casaZero is covered with 50 m^2 of PV panels with a nominal effect of 0.18. The PV panels in the model were placed separate from the roof to simulate the measured amount of electricity produced. Placing PV panels on the roof did not provide enough electricity compared to the actual amount measured in the building. They were however, mounted with a 36 degree of inclination to match the angle of the roofs.

3.2.1 Building envelope

The input parameters for the envelope was calculated based on chosen materials and depth of the construction. Table 1 shows an overview of the physical parameters of the building envelop.

Table 1: Overview of the physical parameters of the building.

Description	**Value**	**Unit**
U-value outer wall	0,11	$[W/m^2K]$
U-value roof	0,12	$[W/m^2K]$
U-value basement floor	0,1	$[W/m^2K]$
U-value for basement wall	0,14	$[W/m^2K]$
U-value outer door/window	0,8	$[W/m^2K]$
Normalized value of thermal bridge	0,08	$[W/m^2K]$
Area outer wall	173	$[m^2]$
Area roof	108	$[m^2]$
Area basement floor	83	$[m^2]$
Area outer door/window	36	$[m^2]$
Total heated area	226	$[m^2]$
Heated air volume	490	$[m^3]$
Leakage number	1	$[1/h]$

3.2.2 Climate and location

As IDA ICE offers a limited amount of climate files and locations, Oslo/Gardemoen was chosen as it was the closest available location to Kolsås. The weather files available in IDA ICE are "typical" weather files, established based on several years of data gathering and calculations of mean values. Due to this, the weather files do not reflect a specific year. It was therefore decided to make an attempt at establishing a weather file based on downloaded weather data from shinyweatherdata.com. The established file was, however, not readable in IDA ICE, so the "typical" weather file was therefore chosen. Figure 11 shows the ambient air temperatures used for the one year simulation. The temperature file shows ambient air temperatures above 25 only in July and August, while the lowest temperatures are found in January. The wind profile was set to suburban.

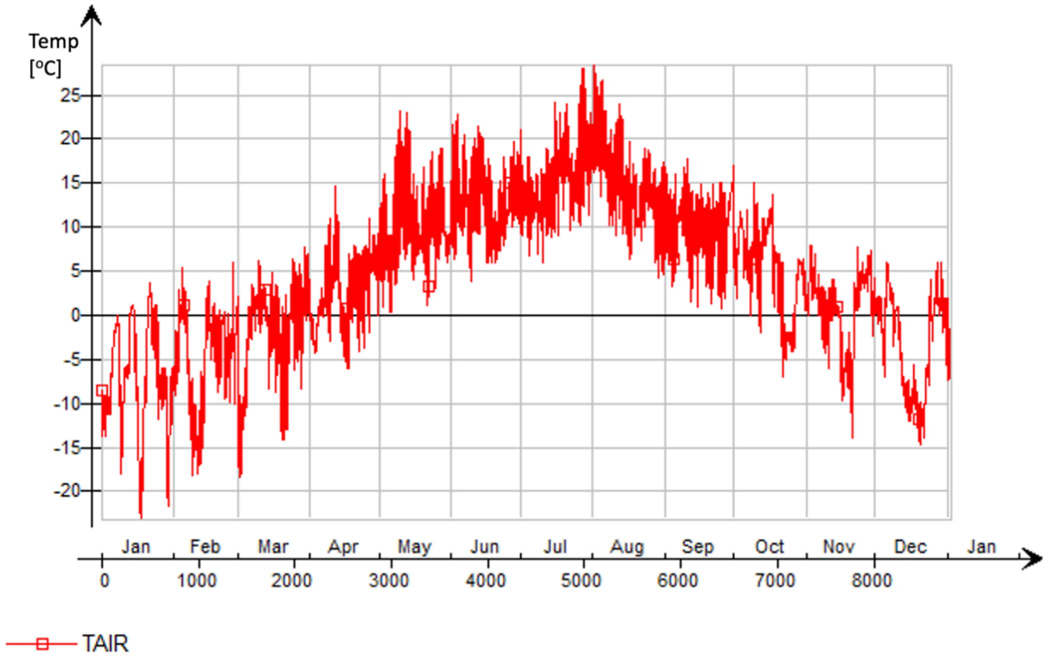

Figure 11: The ambient air temperatures used for simulation in IDA ICE.

3.2.3 Internal gains and human behaviour

As mentioned in the literature review, the occupancy behaviour might influence the electricity consumption greatly and can therefore cause a source of error in the estimations. As the model was calibrated based on measured values for produced and consumed electricity for 2021, the occupancy behaviour might differ from an average year, due to more frequent utilization of home office and home schooling during the period with covid restrictions. However, the input values for lighting and equipment were based on standard values presented in SN/TS 3031:2016 [40]. The SN/TS 3031:2016 schedules for equipment and lighting are shown in Figure 12. The percentage of supplied heat energy to the zones compared to the electricity consumed by lighting and equipment was set to respectively 100 and 60 according to SN/TS 3031:2016.

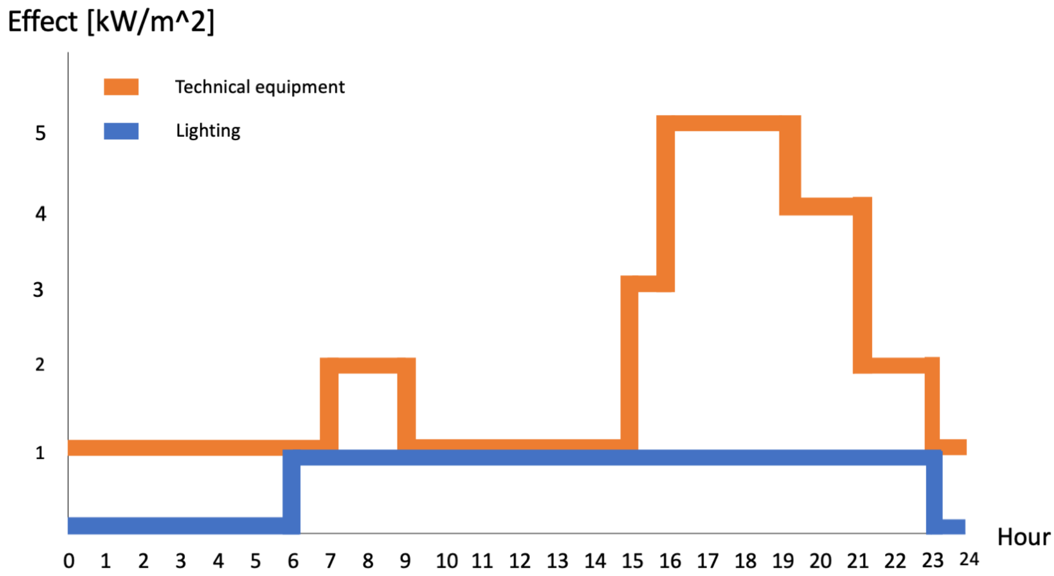

Figure 12: The schedules for lighting and equipment in residential buildings based on the schedules found in SN/TS 3031:2016.

For the occupancy it was decided to implement two different schedules, one for the bedrooms and another for the living rooms of the building. The occupancy of the bedrooms was set to 1 during the night and 0 during the day while the living rooms had the opposite occupancy schedule.

3.2.4 Ventilation and AHU

CasaZero is equipped with a balanced ventilation system of the type FLEXIT Nordic S4 with a heat recovery between 80% and 85%. A graph was used in the model to decide the set point temperature for supply air. When the ambient air temperature was lower than 0 degrees, the supply air temperature was set to 20. With ambient air temperatures between 0 and 10 degrees, the supply temperature was 18 and for ambient air temperatures above 10 degrees, the supply temperature was set to 16 degrees. The schedule was established to simulate electricity consumption and temperatures matching the measured values from the building.

3.2.5 The plant

The main source of heat supply to casaZero is through a F1155 NIBE GSHP, providing heat for both the DHW system and the space heating system. The plant in IDA ICE included the GSHP system and the energy and heat distribution system. Figure 13 shows part of the plant for casaZero. The PV panels are not shown in the plant as they were implemented to the electrical system of the model. The average use of DHW was set to 60L/day for each of the 5 occupants of the building. A brine to water heat pump with ground heat exchange was chosen in IDA ICE. The capacity of the GSHP was set to 6kW and the COP was set to 4.

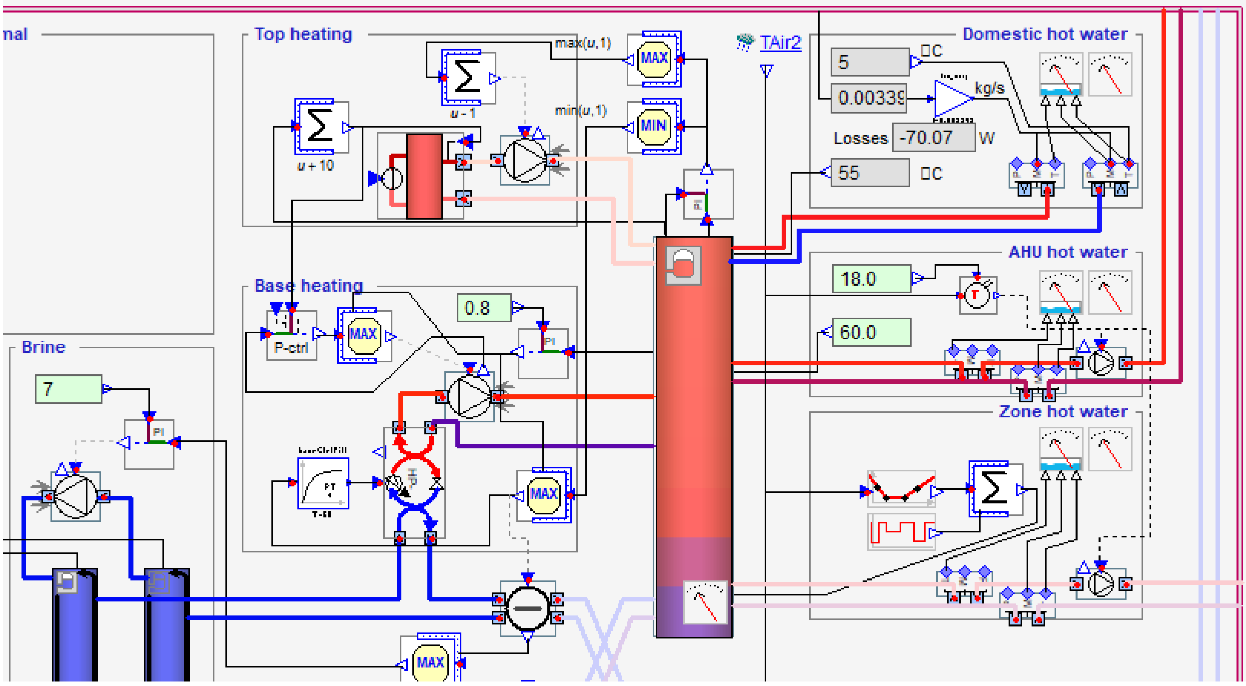

Figure 13: Part of the plant established in IDA ICE for casaZero.

For the space heating system, the basement and 1st floor was equipped with water borne heating coils integrated in the floor. The space heating system was divided into three coils supplying different zones of the building, one for the bathrooms and the laundry, one for the basement and one for the 1.st floor. Each coil was provided with pumps and a unique set point temperature. A cold water tank was implemented in the model to simulate the ability to use the GSHP for cooling, during days with a cooling need.

The water tank was set to 224L. Figure 14 shows the heat and electricity flow between equipment in casaZero. In this chart, electricity for pumps in the space heating system is included in "Other el. specific loads". The battery of the EV is also included in el. specific loads. As shown in the chart, excess electricity from the PV panels are transported back to the grid when the el. specific loads and electricity for GSHP and ventilation is covered. The heat transfer from the heating demand to the ventilation system represents the heat from the heat recovery of the AHU.

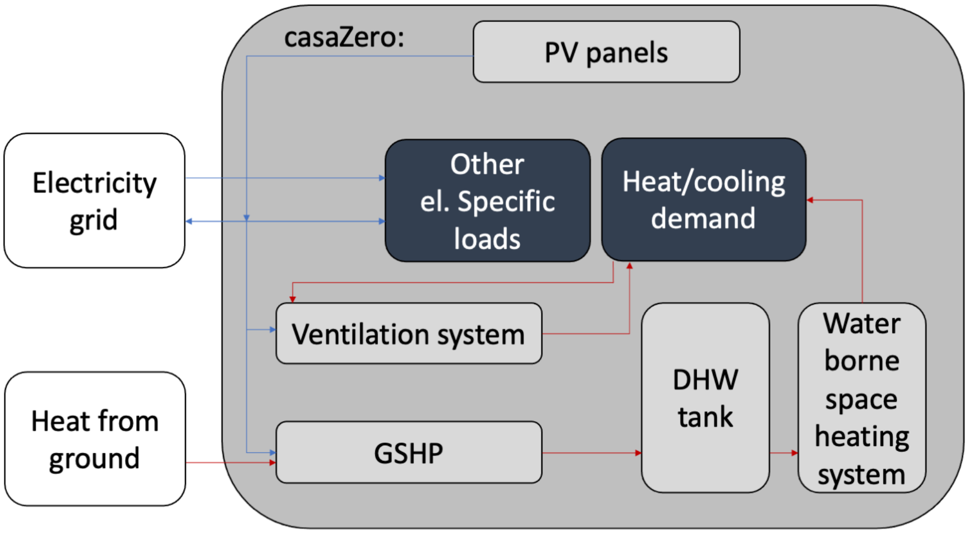

Figure 14: The technical equipment of casaZero including the electricity and heat flow between the equipment.

3.2.6 Electricity prices

The schedules for electricity prices were established based on data from NordPool [41]. To estimate the selling price, the spot price for ten randomly chosen days for each month were studied in detail to find an average price curve for each month. The twelve curves were implemented in the electricity contract function in IDA ICE. The prices for 2021 were utilized to establish the curves. The curve for the average spot prices for December 2021 is shown in Figure 15.

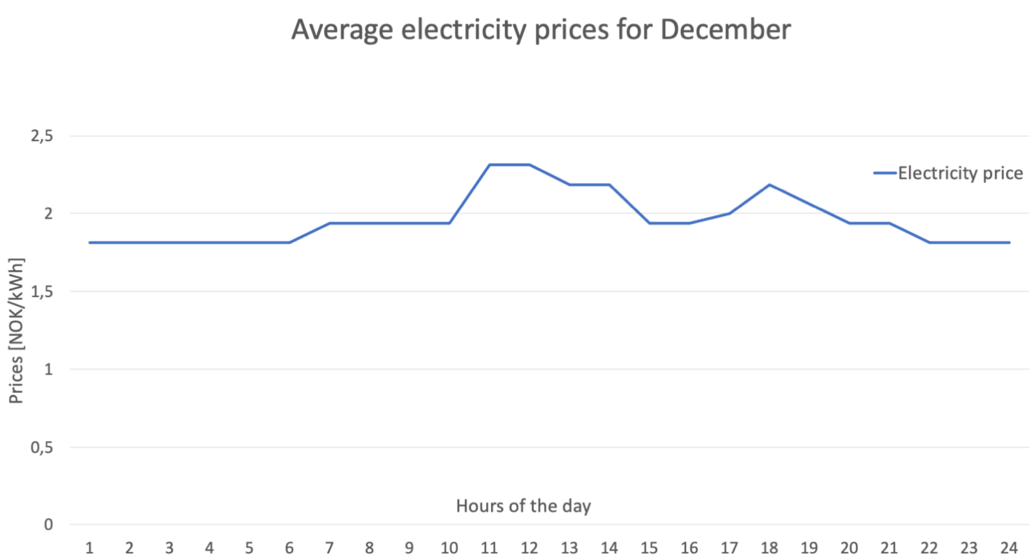

Figure 15: The electricity cost curve for December 2021 implemented in the model.

To find the cost for bought electricity Equation 1 was used, where C_{tot} is the total cost in NOK/kWh, C_{const} is the constant grid fee, C_{var} is the variable grid fee, C_{tax} is the consumer taxes and C_{spot} is the spot price for electricity. The constant grid fee was set to 115 NOK/month, while the variable grid fee was 44.8 øre/kWh. The consumer taxes for 2021 was 16.69 øre/kWh. The prices for Oslo region was chosen for both selling and buying prices.

$$C_{tot} = C_{const} + (C_{var} + C_{tax} + C_{spot}) * 1.25 \tag{1}$$

The Norwegian government decided to give compensation for high electricity prices for the period from December 2021 to March 2022 [42]. However, this is not included in the electricity prices implemented in the model.

3.3 Key Performance Indicators

To assess the energy flexibility potential of casaZero, three KPIs were chosen as evaluation criteria. The chosen KPIs in this thesis were electricity import peak, cost associated with electricity consumption and self-consumption. For all three KPIs a set of common criteria were made. The first criteria was made as a result of the ZEB definition, considering the energy balance. As shown in Equation 2, the total electricity consumption could not exceed the total electricity production for the one year period. For each simulation this was checked to ensure a positive energy balance.

$$El^{imp} < El^{exp} \tag{2}$$

El^{imp} and El^{exp} is respectively total electricity imported and total electricity exported during a period of one year.

The second criteria was the indoor thermal comfort. It was chosen to evaluate the thermal comfort by using the percentage of total occupancy hours with thermal dissatisfaction, referred to as the percentage of people dissatisfied (PPD). This was done by separately summing up the total occupancy hours for all zones and the total hours of thermal dissatisfaction. The two numbers were then implemented in Equation 3.

$$PPD = \frac{h^{PD}}{h^{occ}} \tag{3}$$

Where h^{PD} is the hours of people dissatisfied and h^{occ} is the occupancy hours. Only schedules with PPD<10% were qualified as satisfactory based on the standards given by NS-EN ISO 7730:2005 [43].

3.3.1 Self-consumption

The self-consumption for each model simulated in IDA ICE was calculated using Equation 4.

$$SC = \frac{El^{prod} - El^{exp}}{El^{prod}} \tag{4}$$

Where SC is the self-consumption, El^{prod} is the produced electricity and El^{exp} is the exported electricity for the hole year. The exported electricity was found by subtracting the produced electricity from the total consumed electricity for each time step of the simulation period.

3.3.2 Peak load

The second KPI evaluated in this thesis was the imported electricity peak load. The equation used for calculating the total imported electricity for each time step is shown in Equation 5. A code was established in Python to find the highest value of imported electricity during a year. The code is displayed in Appendix 1.

$$El_t^{imp} = El_t^{heat} + El_t^{eq} + El_t^{hvac} + El_t^{light} - El_t^{prod} \tag{5}$$

El_t^{imp} is the imported electricity, El_t^{heat} is the electricity consumed by electric heating, El_t^{eq} is the electricity consumed by equipment, El_t^{hvac} is the electricity consumed by the HVAC system, El_t^{light} is the electricity consumed by lighting and El_t^{prod} is the produced electricity, with t representing the time step of the consumption and production for each hour of the simulation period.

Due to the planned fees for electricity peaks mentioned in the theory chapter, a Python script was established to find the electricity peak for each month of the year. The script is displayed in Appendix 2.

3.3.3 Cost

For the cost analysis the total cost calculated by IDA ICE, based on the implemented costs and earnings from electricity import and export, was used.

3.4 Assessing the energy flexibility potential

An overview of the procedure followed in this thesis for assessing the energy flexibility potential of casaZero is shown in Figure 16. Base case represents the building when the GSHP is regulated only by a thermometer in the DHW tank. After running the first 20 schedules, Case 1, Case 2 and Case 3 were established, containing the three schedules with best results for respectively self-consumption, peak load and cost.

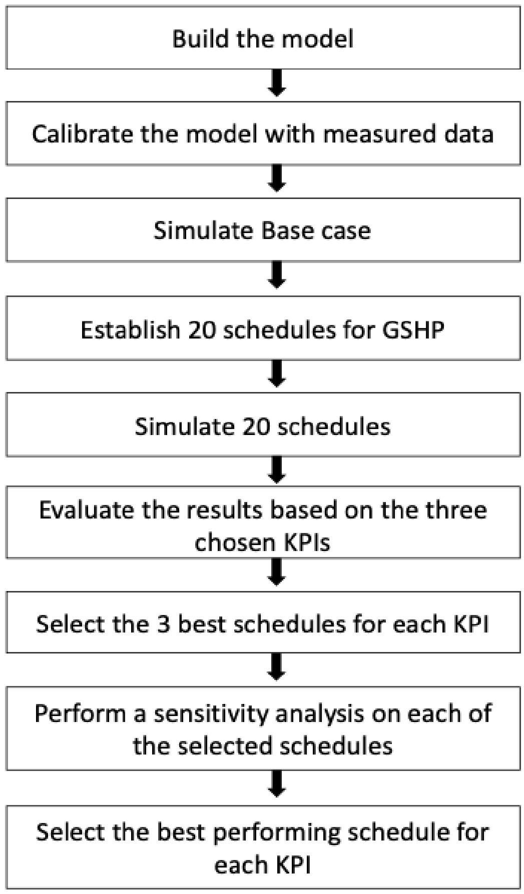

Figure 16: Overview of the methodology used in this thesis.

A total of 65 schedules were implemented and evaluated during the process of finding the best results. Detailed information on each of the four cases is found in chapter 4.

4 Case study

The first section of this chapter presents Base case. The second section presents the implementation of the 20 schedules utilized when deciding Case 1, Case 2 and Case 3. Last is a sub chapter describing the three cases and the sensitivity analysis performed on each case. Furthermore, it describes the process of finding the schedule with best overall result.

4.1 Base case

Base case was established to simulate the energy use for a one year period, without schedules controlling the GSHP. It was established as described in the methodology chapter. The GSHP was regulated by a thermometer in the DHW tank. Base case also included an electric boiler for top heating to assist the GSHP during the days with highest heating need. The results found for Base case was used as a starting point to compare the results found for each of the schedules implemented to the GSHP.

4.2 GSHP schedules

To control the GSHP a set of 20 schedules were established. They were implemented in the plant of the model, controlling the flow from the GSHP to the DHW tank. A simulation was run for each schedule. The schedules had a 24 hour time span as shown in Figure 17, and did not vary between weekdays and weekends, nor did they change with the seasons. The Top heating shown in Figure 13 was removed, but the thermometer in the DHW tank was kept. Hence, the GSHP was only operating when both the schedules and the thermometer allowed it. All 20 schedules are shown in Appendix 3. The schedules were named S1, S2, ..., S20.

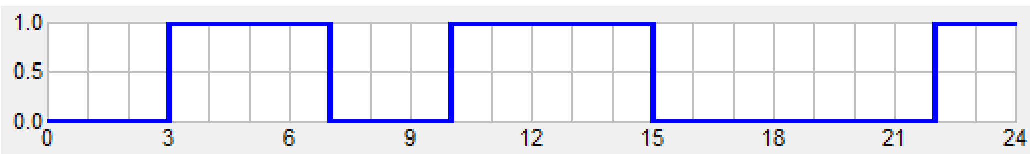

Figure 17: GSHP schedule for S1.

4.3 Case 1, Case 2 and Case 3

The 20 schedules described in 4.2 were evaluated based on the results for each KPI. The schedules with best results were categorized as follows:

- Case 1: the three schedules with highest self-consumption.
- Case 2: the three schedules with lowest yearly peak load.
- Case 3: the three schedules with lowest yearly cost.

A sensitivity analysis was performed on each schedule in the three cases by making minor changes in the schedules. For each case a total of 15 new schedules were established, 5 for each schedule in the case. A total of 45 new schedules were established during the sensitivity analyses of the three cases. The new schedules were named after the schedules in each case, for example, S1(1), S1(2), ... , S1(5).

After finding the optimal schedule for Case 1 an additional load was implemented in IDA ICE to simulate the battery of an EV. This was done to find the effect on self-consumption provided by the EV for the optimal schedule. A schedule was added to the load to control the charging of the battery. It was set to charge from 10 to 13 every day. The charging period was decided based on when the electricity production was highest. The vehicle was assumed to consume 2kW electricity for each mile, and the yearly driving distance was set to 11200km. This gave a daily driving distance of approximately 3 miles. Hence, a total of 6kWh per day.

In addition to finding the schedule providing the best result for each KPI, the schedule with the highest overall score was found, considering all 65 schedules. To find the schedule with best overall score when weighting each of the KPIs equally, points between 0 and 1 were given for each KPI for all schedules with acceptable thermal comfort. This was done by finding the most optimal result for each KPI and divide the respective value for each schedule by the optimal value. The score for each KPI were added and the schedule with a value closest to 3 was designated as the best overall model.

5 Results and Analysis

This chapter presents and analyses the results found in this thesis. First the results from Base case are presented, followed by a sub chapter on identifying Case 1, Case 2 and Case 3. The results from the sensitivity analyses of each of the three cases are presented in separate sub chapters. The last part of this chapter describes the schedule with the best overall result.

5.1 Base case

The energy and indoor climate simulation for the one year period with Base case gave the following main results:

- Total produced electricity: 10 479 kWh.
- Total consumed electricity: 9559 kWh.
- Total purchased electricity: 5732 kWh.
- Total exported electricity: 6653 kWh.

Figure 18 and Figure 19 shows the load profile for the three days in a row with highest total electricity demand for each of the four seasons. While the load profile for winter season has two significant peaks for each day, these peaks are less prominent for the other seasons. It can also be seen that while the electric heating is the most varying factor for autumn, winter and spring season, the electricity consumption from electric heating is rather stable for the summer load profile. The heating, ventilation and air conditioning (HVAC), however, varies more in the load profile for August. This causes higher peaks in the afternoon from 15 to 18 when the cooling need is high. As the total electricity load is significantly reduced during the summer season, the energy flexibility potential measured in self-consumption, peak load reduction and cost reduction is at its lowest during the summer, unless, for instance, another shiftable load is introduced to the building.

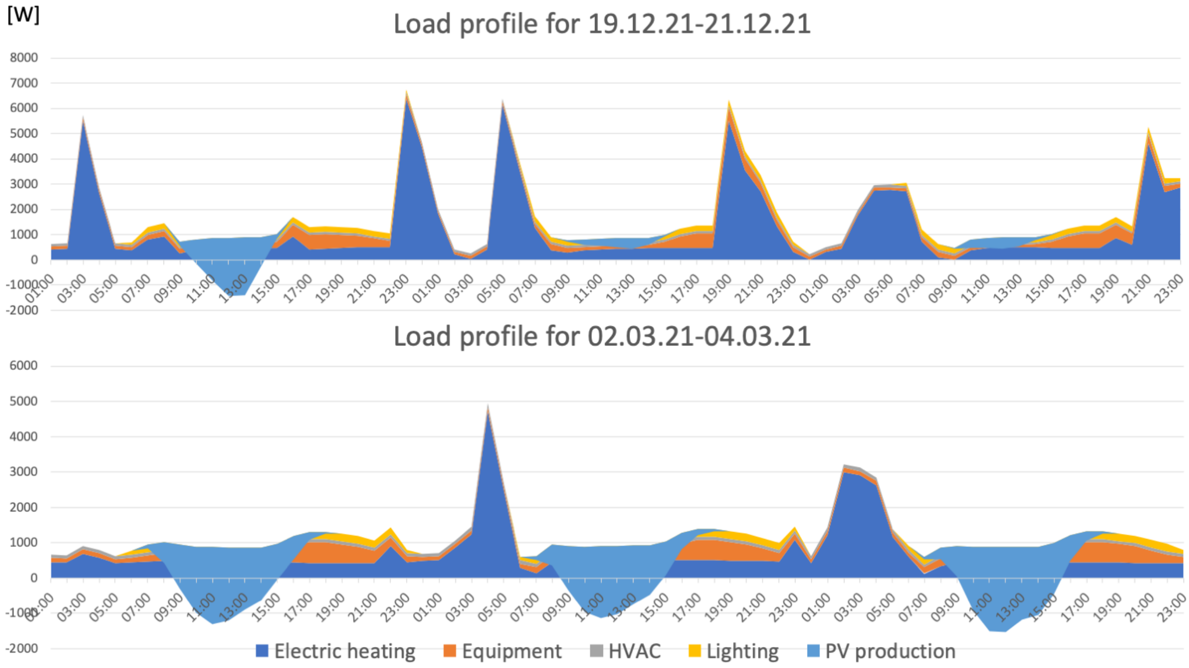

Figure 18: Load profile for the 72 hour periods with highest electricity consumption for winter and spring season for Base case.

As the equipment and the lighting follows set schedules for the entire year, the electricity consumption for these two loads does not vary between days or seasons. This is confirmed in the load profiles found for each season.

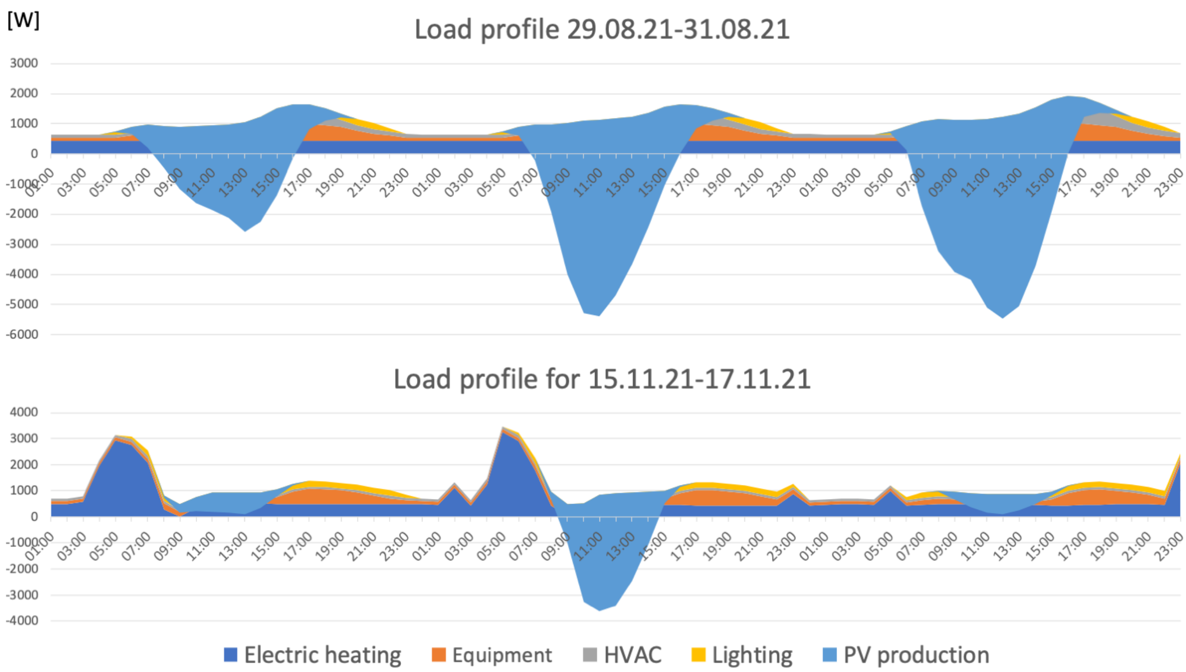

Figure 19: Load profile for the 72 hour periods with highest electricity consumption for summer and autumn season for Base case.

The self-consumption found for Base case was 0.379. Hence, more than half of the produced electricity was exported to the grid during the simulation period. The yearly peak load was found to be 7788W. While the monthly peak loads from November to March varied between approximately 5000W and 8000W, the monthly peak loads from April to October were stable below 2000W. The yearly cost for Base case was 9924.3NOK.

5.2 Identifying Case 1, Case 2 and Case 3

The results from the simulations with the first 20 schedules are shown in Figure 20. Case 1 is identified as S6, S13 and S16, marked in green. Case 2 is marked in yellow as S7, S9 and S20. Case 3 is marked in blue as S2, S12 and S13. It is noticeable that both S13 and S16 have a PPD above the acceptable limit. They were, however, not rejected as the sensitivity analysis would effect the PPD value.

Schedule	SC [-]	Peak in [W]	Cost [NOK]	PPD [%]
Base case	0,37913978	7788	9924,3	9,81
S1	0,342074	5215	9419,1	9,75
S2	0,25855508	5831	9213,9	9,82
S3	0,32352651	5671	9692,3	9,72
S4	0,33175741	5328	9610,5	9,7
S5	0,25859354	5877	9791,5	9,82
S6	0,39836312	5897	9470,6	9,79
S7	0,32640015	4700	9712,3	9,72
S8	0,32071676	5204	9666,2	9,72
S9	0,32886731	4898	9643,3	9,74
S10	0,33634469	5189	9506,4	9,78
S11	0,25856105	5970	9279,1	9,74
S12	0,25855362	5610	8962,2	9,84
S13	0,43269587	5445	8751,7	10,5
S14	0,39073711	5930	9296,7	9,81
S15	0,35545245	5570	9358,6	9,67
S16	0,43794003	5780	9278,1	10,2
S17	0,34409583	5498	9237,2	9,77
S18	0,32001374	5009	9545,3	9,78
S19	0,35301498	4959	9515,8	9,77
S20	0,34216941	4949	9490,5	9,78

Figure 20: Result from the first 20 schedules implemented in the simulation model. The three best results considering each KPI is marked in green, yellow and blue.

The schedule with highest score for cost minimization, peak load reduction and self-consumption from the first round of simulation were respectively S13, S7 and S16. These are displayed in Figure 21. In addition to having the lowest cost compared to the 20 first models, S13 also had one of the best results for self-consumption. This schedule was therefore further improved according to both self-consumption and cost.

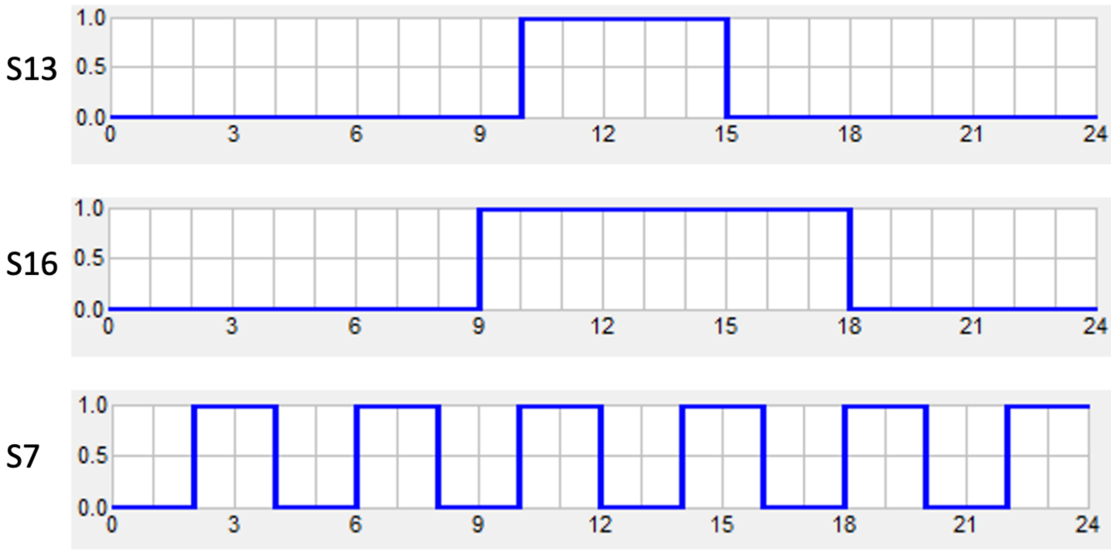

Figure 21: The three schedules with highest score of the 20 first schedules. S13 gave the lowest cost, S16 gave the highest self-consumption, while S7 gave the lowest imported electricity peak.

5.3 Case 1

The 15 schedules established based on Case 1 is presented in Figure 22. The row written in red shows the schedule with the highest self-consumption and acceptable thermal comfort. The schedules from Case 1 are marked in green. All 15 schedules are displayed in Appendix 4.

Schedule	SC [-]	Peak load [W]	Cost [NOK]	PPD [%]
S6(1)	0,38881859	5868	9538,1	9,77
S6(2)	0,38829516	5811	9579,9	9,76
S6(3)	0,41753634	5995	9476,5	9,87
S6(4)	0,41346548	5981	9518,9	9,88
S6(5)	0,37671711	5616	9482,1	9,73
S13(1)	0,43698146	5556	8870,9	10,37
S13(2)	0,43854168	5509	8989,6	10,43
S13(3)	0,43466116	5549	9107,2	10,34
S13(4)	0,42937036	5591	9221,5	10,28
S13(5)	0,42786048	5305	8795,5	10,5
S16(1)	0,43295207	5758	9378	10,15
S16(2)	0,42786149	5755	9466,1	10,11
S16(3)	0,43092801	5873	9405,4	9,98
S16(4)	0,42692416	5845	9496,1	10
S16(5)	0,42230581	5853	9554,2	9,99
S6	0,39836312	5897	9470,6	9,79
S13	0,43269587	5445	8751,7	10,5
S16	0,43794003	5780	9278,1	10,2

Figure 22: An overview of the main results from sensitivity analysis of Case 1.

As seen in the right column of the figure, the PPD is not satisfactory for many of the schedules. This is caused by the need to increase the electricity consumption during PV production hours. By focusing most of the heating hours to the middle of the day, the risk of not meeting the heating need during evening and morning increases. As shown in Figure 21, for both S13 and S16 the GSHP is on only during the middle of the day. For S13 this resulted in all five new schedules not reaching acceptable value of PPD. For S16 however, some of the new schedules have acceptable indoor thermal climate. Of the schedules with PPD<10%, S16(3) has the highest self-consumption with an increasing of 13.7%, compared to Base case. Furthermore, S16(3) has a 25.1% decrease in imported electricity and a 12.9% decrease in exported electricity. This can be considered a significant reduction of interaction with the grid. For this schedule, both cost and peak load decreased, compared to Base case.

Figure 23 shows the GSHP schedule for S16(3). Though the working hours of the GSHP is only extended with one hour compared to the S16 schedule, the effect on the PPD is valuable as it reaches an acceptable level. However, the increased number of operational hours of the GSHP resulted in a slightly decrease in self-consumption, compared to S16. This is due to operation distributed on one more hour outside the PV production hours. It was found that the annual electricity consumption for S16(3) was reduced by 6.1%, compared to Base case. Hence, with smart controlling of the GSHP the annual electricity consumption can be reduced, while still increasing the self-consumption.

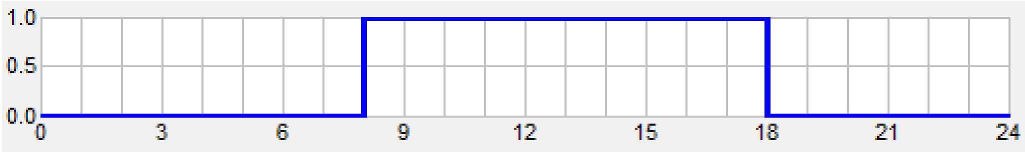

Figure 23: GSHP schedule for S16(3).

To assess the difference in self-consumption between different days of the year, the self-consumption for some selected days were studied. The electricity production and consumption for the first day of January, April, August and November are displayed in Figure 24. The self-consumed electricity is the area below both the production curve and the consumption curve. It is obvious from the figure that 1. August has the lowest self-consumption compared to the three other days. It shows a gap of almost 7kW at 12 o clock, when the heating and cooling demand is low, causing a low electricity consumption. The curve for 1. January and 1. November shows a significantly higher self-consumption. As seen in the figure, the self-consumption could be further increased by postponing the morning peak load. An attempt at this was done in S16(1) where the GSHP could operate from 9 to 19. Though this improved the self-consumption, the PPD increased to above 10.

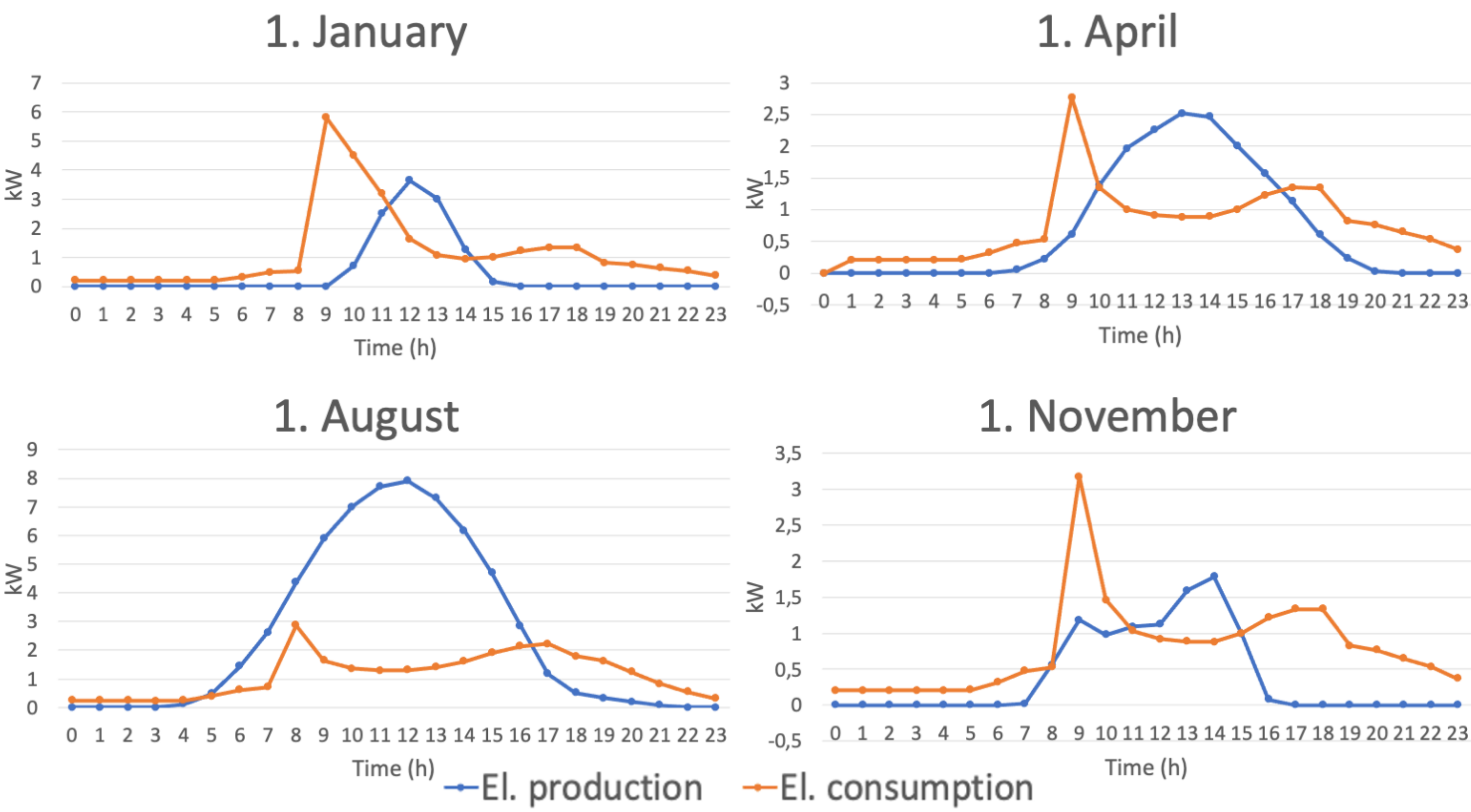

Figure 24: Electricity production vs electricity consumption for four selected days during the one year simulation period with S16(3).

A comparison of the seasonal differences was investigated comparing Base case and

S16(3). The results are shown in Table 2. Though the self-consumption for all seasons were improved for S16(3), the largest increase was found during the winter when the heating need is at its highest. The lowest increase was found during the summer. For both Base case and S16(3), the self-consumption value for summer is closest to the overall value for the entire year. This implies that to significantly increase the self-consumption an increase in self-consumption during summer is necessary. This can be done by introducing a controllable load to match the high electricity production during summer, or by introducing an electric battery for electricity storage.

Table 2: The self-consumption for S16(3) and Base case for each season and for a hole year.

	Base case	**S16(3)**
Winter	0.459	0.603
Spring	0.348	0.391
Summer	0.372	0.404
Autumn	0.413	0.478
Yearly	0.379	0.431

By introducing an additional load representing the EV, the yearly self-consumption increased to 0.581. This is a 53.3% increase from Base case and a 34.8% increase from S16(3). Hence, the ability to utilize smart charging of an EV increases the energy flexibility potential of the building. However, it should be mentioned that the peak hours of electricity production coincides with normal office hours. The EV might therefore not be connected to the charging system of the house at this time of the day. The import peak load and the yearly cost were increased to respectively 5904W and 11 269NOK.

5.4 Case 2

The 15 schedules established based on Case 2 is presented in Figure 25. The row written in red shows the schedules with the lowest yearly peak load and acceptable thermal comfort. The schedules from Case 2 are marked in green. All 15 schedules are displayed in Appendix 5.

Schedule	SC [-]	Peak load [W]	Cost [NOK]	PPD [%]
S7(1)	0,37692517	4145	9790,5	9,81
S7(2)	0,36270583	4411	9734,4	9,77
S7(3)	0,353194	4355	9769	9,75
S7(4)	0,38211529	4627	9660,7	9,8
S7(5)	0,32603356	4842	9766,2	9,78
S9(1)	0,34732003	4798	9654,8	9,76
S9(2)	0,30728642	3896	9763,8	9,76
S9(3)	0,35052978	4885	9673,5	9,74
S9(4)	0,32448456	4901	9750,9	9,71
S9(5)	0,34368623	4510	9793,2	9,76
S20(1)	0,37670432	4238	9808,4	9,79
S20(2)	0,34504328	5021	9470,8	9,71
S20(3)	0,37449012	5380	9405	10,09
S20(4)	0,40187575	5447	9349,9	10,19
S20(5)	0,34074366	4989	9398,9	9,77
S7	0,32640015	4700	9712,3	9,72
S9	0,32886731	4898	9643,3	9,74
S20	0,34216941	4949	9490,5	9,78

Figure 25: An overview of the main results from the sensitivity analysis of Case 2.

Based on the results in Figure 25, schedule S9(2) gives the lowest result for yearly peak load. The schedule for S9(2) is displayed in Figure 26, showing a constant value of 0.5 except from 8 to 11 and 15 to 18 when the GSHP is off.

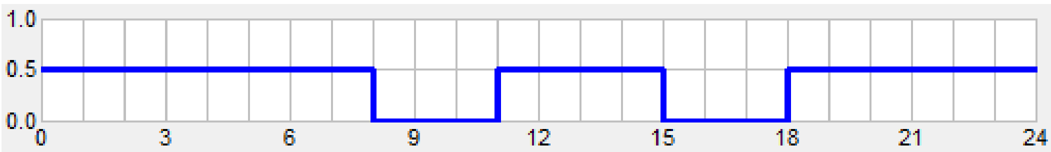

Figure 26: GSHP schedule for S9(2).

Further analyses of the results were done utilizing the Python code for monthly peak load. Figure 27 gives an overview of the peak load for each month in Base case compared to S7, S9, S7(1) and S9(2). The months from April to October have a low monthly peak load. This is due to the reduction in heating demand as well as an increase in electricity production. The peak for each of the mentioned months was found between 6 and 9 in the evening for all four schedules. From Figure 29 it can be seen that the electricity production is low at 18 and zero at 21. If the import electricity peaks were shifted to the period when the electricity production was larger, the monthly peak loads might decrease further, and the yearly self-consumption might increase. The risk of increasing the value of PPD would, however, be significant as hours with large electricity production are the hours with less heating need.

Though the S9(2) schedule has the lowest yearly peak load, the figure shows that S7(1) puts a lower pressure on the grid for all months except January and March. In April the peak load for S7(1) was reduced by 37.4% compared to S9(2), and the average peak load reduction for the 12 months was 11.3%. It can also be noted from the figure that Base case has a low peak load for the months from April to October. However, the peak loads during the winter months are about doubled compared to the ones for S7(1) and S9(2). Considering the new electricity fees it can be assumed that S7(1) is the preferred schedule for a house owner. S9(2) is the preferred schedule in regard to dimensioning of the grid, as it has the lowest maximum peak load.

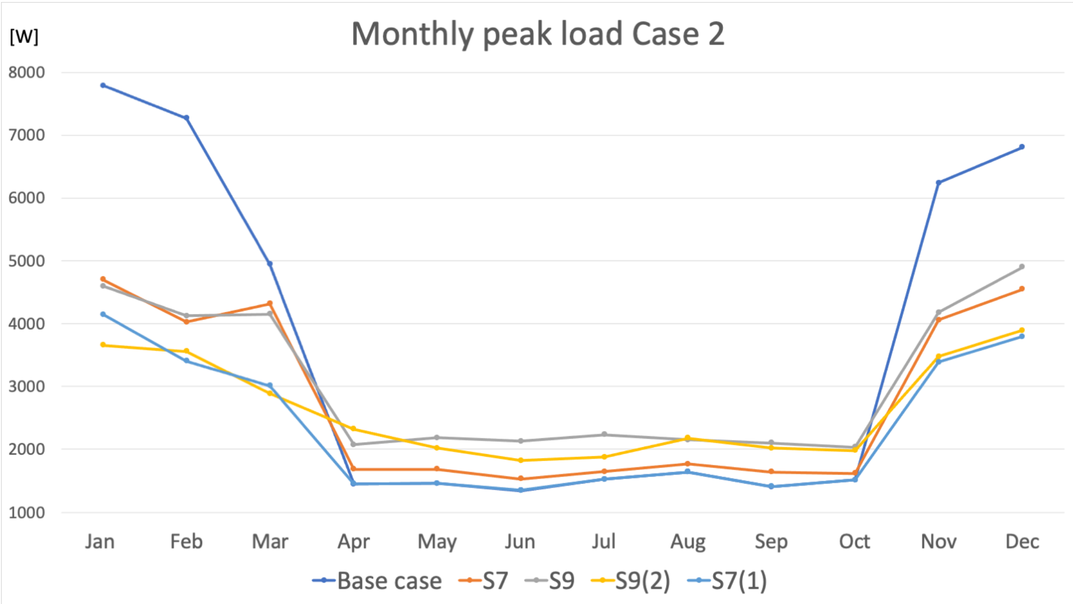

Figure 27: Monthly peak load for Base case, S7, S9, S7(1) and S9(2).

The three days for each season with highest electricity consumption are displayed in Figure 28 and Figure 29. It can be noted that the dimentioning load for summer and autumn falls on the same date as for Base case. The figure shows a slightly lower self-consumption value for S9(2), due to the off-periods for the GSHP. Furthermore, it can be seen from Figure 28 and Figure 29 that the dimensioning load for winter and spring season is significantly lower for S9(2), compared to Base case. This is reasonable as the schedule for S9(2) limits the highest peaks. However, the off periods of the GSHP is compensated with higher peaks during operating hours of the GSHP. This causes slightly higher peaks during the summer season for S9(2), compared to Base case.

The compensation for the off-periods of the GSHP might also be one of the reasons for S7(1) having the lowest monthly peak load for 10 out of 12 months. As the schedule for S7(1) is a constant value of 0.5, the load from the GSHP can be distributed on 24 hours. A way of finding a better schedule for lowering the average monthly peak load could therefore be to find the lowest constant value for regulating the GSHP, without compromising the thermal comfort of the building.

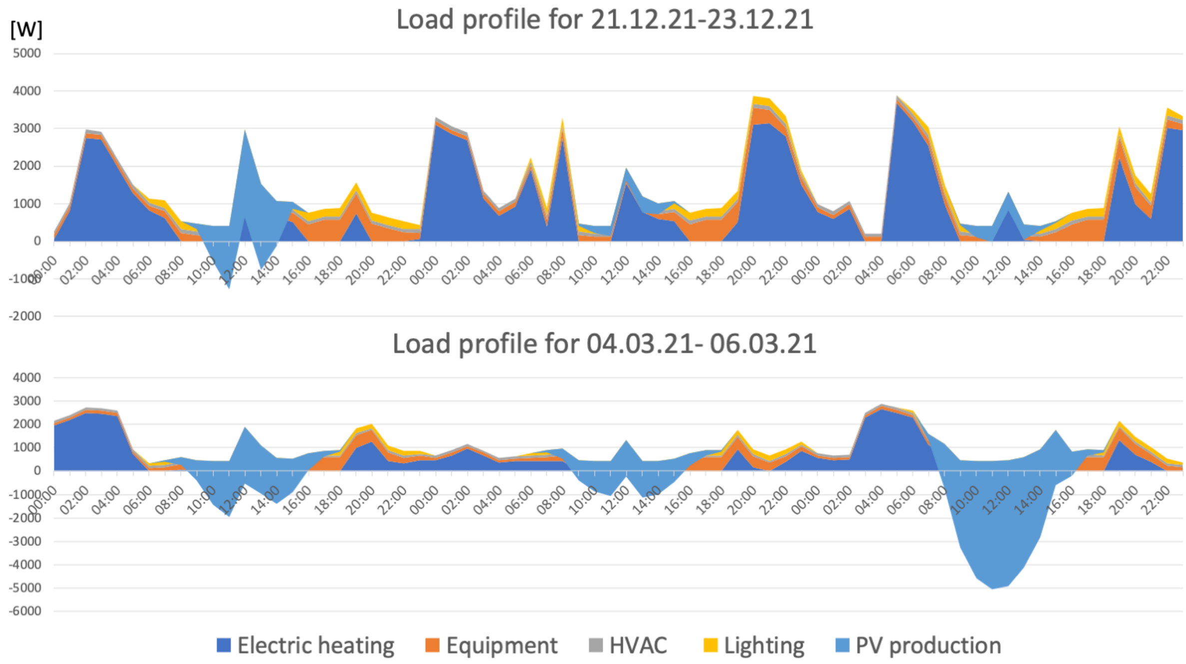

Figure 28: Load profile for the 72 hour periods with highest electricity consumption for winter and spring season for S9(2).

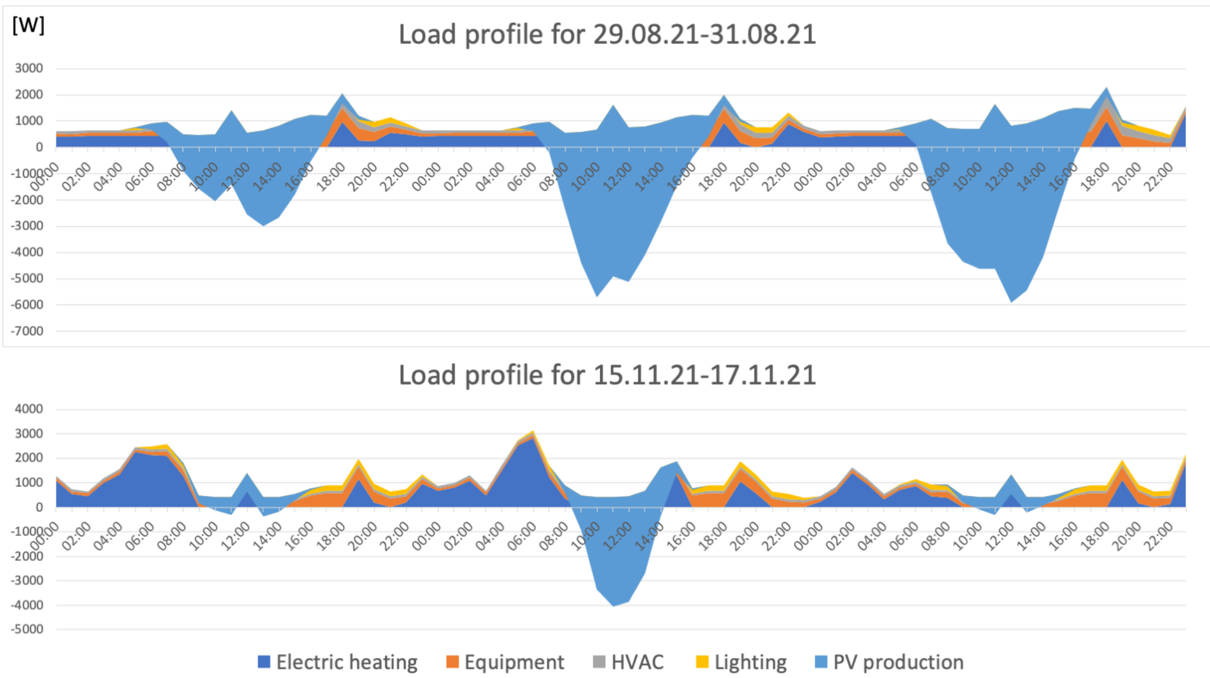

Figure 29: Load profile for the 72 hour periods with highest electricity consumption for summer and autumn season for S9(2).

Though S7(1) is considered the best solution regarding monthly peak load, S9(2) has the highest reduction in yearly peak load with a reduction of 50%. The equivalent number for S7(1) is 47%. Hence, the S9(2) is the best model found in this thesis for yearly peak load reduction.

5.5 Case 3

The 15 schedules established based on Case 3 is presented in Figure 30. The row written in red shows the schedule with the lowest yearly cost and acceptable thermal comfort. The schedules from Case 3 are marked in green. All 15 schedules are displayed in Appendix 6.

Schedule	SC [-]	Peak load [W]	Cost [NOK]	PPD [%]
S12(1)	0,26370669	5639	9096,5	9,8
S12(2)	0,2719665	5607	9212,8	9,79
S12(3)	0,28355494	5672	9320,6	9,78
S12(4)	0,26371318	5645	9095	9,8
S12(5)	0,27195027	5665	9210,2	9,79
S2(1)	0,25850281	5905	9366	9,82
S2(2)	0,25718668	6002	9247,1	9,85
S2(3)	0,27722005	5818	9084,2	9,88
S2(4)	0,25850171	5727	9390,5	9,83
S2(5)	0,2585603	5817	9213,1	9,82
S13(1)	0,43211203	5639	9266	10,03
S13(2)	0,43623544	5541	8903	10,41
S13(3)	0,43232551	5634	9266	10,03
S13(4)	0,42677652	5699	9191,3	10,06
S13(5)	0,43474073	5403	9402,8	10,15
S2	0,25855508	5831	9213,9	9,82
S13	0,43269587	5445	8751,7	10,5
S12	0,25855362	5610	8962,2	9,84

Figure 30: An overview of the main results from the sensitivity analysis of Case 3.

It is noticeable that the self-consumption is significantly reduced for all schedules with acceptable PPD. A high self-consumption requires large loads during the hours with PV production, while low costs are achieved when the load is shifted from hours with high electricity prices to hours with low electricity prices. This is demonstrated in Figure 31 using the three schedules displayed in Figure 32. The curves for imported electricity and the total cost found for each of the schedules implies a correlation between load shifting from day time to night time and reduction in cost.

As hours with high electricity prices mostly coincides with hours of PV production, it might be difficult to achieve high self-consumption and low cost at the same time. In an attempt to avoid this issue, the S13 schedule was extended in hours of operation of the GSHP and reduced in maximum operation capacity for the hours with highest cost. The results of this is shown in Figure 30 as S13(1), S13(2),...,S13(5). However, none of the modified schedules for S13 resulted in acceptable PPDs.

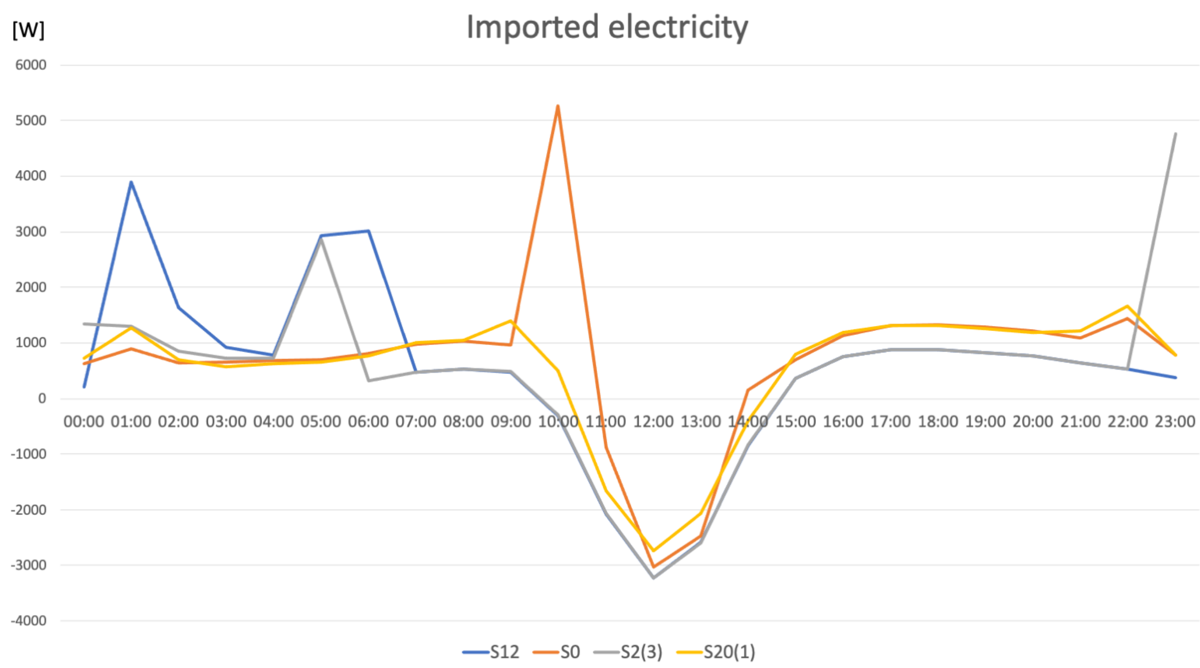

Figure 31: Imported electricity for Base case, S12, S2(3) and S20(1).

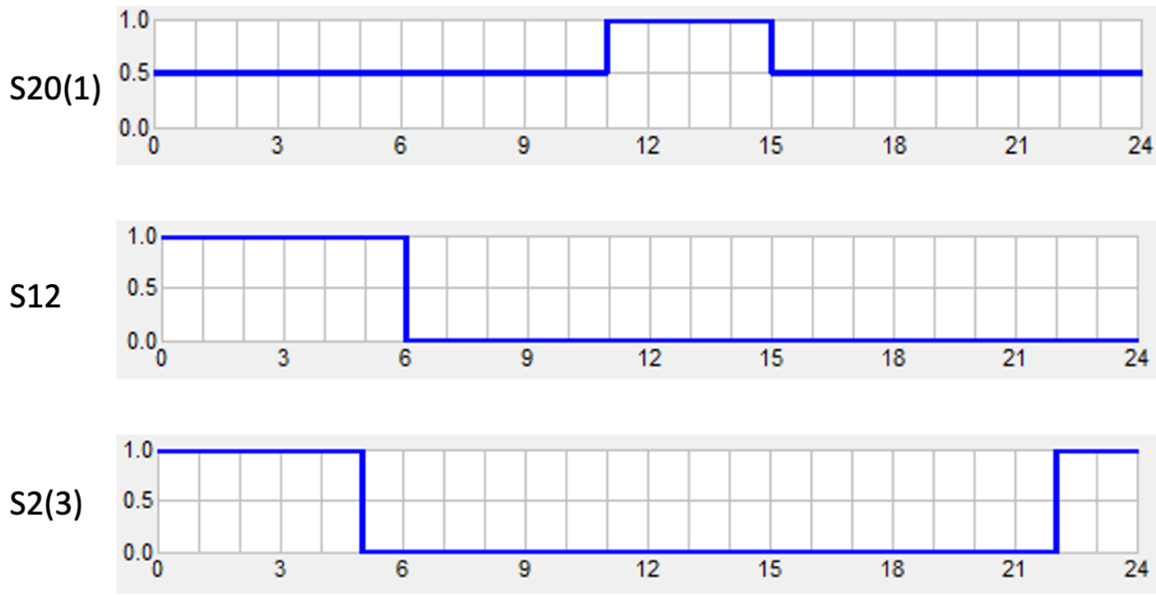

Figure 32: GSHP schedules for S12, S2(3) and S20(1).

As previously mentioned, the cost estimations and analysis in this thesis does not take into account the new peak fee soon to be implemented in the Norwegian electricity prices. However, the models with acceptable PPD were analysed using the Python script for monthly peak load. A selection of the results are shown in Figure 33. The figure shows that even with similar yearly electricity peaks S12(5) and S2(5) have significant variation in the monthly electricity peaks. This implies that further cost analysis should be done to find the optimal GSHP schedule when considering the new fees. With the cost estimations done in this research, the S12 model was found to have the lowest cost for operation, with a decrease of 9.7% compared to the base model.

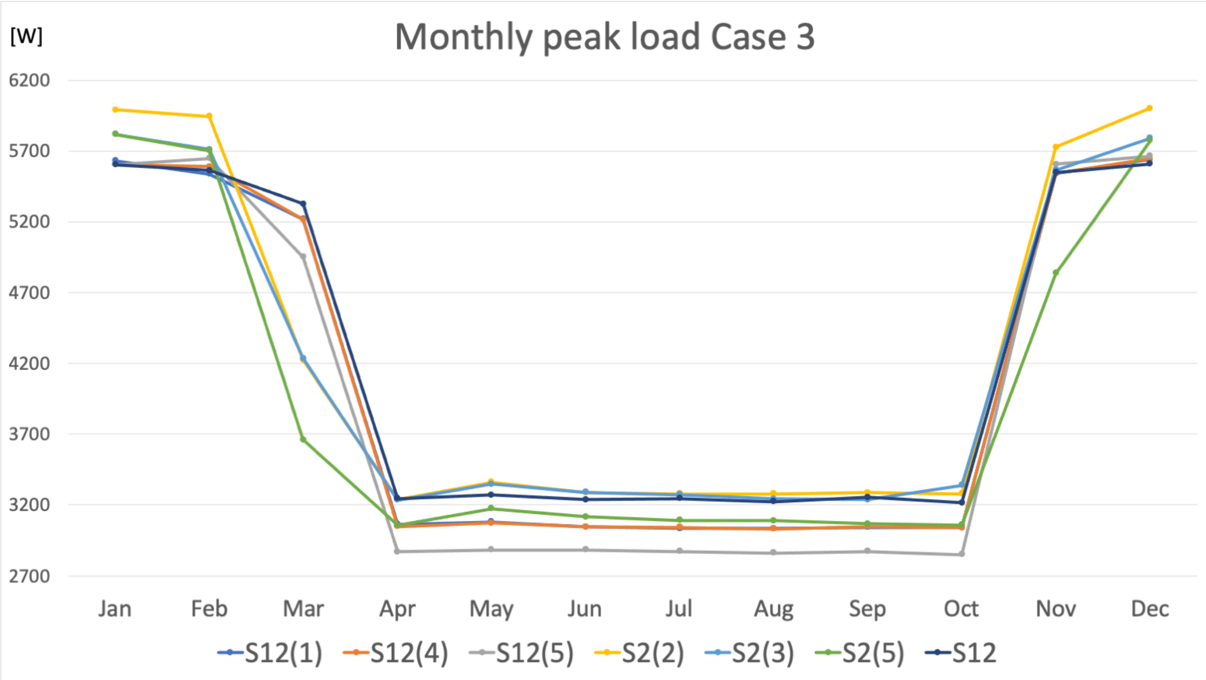

Figure 33: Monthly peak load for some selected schedules during sensitivity analysis of Case 3.

5.6 Optimal overall model

As previously mentioned, a correlation between some objectives was found causing, for instance, an increase in one value when decreasing another. The strongest relation was between low cost and low self-consumption. The schedule with highest total score was S7(1). The schedule for S7(1) is shown in Figure 34. Though the schedule did not have the best result found in this thesis for any of the three KPIs, it had above average scores for all three KPIs. Only some of the schedules with unsatisfactory results for PPD had a higher total score.

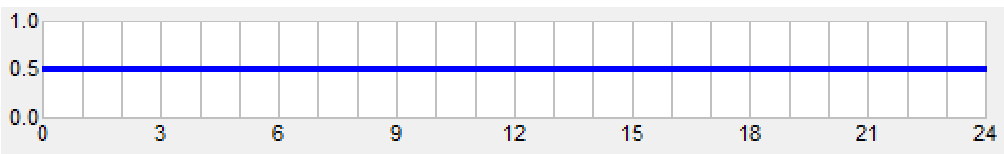

Figure 34: GSHP schedule for S7(1).

Figure 35 shows that the load profile for the three days with highest electricity consumption during summer season is equal to the load profile found for Base case in Figure 19. This implies that even with S7(1) limiting the capacity of the GSHP, the electricity load is small enough to be covered by the GSHP for each hour of the three days studied in the figure. For the winter season the load profile for S7(1) differs from the load profile for Base case. As the GSHP is not capable of covering the highest peaks, the peaks for S7(1) are wider and lower. Furthermore, the location of the peaks in Figure 35 differ from Figure 18. While the peaks for Base case are only found in the evening or during the night, the electricity consumption for S7(1) also peaks during the day. To increase the self-consumption it is favorable to increase the load during hours of PV production, but with the limitation in peak value the schedule for S7(1) reduces the self-consumption by 0.6%. For the cost it is favorable to shift the load to night hours as the cost is lower during the night. For S7(1) the total yearly electricity consumption is slightly reduced, causing a 1.4% reduction in total cost.

The weighting of each KPI in a multi objective optimization of the operation of a ZEB might vary. However, for most private house owners economics and laws, in addition to thermal comfort, are the major influences on decisions made when designing and operating a building. In this case it was found that the yearly cost for operation of casaZero differed with a maximum of 1000 NOK. Compared to a normal budget for a Norwegian family this can be considered a minor budget burden. However, with the new fees for electricity peaks it is reasonable to assume that for an average residential building owner the reduction of cost and electricity peaks will weight higher than the increasing of self-consumption.

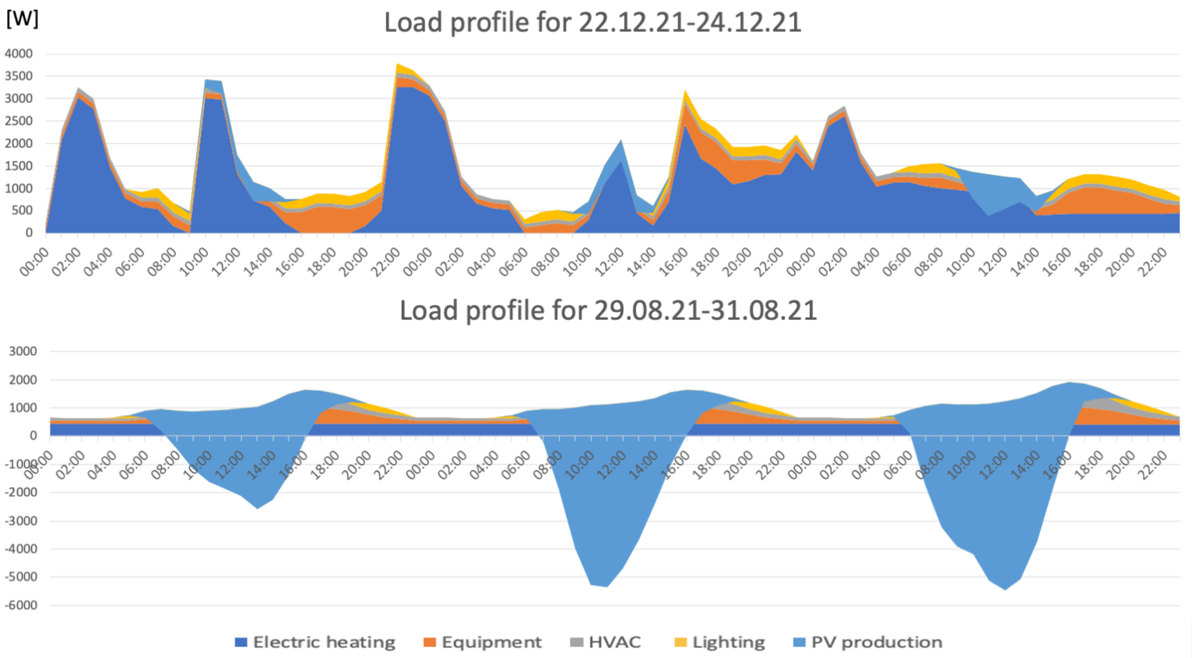

Figure 35: Load profile for the 72 hour periods with highest electricity consumption for winter and summer season for S7(1).

6 Discussion

This section describes some of the sources of inaccuracy and errors found in this thesis. The last part of this section includes an assessment of the DHW tapping schedule utilized in this thesis.

During the work of this thesis, some assumptions and simplifications were made to establish a model in IDA ICE. Examples of such simplifications and assumptions are the implementation of schedules for lighting and equipment. It can be assumed that for each individual house hold the exact consumption will differ from standards given by Norsk Standard. However, this is considered as minor sources of error, as this study aims to find the influence of different operational strategies on the GSHP. Hence the most important load for the results is the electricity consumption for heating. The weather profile used in the model is an estimation based on gathered weather data from previous years, not the exact weather data from 2021. Due to these simplifications, the results found in this thesis might deviate from the actual energy flexibility of the building.

Another source of error found in this thesis was the simplifications done while establishing cost schedules. The work of implementing one cost schedule for each day to simulate the actual daily variations in cost was too time demanding. Due to this, only some days were studied in an attempt to find a suitable cost schedule for each month. The highest peaks and the lowest valleys of the cost curve were therefore not reflected in the simulations.

6.0.1 Schedule for DHW tapping

A source of error was found in the lack of schedule for tapping of DHW. According to NS/TS 3031:2016, the tapping of DHW in a small house is zero from 23 to 5 in the morning and peaks from 7 to 8 and 15 to 19 with a peak value of 1.442 kWh. In the model simulated in this task a constant distribution of tapping of DHW was implemented. A test simulation was therefore run to find the difference in Base case with and without the schedule for tapping of DHW found in NS/TS 3031:2016. The results are shown in Table 3, where BCs is the base model with the correct tapping schedule for DHW.

Table 3: Main results from Base case and BCs.

Model	**SC [-]**	**Peak load [W]**	**Cost [NOK]**	**PPD [%]**
Base case	0.37913978	7788	9924.3	9.81
BCs	0.36684745	7823	10052	9.81

As the peaks of the curve for tapping of DHW coincides with the peaks of the cost curve for electricity import, the cost of BCs is naturally increased from the original model. It is reasonable to assume that the cost of each of the 65 models will increase by the same amount by changing only the schedule for DHW tapping. Hence, the cost comparison is not affected by the lack of schedule. The peak loads might increase if the peaks coincides with the peak for DHW tapping. To find the probability of the tapping schedule changing the peak load, the time of the peaks where checked for each GSHP schedule. It was found that the peak load for most of the schedules simulated in the sensitivity analysis of Case 2 peaked during off peak hours compared to the tapping schedule. Hence, the lack of tapping schedule is only a minor influence on the peak load analysis.

The self consumption decreases in the case of BCs compared to Base case. This can be explained studying Figure 36. The figure shows the solar radiation of an 8 day period in January. As shown in the figure, the solar radiation is 0 during the first DHW tapping peak. Hence, the electricity from PV production is 0 from 6 to 8 during the winter season. Parts of the 15 to 19 peak is also during hours of 0 electricity production. In Base case the DHW tapping is equally divided throughout the day, causing a higher consumption during hours of PV production. This gives a slightly decrease in the self-consumption for the BCs model. Though the possibility of inaccuracy in the results increases when not utilizing a proper schedule for tapping of DHW, it is considered insignificant in this thesis. Furthermore, it should be mentioned that the restrictions of the covid year of 2021 might have influenced the tapping schedule to deviate from the standard schedule given by SN/TS 3031:2016.

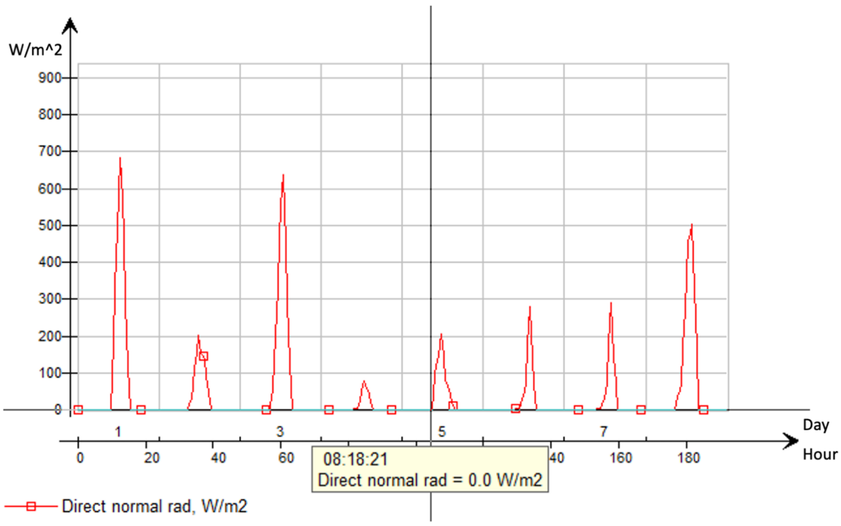

Figure 36: The solar radiation of a 8 day period in January.

7 Conclusion

65 different GSHP schedules were simulated in this thesis in an attempt to assess how operational strategies of the GSHP affected the energy performance of a residential ZEB. The three KPIs analysed in this thesis were self-consumption, peak load and cost. Table 4 shows the results from the best schedules for each KPI and the schedule with best overall result for all three KPIs. The greatest energy flexibility potential was found in the peak load reduction. The largest reduction in peak load was found to be 50%, but the model providing the lowest yearly peak load was not the model with the lowest average of monthly peak load. It was found in the results that every schedule gave a reduction in peak load compared to Base case. The cost was the least flexible KPI with a maximum reduction of 9.7%. The self-consumption was increased by 13.7% and it was found that the summer season was the most influential season considering reduction of self-consumption.

Table 4: KPI values for the best schedule in each case and the overall best schedule compared to the results from Base case.

Schedule	**Base case**	**S16(3)**	**S7(1)**	**S12**	**S9(2)**
SC	0.379 [-]	+13.7%	-0.6%	-31.8%	-19%
Peak load	7788 [W]	-24.6%	-46.8%	-28%	-50%
Cost	9924.3 [NOK]	-5.2%	-1.4%	-9.7%	-1.6%

It was found that without an additional controllable load implemented during the summer months or an electrical battery to store excess electricity, the self-consumption was limited. This was due to a low total electricity consumption during these months. By introducing a load representing the battery of an EV and implementing a schedule for daily charging from 10-13, the self-consumption was increased by 53.3% compared to Base case. However, due to normal office hours this charging schedule was considered unlikely.

When weighting the KPIs equally, the overall best score was found in a schedule with a constant value of 0.5. A relation between the KPIs analysed in this study was found. The schedules with lowest cost also had the lowest values for self-consumption. This thesis concludes that controlling the GSHP in casaZero has a great impact on the energy performance of the building.

8 Further work

Based on the research done in this thesis, a set of suggestions for further research on this topic was made to encourage wider knowledge on optimal and flexible operation of ZEBs.

- Further research on monthly peak load and the cost effect of the new fees for electricity peak is recommended, as the results of this thesis implies a significant variety in monthly peak load.
- Further research on seasonally adapted operation should be done, as this thesis implies a significant change in load profile for the different seasons.
- In this study, a sensitivity analysis was performed on a selection of defined schedules. To investigate the possibility of finding an even better schedule for GSHP operation, more research utilizing optimization tools should be conducted.

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A Appendix 1

Python script for finding the yearly peak load.

```
import numpy as np
import pandas as pd

load = pd.read_csv("/Users/ashildryen/PycharmProjects/pythonProject/S8-18PV.csv", sep=";", names=['time', 'value'])


X_f = load['time'] #pandas.core.series.Series
Y_f = load['value']
x_list_f = load['time'].tolist()
y_list_f = load['value'].tolist()
y_f = np.array(Y_f)
x_f = np.array(X_f)
a=0
b=0
i=0
while i<8761:
    i += 1
    y = float(y_f[i])
    x = float(x_f[i])
    current = y
    if current > a:
        a = current
        b = x

print(a)
print(b)
```

B Appendix 2

Python script for finding the monthly peak load.

```python
import numpy as np
import pandas as pd

load = pd.read_csv("/Users/ashildryen/PycharmProjects/pythonProject/S12.csv", sep=";", names=['time', 'value'])


X_f = load['time'] #pandas.core.series.Series
Y_f = load['value']
x_list_f = load['time'].tolist()
y_list_f = load['value'].tolist()
y_f = np.array(Y_f)
x_f = np.array(X_f)
a=0
b=0
i=1
while i<744:
    y = float(y_f[i])
    x = float(x_f[i])
    current = y
    if current > a:
        a = current
        b = x
    i += 1
print("Jan")
print(a)
print(b)
a=0
b=0
while i<1416:
    i += 1
    y = float(y_f[i])
    x = float(x_f[i])
    current = y
```

```
    if current > a:
        a = current
        b = x
print("Feb")
print(a)
print(b)
a=0
b=0
while i<2160:
    i += 1
    y = float(y_f[i])
    x = float(x_f[i])
    current = y
    if current > a:
        a = current
        b = x
print("Mar")
print(a)
print(b)
a=0
b=0
while i<2880:
    i += 1
    y = float(y_f[i])
    x = float(x_f[i])
    current = y
    if current > a:
        a = current
        b = x
print("Apr")
print(a)
print(b)
a=0
b=0
```

```python
while i<3624:
    i += 1
    y = float(y_f[i])
    x = float(x_f[i])
    current = y
    if current > a:
        a = current
        b = x
print("Mai")
print(a)
print(b)
a=0
b=0
while i<4344:
    i += 1
    y = float(y_f[i])
    x = float(x_f[i])
    current = y
    if current > a:
        a = current
        b = x
print("Jun")
print(a)
print(b)
a=0
b=0
while i<5088:
    i += 1
    y = float(y_f[i])
    x = float(x_f[i])
    current = y
    if current > a:
```

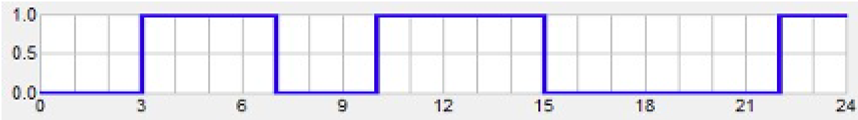
```
            a = current
            b = x

    print("Jul")
    print(a)
    print(b)
    a=0
    b=0
    while i<5832:
        i += 1
        y = float(y_f[i])
        x = float(x_f[i])
        current = y
        if current > a:
            a = current
            b = x
    print("Aug")
    print(a)
    print(b)
    a=0
    b=0
    while i<6552:
        i += 1
        y = float(y_f[i])
        x = float(x_f[i])
        current = y
        if current > a:
            a = current
            b = x
    print("Sep")
    print(a)
    print(b)
    a=0
    b=0
```

```
while i<7296:
    i += 1
    y = float(y_f[i])
    x = float(x_f[i])
    current = y
    if current > a:
        a = current
        b = x
print("Okt")
print(a)
print(b)
a=0
b=0
while i<8016:
    i += 1
    y = float(y_f[i])
    x = float(x_f[i])
    current = y
    if current > a:
        a = current
        b = x
print("Nov")
print(a)
print(b)
a=0
b=0
while i<8760:
    i += 1
    y = float(y_f[i])
    x = float(x_f[i])
    current = y
    if current > a:
```

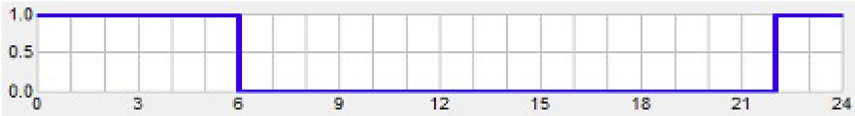
C Appendix 3

The 20 first schedules established for regulation of the GSHP.

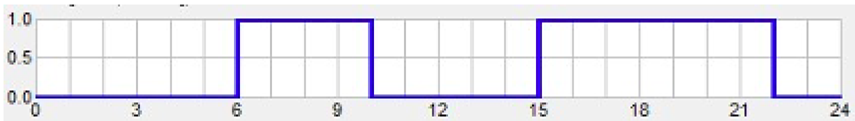
S1



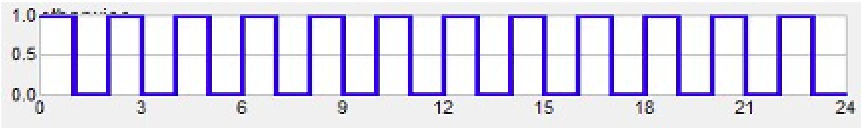
S2



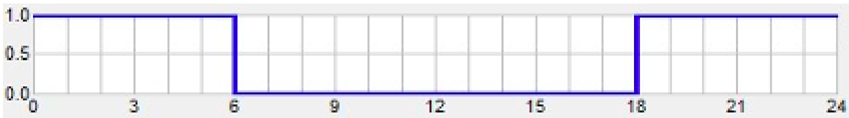
S3



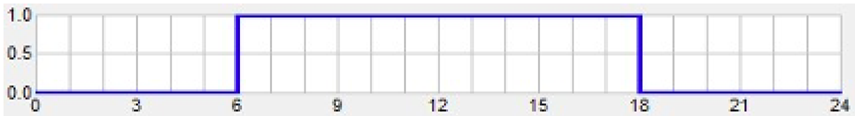
S4



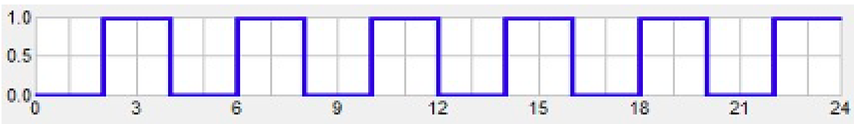
S5



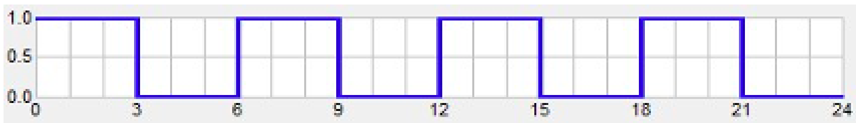
S6



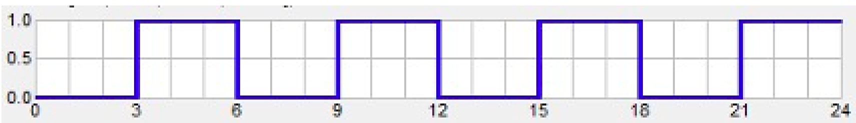
S7



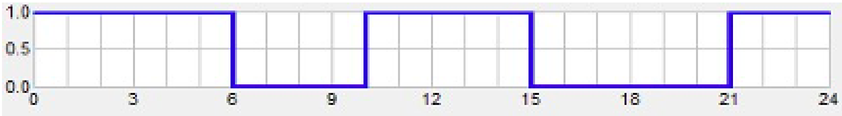
S8



S9



S10



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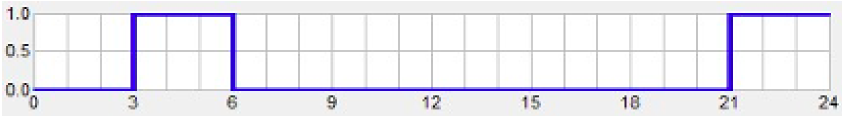

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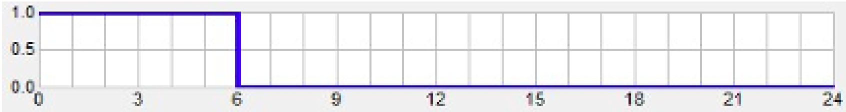

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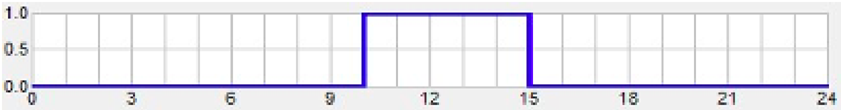

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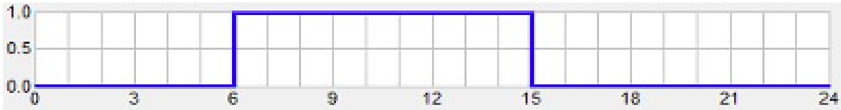
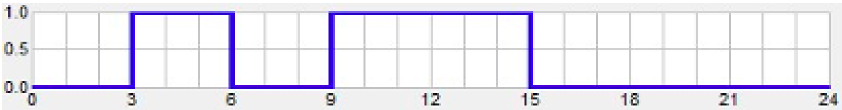
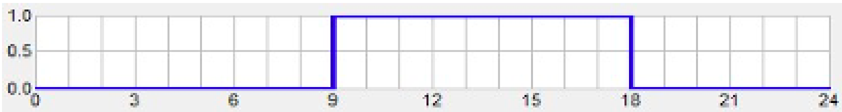


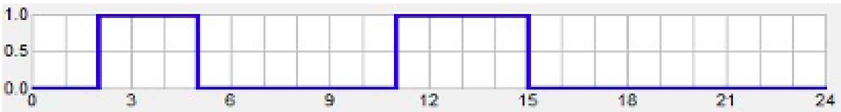
S15



S16



S17



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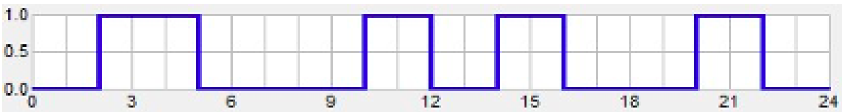
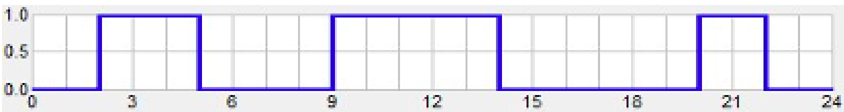
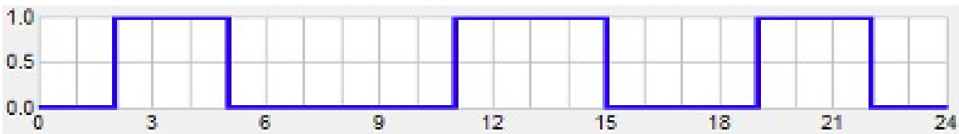


S19



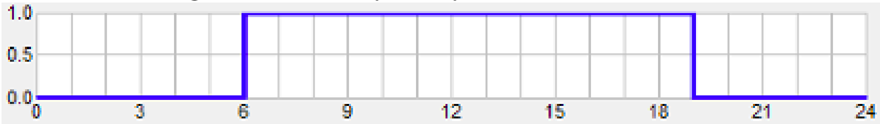
S20



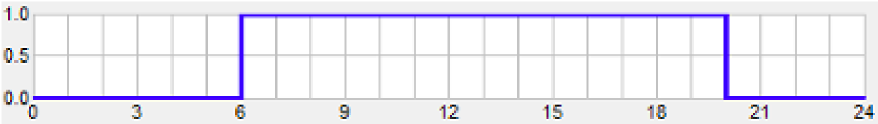
D Appendix 4

The 15 schedules established during the sensitivity analysis of Case 1.

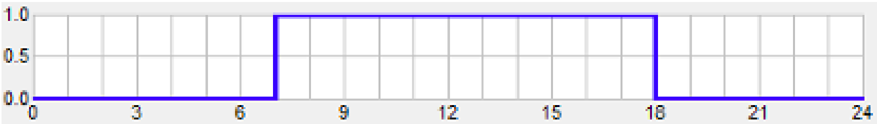
S6(1)



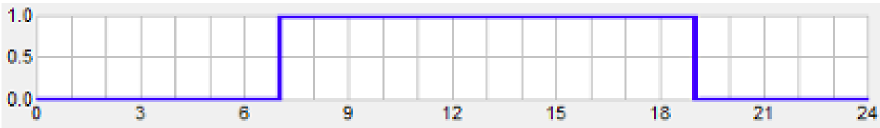
S6(2)



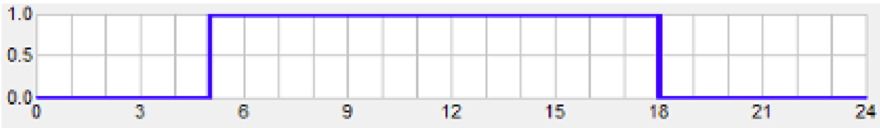
S6(3)



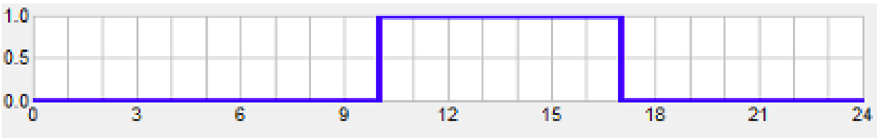
S6(4)



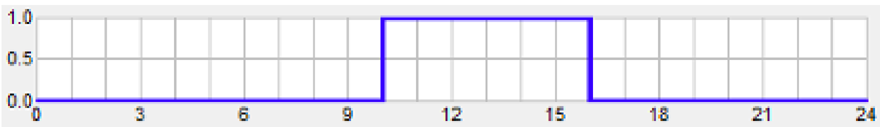
S6(5)



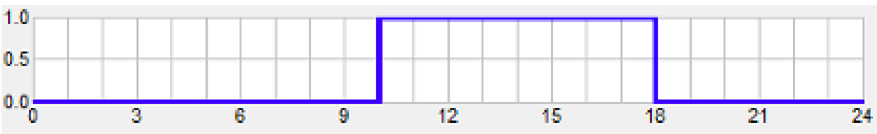
S13(1)



S13(2)



S13(3)



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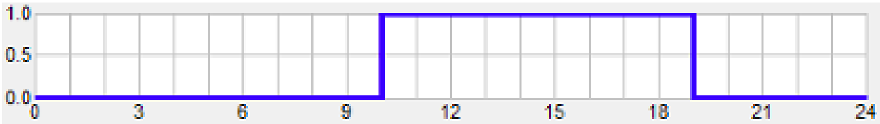

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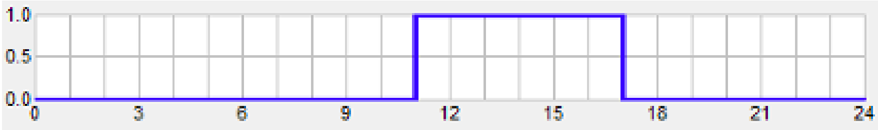

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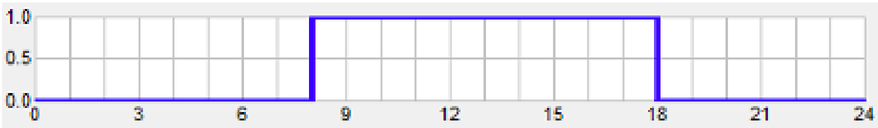

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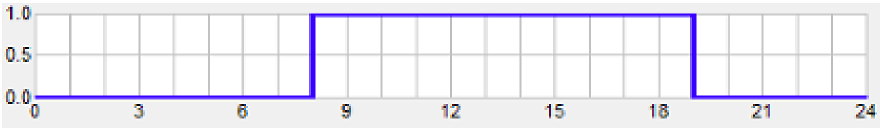

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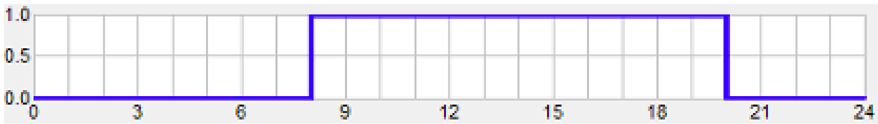

E Appendix 5

The 15 schedules established during the sensitivity analysis of Case 2.

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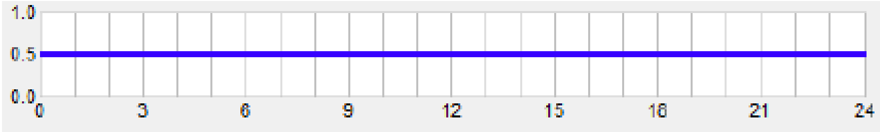

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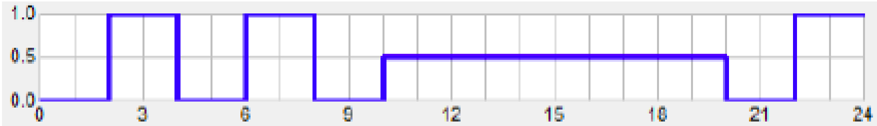

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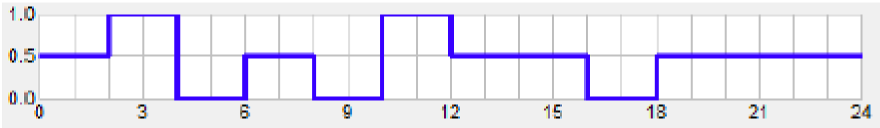

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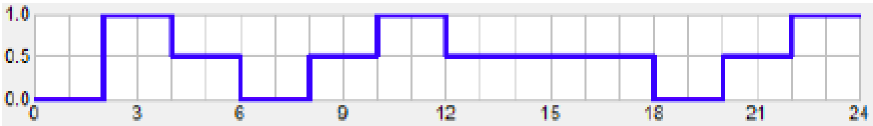

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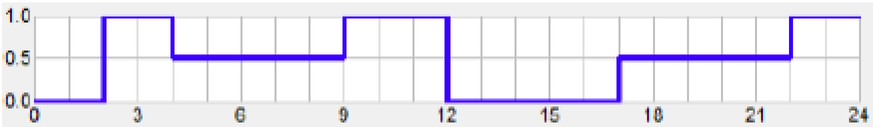

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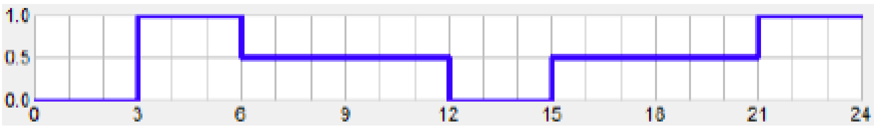

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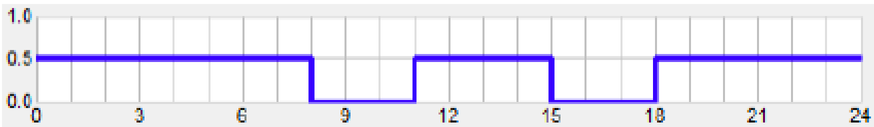

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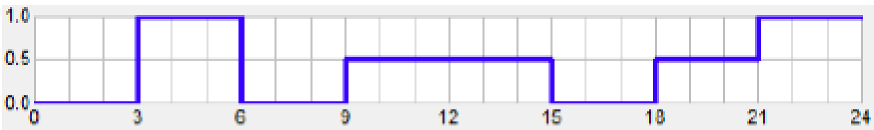

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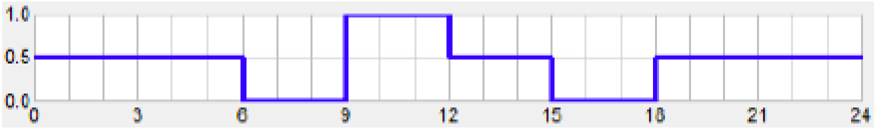

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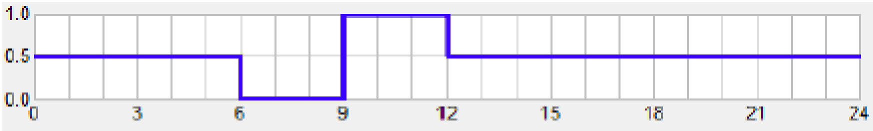

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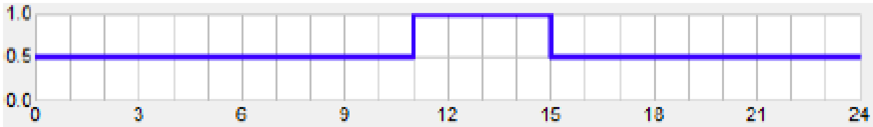

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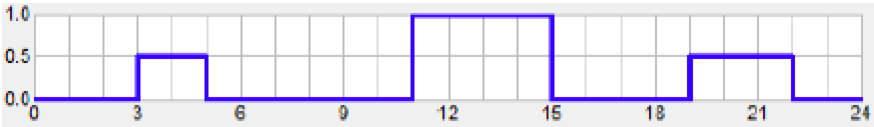

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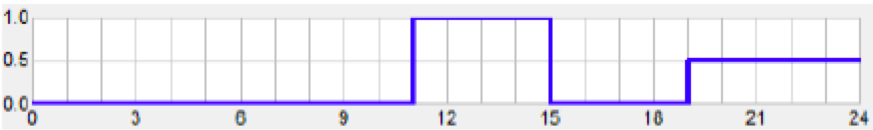

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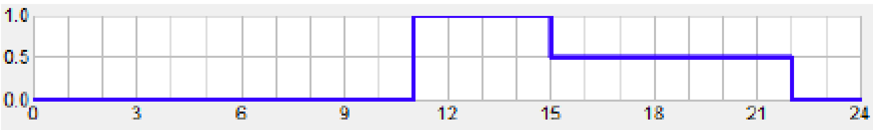

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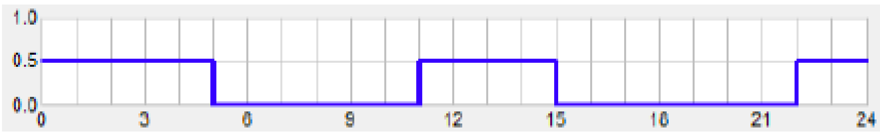

F Appendix 6

The 15 schedules established during the sensitivity analysis of Case 3.

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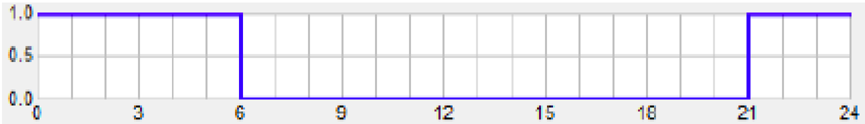

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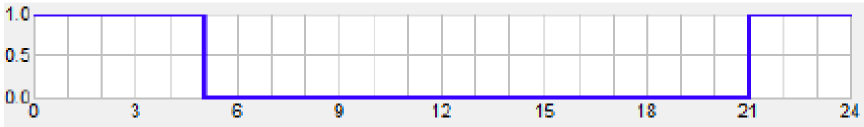

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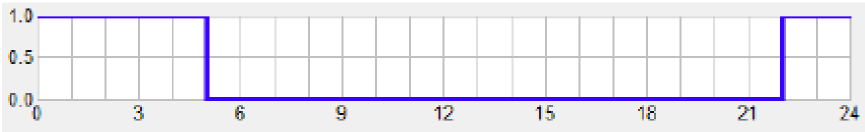

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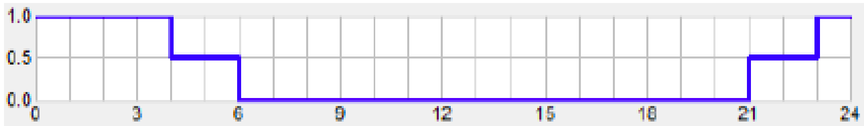

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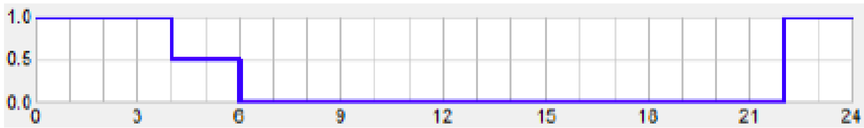

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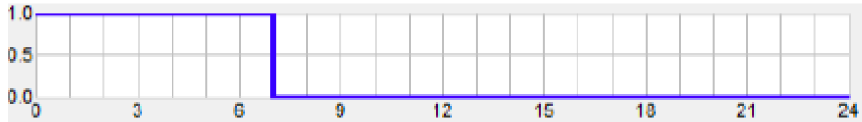

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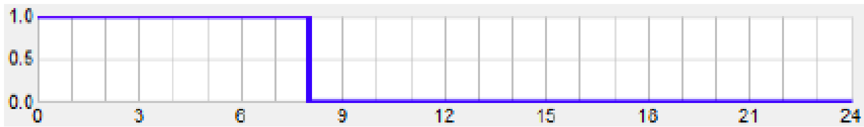

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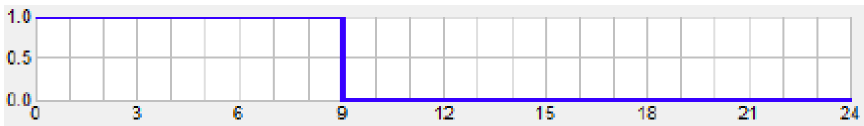

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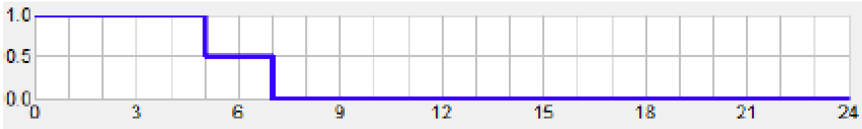

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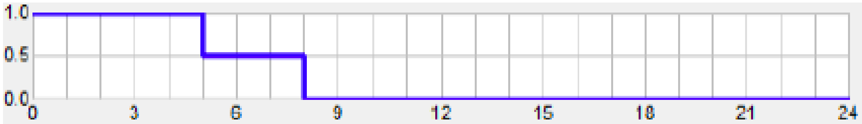

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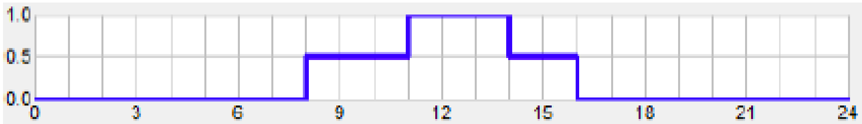

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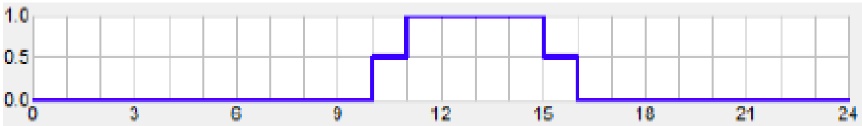

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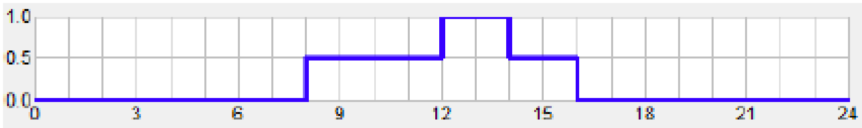

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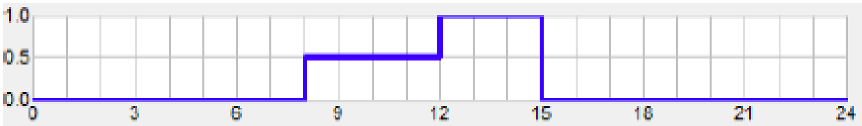

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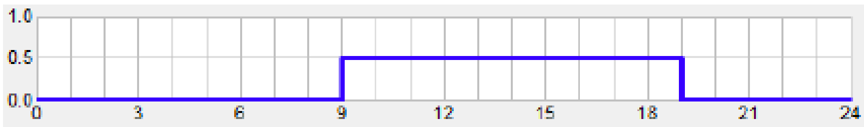

G Appendix 7

The following pages shows a scientific paper based on some of the results found in the master´s thesis.

Assessing energy flexible operation of a residential Zero Emission Building (casaZero)

Åshild Ryen Vespestad, Vojislav Novakovic, Karen Byskov Lindberg

Norwegian University of Science and Technology (NTNU), June 2022

Abstract

With an increasing amount of new and retrofitted buildings qualifying as ZEBs, the interaction between buildings and the grid has increased. Prosuming buildings that both produces and consumes electricity, are likely to both import and export electricity to the grid. Hence, the need to utilized smart controlling of the electricity consumption in buildings is reinforced as an attempt to reduce the stress on the grid. This study is a contribution to increase the knowledge on flexible operation of ZEBs. By implementing 35 different operational schedules for the GSHP of a residential ZEB, the impact on the performance of the building was studied. The KPI analysed in this study was the potential of peak load reduction. It was found to be 50%, when the GSHP was regulated to half the original potential at all time interrupted by two off-periods during the day. It was also found that by reducing the yearly peak load, values for both self-consumption and cost were affected.

1 Introduction

1.1 Background/Motivation

As the building sector today causes one third of the global energy use [1], ZEBs have become an important contribution to reducing the world wide energy use. The European Union goal of reducing the CO2 emission associated with the building sector by 80-95% compared to the 1990 level by 2050 [2], requires reduction in building energy use as well as increased utilization of on-site generated renewable energy.

All buildings require a minimum amount of electricity. Hence, ZEBs depend on on-site renewable electricity production to fulfill the ZEB requirement. Often the renewable electricity sources available are fluctuating, leaving the building dependent on electricity from the grid in hours when the local electricity sources are not supplying sufficient amount of electricity to the building [3]. When the electricity sources produce more electricity than consumed by the building, the excess electricity can be supplied to the grid. This way of buying and selling electricity to the grid characterizes the building as a prosumer [4]. With an increasing number of prosumers intermittently supplying electricity to the grid, the grid companies are facing challenges handling the unpredictability in the grid. Both considering hourly mismatch and seasonal mismatch [5]. This calls for an increased utilization of energy flexibility measures in ZEBs to increase the self-consumption and reduce the peak loads in the building to reduce the pressure on the grid.

By the end of 2022 a new law will be implemented in the Norwegian electricity regulations [6]. The new electricity prices includes a variable grid fee based on the monthly peak load. Peak load reduction can therefore be motivated by financial gain as well as decreasing the pressure on the grid.

Since the term ZEB was introduced in 2006 [7], several research papers have been written focusing on optimizing ZEBs. New and improved technology has emerged, enabling communication between technical equipment in the building. This increases the possibility of operating buildings in an optimal way considering cost, CO2 emission, indoor environment etc. Despite this, to the authors knowledge, the main research area on ZEBs has been on optimizing the design rather than the operation. To find out how optimal operation of a ZEB can effect the energy use and CO2 emission, more research on optimization of the operation of a ZEB is coveted.

1.2 Objectives of this research

The objective of this study was to asses energy flexible operation of a detached residential ZEB in Norway, named casaZero. The building was equipped with a GSHP, a water borne space heating system, a balanced ventilation system and PV panels for electricity production. Different operational strategies for the GSHP were tested to find the impact on the performance of the building, focusing on the potential of peak load reduction.

2 Methodology

2.1 casaZero

The building analysed in this study was a ZEB located in Kolsås, close to Oslo. The residential building had a total heated area of 233.6 m^2. It consisted of basement, 1.floor and 2.floor. The building was equipped with a balanced ventilation system and was heated through water pipes built into the floor. Only the 1. floor and the basement were equipped with the water borne heating system. The water was heated by a 6kW GSHP with an average COP of 4, and stored in a 224L DHW tank. The tank provided hot water for both the space heating system and the DHW tapping system. The south side of the roof was covered with 50 m^2 of PV panels generating an accurate amount of 10500 kWh yearly. The model of casaZero established in IDA ICE utilized schedules for lighting and equipment found in SN/TS 3031:2016 [8]. The simulation period was set to one year, utilizing a climate file from Oslo, Gardemoen. A detailed description of the building and the model established in IDA ICE is found in [9].

2.2 Key performance indicator

The KPI analysed in this study was the peak load. The aim was to reduce the electricity import peak. In addition to the KPI analysed, two criteria were given for the simulations. The first criteria was made as a result of the ZEB definition, considering the energy balance. As shown in Equation 1, the total electricity consumption could not exceed the total electricity production for the one year period. For each simulation this was checked to ensure a positive energy balance.

$$El^{imp} < El^{exp} \tag{1}$$

El^{imp} and El^{exp} is respectively total electricity imported and total electricity exported during a period of one year.

The second criteria was the indoor thermal comfort. It was evaluated by using the percentage of total occupancy hours with thermal dissatisfaction, referred to as the percentage of people dissatisfied (PPD). This was done by separately summing up the total occupancy hours for all zones and the total hours of thermal dissatisfaction. The two numbers were then implemented in Equation 2.

$$PPD = \frac{h^{PD}}{h^{occ}} \tag{2}$$

Where h^{PD} is the hours of people dissatisfied and h^{occ} is the occupancy hours. Only schedules with PPD<10% were qualified as satisfactory based on the standards given by NS-EN ISO 7730:2005 [10].

2.2.1 Peak load

The equation used for calculating the total imported electricity for each time step is shown in Equation 3. A script was established in Python to find the highest value of imported electricity during a year, as well as a script for finding the monthly peak load.

$$El_t^{imp} = El_t^{heat} + El_t^{eq} + El_t^{hvac} + El_t^{light} - El_t^{prod} \tag{3}$$

El_t^{imp} is the imported electricity, El_t^{heat} is the electricity consumed by electric heating, El_t^{eq} is the electricity consumed by equipment, El_t^{hvac} is the electricity consumed by the HVAC system, El_t^{light} is the electricity consumed by lighting and El_t^{prod} is the produced electricity, with t representing the time step of the simulation period.

2.3 Base case

In the Base case model the GSHP was regulated by a thermometer in the DHW tank. The GSHP was turned on if the temperature was too low. An electric boiler acted as the top heater, supplying heat to the DHW tank when the GSHP could not supply enough heat.

2.4 Case with GSHP schedules

To evaluate the influence of applying different operational strategies to the GSHP, 20 schedules were established to control the work of the GSHP. The schedules were named S1, S2, ..., S20. The electric top heating of the DHW was removed, but the thermometer regulating the GSHP was kept. Hence, the GSHP was only operating in hours when both the schedule and the thermometer allowed it.

Each schedule was analysed according to the KPI. The three schedules with lowest result for yearly peak load were selected and a sensitivity analysis was performed on each of the three schedules. The sensitivity analysis was performed by developing 5 new schedules for each of the three chosen schedules. The new schedules had only minor adjustments compared to their origin schedule. A total of 15 new schedules were established during the sensitivity analysis.

3 Results and analysis

3.1 Base case

The following main results were found from the simulation of Base case:

- Total produced electricity: 10 479 kWh
- Total consumed electricity: 9559 kWh
- Total purchased electricity: 5732 kWh
- Total exported electricity: 6653 kWh
- Self-sufficiency: 0.3791
- Peak load: 7788 W
- Cost: 9924.3 NOK

3.2 Case with GSHP schedules

The 15 schedules established during the sensitivity analysis is presented in Figure 1. The row written in red shows the schedules with the lowest yearly peak load without compromising the thermal comfort. The three schedules marked in green are the schedules with best results from the first round of simulation.

Schedule	SC [-]	Peak load [W]	Cost [NOK]	PPD [%]
S7(1)	0,37692517	4145	9790,5	9,81
S7(2)	0,36270583	4411	9734,4	9,77
S7(3)	0,353194	4355	9769	9,75
S7(4)	0,38211529	4627	9660,7	9,8
S7(5)	0,32603356	4842	9766,2	9,78
S9(1)	0,34732003	4798	9654,8	9,76
S9(2)	0,30728642	3896	9763,8	9,76
S9(3)	0,35052978	4885	9673,5	9,74
S9(4)	0,32448456	4901	9750,9	9,71
S9(5)	0,34368623	4510	9793,2	9,76
S20(1)	0,37670432	4238	9808,4	9,79
S20(2)	0,34504328	5021	9470,8	9,71
S20(3)	0,37449012	5380	9405	10,09
S20(4)	0,40187575	5447	9349,9	10,19
S20(5)	0,34074366	4989	9398,9	9,77
S7	0,32640015	4700	9712,3	9,72
S9	0,32886731	4898	9643,3	9,74
S20	0,34216941	4949	9490,5	9,78

Figure 1: An overview of the main results from the sensitivity analysis.

The results in the figure shows that by improving only peak load, the value for both self-consumption and cost are affected. Based on the results in Figure 1 schedule S9(2) gives the lowest yearly peak load. The S9(2) schedule is shown in Figure 2.

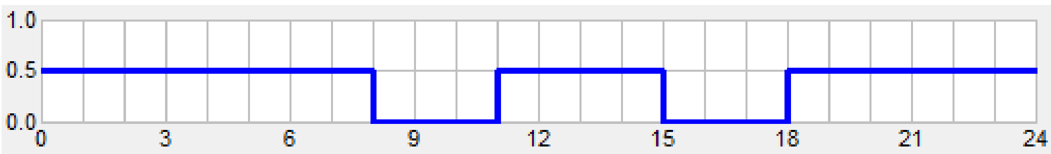

Figure 2: GSHP schedule for S9(2).

Figure 3 gives an overview of the peak load found for each month in the Base case compared to S7, S9, S7(1) and S9(2). Though the S9(2) schedule has the lowest yearly peak load, the figure shows that S7(1) puts a lower pressure on the grid for larger parts of the year. For April, the peak load for S7(1) is reduced by 37.4% compared to S9(2) and the average peak load reduction for the 12 months is 11.3%. It can also be noted from the figure that the Base case has a low peak load for the months from April to October. However, the peak loads during the winter months are about doubled compared to the values for S7(1) and S9(2).

In addition to affecting the pressure on the grid, it is reasonable to assume that the difference in peak load for S9(2) and S7(1) will influence the cost. In this study, a cost analysis including the new electricity fee was not performed, however the variety in monthly peak load between the two schedules indicates a lower yearly cost for S7(1).

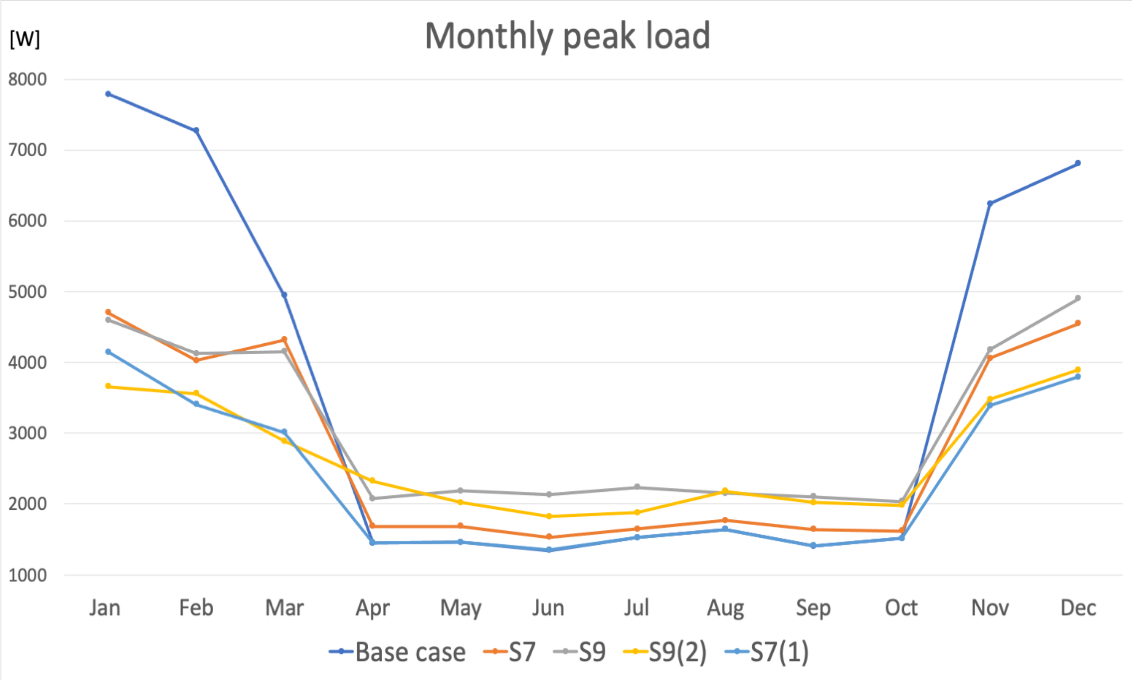

Figure 3: Monthly peak load for Base case, S7, S9, S7(1) and S9(2).

A load profile for Base case and S9(2) is displayed in Figure 4. The load profile shows the three days during the winter season with the highest total electricity consumption. Though the peaks are mostly coinciding, the peak values are strongly reduced for the S9(2) schedule. The lower and wider peaks found in S9(2) is due to the regulation of the GSHP found in Figure 2. As S9(2) never allows the GSHP to operate with full capacity, the load is distributed on a larger interval to cover the same heating demand as found for the peaks in Base case.

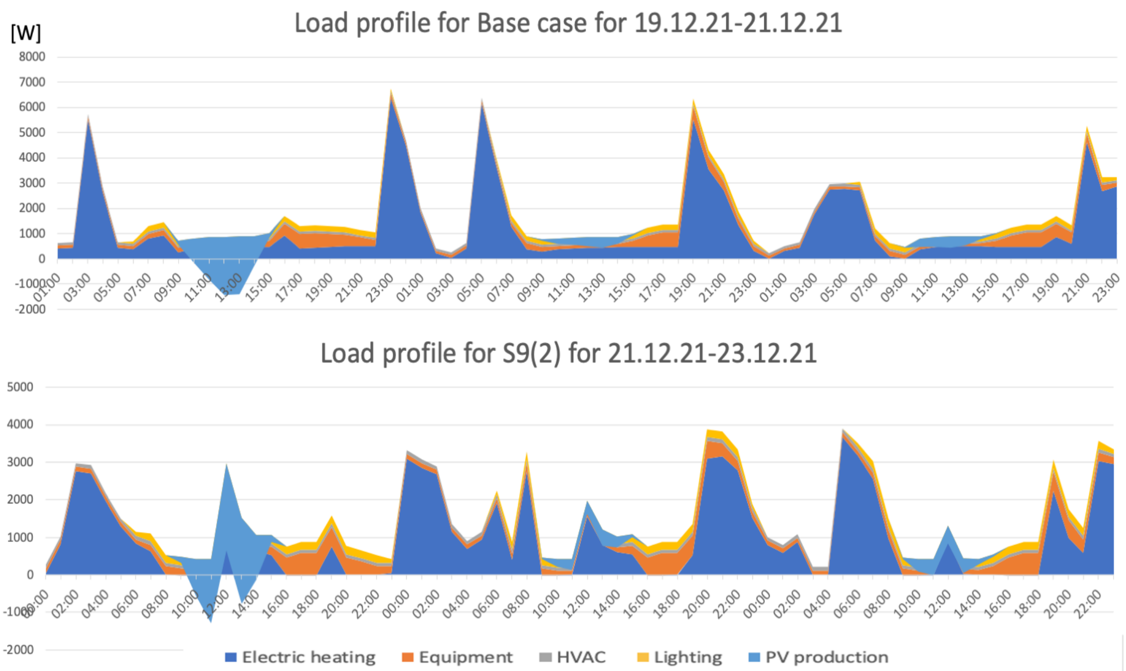

Figure 4: Load profile for the 72 hour periods with highest electricity consumption for winter season for S9(2) and Base case.

The S9(2) schedule turns off the GSHP during periods of the day. Due to this, more peaks are found in the graph for S9(2) compared to base case. This is also seen in Figure 5 where Base case resulted in a smooth curve with little slope, while S9(2) has several minor peaks during the day. During summer, the peaks are slightly higher for S9(2) compared to Base case. However, the off periods of the GSHP during PV production hours causes a decrease in the self-consumption for S9(2).

Though the S7(1) schedule was the best solution considering monthly peak loads, the S9(2) schedule had the highest reduction in yearly peak load with a reduction of 50%. The equivalent number for S7(1) was 47%. Hence, S9(2) was the best schedule found in this study for yearly peak load reduction.

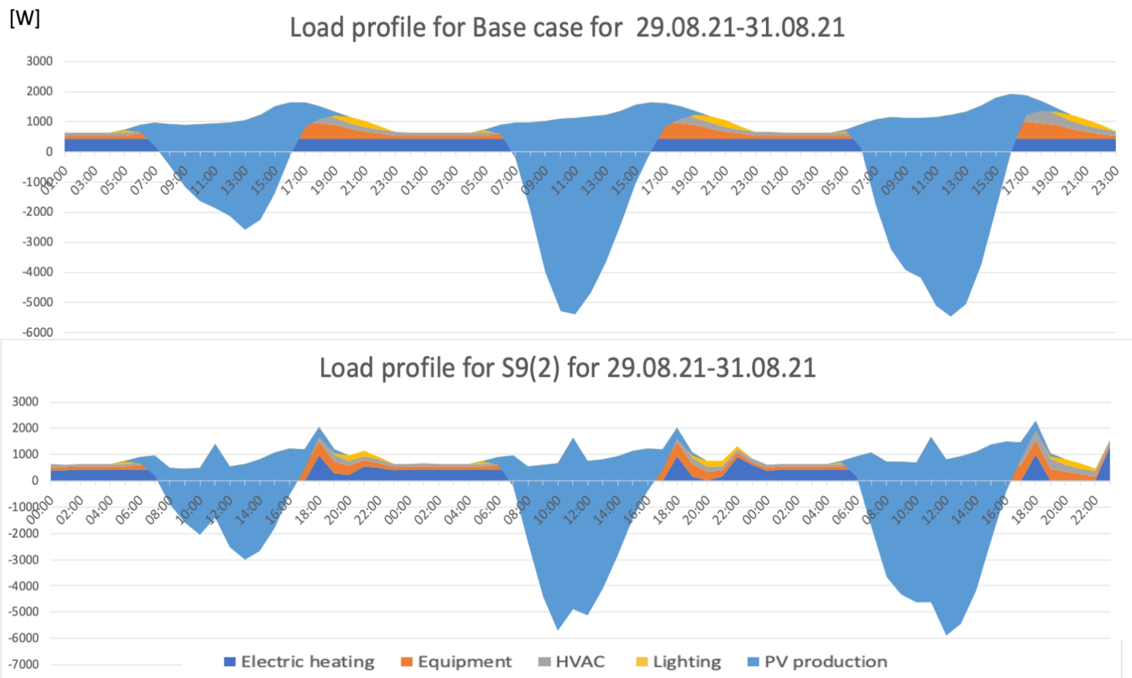

Figure 5: Load profile for the 72 hour periods with highest electricity consumption for summer season for S9(2) and Base case.

4 Conclusion

This study investigated 35 different operational strategies for the GSHP in a residential ZEB. The aim was to find the influence on the energy performance of the building. According to the chosen KPI of the study, S9(2) had the best result. The S9(2) schedules improved the yearly peak load by 50% compared to Base case. However, for 10 out of 12 months the monthly peak loads were higher than for the S7(1) schedule. It was also found in the results of this study that when improving the peak load both self-consumption and cost were affected.

4.1 Further work

Based on the results of this study it was found that further research on the cost effect of the monthly peak load fee soon to be implemented in Norwegian electricity prices is of interest. As the load curve for winter differed significantly from the load curve for summer, more research on seasonal differences and its influence on different KPIs would be of interest in regions with significant seasonal differences. Furthermore, utilization of optimization tools like GenOpt or AutoMOO would be desired, as the results would give more exact values for the KPI compared to the once found in this study.

5 Acknowledgment

Acknowledgement should be given to NTNU for providing the opportunity to perform this study.

References

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