Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Electric Power Engineering

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A study on optimal utilization of electric heating for buildings

Master's thesis in Energy Use and Energy Planning
Supervisor: Karen Byskov Lindberg
February 2020

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Abstract

From January 2020, heating systems based on oil or gas are not allowed in Norway. In addition, stricter building regulations in order to meet the goals set for reduced CO_2-emissions is expected. This enforces new solutions for optimal use of electricity and heating in buildings.

This master thesis is a further development of an existing model developed in a master thesis from 2018 [1], and further developed in a master thesis from 2019 [2]. The model is a Mixed Integer Linear Program (MILP) implemented in the programming language Python, with the modelling extension library Pyomo. The use of the model has been limited to an energy-efficient Single Family House (SFH)

The objective of this thesis is to use the already existing model in order to decide whether a point-source or a waterborne heating system is the favorable option in regard to heating. This is investigated for a SFH, an apartment block and an office building. In addition to the heating system itself, all three buildings have been investigated for two different building standards. The objective was to see if the insulation of the building had an impact on which heating system that was the favorable option. For this purpose, an implementation of new building types with associated heating loads has been done. In addition to this, a review of input values for the model has been done, and new investment costs for larger building has been found.

In order to compare the results, four different cases has been decided. Whereas the base case **PS** is a point-source system where the building standard implies an old badly insulated building, an upgrade including post-insulation of the building can be done. This upgrade results in the second case for the point-source system, **PS_R2**.

The two other cases have both updated from point-source system to a waterborne heating system which results in different applicable technologies for the heating. These two cases are also divided in one case where the building standard is the same as in the base case **WB**, and one case where the building standard is upgraded by post-insulating **WB_R2**.

Throughout the work of this thesis, the complexity of the choice of heating system has become clear. It can be stated that an upgrade of heating system from point-source to waterborne system will reduce energy system costs. Nevertheless, the results show that the reduction of costs for the energy system is not high enough in order to earn the cost of the renovation. At the same time, changes in electricity price and stricter restrictions of CO_2 emissions will favor the waterborne solution when seeing the problem in a long-time perspective.

Sammendrag

Fra januar 2020 er oppvarming i bygninger basert på olje og gass ulovlig i Norge. I tillegg forventes det et strengere lovverk for bygninger fremover, for å kunne møte målene som er satt med tanke på reduksjon av CO_2-utslipp. Dette påtvinger nye løsninger for optimal bruk av elektrisitet og varme i bygninger.

Denne masteroppgaven er en videreutvikling av en allerede eksisterende modell som er utviklet gjennom en masteroppgave skrevet i 2018 [1], og videreutviklet i en masteroppgave skrevet i 2019 [2]. Modellen er et MILP implementert i programmeringsspråket Python, med modellbyggingsbiblioteket Pyomo. Bruken av denne modellen har tidligere vært begrenset til en energieffektiv enebolig.

Målet med denne masteroppgaven er å bruke den allerede eksisterende modellen til å bestemme om punktkilde-varme eller vannbåren varme er den beste løsningen for oppvarming. Dette blir testet for en enebolig, et leilighetskompleks og et kontorbygg. I tillegg til å teste selve varmesystemet, blir alle tre bygnings-typene testet for to forskjellige bygnings-standarder. Dette er for å se om isoleringen av ytterveggene på boligen har innflytelse på hvilket system som er foretrukket. På bakgrunn av dette er nye bygnings-typer med tilhørende lastprofiler implementert i modellen. I tillegg er det gjennomført en gjennomgang av de eksisterende input-verdiene for modellen, og nye investeringskostander for større systemer er innhentet.

For å sammenligne resultatene har det blitt laget fire forskjellige løsninger for utforming av systemet som sammenlignes med hverandre. Den enkleste løsningen er et punktvarme-system i en bygning med eldre bygnings-standard som innebærer dårlig isolerte yttervegger. Denne løsningen er kalt **PS**. En etter-isolering av denne bygningen kan gjøres, som resulterer i den andre løsningen, **PS_R2**.

De to siste løsningene som testes har oppgradert fra punktvarme til et vannbårent varmesystem. Dette resulterer i andre typer teknologier som kan brukes til å varme opp bygningen. Disse to løsningene testes også for en eldre dårlig isolert bygning, **WB** og en etter-isolert bygning **WB_R2**.

Gjennom arbeidet med denne masteroppgaven har kompleksiteten i valget av varmesystem for en bygning blitt tydelig. Fra resultatene kan det ses at en oppgradering fra punkt-varme til vannbårent system resulterer i reduserte kostnader for selve energisystemet og energibruken. Likevel viser de totale kostnadene for energisystemet og renoveringene at reduksjonen i energikostnadene ikke er store nok til å veie opp for renovasjonskostnadene. Samtidig vil endringer i strømprisene og strengere krav for CO_2-utslipp favorisere det vannbårne systemet på lengre sikt.

Preface

This thesis marks the end of the two-year Master degree in Energy use and energy planning with specialisation within energy supply. It has been carried out during the autumn of 2019.

I would like to thank my supervisor during this master thesis, Karen Byskov Lindberg, for valuable sharing of her knowledge in addition to her great willingness of sharing her time whenever I have needed. Thanks to Marius Bagle at SINTEF Community for his abilities in coding and the model used in this thesis, and for sharing all of this with me. Also a great thanks to the others working in SINTEF Community for being open and motivating towards me at my visits and for letting me use an office at their workplace in Oslo when I have been visiting.

Finally I must thank all friends and family that have supported me and motivated me through this work. A special thanks to my study companions who have been working with me and sharing their valuable input and experiences with me.

Trondheim, February 2020

Camilla Hengebøl

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Abbreviations

A2A Air-to-Air

AMS Advanced Measuring System

ASHP Air Source Heat Pump

BA Battery

BB Bio Boiler

COP Coefficient of Power

DER Distributed Energy Resources

DHW Domestic Hot Water

DR Demand Response

EB Electric Boiler

FP Fireplace

GSHP Ground Source Heat Pump

HS Heat Storage

HWT Hot Water Tank

MILP Mixed Integer Linear Program

noZEB no Zero Emission Building

PO Panel oven

PV Photovoltaic

SFH Single Family House

SH Space Heating

ZEB Zero Emission Building

1 Introduction

1.1 Thesis Motivation

The importance of energy efficient and environmental friendly solutions for heating and electricity in buildings are severly increased the past years for both industrial and residential buildings. New regulations and laws are implemented so that each and everyone fulfills their duty in regards to their homes, to reduce CO_2-emissions.

"Regulations on technical requirements for construction works - TEK 17" is the minimum requirements a building must hold, in order to be legally built [11]. Throughout the years, this regulation has been more focused on energy efficiency and flexible energy resources. For this assignment, section 14-4; Requirements for energy supply solutions, is highly relevant. Firstly, the section states that installation of fossil fuel heating installations is not permitted. In other words, no new buildings in Norway is built with a fossil fuel heating system. Secondly, buildings with a heated gross internal area of more than 1000 m^2 shall:
a) have multi-source heating systems
b) be adapted for use of low-temperature heating solutions.
For offices and large apartment buildings for instance, this regulation can have an impact on how to design energy resources for domestic tap water and space heating.

The concept of heating flexibility in regards to buildings gives an understanding of how to implement different technologies so that the building can be heated with different methods. This is important for both the security of supply in addition to efficiency of costs and the environment.

In additon to "TEK-17", the Ministry of Petroleum and Energy in cooperation with the Ministry of Climate and Environment decided to adopt a law concerning the use of mineral oil for heating of buildings. This law prohibits the use of mineral oil and fossil fuel, effective from 01.01.2020. This has resulted in a change of heating system for both Single Family Houses and larger buildings [12].

1.2 Problem Description

The purpose of this thesis is to determine the best solution for covering the heating demand of residential buildings, apartment blocks and office buildings.

Energy use in buildings is responsible for 40 % of global greenhouse gas emissions. One way of reducing these emissions is to heat buildings with electricity rather than oil and gas. Norway has a vast experience in electric heating, and may be seen as a laboratory for the future renewable energy system. However, we need more knowledge on how to utilise electricity in the most cost-effective way. Is it water-based heat pumps that require costly waterborne heating systems inside the buildings, or electric radiators that have far lower efficiency, but are cheap and easy to install, that will be the future?

How to cover the electricity demand is also a challenge with prospects of an increase in the electricity price. A solution could therefore be on-site production of Photovoltaic (PV), which is a technology with increased popularity in Norway the past years. This solution is to be explored throughout this thesis.

Relevant background for this thesis is the current technical regulations of buildings (TEK 17), and the optimisation model developed in earlier master thesis for studying design of energy technologies within buildings.

1.3 Approach and Limitations

The model used in this thesis is developed through earlier work [1], [2] and is a deterministic MILP. Through this work, a new grid tariff has been implemented in the model, in addition to gathering of new input data with the objective of expanding the model to larger buildings, hence larger capacities for the technologies. The new gird tariff is also implemented with the objective of a more realistic approach to commercial buildings, as they have other regulations in regard to electricity pricing.

The work approach in this thesis has been gathering of data, processing and implementing this in the model. Because of the fact that the model has been further developed in the time from my project thesis to the start of my master thesis, familiarizing myself with the improved model was quite time consuming in the start and has been a large part of the workload in this thesis work.

The fact that the Zero Emission Building (ZEB)-constrictions in this model only count for the operation phase in the building lifetime is one of the main limitations of the model. The level of ZEB included in this model is called ZEB-O EQ [13] and concerns the operation phase, but excludes the emissions of the equipment of the technologies.

1.4 Structure

The structure of the thesis is as follows:

- Chapter 2: In this chapter, the theory of the most important aspects in order to understand the model and the results, are explained. This includes the concept of ZEB and the technologies which are included in the model. An introduction of electricity pricing is also included in this chapter, in addition to an introduction in the concept of demand side flexibility.
- Chapter 3: After the theory, a chapter which introduces the different cases follows. This

is also where all input data for the model is introduced for the reader, in addition to an explanation of how the input data was gathered.

- Chapter 4: A review of the mathematical aspects of the model, and a more thoroughly explanation of variables and parameters are shown in this chapter. This is where the reader is able to get an insight of how the model is able to calculate the optimal solution.
- Chapter 5: A presentation of the main results are given at first, followed by discussion with regards to different approaches of the results. In addition to main results, sensitivity analysis of the most important aspects of the thesis which are the energy prices and PV prices are presented and discussed.
- Chapter 6: The final conclusion is presented, in addition to suggestions for further work.
- Appendices: Includes both the waterborne model and point-source model which are used for the optimization problem. Load profiles for different buildings that are not presented in chapter three are also included.

2 Theory and Research

2.1 Zero Emission Buildings

ZEB is a concept of measuring emissions throughout the lifespan of a building. More regulations on especially commercial buildings requires an interpretation of the concept which can be widely utilized and easily understood.

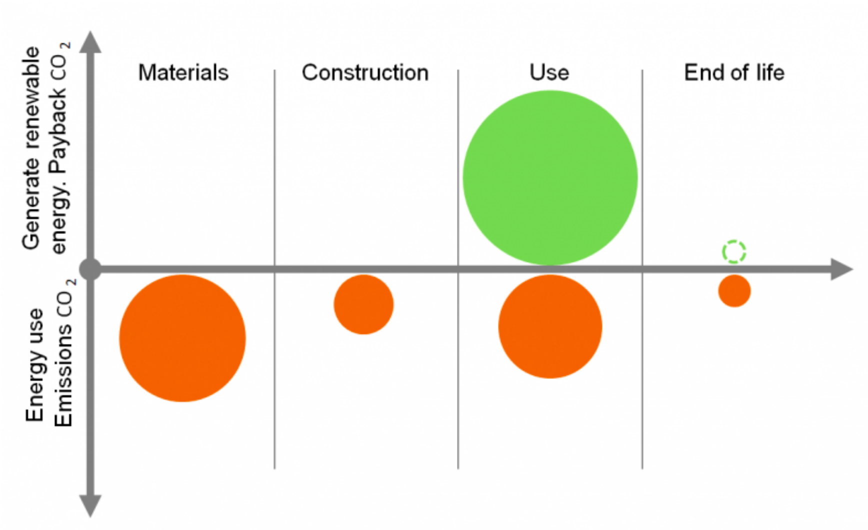


Figure 2.1: Illustration of ZEB definition [3]

In figure 2.1 an illustration of the concept can be seen. The four elements, materials, construction, use and end of life are the phases of the lifetime of a building which can be counted for in a ZEB. The more phases counted for, the more strict is the level of ZEB, hence more difficult to reach. For the strictest ZEB-level, *ZEB-COMPLETE*, the green circle compensates for energy use from all phases of the life of the building. It is also possible to reach a degree of ZEB if for some reason, the achievement of the strictest level is an unrealistic accomplishment. For instance, a common ZEB-level is to compensate for the energy use, called *ZEB-O*. As seen from the figure, reaching a level of ZEB requires on-site production of energy as *Payback* CO_2 in addition to low emissions from energy use.

A building that compensates for its energy use during operation, *ZEB-O* is also referred to as net zero emission building. A definition can be found in [13]:

The building produces the same amount of energy from renewable sources (e.g. PV, solar thermal collectors) as the energy needed for its operation.

From figure 2.2, the concept of net ZEB can be seen graphically. The arrow along the x-axis represent the decrease in demand of a high-efficient building in comparison with a reference building, which is built according to the minimal requirements of the national building code.[4]. Along the y-axis the amount of energy supply needed to reach the goal of net ZEB can be found by the red arrow.

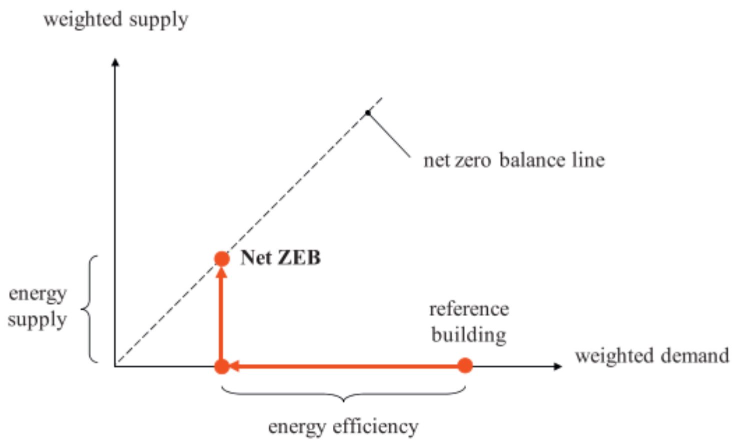


Figure 2.2: Graphically representation of net ZEB balance [4]

From figure 2.2, it can be seen that the approach of reaching net ZEB balance is to either increase amount of energy supply or decreasing the amount of energy demand. The challenge of increasing the energy supply can be that most of on-site renewable energy generation is limited. The limitations are for instance wind, sun or area. Introducing energy-saving measures in the building is therefore important in order to reach the goal of net ZEB balance.

$$\sum_i import_i \times f_i - \sum_i export_i \times f_i = G \qquad \forall i \in I \tag{2.1}$$

From equation 4.8 it can be seen that the sum of all energy carriers imported energy times its respective weighing factor, subtracted the export of all energy carriers times its respective weighing factor, equals G. When G = 0, the building fulfills the requirements of net ZEB.

The weighing factor in the case of zero emission is called CO_2 factor. This is a factor which tells how much CO_2 is produced per kWh generated electricity. The weighing factors used in this work are given in table 3.5.

2.2 Technologies

In this chapter, the most important technologies of the model is described.

2.2.1 Heat Pumps

The basic principle of a heat pump is to transport heat from a lower to a higher temperature level. Electricity is needed to transport the heat, but because of the Coefficient of Power (COP), a heat pump is still a technology which is used to reduce electricity use. COP is the amount of heat produced relative to effect consumption. Heat pumps are often divided into two categories based upon from where the heat is extracted. Air-source heat pumps extract the heat from ambient air, while ground-source heat pumps extract heat from the ground [14].

Air-Source Heat Pump

Air Source Heat Pump (ASHP), also extract heat from ambient air, but for the indoor heating system it is connected to a water-based heating system. Because of the transfer from air to water, this system can also be used for the domestic hot water demand. This heat pump is very common because of low investment costs. At the same type it has a lower yearly COP and shorter lifetime than other variants. This is caused by the difference in outdoor temperature and heat demand. When heat demand is at its highest, the temperature is at its lowest. This makes it very hard for the heat pump to produce domestic hot water on the days with coldest temperatures [15].

Ground-Source Heat Pump

Ground Source Heat Pump (GSHP) are also connected to a water-based indoor heating system so that the system cover both the space heating demand, and domestic hot water demand. GSHP can be divided into two different system designs, indirect and direct, but the indirect design is more commonly used and will therefore be the design focused on in this thesis. The indirect design uses an anti-freeze fluid which circulates in a closed loop, taking advantage of the temperature 80-200 meters below ground. Because of the deep borehole, this technology has higher investment cost than ASHP, but working on a more even temperature throughout the year, it can achieve a high COP and longer lifetime than other technologies.

To calculate COP for heat pumps with waterborne system, equation 2.2 is suggested [16]:

$$COP_{ashp,gshp} = k_0 - k_1 \cdot \Delta T - k_2(\Delta T)^2 \tag{2.2}$$

where the k-values are retrieved from manufacturers data, and ΔT is the difference between supply and source temperature as seen in equation 2.3

$$\Delta T = T_{supply} - T_{source} \tag{2.3}$$

The supply temperature is given by equation 2.4

$$T_{supply} = AT_{amb}^2 + BT_{amb} + C \tag{2.4}$$

where the coefficients are given by the building standard. All k-values and coefficients used in calculations are given in table 3.3 and 3.4.

Air-to-Air Heat Pump

Air-to-Air (A2A) heat pumps have one outdoor unit which extracts heat from the ambient air, and one or several indoor units for space heating. An A2A heat pump can be used both for heating and cooling, which can be a great advantage in times with higher temperatures. At the same time, a disadvantage with this system is that it can not cover the domestic hot water demand [17].

The COP for this type of heat pump is calculated in a slightly different manner than for heat pumps functioning on a waterborne system. From [18] where different COPs for a specific Mitsubishi A2A heat pump is stated, polynomials are developed to fit the equation for the COP. The curve used for finding the polynomial is shown in figure 2.3 and is based upon a regression analysis of the data found in [18].

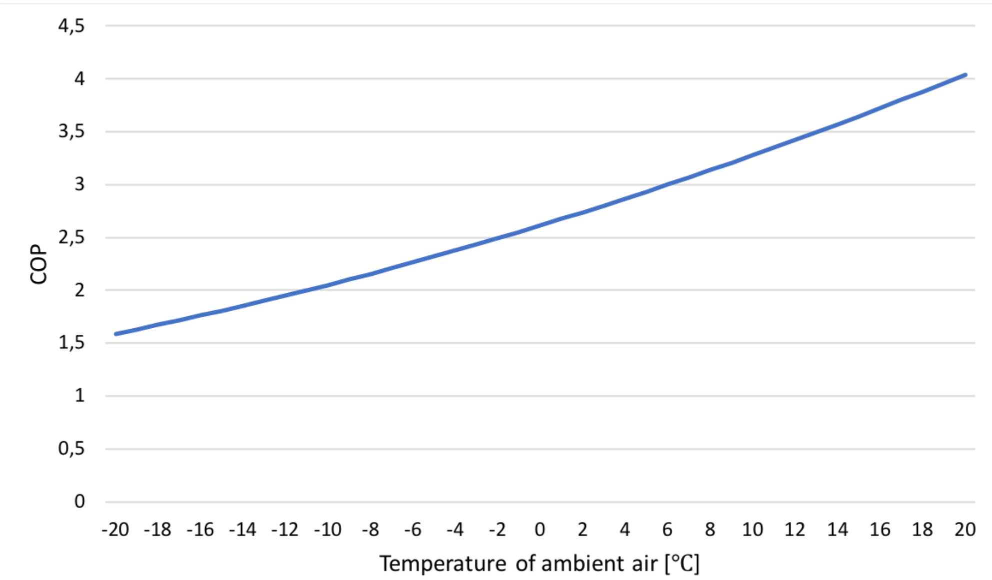


Figure 2.3: Connection between temperature and COP for a2a heat pump

Thus, the equation for COP for A2A heat pump is as follows:

$$COP_{a2a} = k_0 T_{amp}^2 + k_1 T_{amb} + k_2 \tag{2.5}$$

where the values for k_0, k_1 and k_2 can be found in table 3.3.

2.2.2 Photovoltaic Systems

A photovoltaic system, also called PV, is a device converting sunlight into energy. Technically, this is done by using a semiconductor, typically Silicon, and mixing it with other elements with different number of electrons. From figure 2.4 it can be seen that it has been created a negative-type silicon in the top layer, and a positive-type silicon in the bottom layer. Where these two layers come together, some of the positive holes and negative electrons will work together and form an electric field, preventing the other holes and electrons from moving between the layers. When the sunlight hits the surface, the energy will make the holes and electrons jumps from their respective layers. Connecting both layers to a circuit creates a favorable way for the excess electrons and holes to come together, creating an electric circuit.

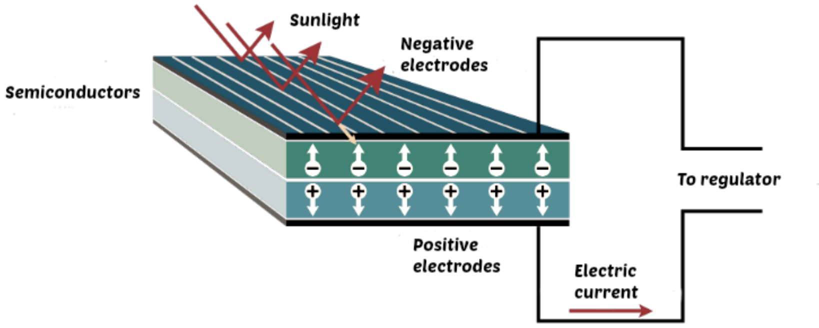


Figure 2.4: Cross-section of a solar cell

When talking about a building connected to both PV system and grid, a schematic drawing can be seen in 2.5. A way of connecting the PV panels to the building is to put them on the roof either on a pitched roof as seen in figure 2.5, or on a flat roof. They can also be attached on the facade of the building. This is decided upon the orientation and design of the building, in addition to the irradiation and climate of the geographical cite.

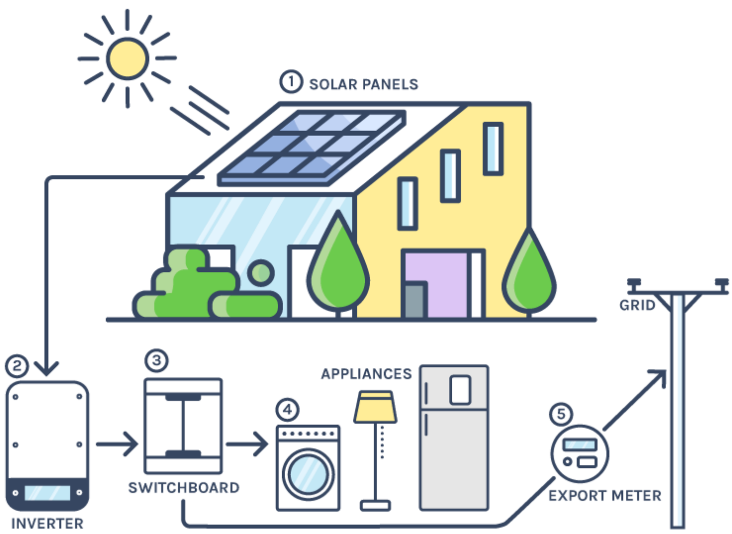


Figure 2.5: PV system connected to grid [5]

The electricity produced by the PV panels goes through an inverter which turns the DC power into AC power so that the power can be used for home appliances. When connected to grid, the system needs a switchboard for regulating power delivered to the appliances in the building, and excess power sold to the grid. In periods with less power production than appliances demand, electricity must be bought from grid.

As mentioned, the orientation and tilting of the PV-panels are decided upon the design of the building in addition to the irradiation and climate of the building cite. If the building is already built, the orientation and area of walls and roof will add restrictions on how to install the panels. On the other hand, when a new building is to be designed, the optimal solution for producing electricity from the PV-panels can be used as a guideline for how to design the building.

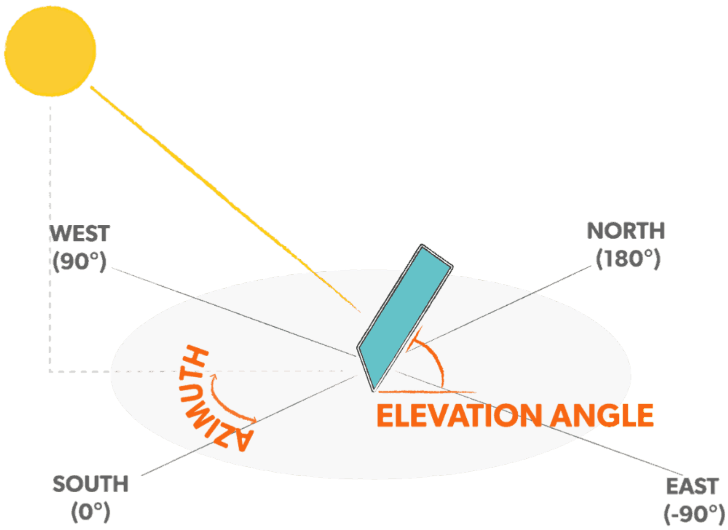


Figure 2.6: Azimuth and tilt angle for PV-panel [6]

From figure 2.6, the azimuth and elevation angle, also called *tilt*, is shown. When south is set as 0°, the other orientations are calculated clockwise from south. Therefore, west is called 90°, north is 180°and east can be called both -90°as in figure 2.6 or 270°. On the northern hemisphere this is the normal explanation of the orientation because the sun is at its highest in south. Therefore, on the southern hemisphere north is used as reference.

Depending on weather the PV-panels are facing south or not, the optimal tilting angle may vary. The tilting angle is also highly dependent upon the cite of the building because of the difference in both hours of sun throughout a day, and how high on the sky the sun gets each day.

2.2.3 Electric Boiler

The concept of an electric boiler is to use electricity for heating water. The heated water can then be used either for domestic hot water or as a source for waterborne space heating. Because of its low investment costs, it is a popular technology used for peak loads. It is often integrated with heat pumps or biomass boiler for carrying peak loads or as a backup [15].

2.2.4 Biomass Boiler

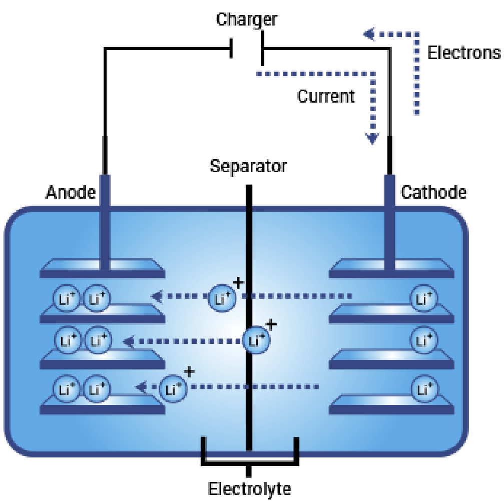
Bio Boiler (BB) is a technology which uses biomass as fuel for heating water. The water can be used for domestic hot water and waterborne space heating in the waterborne model. In this thesis, the fuel for the BB is wood-pellets. Wood-pellets are energy-efficient, hence the BB is often used as an alternative when the objective is to reduce CO_2-emissions.

2.2.5 Electric Battery

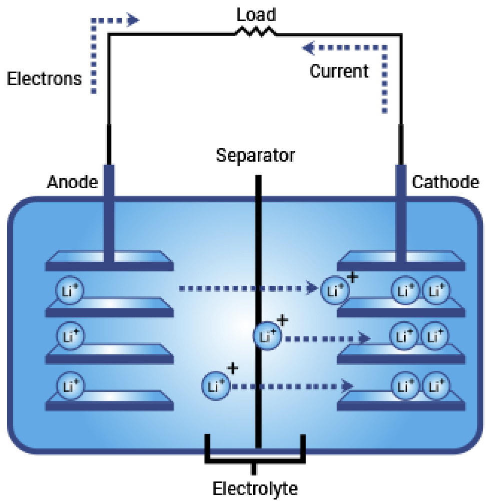
The introduction of weather dependent technologies introduces the need for storage on the building cite. For electricity, a possibility that has been introduced the last years, is to sell energy to the grid. But as the price for batteries decreases, storing the energy for later use instead of selling is an alternative.

An electric battery can be seen as a power bank which is able to store energy. The technology can be profitable in cases where the income of selling energy is low. As the consumers are able to manage more of their energy use with Smart-meters, the need and desire for battery are also increasing.

For PV-systems, a common battery technology used is lithium-ion. As the name suggests, the chemical element stored in the anode and cathode is Lithium. When discharging, the anode releases lithium ions to the cathode [19]. The generated flow of electrons from one side to the other provides an electric current in the opposite direction, as can be seen in figure 2.7.



(a) Charging



(b) Discharging

Figure 2.7: Lithium-ion battery operation [7]

Due to losses in the charging and discharging process the efficiencies for each process are a little below 1, often around 0.95. A more accurate measurement of the efficiency of a battery is the round trip efficiency, which is the ratio of energy put into the batteries to the energy retrieved from the battery. This can also be understood as one charging and discharging cycle. The round trip efficiency can be found by equation 2.6.

$$\eta_{rt} = \eta_{ch} \cdot \eta_{dch} \tag{2.6}$$

2.2.6 Hot Water Accumulator

A hot water accumulator is a storing opportunity for managing the heating demand. For a waterborne system, the heating demand consists of both domestic hot water and space heating. Otherwise, for point-source systems, the heating demand covered by the hot water accumulator is the domestic hot water.

2.3 Electricity Pricing

The electricity price is dependent upon both the grid tariff, see chapter 2.4, and the spot price. The total cost for electricity can be seen in equation 2.7, adapted from [1].

$$\text{Total electricity price} = \text{Power price} + \text{Grid tariff} + \text{VAT} \tag{2.7}$$

The spot price varies throughout the entire year because of weather conditions as rainfall and wind. Especially in Norway where most energy is produced by hydropower, rainfall is an important factor. In addition to the weather, the spot price is also dependent upon the situation and spot price in the rest of Europe. Since the seventies, Norway has been connected to Europe through power cables which allows an exchange of power between Norway and the rest of Europe [20].

In a report from NVE from 2019 [8], it is stated that the power price is assumed to increase in the next years which can be seen from figure 2.8. Prices in the figure are given in øre/kWh which is equivalent to $\frac{1}{100}NOK$. This increase is due to higher CO_2-prices which influence the spot price in Europe caused by their high ratio of non-environmental-friendly technologies for producing electricity. At the same time, an outlook of this ratio to decrease, the spot price will not increase by a large amount.

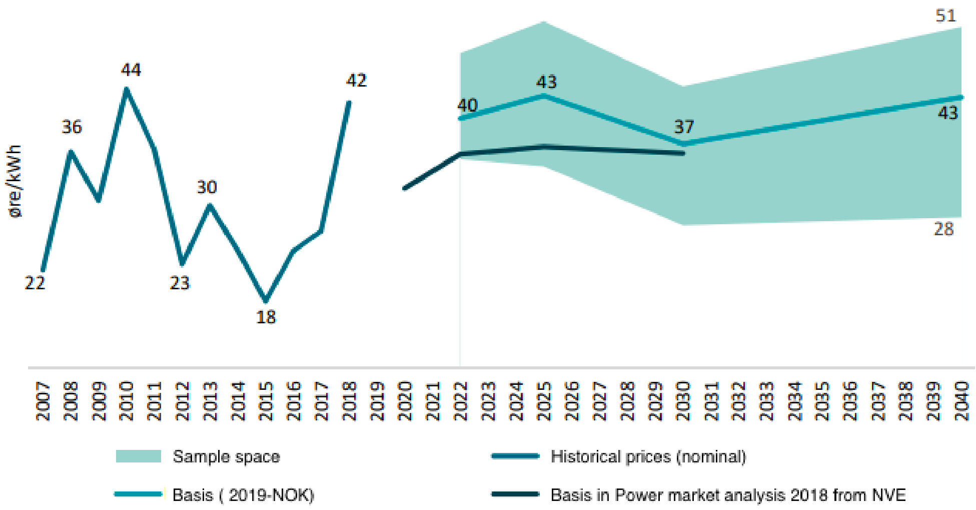


Figure 2.8: The outlook in the spot price from 2019-2040 [8]

2.4 Grid Tariffs

From before, managing consumption inside a building is not common for the average electricity consumer. Nowadays almost every consumer in Norway has its own Advanced Measuring System (AMS), which is a device that measures and collects data from the consumption of energy in the building. For the customers, this means that they do not need to measure their own consumption and report this to their respective network companies. In addition, it allows the consumers to monitor their own consumption and managing the consumption if wanted.

Because of the grid tariff used today, energy pricing, managing your own consumption does not have a large effect on your bill except from the solution of decreasing your consumption. However, other tariff solutions have been proposed in order to create an incentive for the consumers to avoid peak loads. Reducing peak loads in periods with high consumption will contribute to a postponement or avoidance in the need of new network installations [21].

The value of each charge is given in table 3.10 in chapter 3.6.2.

2.4.1 Energy Pricing

The total price is divided into a fixed and variable charge. The fixed charge can be seen as a rent of the utility grid and is independent of the energy use. The variable charge is a cost of energy consumed throughout the year. The expression for the yearly cost is given in equation 2.8.

$$\begin{aligned}\text{Yearly cost} = {} & 12 \times \text{Fixed charge} \\ & + \text{Total energy consumed} \times \text{Variable charge}\end{aligned} \tag{2.8}$$

2.4.2 Power Subscription Pricing

This model is proposed by NVE and taken into use by a few grid companies as trial projects. This model benefit those who are able to avoid high peaks in their consumption. As consumer, you subscribe to a certain amount of effect that can be used at one point of time. If this amount of effect is exceeded, a penalty charge is to be paid.

$$\begin{aligned} \text{Yearly cost} = 12 \times (&\text{Fixed charge} + \text{Subscription charge} \times \text{Subscription}) \\ &+ \text{Variable charge} \times \text{Total energy consumed} \\ &+ \text{Penalty charge} \times \text{Penalty volume} \end{aligned} \tag{2.9}$$

2.4.3 Peak Power Pricing

For companies, a different pricing is given. This pricing requires time measurement of the power consumed and is higher in the winter months than for the summer. The purpose of the difference in pricing is to reflect the fact that the cost of building the energy grid is dependent upon the power peaks in the winter months. In addition to the fixed and variable charge, the power pricing has an effect charge which is dependent upon the highest measured power peak each month.

$$\begin{aligned} \text{Yearly cost} = 12 \times &\text{Fixed charge} \\ &+ \text{Variable charge} \times \text{Total energy consumed} \\ &+ 12 \times \text{Effect charge} \times \text{Peak effect} \end{aligned} \tag{2.10}$$

2.5 Demand Side Flexibility

This chapter is adapted from my own specialisation project, carried out in autumn 2018.

In order to meet the regulations given by the government in regard to energy efficient buildings and more management of each customers electricity use, demand side flexibility is of great value. Flexibility of the end-user, in the distribution grid, is called demand side flexibility. Demand side flexibility can be denoted into two parts, Demand response and Distributed storage. Demand response means that you change the electricity-usage from their normal patterns [9] while distributed storage are batteries or larger storage systems. It is also a known fact that high levels of Distributed Energy Resources (DER) affects grid stability. Hence, using flexibility services as Demand Response (DR) will contribute to keeping the frequency of the grid within allowable limits.

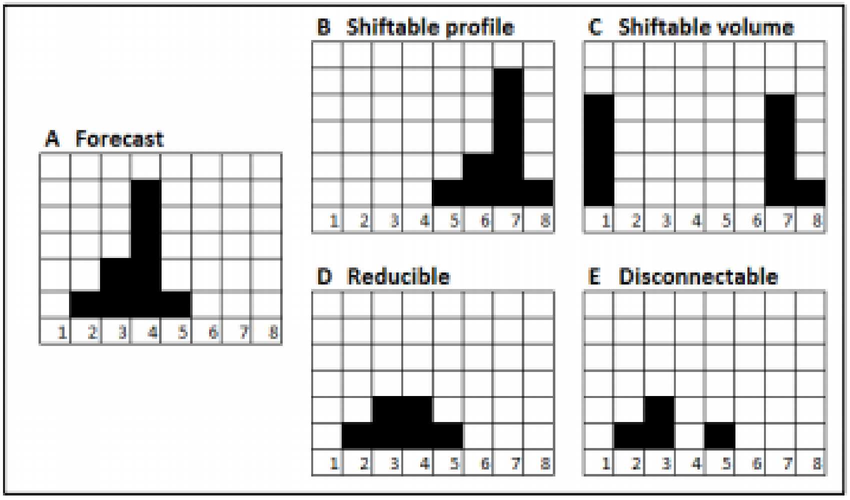


Figure 2.9: Illustration of different load flexibility classes [9]

From figure 2.9, the two most common ways of Demand response is shown, which are shifting the loads in time or curtailing loads. The easiest method for the end-user, which is most common nowadays, is curtailing loads. This method is divided into two classes; reducible and disconnectable loads. Many Single Family Houses already use this method when they turn off lights or reduces/turn off heat in rooms which are not used. This results in reducing the electricity-load at that exact time.

Shifting the loads needs a bit more planning, but is used to avoid having a large load in times with high electricity prices. In addition, avoiding peak loads will decrease the need for high installation capacities of the technology which results in a decrease in the investment cost. It is possible to change both the profile of the and the volume of the load, as shown in figure 2.9. Both for the corporate market which operates with peak power pricing, and the private market if power subscription pricing becomes a reality, shifting the loads is an effective method for saving operational costs.

3 Methodology

3.1 Introduction to Model and Cases

The model used in this master thesis is based on two previous master thesis at NTNU, first created by Ingrid Andersen [1] and then further developed by Marius Bagle [2]. Additions to the model from this thesis, are new investment costs especially developed for larger systems than used before. Also new heating loads have been implemented for choosing between different building types. In stead of calculating the PV generation as it has been done earlier, the PV production in this thesis has been simulated using PVsyst. PVsyst is a simulation software which is used for studying, sizing and data analysis for PV systems. The simulated PV generation is implemented in the model with the objective of giving a more accurate calculation of the size of the PV system needed in the optimal solution. This is further explained in chapter 3.7.

In this thesis the objective is to compare the waterborne system with the point-source system, which system designs can be seen in figure 3.1 and 3.2. It can be seen from the figures that there are some differences in available technologies for producing heat, but also in the availability of heat storage.

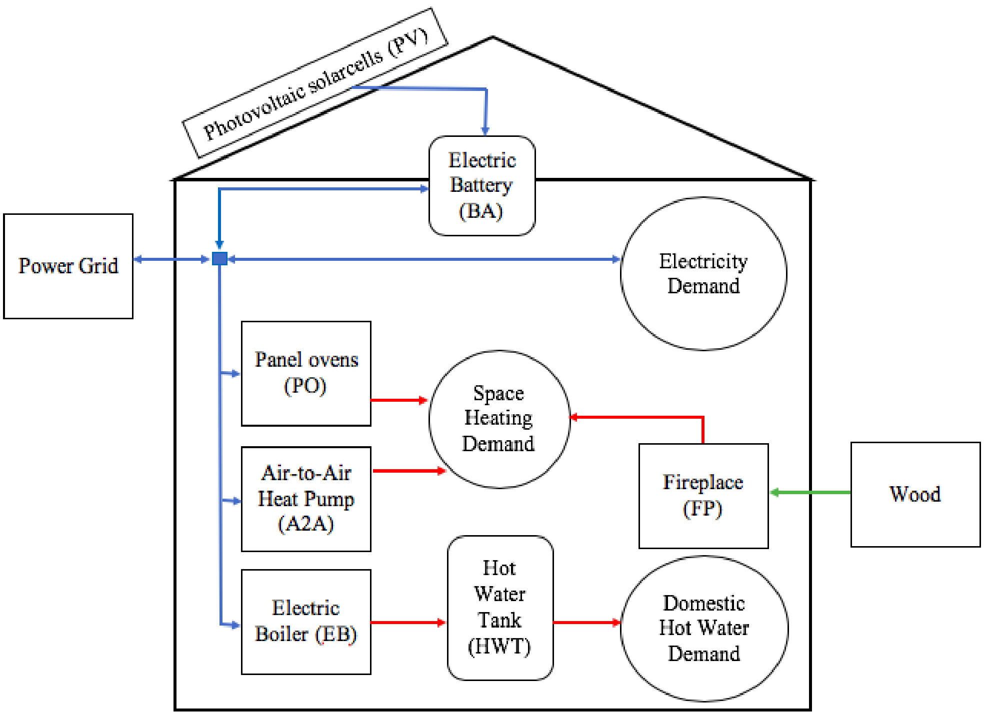


Figure 3.1: System design of point-source system. Adapted from [1]

In the point-source system, shown in figure 3.1, it can be seen that heat can only be stored for the Domestic Hot Water (DHW) using a Hot Water Tank (HWT). The Electric Boiler (EB) is in the point-source system only available for DHW, which leaves the Panel oven (PO), A2A and

Fireplace (FP) to cover the space heating demand. In the waterborne system on the other hand, the EB can be used for both the Space Heating (SH) demand and DHW demand. The storage possibilities are also expanded by a heat storage for the SH demand. As a result of changing the technologies and storage opportunities, the waterborne system is able to store heat from all technologies which gives the system a larger amount of flexibility than for the point-source system.

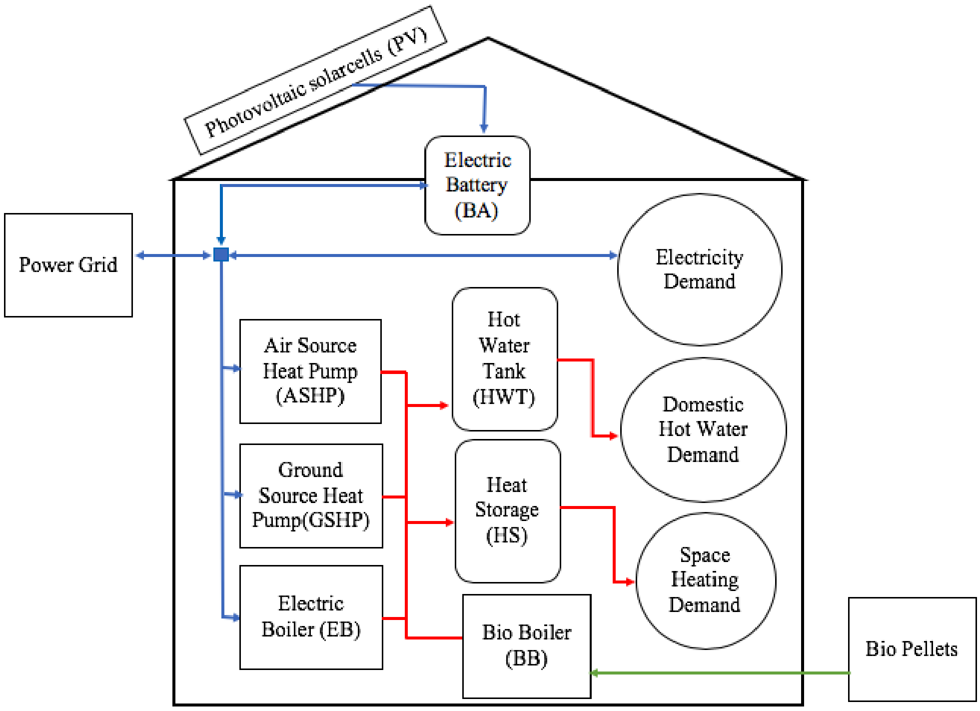


Figure 3.2: System design of waterborne system. Adapted from [1]

As a base case, the point source system is being used. From figure 3.3 it can be seen that when adding additional costs, one for extra insulation and one for waterborne heating system we get three more cases. For the additional insulation cost, R2, new heating loads will be implemented because of less heat losses in the building.

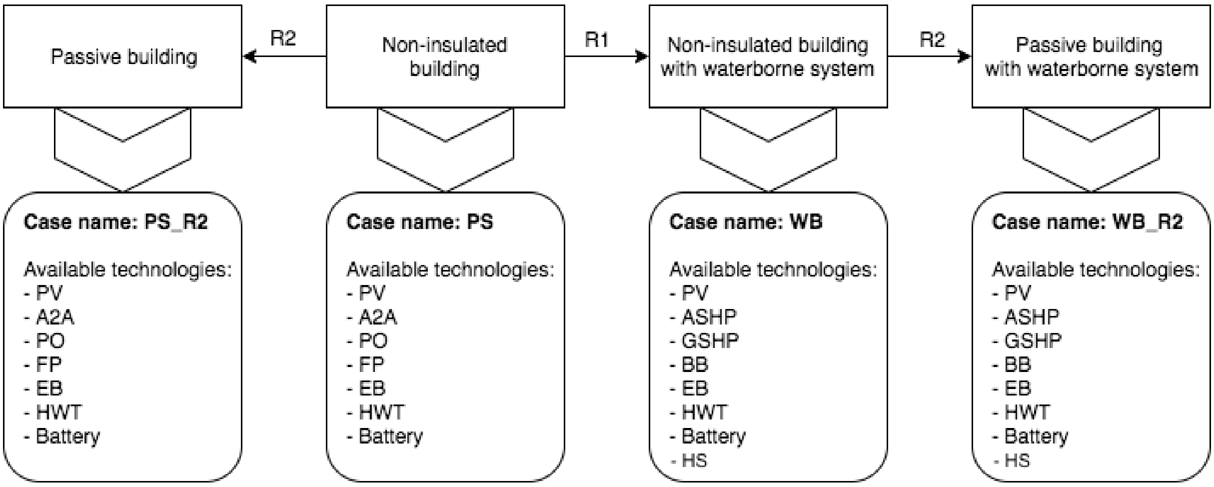


Figure 3.3: Overview of the different cases investigated in this thesis

Further on in the thesis, the cases will be named after their heating system combined with its associated renovation cost. Therefore, the four cases will be called PS_R2, PS, WB and WB_R2, seen from left to right in figure 3.3.

In addition to the difference in heat system design, an analysis of different building types will be carried out. The different building types and their sizes can be seen from table 3.1.

Table 3.1: Building types

Type of building	Size
Single Family House	200 m^2
Apartment Block	3000 m^2
Office Building	10 000 m^2

The sizes of the different building types have been estimated through building statistics and data from Norwegian buildings within same type [22] [23].

3.2 Electricity and Heat Loads

In this thesis, the same heating and electricity load as in [1] and [2] has been used for post-insulated SFH. In addition to this load data, new data have been gathered for apartment block and office building both for regular and passive building. New heating loads for the regular SFH have also been implemented as input data.

From figure 3.4 and 3.5 the heat demand for regular and post-insulated SFH can be found. The comparison of these figures shows the effect of the post-insulation on the SH-demand. This trend can be seen for the apartment block and office building as well, which is attached in appendix C.

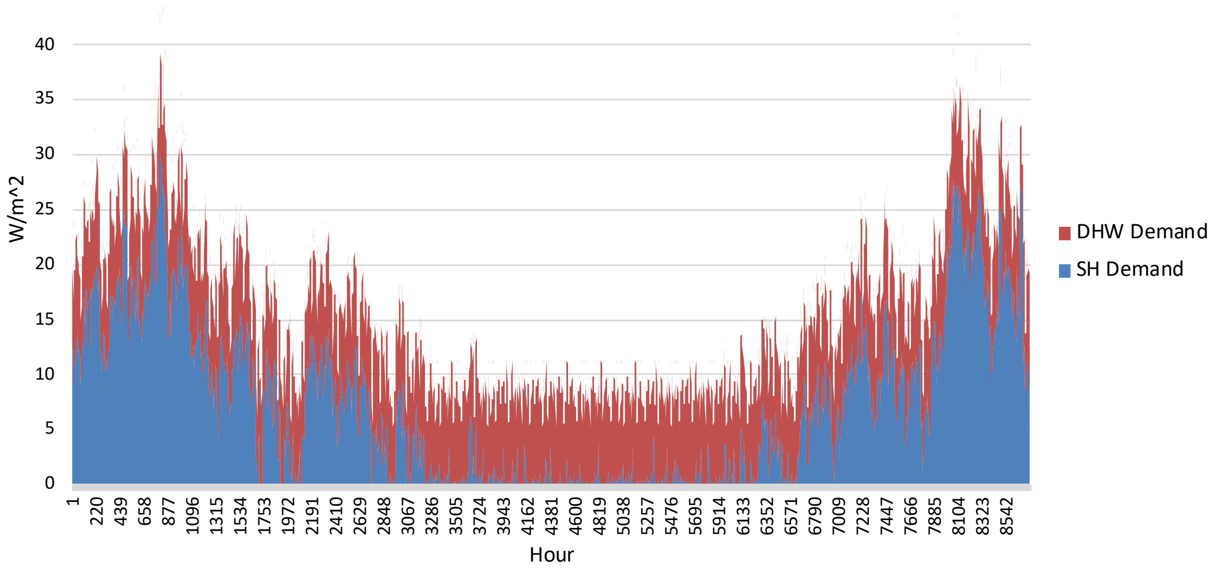


Figure 3.4: Heat Demand for Regular SFH

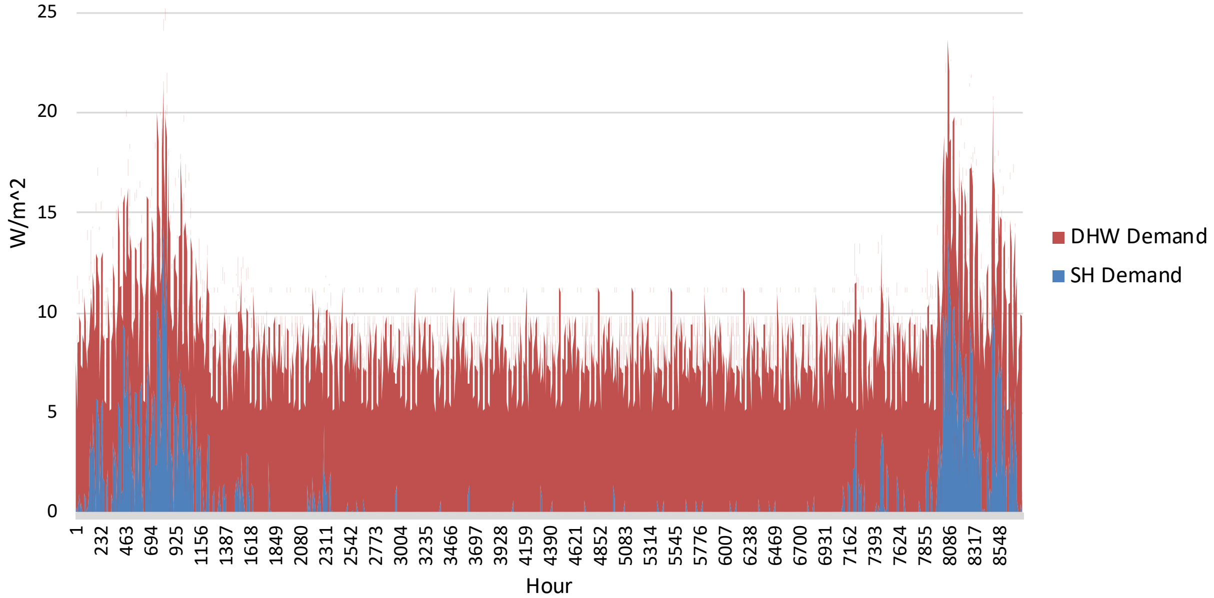


Figure 3.5: Heat Demand for Post-insulated SFH

The electricity demand for a regular apartment block and a regular office building can be seen in figure 3.6 and 3.7. From these figures, the difference in electricity demand for a SFH and an office building is illustrated. As expected, the electricity demand is higher for the office building. This is caused by the fact that more computers and electric gears are present and in use every day for the office building. The other trend which is observed, is that the apartment building is more dependent upon the seasons. The electricity demand is higher in winter periods where the temperature is lower. The office on the other hand, is quite similar throughout the year.

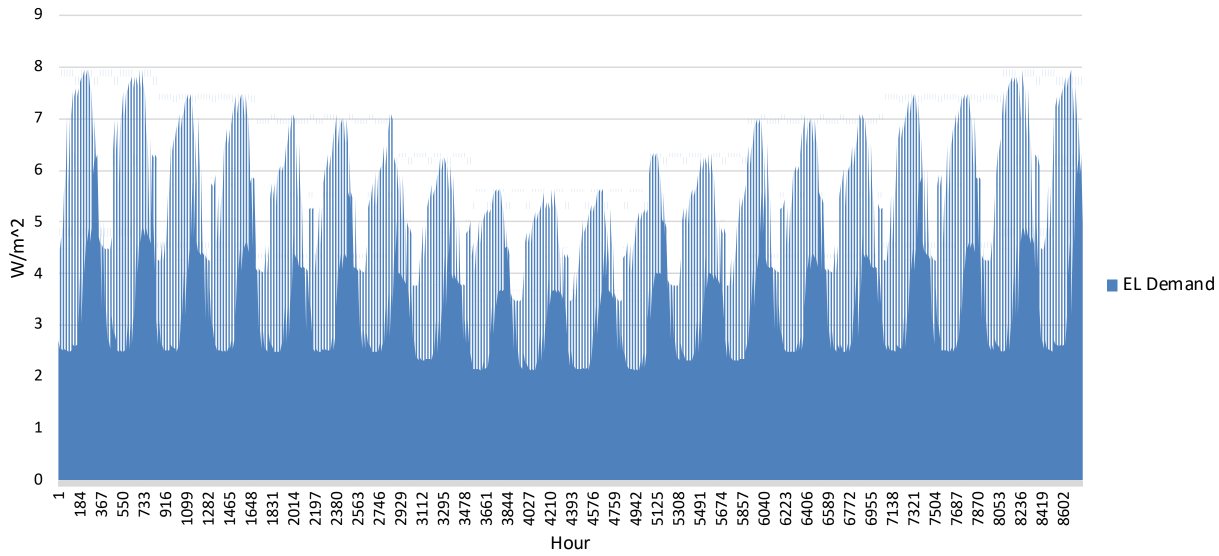


Figure 3.6: Electricity Demand for Regular Apartment Block

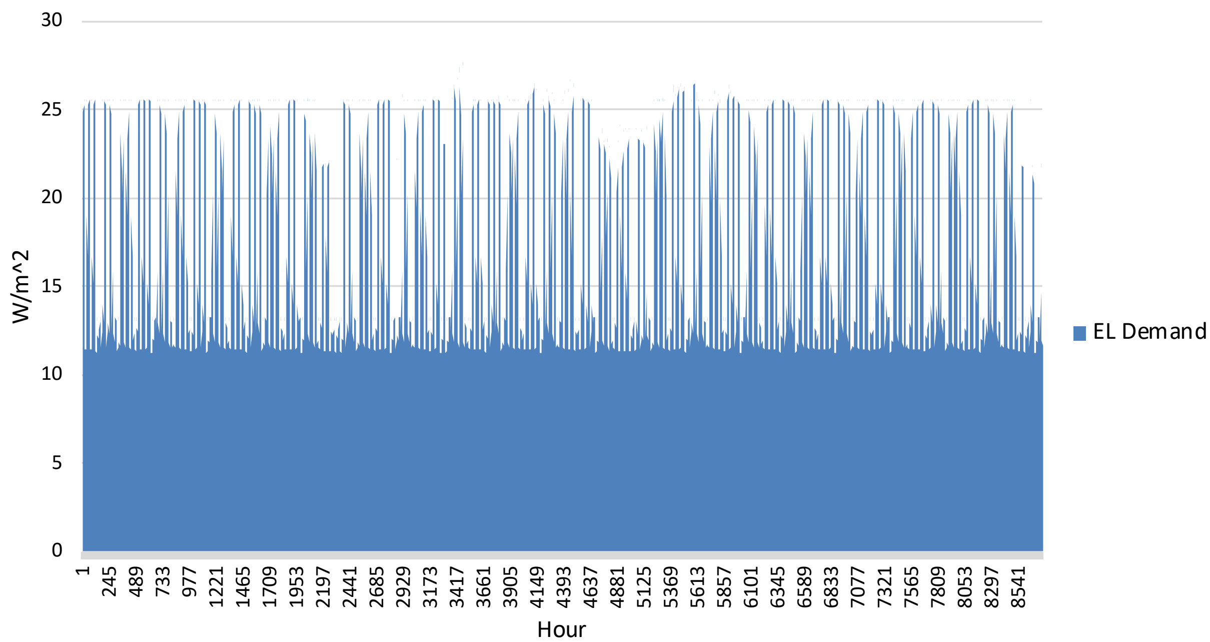


Figure 3.7: Electricity Demand for Regular Office

3.3 Technology Performance

The performance data is mostly gathered from [1] and [2] with minor modifications. All performance data can be found in table 3.2.

From the table it can be seen that the efficiency of PV is set to η instead of a specific value. This is caused by the fact that the efficiency of PV is now included in the simulation results, which is described further in chapter 3.7.

Table 3.2: Technology performance data

i	L_i [years]	Efficiency	Lower-upper bound*	Comment
PV	25	η	1- 10000 kWp	Efficiency is included in simulation
ASHP	20	$COP^{dhw}_{ashp,t}$, $COP^{sh}_{ashp,t}$	1.5 - 500 kW	Efficiency depends on temperature
GSHP	20	$COP^{dhw}_{gshp,t}$, $COP^{sh}_{gshp,t}$	1.5 - 500 kW	Efficiency depends on temperature
A2A	20	$COP^{sh}_{a2a,t}$	1 - 5000 kW	Only operates on SH-load
EB	20	0.98	0.5 - 10000 kW	
BB	15	0.91	0.5 - 10000 kW	
PO	10	1	0 - 10000 kW	
FP	60	0.84	0 - 7000 kW	
BA	10	rt = 0.95, β = 0.433	1 - 10000 kWh	β is charging/discharging rate
HS/HWT	20	η = 0.99, β = 0.667	1 - 10000 kWh	β is charging/discharging rate

* Lower bound is for small buildings, upper bound for large buildings

For the heat pumps, the efficiency is included as COP in time series, and they are divided into space heating and domestic hot water. The COP values are calculated using equation 2.2 for the ASHP and GSHP and 2.5 for the A2A heat pump using the values found in table 3.3.

Table 3.3: Coefficient values for calculating COPs

	k_0	k_1	k_2
ASHP	7.1299	0.1239	0.0007
GSHP	10.181	0.1839	0.0008
A2A	0.0005	0.0613	2.6141

For the supply temperature, equation 2.4 can be used as explained in chapter 2.2.1. For the building standards used in this thesis, the supply temperature can be seen as a function of ambient temperature in figure 3.8.

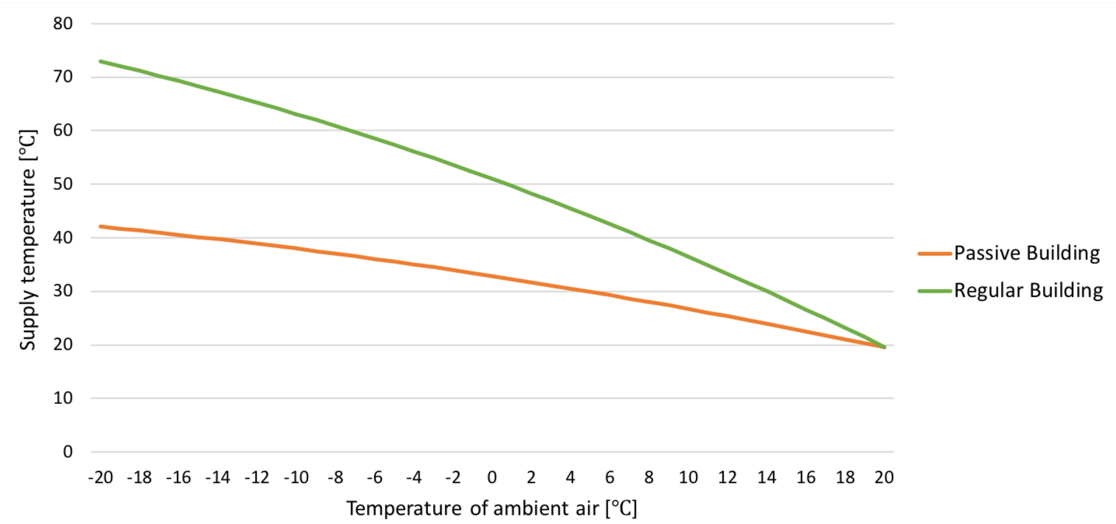


Figure 3.8: Supply temperature as a function of ambient air temperature

Table 3.4: Values for calculating supply temperature

	A	B	C
Passive building	-0.0051	-0.5633	32.844
Regular building	-0.0117	-1.3333	50.948

The COP values for the passive building can be seen in figure 3.9.

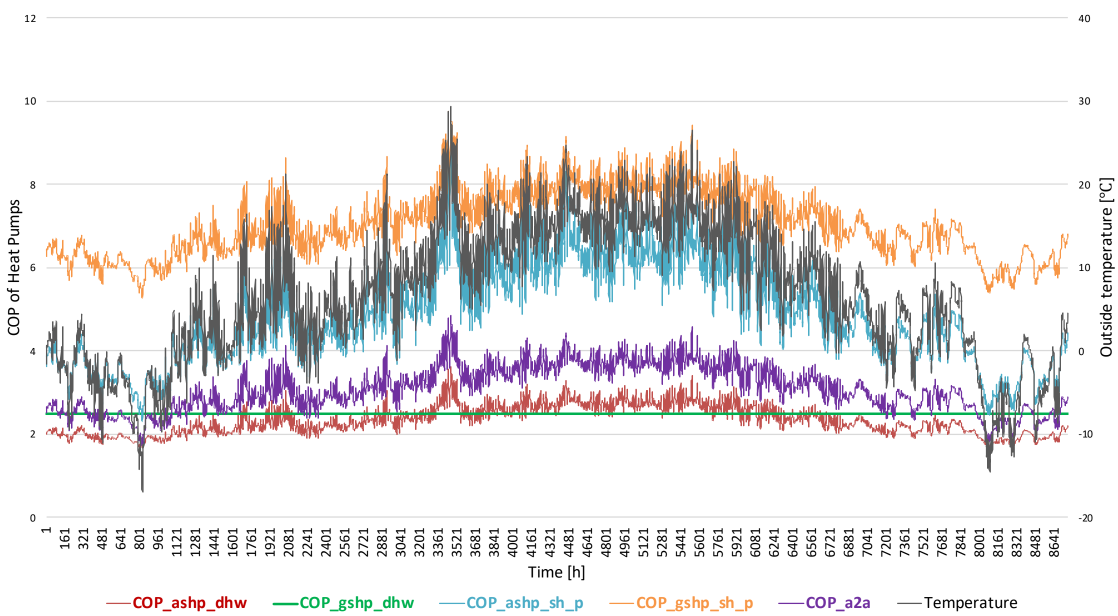


Figure 3.9: COPs for passive building vs. Temperature

For the regular building, the COP values can be seen for the whole year in figure 3.10.

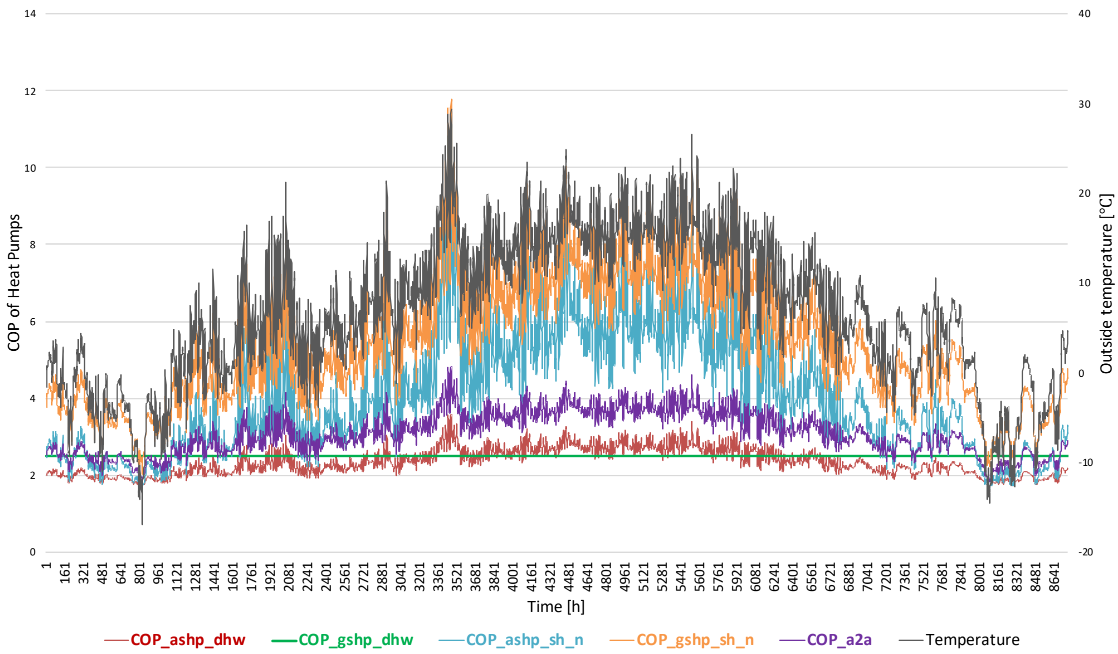


Figure 3.10: COPs for regular building vs. Temperature

3.4 Weighing factors

For the calculation of ZEB-restriction the weighing factors are an important input. As mentioned, the weighing factors in this work are CO_2-factors. The CO_2 factor for electricity import can vary for different places in the world because of different technologies for the production of energy. In Norway, most of the electricity is produced by hydro with a low carbon intensity. Because of the fact that the site for this project is in Oslo, the weighing factors are therefore given for the Norwegian market. The CO_2-factors used for the calculations can be seen in table 3.5.

Table 3.5: Weighing factors

Parameter	Value [gCO_2/kWh]
Electricity import/export	17
Bio Pellets import	15.63
Wood import	15.63

3.5 Investment Costs

3.5.1 Technology Investment Costs

When expanding the model and heating loads so that an optimization of larger buildings can be performed, new technology investment costs need to be implemented in the model. The investment costs are divided into three different sizes, one set for use on buildings below 500

m^2, one set for buildings above 5000 m^2, and one set for buildings in between. For the smallest sizes, the approach and costs have been gathered from one of the earlier master thesis at NTNU [1] with some minor changes when needed caused by changes in the market price. These costs can be seen in table 3.6.

Table 3.6: Investment costs used in calculations

	Area < 500		500 < Area < 5000		Area > 5000		
	Fixed [€]	Specific [€/kW]	Fixed [€]	Specific [€/kW]	Fixed [€]	Specific [€/kW]	Run [%]
PV_{roof}	955	1329	0	1290	0	992	0.01
ASHP	6740	740	0	1238	0	805	0.02
GSHP	9902	1511	0	2306	0	1666	0.02
A2A	393	518	562	312	562	312	0.01
EB	124	161	0	285	0	115	0.02
BB	1517	386	0	1114	0	854	0.03

Same costs for all sizes			
	Fixed [€]	Specific [€/kW]	Run [%]
PV_{facade}	0	2182	0.01
PO	0	180	0
FP	250	131	0.01
BA	0	707	0
HS / HWT	0	83	0

For the technologies that have same costs for all sizes, the common aspect is that they are not built for large sizes. Instead of larger installed capacity, it needs to be installed more than one unit for the installed capacity in a building to increase. Hence, the costs are the same as the small sizes.

An exception is the cost of PV on the facade of a building. It can be seen that for the PV installed on roof, the cost decreases per installed kW. The costs for both the PV-options are based upon both prices from dealer [24], and a technical report where PV-costs are discussed [25].

3.5.2 Investment Costs for the Waterborne Heating System

Table 3.7: Investment costs for waterborne heating system inkl. MVA for different building types [10]

Source	Building type	Size [m2]	Cost [NOK/m2]
COWI	Single family house	127	618
COWI	Apartment Block	3091	396
COWI	Kindergarten	303	645
COWI	Office	3613	386
COWI	Office	7241	313

Using the costs from COWI and the sizes for the different building types found in 3.1, we can find the costs of installing waterborne heating system.

Table 3.8: Additional renovation costs for waterborne heating system

Building type	Size [m2]	Cost [NOK]	Cost [EUR]
Single family house	200	123 500	12 243
Apartment Block	3000	1 118 750	110 902
Office	10 000	3 125 000	309 781

3.5.3 Investment Costs for the Insulation of Buildings

The price for insulating the building in order to minimize heat losses, is dependent upon the size of external walls. Since the buildings in this thesis are fictional, the calculation of such a cost can be hard to define. Nevertheless, from a database made by *Byggstart* [26], it can be found that most of the projects taken into consideration had a price-range of 168-297 EUR/m^2 of wall area. It is also stated that insulating the building in connection with other exterior renovations will reduce the cost. For insulation on exterior walls, 198 EUR/m^2 appears to be a common pricing.

As a method for finding exterior wall area of a 200 m^2 SFH, imaging a two floors cube where each wall has a length of 10 meters. If each floor is 2.5 meters high, the total exterior area is 200 m^2.

The apartment block can be seen as a 6 floors cube with two walls with length of 25 meters, and two walls with length 20 meters. With a height of each floor of 2.5 meters, the total exterior wall area is 1350 m^2.

For the office building, imaging a 10 floors cube with two walls as 25 meters and the other two with a length of 40 meters. If each floor is 2.5 meters high i has a total height of 25 meters. This equals a total exterior wall area of 3250 m^2.

Table 3.9: Insulation cost

	Total cost for insulating the building [EUR]
Single family house	39 600
Apartment block	267 300
Office	643 500

3.6 Price for Electricity

The total price for electricity in a SFH is dependent upon both the hourly spot price for electricity and the grid tariff price. In the model, these costs are included in the operational costs, given in equation 4.4

3.6.1 Spot Price

The hourly spot price is found from *Nordpoolspot.no* [27] and is given in figure 3.11. The figure shows that the price is quite even throughout the year, except for some high peaks during winter season. It is assumed in this thesis that the spot price is equal all years in the lifetime of the analysis. This is a simplification, in reality the spot price varies every year and it is dependent upon weather as temperature and rainfall. The average spot price for the whole year is 0.029 EUR/kWh which corresponds to 29 $\frac{1}{100}$ NOK/kWh in order to compare it to the data given in figure2.8.

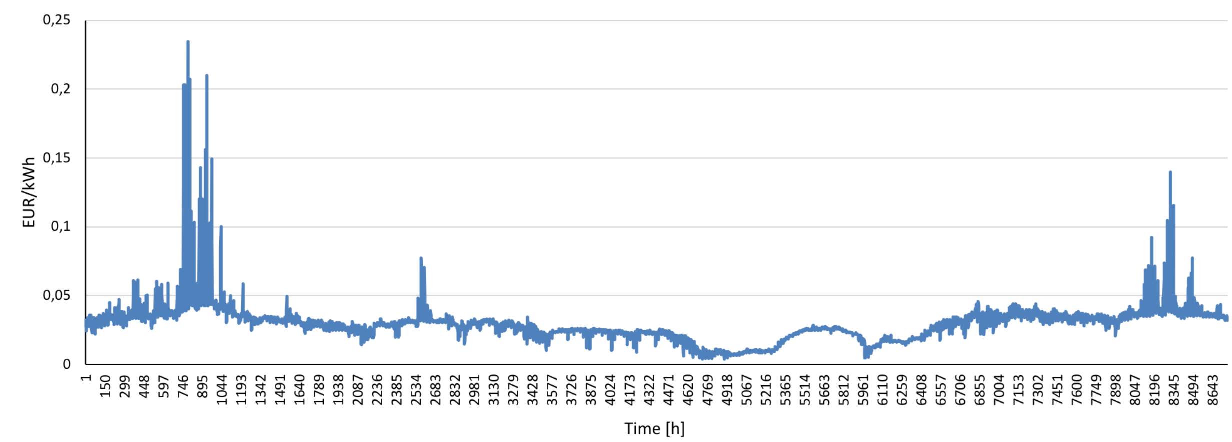


Figure 3.11: Spot price Oslo

3.6.2 Grid Tariffs

For SFH and apartment block, two different grid tariff prices are compared which are explained in chapter 2.4. For the *Energy pricing* alternative which are used today the prices are gathered from *Hafslund* due to the location of the building site. For *Power Subscription* the prices are found from the NVE proposal.

The same approach in regards of the location is used for the prices of the grid tariff for the office, and these prices are therefore also collected from "Hafslund".

Table 3.10: Investigated grid tariffs

SFH/Apartment	Fixed charge [EUR/month]	Variable charge [EUR/kWh]	Penalty charge [EUR/kWh]
Energy pricing [28]	9,913	0,048	
Power subscription[21]	(8,756 + 5,692 · x**)	0,005	0,099
Office [29]	Fixed charge [EUR/month]	Variable charge [EUR/kWh]	Effect charge [EUR/kWh/month]
Winter 1 (Jan, Feb, Dec)	33,67	0,0069	14,85
Winter 2 (March, Nov)	33,67	0,0069	7,92
Summer (Apr - Oct)	33,67	0,0039	2,28

** x is the subscribed power [kW]

The subscribed power for the power subscription is supposed to be decided for each consumer in cooperation with their respective grid company. A presentation on the grid tariff by *EnergiNorge* [30] states that a typical conservative customer will choose a subscription power for a value where overspending is assumed for 8% of the time. Ambitious customers are assumed to choose a subscription power for a value where overspending is assumed for 22% of the time. The case used for the example is a SFH where 8% is equivalent to a subscribed power of 3 kWh/h and 22% is equivalent to a subscribed power of 4 kWh/h.

For the optimisation later in this project, a stricter approach to the chosen value of subscribed power has been selected. In addition to the hours of overspending, the differences in maximum and minimum load has been taken into consideration. The thought behind the strict approach is also that the objective of this optimisation is not to find the optimal power subscription value. The objective of the optimisation is to see how the different heating systems behaves when a stricter grid tariff in regard to power peaks is implemented. The chosen values for subscribed power can be seen in table 3.11.

Table 3.11: Subscribed power for apartment block, noZEB

Case Name	**PS**	**PS_R2**	**WB**	**WB_R2**
Subscribed power [kWh/h]	45	35	28	20

3.6.3 Bio fuel price

For the technologies which are not electricity driven, a different pricing is valid. The prices used in the calculation are obtained from dealers and can be seen in table 3.12.

Table 3.12: Bio fuel prices

	Price [EUR/kWh]
Bio Pellets	0.058
Wood	0.088

3.7 Simulations in PVsyst

PVsyst is a simulation software which is used for studying, sizing and data analysis of PV systems [31]. Both specific and generic systems can be simulated, depending on the accuracy and amount of input data. It also contains a large Meteonorm database which can be used to customize the data to fit your location. If even more specific weather data is required for your project, it is possible to import personal data into the model.

3.7.1 Input Data for PVsyst Simulations

The input data applicable for all of the variants in the project can be found in table 3.13. The location for this simulation is set to Slemdal in Oslo. For this location, the albedo values can be set to 0.2 for all months without snow. In winter months, it is assumed that there will be some snow laying in the location which will result in a higher reflection of sun. Therefore, the albedo values are set to 0.4 throughout these months. The weather data is from the Meteonorm database.

Table 3.13: Input data for the project applicable for all variations

Location	Latitude 59.95°N, Longitude 10.70°E, Altitude 142m
Monthly albedo values	Dec, Jan, Feb, Mar, Apr: 0.4, May, Jun, Jul, Aug, Sep, Oct, Nov: 0.2
PV Module	Si-Poly, 295 Wp (REC295TP2), 1.670m^2
Inverter	3kWac inverter(generic)

From *Technic spesification SN/TS 3031:2016 - Energy performance of buildings, Calculation of energy needs and energy supply* [32] the values for soiling loss were found. These losses take into account coverage of the PV modules caused by snow, leaves, dust etc. The values used in the simulation is found in table 3.14 for their respective tilting solutions.

Table 3.14: Soiling loss [%]

Tilting	Month											
	J	F	M	A	M	J	J	A	S	O	N	D
0-15 °	60	75	60	2	2	2	2	2	2	2	15	45
15-25 °	40	50	40	2	2	2	2	2	2	2	10	30
25-40 °	20	25	20	2	2	2	2	2	2	2	5	15

The simulated systems are differentiated by their orientation and tilting. Otherwise the input data for the simulated systems are the same. For systems located on tilted roof, the tilting options simulated are 20 °and 30 °. In addition, an option for flat roof has been simulated where the tilting is 10 °. The orientation of the flat option is east-west which means that each row is orientated in the opposite direction of the one before. A simulation of PV systems on building facades has also been made. Both the tilted roof option and facade option is simulated for orientations south, west and east.

3.7.2 Results

From the simulation in PVsyst, the important result for the optimization problem in this thesis is the specific production of different PV systems.

In table 3.15 the specific production for a year is found. As input data for the optimization problem, the specific production per hour was imported.

Table 3.15: Production of simulation variants

Simulation variant			Specific production [kWh/kWp/yr]
Type	Orientation	Tilt	
Roof Flat	East-West	10 °	689
Roof	South	20°	831
Roof	South	30°	896
Roof	East	20°	705
Roof	East	30°	717
Roof	West	20°	704
Roof	West	30°	715
Fasade	South	90°	740
Fasade	East	90°	531
Fasade	West	90°	531

In figure 3.12 an example of how the specific production is distributed throughout a year can be seen. As it can be seen from the figure, most of the production is made in the summer months. This figure is the specific production of a PV-system on tilted roof with 30°tilting facing south.

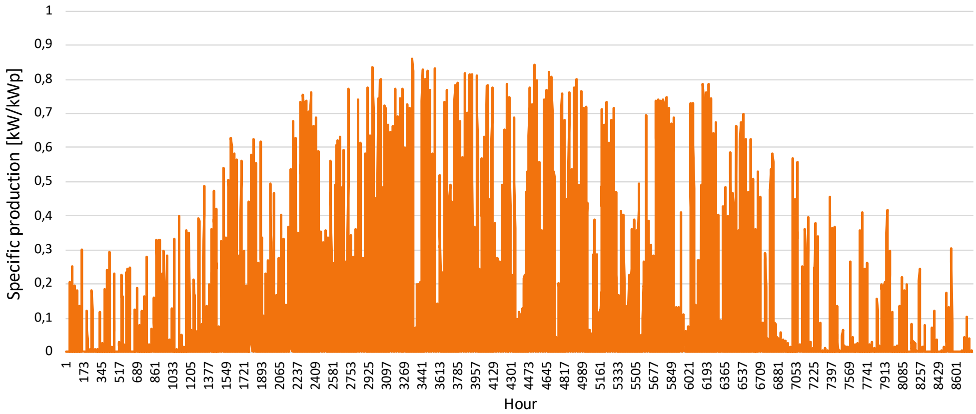


Figure 3.12: Specific production

4 Model

In this section, an overview of the most important aspects of the model will be described from a mathematical point of view. The waterborne system is shown in figure 4.1 and the point-source system in figure 4.2.

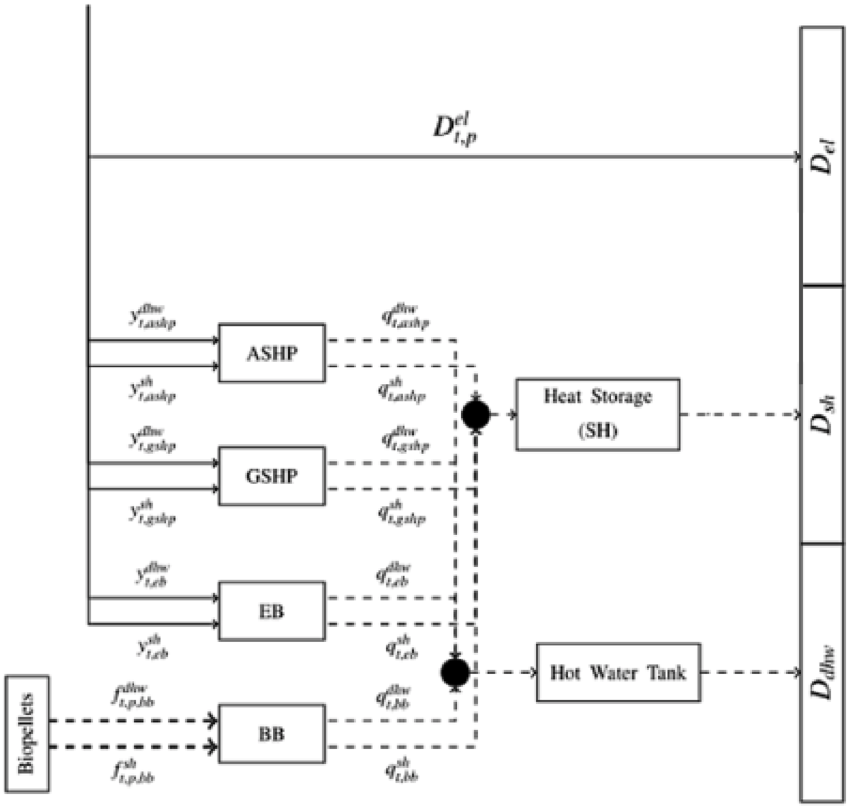


Figure 4.1: Energy flow of the waterborne system

As mentioned in chapter 3.1, the main difference between the two models are applicable technologies for the heating demand. From the energy flow of the waterborne system it can be seen that all heating technologies have the ability to produce heat for both the SH demand and the DHW demand. Both heating demands have a storage opportunity available.

For the point-source system on the other hand, the technologies can only be used for either SH or DHW. This affects the flexibility of the system for instance by the fact that EB must be present for all cases in order to meet the DHW demand.

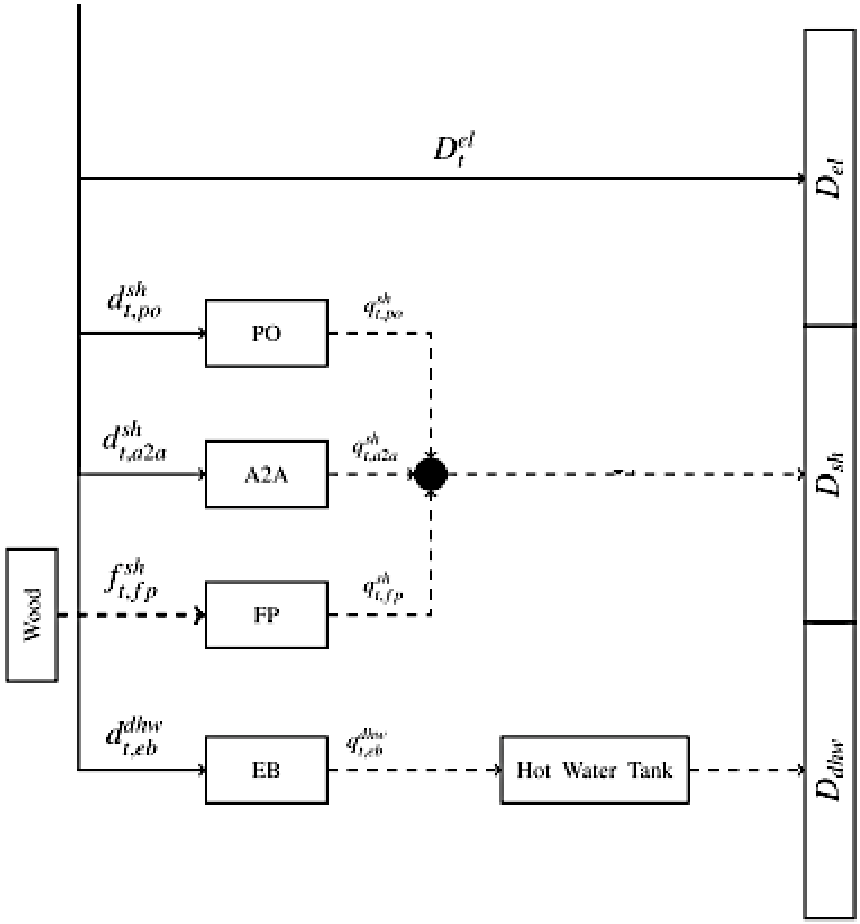


Figure 4.2: Energy flow of the point-source system

4.1 Notation

In this chapter the notation of all variables and parameters in the model is described.

Table 4.1: Sets and indices for the model

Set	Index	Description
I^{dhw}	i	DHW-technology i
I^{sh}	i	SH-technology i
I	i	Technology i ($I^{dhw} \cup I^{sh} = I$)
I^{z}	i	Storage technology i
ϵ	e	Import energy carrier e
T	t	Hourly time-step t
Υ	yr	Yearly time-step of modelling period
M	m	Month-set, used for finding max import per month in Peak Power tariff
S	s	scenario s for PV-simulations

Table 4.2: Parameters for the model

Strategic Parameters		
C_i^{fxd}	Fixed investment cost for technology i	€
C_i^{spe}	Specific investment cost for technology i	€$/kW(kWh)$
C_i^{run}	Yearly running cost for technology i	% of C_i^{spe}
C_{ep}^{fxd}	Monthly fixed grid tariff for ep (incl. VAT)	€)
C_{ps}^{fxd}	Monthly fixed grid charge for ps (incl. VAT)	€$/kW$
C_{pp}^{fxd}	Monthly fixed grid charge for pp (incl. VAT)	€$/kW$
C_{ep}^{spe}	Monthly specific grid tariff for ep (incl. VAT)	€$/kWh$
C_{ps}^{spe}	Monthly specific grid tariff for ps (incl. VAT)	€$/kWh$
$C_{pp,w1}^{spe}$	Monthly specific grid tariff for pp, winter 1 (incl. VAT)	€$/kWh$
$C_{pp,w2}^{spe}$	Monthly specific grid tariff for pp, winter 2 (incl. VAT)	€$/kWh$
$C_{pp,s}^{spe}$	Monthly specific grid tariff for pp, summer (incl. VAT)	€$/kWh$
C_{ps}^{pty}	Penalty charge for ps (incl. VAT)	€$/kWh$
$C_{pp,w1}^{pty}$	Penalty charge for pp, winter 1 (incl. VAT)	€$/kWh$
$C_{pp,w2}^{pty}$	Penalty charge for pp, winter 2 (incl. VAT)	€$/kWh$
$C_{pp,s}^{pty}$	Penalty charge for pp, summer (incl. VAT)	€$/kWh$
Y^{sub}	Power subscription for ps pricing (incl.VAT)	kW
C^{bf}	Price of imported bio fuel (pellets)	€$/kWh$
C^{wo}	Price of wood	€$/kWh$
R	Discount rate	-
η_i	Efficiency of technology i	-
β_i	Charging/discharging rate of storage technology i	-
L_i	Expected lifetime of technology i	Years
$\overline{X_i}$	Upper capacity bound for technology i	$kW(KWh)$
$\underline{X_i}$	Lower capacity bound for technology i	$kW(KWh)$
Operational Parameters		
C_t^{spot}	Spot price of electricity at time step t	€$/kWh$
$COP_{t,ashp}^{sh}$	Coefficient of performance for ASHP for SH at time step t	-
$COP_{t,ashp}^{dhw}$	Coefficient of performance for ASHP for DHW at time step t	-
$COP_{t,gshp}^{sh}$	Coefficient of performance for GSHP for SH at time step t	-
$COP_{t,ashp}^{dhw}$	Coefficient of performance for GSHP for DHW at time step t	-
$COP_{t,a2a}^{sh}$	Coefficient of performance for A2A for SH at time step t	-
D_t^{el}	Building electricity demand at time step t	kWh/h
D_t^{sh}	Building space heating demand at time step t	kWh/h
D_t^{dhw}	Building domestic hot water demand at time step t	kWh/h
T_t	Outdoor temperature at time step t	°C
$Y_{t,s}^{pv}$	Specific production of PV at time step t, scenario s	kW/kWh

Table 4.3: Continuation of parameters for the model

Control Parameters		
$\overline{X}^{imp}$	Maximum grid import capacity	kW
$\underline{X}^{exp}$	Maximum grid export capacity	kW
G_e	CO_2-factor for energy carrier e	gCO_2eq/kWh
G_{ref}	Yearly emissions reference (consider cutting)	gCO_2eq/yr
γ	Relaxation coefficient for ZEB-restriction	$\in(0,1)$
Λ^{ep}	Activation of energy pricing	0,1
Λ^{ps}	Activation of power subscription pricing	0,1
Λ^{pp}	Activation of peak power pricing	0,1
Λ_i	Pre-activation of technology i	0,1
Λ^{imp}	Activation of import	0,1
Λ^{exp}	Activation of export	0,1

Table 4.4: Variables for the model

Strategic Decision Variables		
x_i	Installed capacity for technology i	$kW(kWh)$
δ_i	= 1 if technology i is installed	$0/1$
Operational Decision Variables		
$q^{sh}_{t,ashp}$	Heat generated by the ASHP for SH at time step t	kWh/h
$q^{dhw}_{t,ashp}$	Heat generated by the ASHP for DHW at time step t	kWh/h
$q^{sh}_{t,gshp}$	Heat generated by the GSHP for SH at time step t	kWh/h
$q^{dhw}_{t,gshp}$	Heat generated by the GSHP for DHW at time step t	kWh/h
$q^{sh}_{t,bb}$	Heat generated by the BB for SH at time step t	kWh/h
$q^{dhw}_{t,bb}$	Heat generated by the BB for DHW at time step t	kWh/h
$q^{sh}_{t,eb}$	Heat generated by the EB for SH at time step t	kWh/h
$q^{dhw}_{t,eb}$	Heat generated by the EB for DHW at time step t	kWh/h
$q^{sh}_{t,a2a}$	Heat generated by the A2A for SH at time step t	kWh/h
$q^{sh}_{t,fp}$	Heat generated by the FP for SH at time step t	kWh/h
$q^{sh}_{t,po}$	Heat generated by the PO for SH at time step t	kWh/h
q^{hwt}_{t}	Net heat to hot water tank (HWT) at time step t	kWh/h
q^{hs}_{t}	Net heat to heat storage/accumulator (HS) at time step t	kWh/h
$y^{pv}_{t,s}$	Electricity generated by PV at time step t, scenario s	kWh/h
$y^{sh}_{t,ashp}$	Electricity consumed by the ASHP for SH at time step t	kWh/h
$y^{dhw}_{t,ashp}$	Electricity consumed by the ASHP for DHW at time step t	kWh/h
$y^{sh}_{t,gshp}$	Electricity consumed by the GSHP for SH at time step t	kWh/h
$y^{dhw}_{t,gshp}$	Electricity consumed by the GSHP for DHW at time step t	kWh/h
$y^{sh}_{t,a2a}$	Electricity consumed by the A2A for SH at time step t	kWh/h
$y^{sh}_{t,eb}$	Electricity consumed by the EB for SH at time step t	kWh/h
$y^{dhw}_{t,eb}$	Electricity consumed by the EB for DHW at time step t	kWh/h
$f^{sh}_{t,bb}$	Fuel consumed by the BB for SH at time step t	kWh/h
$f^{dhw}_{t,bb}$	Fuel consumed by the BB for DHW at time step t	kWh/h
$f^{sh}_{t,fp}$	Fuel consumed by the FP for SH at time step t	kWh/h
y^{ch}_{t}	Electricity charged from the battery at time step t	kWh/h
y^{dch}_{t}	Electricity discharged from the battery at time step t	kWh/h
y^{imp}_{t}	Electricity imported from the grid at time step t	kWh/h
y^{exp}_{t}	Electricity exported to the grid at time step t	kWh/h
y^{pty}_{t}	Electricity exceeding subscription at time step t	kWh/h
z^{hwt}_{t}	Energy content of HWT at time step t	kWh/h
z^{hs}_{t}	Energy content of HS at time step t	kWh/h
z^{ba}_{t}	Energy content of battery at time step t	kWh/h
δ^{ch}_{t}	=1 if battery is charging at time step t	$0/1$
δ^{dch}_{t}	=1 if battery is discharging at time step t	$0/1$
Functions		
c_{inv}	Discounted investment cost	€
c_{run}	Discounted operational cost	€
Objective function		
C_{tot}	Total system cost	€

4.2 Objective Function

The objective function of the optimisation problem is the total cost of all technology investment and operational costs throughout the analysis period, as seen in equation 4.1.

$$c_{tot} = min(c_{inv} + c_{run}) \tag{4.1}$$

Where c_{inv} is the investment cost function given by equation 4.2 and c_{run} is the operational cost function given by equation 4.4.

$$c_{inv} = \sum_{i \in I} (C_i^{spe} x_i + C_i^{fxd} \delta_i) \cdot \alpha_i(R, L_i, \Upsilon_n) \tag{4.2}$$

The final discounting factor α_i, is given in equation 4.3.This factor takes into account the lifetime of each technology, and as a result of that lifetime compared with the time of the analysis, the forced reinvestments.

$$\alpha_i(R, L_i, \Upsilon_n) = \frac{1-(1+R)^{-(Y_n - L_i K)}}{1-(1+R)^{-L_i}} \cdot \frac{1}{(1+R)^{KL_i}} + \sum_{k=0}^{K-1} \frac{1}{(1+R)^{kL_i}} \tag{4.3}$$

The operational cost is the sum of operation and maintenance cost for each technology, cost of bio fuel, electricity cost and the grid charge. There are three different grid charge options in this thesis, where the activation of each option is based on the binary variables Λ^{ep}, Λ^{ps} and Λ^{pp}. Only one of the variables can be activated at the same time.

$$\begin{aligned} c_{run} = \Bigg(& \sum_{i \in I} C_i^{run} C_i^{spe} x_i + \sum_{t \in T} y_t^{imp} C_t^{spot} \cdot 1.25 - y_t^{exp} C_t^{spot} + f_t^{imp} C^f \cdot 1.25 \\ & + (12 \cdot C_{ep}^{fxd} + \sum_{t \in T} y_t^{imp}) \Lambda^{ep} \\ & + (12 \cdot (C_{ps}^{fxd} + C_{ps}^{sub} \cdot Y_{sub}) + C_{ps}^{spe} \sum y_t^{imp} + C_{ps}^{pty} \sum_{t \in T} y_t^{pty}) \Lambda^{ps} \\ & + (C_{pp}^{fxd} + C_{pp}^{spe} \sum_{t \in M} y_t^{imp} + C_{pp}^{pty} \cdot y_m^{imp,max}) \Lambda^{pp} \Bigg) \cdot \lambda(\Upsilon_n, R) \end{aligned} \tag{4.4}$$

The total capitalization factor λ is given in equation 4.5. This factor is used to obtain a present value of all yearly running costs throughout the time of analysis.

$$\lambda(\Upsilon_n, R) = \frac{1-(1+R)^{-\Upsilon_n}}{R} \cdot \frac{1}{(1+R)^1} \tag{4.5}$$

4.3 Constraints

To ensure that all variables in the optimal solution calculated by the model are within specified limits, constraints must be implemented in the model. Some of the constraints are based upon limits in order to make the solution as close to real life as possible. Others are important in order to ensure that demands are met. Hence, some of the constraints are operated by ≤ or ≥, while the ones who are to ensure the meeting of demands are operated by = .

4.3.1 Capacity Constraints

The following constraints are important in order to ensure that the installed capacity for each technology are within realistic limits. In addition, the constraints are a part of limiting the amount of possible solutions for the model.

The installed capacity of each technology i must be less than M, which is a large number called *big M* in operations research:

$$x_i \leq \delta_i M \qquad \forall i \in I \tag{4.6}$$

The lower and upper limits of each technology are stated in table 3.2, which sets limitations for the installed capacity in addition to *big M*:

$$\underline{X_i}\delta_i \leq x_i \leq \overline{X_i}\Lambda_i \tag{4.7}$$

4.3.2 ZEB-constraint

As explained in chapter 2.1, the restriction in order to meet the ZEB-goal for the operational phase of the building is to import the same amount of energy as exported throughout a year of operation. How this is coded in the model can be seen from equation 4.8 where the relaxation coefficient γ decides whether the requirement equals ZEB or no Zero Emission Building (noZEB). For $\gamma = 0$ gives noZEB and $\gamma = 1$ signifying ZEB.

$$\gamma \sum_{t \in T} \left(y_t^{imp} G_{el} + f_t^{imp} G_f \right) \leq \sum_{t \in T} y_t^{exp} G_{el} \tag{4.8}$$

4.3.3 Technology Constraints

All energy production on-site is limited by the capacity of their respective technologies. For heat technologies, producing both for SH and DHW the following must hold:

$$q_{t,i}^{sh} + q_{t,i}^{dhw} \leq x_i \qquad \forall t \in T, i \in I \tag{4.9}$$

For the PV production the following prerequisites must be present:

$$y_{t,s}^{pv} = x_s^{pv} Y_{t,s}^{pv} \Lambda_{pv} \qquad \forall t \in T, s \in S \tag{4.10}$$

where all scenarios that have been simulated is taken into consideration for the optimal solution. $Y_{t,s}^{pv}$ is the simulated specific PV-production for each scenario, shown in table 3.15.

For the heat pumps, the generated heat is limited by the COP of each heat pump technology and heat load:

$$q_{t,ashp}^{sh} = y_{t,ashp}^{sh} COP_{t,ashp}^{sh} \Lambda_{ashp} \qquad \forall t \in T \tag{4.11}$$

$$q_{t,ashp}^{dhw} = y_{t,ashp}^{dhw} COP_{t,ashp}^{dhw} \Lambda_{ashp} \qquad \forall t \in T \tag{4.12}$$

$$q_{t,gshp}^{sh} = y_{t,gshp}^{sh} COP_{t,gshp}^{sh} \Lambda_{gshp} \qquad \forall t \in T \tag{4.13}$$

$$q_{t,gshp}^{dhw} = y_{t,gshp}^{dhw} COP_{t,gshp}^{dhw} \Lambda_{gshp} \qquad \forall t \in T \tag{4.14}$$

where the COP can be seen as a hourly time series in figure 3.9 and 3.10 in chapter 3.3 where the performance of each technology is discussed.

For the A2A heat pump, the difference between building types is not taken into consideration when calculating the heat pump. In addition to this, the A2A heat pump is only operating on the SH-load. Hence, only one constraint concerns the heat generated by this technology:

$$q_{t,a2a}^{sh} = y_{t,a2a}^{sh} COP_{t,a2a} \Lambda_{a2a} \qquad \forall t \in T \tag{4.15}$$

In addition to this constraint concerning the A2A heat pump, it is assumed that the technology has a limited ability to transport heat between rooms:

$$q_{t,a2a}^{sh} \leq 0.5 \cdot D_t^{sh} \qquad \forall t \in T \tag{4.16}$$

where D_t^{sh} is the total space heating load for each time-step. In addition to the heat pumps, the EB and PO are also dependent upon the electricity consumption. For the point-source system the EB can only operate on the SH load. The constraints for the two technologies are therefore as follows for the point-source system:

$$q^{sh}_{t,po} = y^{sh}_{t,po}\eta_{po}\Lambda_{po} \qquad \forall t \in T \tag{4.17}$$

$$q^{sh}_{t,eb} = y^{sh}_{t,eb}\eta_{eb}\Lambda_{eb} \qquad \forall t \in T \tag{4.18}$$

On the other hand, for the waterborne system the EB has the ability to operate on both SH and DHW load. Therefore the additional constraint for the waterborne model is as follows:

$$q^{dhw}_{t,eb} = y^{dhw}_{t,eb}\eta_{eb}\Lambda_{eb} \qquad \forall t \in T \tag{4.19}$$

For the technologies which are dependent upon the amount of fuel imported, the waterborne system has the BB and the point-source system have the FP. The BB can be operated on both SH and DHW load:

$$q^{sh}_{t,bb} = f^{sh}_{t,bb}\eta_{bb}\lambda_{bb} \qquad \forall t \in T \tag{4.20}$$

$$q^{dhw}_{t,bb} = f^{dhw}_{t,bb}\eta_{bb}\lambda_{bb} \qquad \forall t \in T \tag{4.21}$$

The fireplace on the other hand, ca only be operated on SH load. It is also restricted to only being able to operate between 16:00 and 24:00. The constraints concerning the fireplace are therefore as follows:

$$q^{sh}_{t',fp} = f^{sh}_{t',fp}\eta_{fp}\lambda_{fp} \qquad \forall t' \in T' \tag{4.22}$$

$$q^{sh}_{t',fp} = 0 \qquad \forall t' \notin T' \tag{4.23}$$

where $t' = t - floor(\frac{1}{24}) \cdot 24$ and $T' = \{16, 17, ..., 24\}$

4.3.4 Storage Constraints

For the energy storage technologies, the HWT and Heat Storage (HS) is modeled in the same way as they both are applicable for the heat load. The generated heat for those technologies are dependent upon the amount of energy stored:

$$q^{hwt,hs}_{t} = z^{hwt,hs}_{t-1} - z^{hwt,hs}_{t} \qquad \forall t \in T \tag{4.24}$$

where the charging rate of the storage can be seen from:

$$|q_t^{hwt,hs}| \leq x^{hwt,hs} \beta_{hwt,hs} \qquad \forall t \in T \tag{4.25}$$

The battery is modeled in a slightly different manner:

$$z_t^{ba} = z_{t-1}^{ba} + y_t^{ch} \eta^c h - y_t^{dch} \frac{1}{\eta^{dch}} \qquad \forall t \in T \tag{4.26}$$

where the charging and discharging are constrained as well:

$$y_t^{ch} \leq (x^{ba} - z_{t-1}^{ba}) \frac{1}{\eta^{ch}} \lambda^{ba} \qquad \forall t \in T \tag{4.27}$$

$$y_t^{dch} \leq z_{t-1}^{ba} \eta^{dch} \Lambda^{ba} \qquad \forall t \in T \tag{4.28}$$

Within one timestep, it is only allowed for the battery to either charge or discharge. This is ensured using following constraints:

$$y_t^{ch} \leq \delta^{ch} M \qquad \forall t \in T \tag{4.29}$$

$$y_t^{dch} \leq \delta^{dch} M \qquad \forall t \in T \tag{4.30}$$

$$\delta_t^{ch} + \delta_t^{dch} \leq 1 \qquad \forall t \in T \tag{4.31}$$

The charging and discharging rate within one hour is restricted with following constraint:

$$y_t^{ch,dch} \leq x^{ba} \beta^{ba} \qquad \forall t \in T \tag{4.32}$$

4.3.5 Grid Interaction Constraints

In the same way that the technologies have a maximum limit, the grid interaction is limited for both the import and export of energy:

$$y_t^{imp} \leq \overline{X}^{imp} \delta_t^{imp} \qquad \forall t \in T \tag{4.33}$$

$$y_t^{exp} \leq \overline{X}^{exp} \delta_t^{exp} \qquad \forall t \in T \tag{4.34}$$

Power Subscription Pricing

For the power subscription pricing, the penalty volume is decided upon following equations:

$$y_t^{imp} - Y^{sub} \leq y_t^{pty} \tag{4.35}$$

$$0 \leq y_t^{pty} \tag{4.36}$$

Peak Power Pricing

For the peak power pricing, the maximum value of imported electricity for each month must be found. For this purpose it is created a month-set, M, which holds all months for the entire year. Each month in the month-set holds every hour for that specific month. When counting through the time-steps of that specific month, the max value is updated if the value for that time-step fulfill the restriction:

$$y_m^{imp,max} \geq y_t^{imp} \tag{4.37}$$

When counted through the entire month, the updated value for the maximum imported electricity is the value used in the calculation for the grid tariff.

4.3.6 Load Constraints

In chapter 3.1 where the model is introduced, it can be seen that there are three different load demands which must be met, **Electric**, **Space Heating** and **Domestic Hot Water**. In order to ensure the fulfillment of these demands, balances for each demand have been defined:

$$D_t^{el} = y_t^{imp} + y_t^{pv} + y_t^{dch} - y_t^{ch} - \sum_{i \in I^{dhw}} y_t^i - \sum_{i \in I^{sh}} y_t^i \qquad \forall t \in T \tag{4.38}$$

$$D_t^{dhw} = z_{t-1}^{hwt} - z_t^{hwt} + \sum_{i \in I^{dhw}} q_t^i \qquad \forall t \in T \tag{4.39}$$

$$D_t^{sh} = z_{t-1}^{hs} - z_t^{hs} + \sum_{i \in I^{sh}} q_t^i \qquad \forall t \in T \tag{4.40}$$

For the space heating balance, the heat storage is only available for the waterborne system.

5 Results

5.1 Main Results

The main results from the optimisation problem is the total cost of each case, in addition to the installed capacities for the respective cases. From these results the main objective for this thesis, to find the most cost-effective system, will be discussed. All cases have been optimized through the model, and the optimal solution for each case can be found for SFH, apartment block and office in table 5.1, 5.2 and 5.3 respectively. In addition to the four cases which was introduced in chapter 3.1, all cases have been tested for both noZEB and ZEB restriction.

In the result tables, some technologies are only available for one of the heating systems. If so, this is marked with the sign "-". In addition the results are categorized as **SH & DHW** if the technologies are applicable in the waterborne heating system. If the technologies are applicable in the point-source system, they are categorized under **SH** and **DHW** separately.

In figure 5.1 the main results are shown per m^2. The renovation costs including insulation cost and cost for the waterborne system, is shown along the x-axis. Along the y-axis are the total energy system costs, which corresponds to the operation- and investment costs for the energy system. The total energy system costs are highest for the two cases *PS* and *WB*, where they are ZEB-restricted. Without the ZEB-restriction the trend is still that the two cases *PS* and *WB* have the highest energy system costs. This was expected due to the fact that the regular buildings have the highest SH demand.

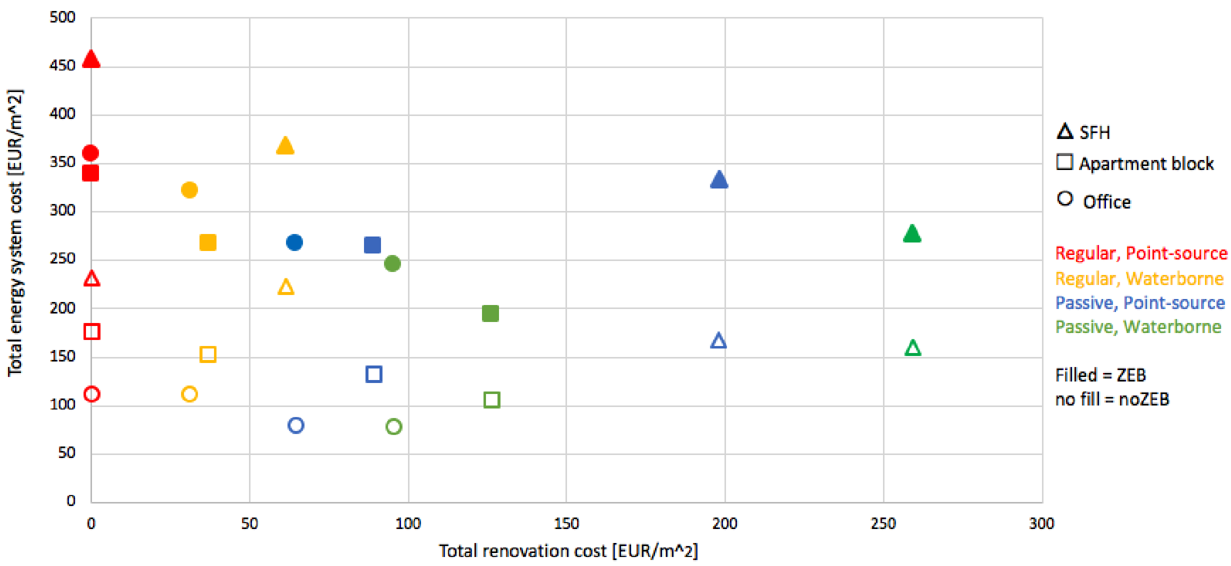


Figure 5.1: Main Results

5.2 Single Family House

Table 5.1 introduce the important results from the optimization of a SFH. It can be seen that the chosen technologies for each case are quite similar. When adding the ZEB restriction, PV occur in the solution because of the ability to produce energy on-site. As explained in chapter 2.1, on-site production is a necessity in order to meet the requirements of a Zero Emission Building.

Table 5.1: Results from all cases with building type *Single family house*

	ZEB		noZEB		ZEB		noZEB	
Case Name	PS	PS_R2	PS	PS_R2	WB	WB_R2	WB	WB_R2
D_{EL} [kWh/year]	7787	7787	7787	7787	7787	7787	7787	7787
D_{SH} [kWh/year]	13215	1864	13215	1864	13215	1864	13215	1864
D_{DHW} [kWh/year]	13264	13264	13264	13264	13264	13264	13264	13264
Electricity [kW]								
PV_S30	34.0	25.2	0.0	0.0	21.1	15.8	0.0	0.0
SH & DHW [kW]								
ASHP	-	-	-	-	5.5	2.6	4.8	0.0
GSHP	-	-	-	-	0.0	0.0	0.0	0.0
BB	-	-	-	-	0.0	0.0	0.0	2.4
EB	-	-	-	-	1.8	1.3	3.1	2.0
SH [kW]								
A2A	2.3	1.0	2.0	0.0	-	-	-	-
PO	4.7	2.3	4.9	3.3	-	-	-	-
FP	0.0	0.0	0.0	0.0	-	-	-	-
DHW [kW]								
EB	3.6	3.6	1.8	1.8	-	-	-	-
Storage [kWh]								
HWT	13.9	14.0	1.2	1.2	6.8	5.3	1.6	1.5
BAT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HS	-	-	-	-	0.0	0.0	1.0	0.0
Costs[kEUR]								
Operation	27	19	42	32	20	15	29	27
Investment	64	48	4	2	53	41	16	5
Tot. Energy Cost	92	67	47	33	74	56	45	32
R1 Cost	0	0	0	0	12	12	12	12
R2 Cost	0	40	0	40	0	40	0	40
Total	**92**	**106**	**47**	**73**	**86**	**108**	**57**	**84**

An interesting observation is the change in technology from BB to ASHP in *WB_R2* when changing from noZEB to ZEB. From the weighing factors used to calculate the ZEB-restriction, it can be seen that the difference between imported electricity and bio pellets is very small. Because of the high efficiency of ASHP, this could be a solution to why the ASHP is chosen in the optimal solution. For the noZEB case, the price could have a larger impact on the optimal solution. The price for bio pellets is 0.058 EUR/kWh for all hours throughout the year. The spot price on the other hand, varies for each hour every day. The spot price is at its highest for the winter weeks where the heating demand also is at its highest. This may have an impact on the choice for the optimal solution.

5.3 Apartment Block

For the apartment block, as for the SFH, it can be seen that PV only occurs in the optimal solution when the ZEB-restriction is active. Whereas the only storage technology present in the optimal solution for the SFH is HWT, both HS and HWT are present for the apartment block. From the investment costs presented in chapter 3.6 it is evident that the investment costs for these two storage possibilities, in comparison with electric battery, is very low. This can explain why the storage opportunities for the heat are present in the optimal solution whereas the electric battery is not.

Table 5.2: Results from all cases with building type *Apartment block*

	ZEB		noZEB		ZEB		noZEB	
Case Name	PS	PS_R2	PS	PS_R2	WB	WB_R2	WB	WB_R2
D_{EL} [kWh/year]	118260	118260	118260	118260	118260	118260	118260	118260
D_{SH} [kWh/year]	149834	29991	149834	29991	149834	29991	149834	29991
D_{DHW} [kWh/year]	146503	146503	146503	146503	146503	146503	146503	146503
Electricity [kW]								
PV_S30	414.2	321.6	0.0	0.0	266.6	214.3	0.0	0.0
SH & DHW [kW]								
ASHP	-	-	-	-	49.8	26.3	44.4	20.3
GSHP	-	-	-	-	6.1	0.0	0.0	0.0
BB	-	-	-	-	0.0	0.0	0.0	0.0
EB	-	-	-	-	24.7	17.2	38.2	24.5
SH [kW]								
A2A	29.8	12.5	27.1	10.5	-	-	-	-
PO	54.5	31.5	57.2	33.5	-	-	-	-
FP	0.0	0.0	0.0	0.0	-	-	-	-
DHW [kW]								
EB	33.3	32.7	19.2	19.2	-	-	-	-
Storage [kWh]								
HWT	140.3	134.5	17.5	17.5	75.1	53.2	27.4	25.1
BAT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HS	-	-	-	-	9.4	1.1	24.1	16.4
Costs [kEUR]								
Operation	315	226	494	375	243	178	359	268
Investment	733	568	37	24	561	409	99	50
Tot. energy cost	1048	794	531	399	805	586	458	318
R1 cost	0	0	0	0	111	111	111	111
R2 cost	0	267	0	267	0	267	0	267
Total	**1048**	**1061**	**531**	**666**	**916**	**964**	**569**	**696**

5.4 Office

The same trends as for apartment buildings can be seen in the optimal solution for the office buildings, shown in table 5.3. A combination of ASHP and EB is used for **SH & DHW** in the waterborne solution while a combination of A2A and PO is used for **SH** in the point-source model. As a result of this, it can be seen that GSHP, BB and FP are the technologies that have not been selected in any cases for the optimal solution. In terms of storage, it can be found that battery is not in the optimal solution for office buildings, as mentioned both for SFH and apartment block as well.

Table 5.3: Results from all cases with building type *Office*

	ZEB		noZEB		ZEB		noZEB	
Case Name	PS	PS_R2	PS	PS_R2	WB	WB_R2	WB	WB_R2
D_{EL} [kWh/year]	1404989	1279917	1404989	1279917	1404989	1279917	1404989	1279917
D_{SH} [kWh/year]	656579	210330	656579	210330	656579	210330	656579	210330
D_{DHW} [kWh/year]	153261	153261	153261	153261	153261	153261	153261	153261
Electricity [kW]								
PV_S30	2247.5	1763.8	0.0	0.0	1952.4	1576.4	0.0	0.0
SH & DHW [kW]								
ASHP	-	-	-	-	171.3	78.6	98.3	45.9
GSHP	-	-	-	-	0.0	0.0	0.0	0.0
BB	-	-	-	-	0.0	0.0	0.0	0.0
EB	-	-	-	-	187.8	73.4	286.3	116.0
SH [kW]								
A2A	131.7	48.5	104.7	38.8	-	-	-	-
PO	257.1	115.9	284.1	125.5	-	-	-	-
FP	0.0	0.0	0.0	0.0	-	-	-	-
DHW [kW]								
EB	21.8	21.8	21.8	21.8	-	-	-	-
Storage [kWh]								
HWT	1.1	1.1	1.1	1.1	7.8	36.2	7.4	17.4
BAT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HS	-	-	-	-	170.8	28.9	43.3	8.1
Costs [kEUR]								
Operation	556	406	999	752	521	375	953	705
Investment	2946	2267	123	53	2694	2086	164	74
Tot. Energy cost	3502	2673	1121	806	3215	2460	1117	779
R1 cost	0	0	0	0	310	310	310	310
R2 cost	0	644	0	644	0	644	0	644
Total	**3502**	**3316**	**1121**	**1449**	**3525**	**3414**	**1427**	**1732**

5.5 Effect of Post-insulation (R2)

From all three result tables it can be seen that SH demand is lower for the pot-insulated buildings. For the office building, the electric demand is also lower for the post-insulated building. This results in a lower installed capacity for all technologies except EB and HWT who are dependent upon the DHW demand.

Because of the lower installed capacities, the investment costs are lower in the post-insulated buildings than for the regular buildings. In addition, the operating costs are lower for the post-insulated buildings as a result of lower total energy demand. Overall, this result in a lower total energy cost for the post-insulated buildings.

At the same time it must be kept in mind that the post-insulation comes with an additional cost, R2. Comparing the regular and post-insulated buildings it can be seen that for both SFH and Apartment Block, the total cost of the regular building is lower than for the post-insulated building. This holds for the Office building as well in regards of the noZEB cases. For the cases with ZEB-restriction on the other hand, the regular buildings have the highest costs.

As mentioned in chapter 3.5.3, the cost for post-insulation can vary within a wide range, which must be kept in mind when reading the results. The most important observation in regards of the post-insulation is therefore that the total energy cost decreases when meeting the demands of a post-insulated building. It must be remembered that an additional cost will occur, but this cost should be more precisely calculated if using this optimisation method for a specific building case.

5.6 Effect of Waterborne Heating System (R1)

The same trends as for the post-insulation can be seen for the effect of waterborne heating system. For all cases, the total energy cost is lower for the waterborne system than for the point-source system. It can be seen that when ZEB-restriction is active, the difference between the costs are the highest. When adding the additional renovation cost for the waterborne system on the other hand, the total price is lower for the point-source system in 9 out of 12 cases.

At the same time, it must be mentioned that the renovation cost for the waterborne system can vary. When comparing the cases with point-source system to the cases with waterborne system, the difference in total price is quite low. As for the post-insulation it is important to differ between the total energy cost and the renovation costs as the renovation costs are more dependent upon each and every specific building case.

6 Sensitivity Analysis

6.1 Power Subscription

A new optimisation has been made for the different cases in regards of apartment buildings for the proposed grid tariff, Power subscription. This has been done without any ZEB-restriction in order to see if the results change only caused by the price incentive. As mentioned in chapter 2.4, this is an incentive which hopefully can be a part of making the private market choose energy-efficient technologies in addition to increased awareness of managing power in times with high demands.

The total cost for the optimal solutions can be seen in table 6.1.

Table 6.1: Results from Power Subscription tariff, Apartment block noZEB

Case Name	PS	PS_R2	WB	WB_R2
Subscribed power [kW]	45	35	28	20
Costs [kEUR]				
Operation	380	262	295	211
Investment	43	29	119	64
Total Energy system cost	423	291	414	275
R1 cost	0	0	111	111
R2	0	267	0	267
Total	**423**	**558**	**525**	**653**

Comparing the total costs to the results in chapter 5.3, it can be found that the possibility of decreasing the total cost for the consumer with right managing of the operation is high. It can also be seen that the difference between the point-source system and the waterborne system is higher when Power subscription is used as grid tariff.

In addition to how the total costs of the apartment block react to the new energy tariff, it is also interesting to see how the value of the penalty charge in Power subscription pricing affect the optimal solution and total cost for the systems. Therefore a sensitivity analysis has been performed for the two cases **PS** and **WB**.

The penalty charge is originally 0.099 EUR, as stated in table 3.10. For both cases it has been tested for values up to 0.6 EUR. From figure 6.1 the effect of C^{plt} on the total energy system cost can be seen. There is a faster increase in costs for the point-source alternative, which can be seen from the steepness of the curve. This implies that the point-source alternative is more cost sensitive in regard to change in the penalty charge.

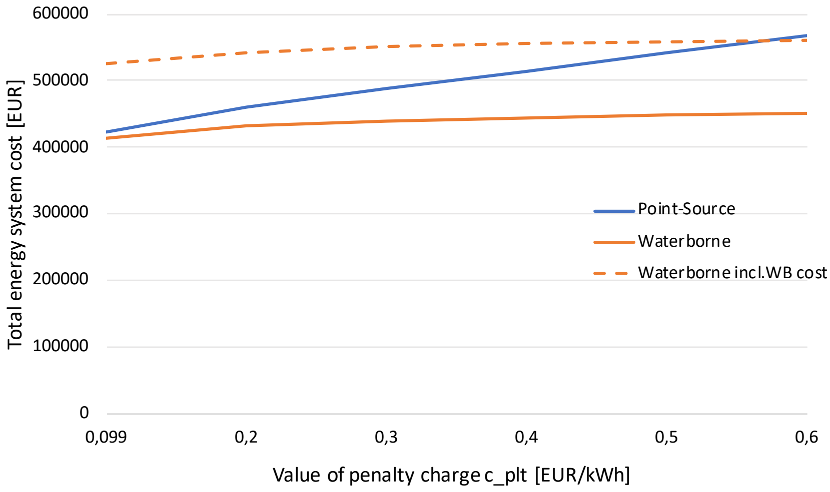


Figure 6.1: Effect of C^{plt} on total energy system cost for Apartment block, noZEB

At the same time, it can be seen from the figure that when adding the cost of the whole system, not only the technologies, the point-source system has the lowest costs even though it is the most cost sensitive. The penalty charge has to increase by 6 times originally value in order to change the results of point-source alternative being the one with the lowest cost.

A solution to why the point-source heating system is more sensitive in regard to higher costs, could be the fact that the technologies available in the point-source system are more dependent upon electricity in order to meet the demand. Figure 6.2 shows the results of the sensitivity analysis of the penalty charge in regard to installed capacity. As expected, the installed capacity of the point-source system increases with installed capacity.

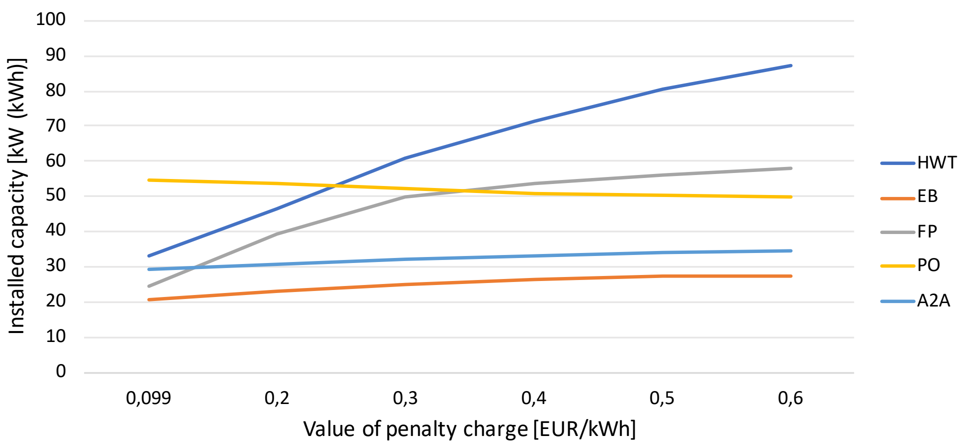


Figure 6.2: Installed capacity per technology for Point-source system Apartment block, noZEB

The two technologies that vary the most are the HWT and FP, which have both increased with more than double of their originally installed capacity. The HWT is used as storage for domestic hot water, and the increase of this technology results in more flexibility in order to managing peak loads. Because of the fact that the EB is only used for domestic hot water in the point-source system, extracting hot water from storage instead of EB in periods where the electricity price is high, will reduce costs.

The FP is used for the space heating demand, and the technology reduces the use of electricity because of the fact that wood is used as fuel instead of electricity. Increasing the use of FP results in a reduction in the use of PO, which can be seen from figure 6.2.

From table 3.2 in chapter 3.3 it can be seen that the efficiency for PO is 1, while the efficiency for FP is 0.84. A result of this is that it needs to be installed higher capacity for FP in order to meet the same demand as the PO was able to meet. Therefore, even though the share of installed capacity by technologies that are not dependent upon electricity is increased, the total cost still increases.

The waterborne system on the other hand, was able to keep the total costs of the energy system more stable even though the penalty charge was increased. The installed capacities for each technology can be seen in figure 6.3.

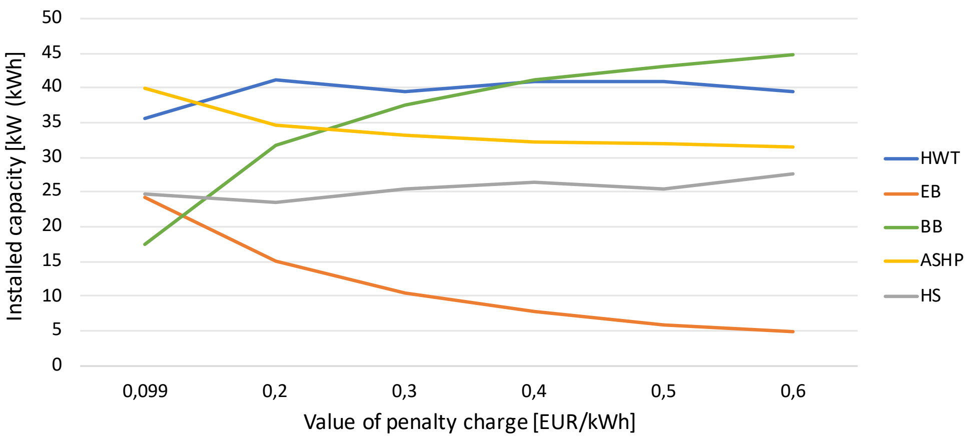


Figure 6.3: Installed capacity per technology for Waterborne system for Apartment block, noZEB

Figure 6.3 shows that the installed capacity of the BB increases with almost three times its original value. The BB can supply both the SH and DHW demand, and the result of the increase of that technology is a decrease in installed capacity for both ASHP and EB. How this affects the use of each technology can be seen in figure 6.4 and 6.5. These figures shows how the technologies in cooperation covers the SH-demand.

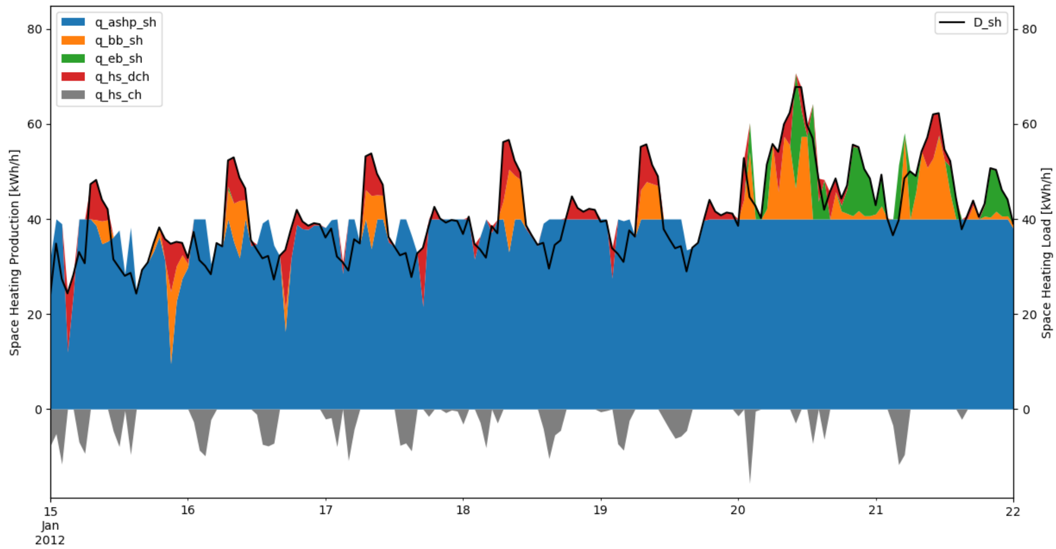


Figure 6.4: Use of technologies for SH on week in January for penalty charge = 0.099, Apartment block

In figure 6.4 the use of technologies can be seen for the scenario where the penalty charge is set to its original value. The ASHP is used for the base load and is continuously producing heat throughout the whole week. Because the week in January has a higher demand than installed capacity for ASHP, both BB and heat from storage is used every day of the week to cover the peak loads. For the coldest days, which results in the highest peak loads, EB is also used to cover the load.

When comparing to figure 6.5, the change in installed capacity can be seen from the fact that ASHP has a lower maximum value than for the previous case. It is still used every day of the week for the base load, but it can be seen that the ASHP is more sensitive of price changes for a higher penalty charge. When the grid charge is high, often at evenings, this result in a change from ASHP to BB. This change is much more significant in this scenario than for the original penalty charge value.

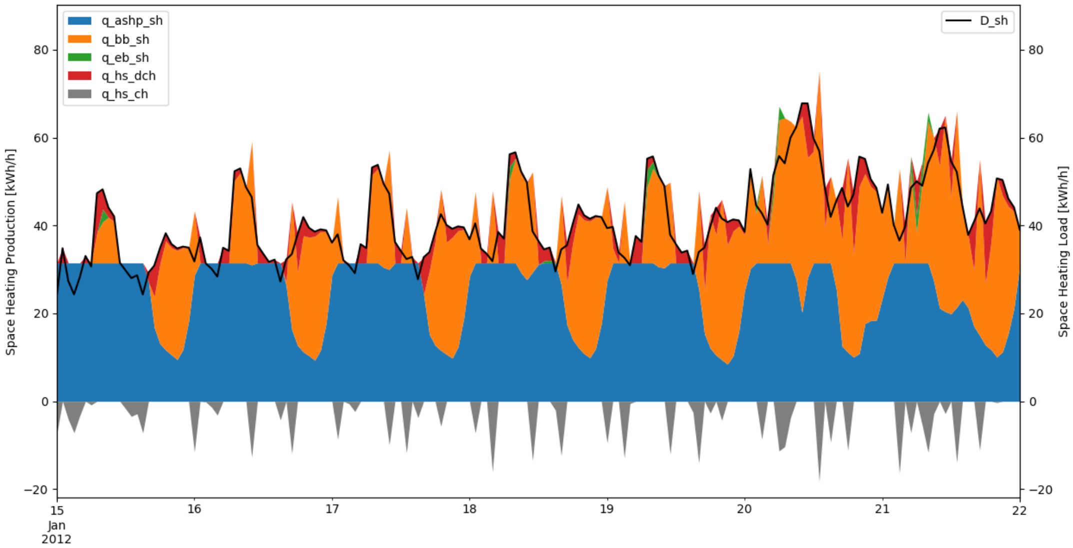


Figure 6.5: Use of technologies for SH on week in January for penalty charge = 0.6, Apartment block

As a conclusion for this sensitivity analysis it have been found that the penalty charge has to be increased by six times its original value for waterborne system to be the system with lowest cost. At the same time, this system is less sensitive to changes in costs and the most favourable option must therefore be decided upon whether the costs are believed to increase in the following years. The reason to why the waterborne system is less sensitive can be seen from the fact that the BB is able to cover both the SH and DHW load with a higher efficiency than FP, which is the non-electric alternative for the point-source system. This can be seen from table 6.2 which shows the total installed capacity for all technologies for the different scenarios. The high increase for the point-source system results in a higher investment cost for the scenario where $C^{plt} = 0.6$. In addition to the higher cost, it implies that the waterborne system have higher flexibility in regards to changing between different technologies.

Table 6.2: Total installed capacity for all technologies [kW], Apartment block noZEB

	$C^{plt} = 0.099$	$C^{plt} = 0.6$
Waterborne system	141.9	148.0
Point-source sysem	162.7	256.6

6.2 Electricity Price

An uncertain factor which can influence the favorable option of either waterborne or point-source system, is the spot price. As mentioned in chapter 2.3, the spot price varies every year and is dependent upon the weather in addition to the spot price in the rest of Europe. With an increase of energy production technologies that are dependent upon wind, sun and rain for instance, the spot price will keep on varying in the future. For these reasons, an analysis has been made in this thesis with objective to see if an increase of the spot price will have an impact on the favorable option of heating system.

From figure 6.6 the same trends as in the analysis of penalty charge in regard to the total costs, can be seen. For an increase up to 30% the point-source system is only a bit more price sensitive, but for values above 30 % the point-source curve is rapidly increasing. It can be seen that the spot price has to increase by 90% of its original value in order to find the waterborne system as the most favorable option when it comes to total costs.

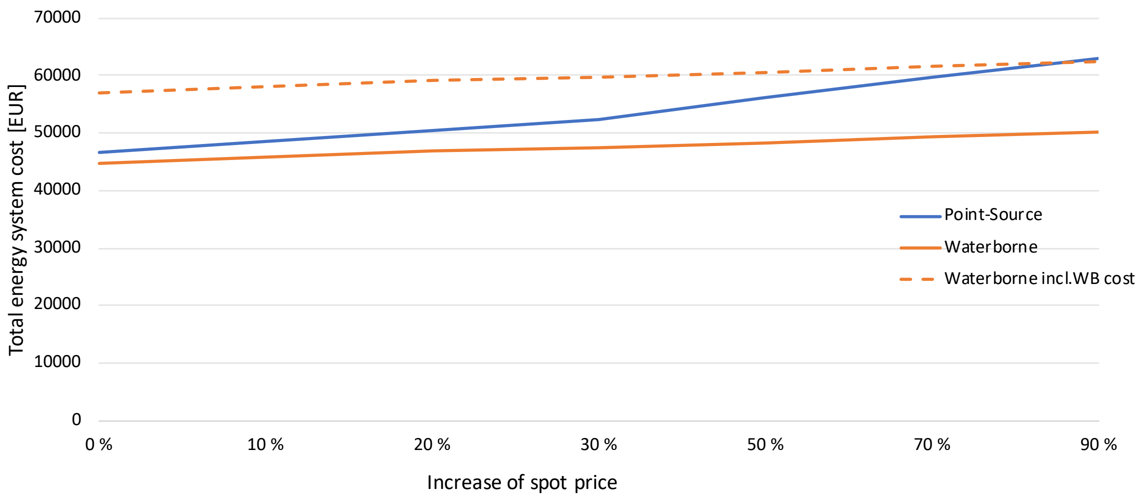


Figure 6.6: Effect of spot price on total energy system cost, SFH noZEB

The installed capacities of the technologies can have an impact on the sensitivity of each system. Figure 6.7 shows the installed capacities of the waterborne system. Similarly to the penalty charge analysis, the BB takes over the load from the ASHP and EB. Since all of these technologies work on both SH and DHW load, the system has high flexibility when it comes to choosing technologies for different scenarios.

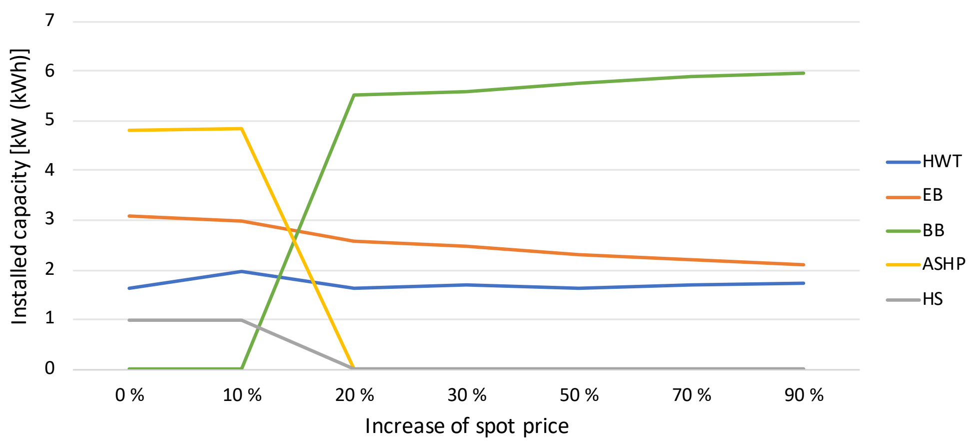


Figure 6.7: Installed capacity per technology for waterborne system in SFH, noZEB

For the point-source heating system, seen in figure 6.8, the FP occurs in the optimal solution when the spot price is increased by 70%. This technology is becoming a part of covering the SH load, in addition to the PO and A2A.

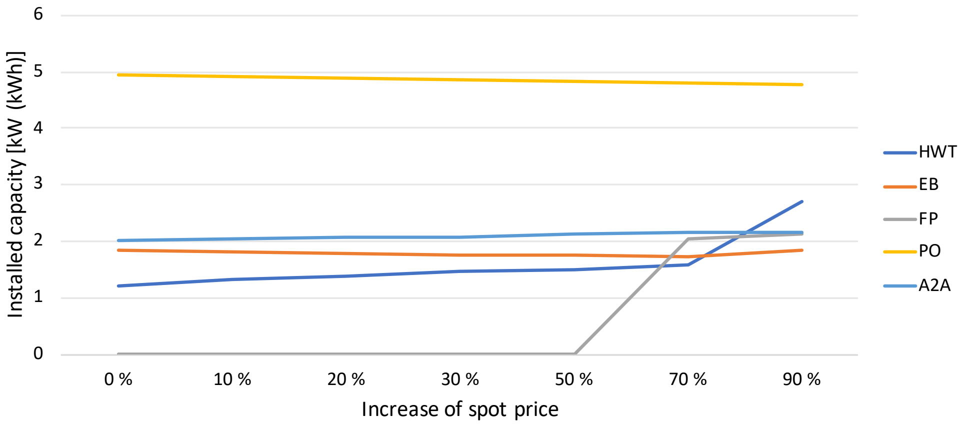


Figure 6.8: Installed capacity per technology for point-source system in SFH, noZEB

It can be seen that the PO slightly decreases as a result of the increased spot price, and is being replaced by FP because of its non-electric fuel. How this is handled in regards of the operation of each technology can be seen in figure 6.9. The FP operates on the evening load because of the fact that it has a restriction which allows it to only operate from 16:00-24:00 each day. Nevertheless, it can be seen that the FP is replacing the PO on some of the SH-load.

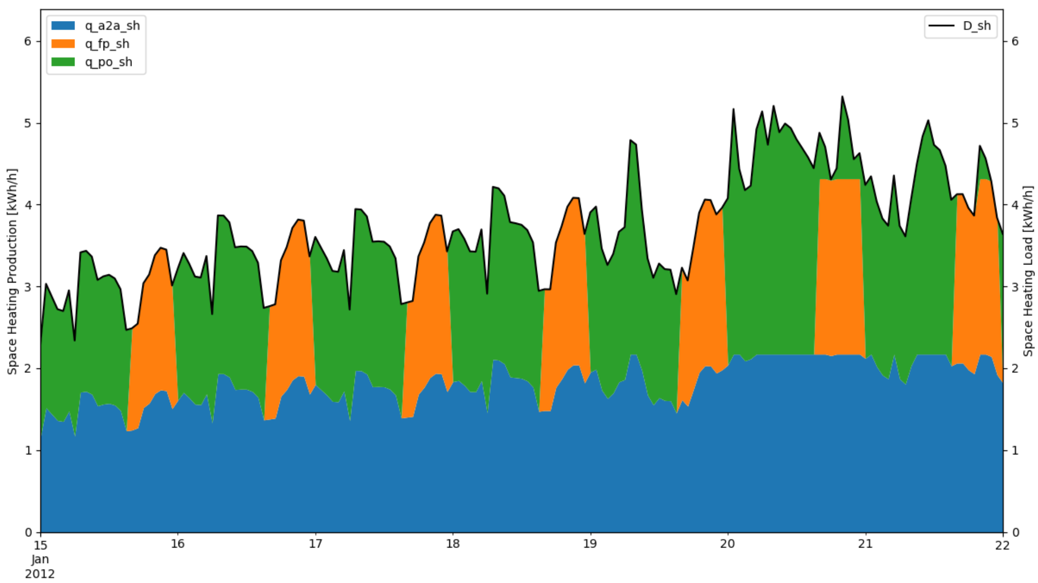


Figure 6.9: Operation of technologies for SH-load for one week in January in SFH

For the DHW-load, it can be seen from figure 6.8 that the HWT is increased when the spot price is increased by 90% of its original value. This results in a usage of heat from the HWT for the peak loads shown in figure 6.10. It can also be seen that some areas have coverage due to the storage, even though it is not a peak load. This is related to the spot price for those hours.

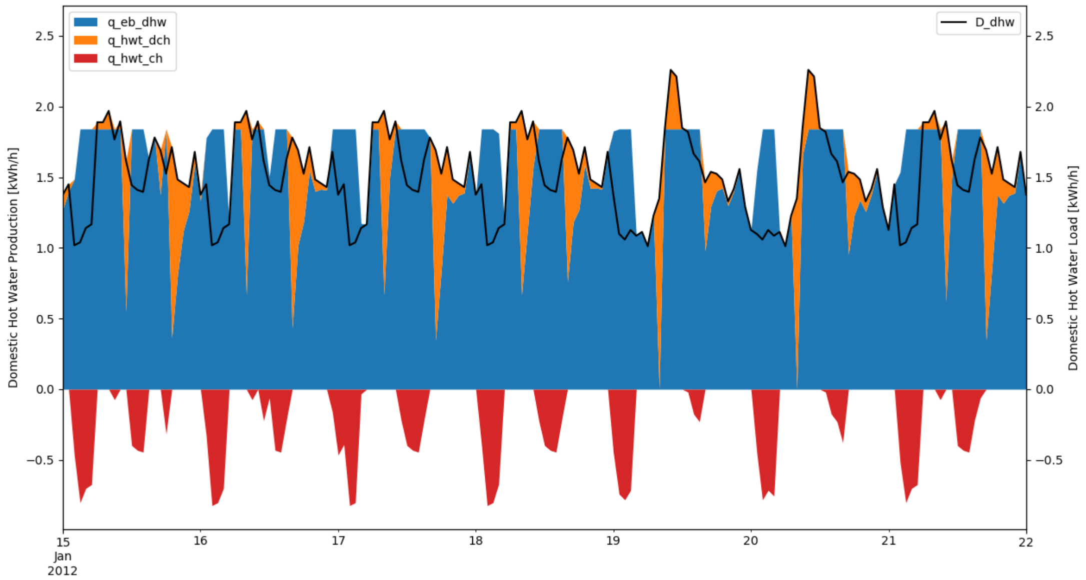


Figure 6.10: Operation of technologies for DHW-load for one week in January in SFH

As a conclusion for the analysis of the total energy system cost in regards to the spot price, it can be seen that the spot price must be close to double of its original value for the waterborne system to be the cheapest. If comparing the spot price to the outlook for year 2019-2040 from NVE which was introduced in chapter 2.3, the expected spot price in year 2040 is 0.43 NOK/kWh. This corresponds to an increase from the original value of 50%. The highest value in the sample space is 0.51 NOK/kWh which corresponds to an increase of 76%. Therefore, it can be said that for the next 20 years at least, an increase of 90% in the spot price is quite unrealistic. As a result of this, the point-source model is favorable in many years to come.

6.3 Cost of PV Panels

From the main results in chapter 5.1, PV only appears in the optimal solution when adding the ZEB-restriction. As the prices of PV have had a trend the last years of decreasing, it could be interesting to see how much the price needs to decrease in order to be implemented in the optimal solution.

Hence, a sensitivity analysis for the cases *PS* and *WB* has been carried out for the apartment block. The results can be seen in figure 6.11 and 6.12. For both cases, the PV becomes a part of the optimal solution for a decrease in investment cost by 50% of its original value. This corresponds to an investment cost of 645 EUR/kW_p. This includes the technical equipment, mounting and installation.

It can be seen from figure 6.11 that the installed capacities for the heating system does not change much even if PV becomes a part of the solution. It is not until the PV price is decreased by 70% that the installed capacities of HWT and EB increases.

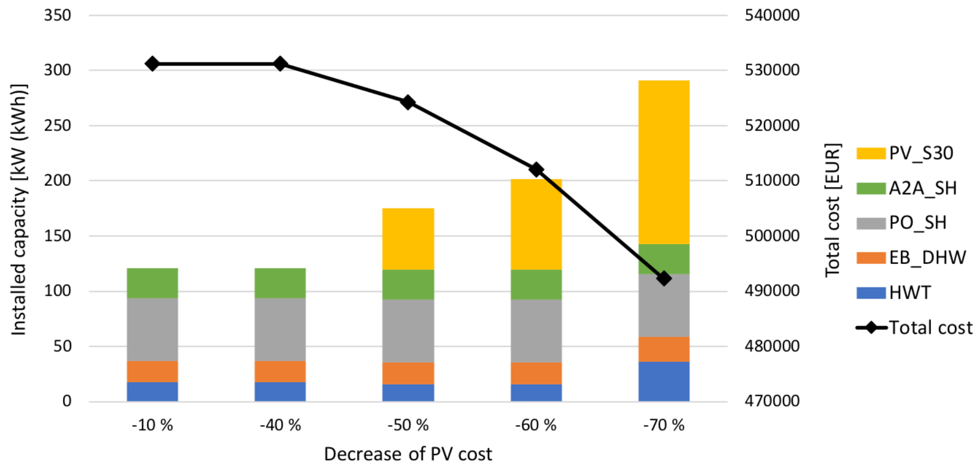


Figure 6.11: Installed capacities for decreasing PV costs, point-source system Apartment block

The same trend can be seen for the waterborne system in figure 6.12, but for a smaller amount of decreased PV cost. The change in installed capacities for the other technologies appear for a decrease in PV cost by 50%, the same scenario which PV appear in the optimal solution. It can be seen that for the waterborne system, the HWT increases as it did for the point-source system, in addition to the fact that the HS decreases. In the waterborne system both the HS and HWT is fed by the same technologies, but for two different purposes. Thus, the SH demand has less coverage by heat from storage when the amount of PV is larger in the system. For the DHW demand it is the opposite, the more installed capacity of PV in the system, the more coverage of heat from the HWT.

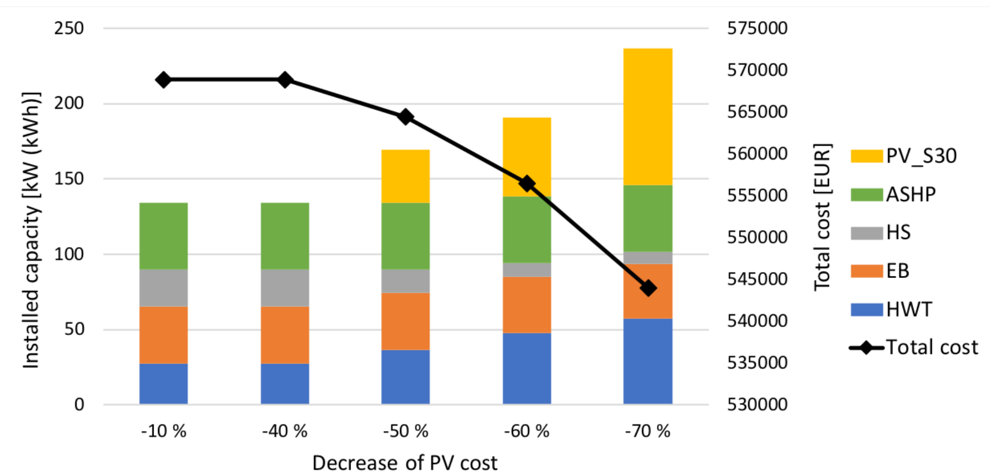


Figure 6.12: Installed capacities for decreasing PV costs, waterborne system Apartment block

The amount of PV in the system has the same impact on the total cost for both the point-source and the waterborne system. Total amount of installed capacity increases, but because of the export of PV the total cost of the system decreases. In other words, the increase of investment cost by installing a larger amount of technology in the building is less than the decrease in operation cost by selling electricity produced by the installed PV.

From this result, it is important to remember that the cite in this thesis is Oslo. In addition to the cite, the panels are also oriented directly towards south, and with a tilting that is close to optimal for this cite. Therefore, PV-production is quite high and favorable, in comparison with the usage of batteries to decrease the electricity import. When using this optimisation model as a decision tool for design of new buildings, the method works very well. But if the model should be used for already built buildings, with a fixed orientation and tilting on the roof that is not optimal, this is important to take into consideration.

7 Discussion

From the results it seems that the investment cost of each technology in cooperation with its respective efficiency is the most valued input for the choice of technologies for the optimal solution. Hence, the same technologies are chosen for almost all cases for all buildings. We know that for some technologies, for instance PV and Battery (BA), the investment cost is decreasing quite rapidly each year. Consequently, if the same optimisation would have been conducted a few years from now with updated investment cost, the optimal solution could have been different.

From the sensitivity analysis for the investment cost of PV,the effect of the investment cost on the chosen technologies in the optimal solution is illustrated. By halving the PV-cost, this technology is a part of the optimal case solution for apartment block. This is an important issue which needs to be taken into consideration as the lifetime of the analysis is 60 years.

Another input value which influences the chosen technologies is the price of electricity. From the analysis on both the spot price and the power subscription tariff, changes in chosen technologies can be seen. If power subscription is chosen as new grid tariff, both FP and BB is a part of the optimal solution. Besides, increasing the penalty charge will increase the amount of installed capacity for both technologies.

When analysing the effect of spot price, the BB is in the optimal solution for the waterborne system when the spot price is increased by 20%. For this value, the BB replaces both the ASHP and the HS in the optimal solution. For the point-source system, FP will be a part of the solution when the spot price is increased by at least 70%. When reading these results, it must be kept in mind that an increase of the spot price by 50% is likely, according to the outlook for year 2019-2040 by NVE.

For the results regarding the total cost, it must be kept in mind that the additional renovation costs R1 and R2 in reality varies between different cases. Hence, the results when adding the additional costs to the energy system cost are less accurate than for only the energy system. The consequence of the difficulties regarding the estimation of renovation costs, is that the cases without renovation is favored.

The renovation costs are included in order to provide an estimate for the additional cost which must be expected when changing system for the base case, PS. At the same time, for a specific building case it must be considered that gathering an offer from a contractor may change the favorable option.

8 Conclusion

Throughout the work with this thesis, an implementation of new building types with associated heating loads has been done. In addition, a review of input values for the model has been done, and new investment costs for larger building has been found. This resulted in three different buildings types in which all four cases have been optimised with respect to the total cost of the energy system.

Whereas the base case **PS** is a point-source system where the building standard implies an old badly insulated building, an upgrade including post-insulation of the building can be done. This upgrade results in the second case for the point-source system, **PS_R2**.

The two other cases have both updated from a point-source system to a waterborne heating system which results in different applicable technologies for heating. These two cases are also divided in one case where the building standard is the same as in the base case **WB**, and one case where the building standard is upgraded by post-insulating **WB_R2**.

For SFH the total cost was the lowest for the base case, **PS**. Comparing the total energy costs for all cases it can be seen that the difference between the base case and **WB_R2** is 15 kEUR. The additional renovation cost is 52 kEUR. This implies that the renovation costs for this building type are high compared to the energy system costs. Hence, a renovation of the building is not favorable.

When adding the ZEB-restriction for this building type on the other hand, **WB** becomes the most favorable solution. This is related to the higher flexibility for storage and heating technologies in the waterborne system. Thus, the waterborne system reacts better to stricter restrictions and higher costs than the point-source system.

As of this time, there is no outlook of restrictions for private residents in regard to ZEB. Hence the most favorable option for this building type remains **PS**.

For apartment block, the exact same trends can be seen as for the SFH. At the same time it can be seen from figure 5.1 that the renovation costs are much lower per m^2 than for the SFH. Hence, an upgrade of the heating system from point-source to waterborne system is more likely to pay off for the apartment block than for the SFH.

When adding the ZEB-restriction, the favorable option for the apartment block is **WB**, with **WB_R2** as the second best option. The probability of a ZEB-restriction for apartment-buildings are more likely to happen than for the SFH. Hence, an upgrade from point-source system to waterborne could be the favorable option for the apartment building if thinking a few years ahead.

For the office building, a ZEB-restriction is more relevant than for the other building types. When ZEB-restriction is active, **PS_R2** is the most favorable solution. The second best option is **WB_R2**. Hence, the low renovation-costs per m^2 have a large impact on the solution for this case.

For all cases it can be seen that the point-source system is the most favorable option. At the same time, seen from the sensitivity analysis and when adding the ZEB-restriction, the waterborne system has a better reaction to higher costs and stricter restrictions. Choosing between a point-source system or a waterborne system must therefore be decided upon whether the investment is seen in a short-time or a long-time perspective. The longer perspective, the more favorable the waterborne system becomes. The additional cost for post-insulation must be decided in the same manner, but it must be kept in mind that the additional cost is more favorable for larger buildings.

9 Further Work

- **Include technology cost as a function of time**
  From the sensitivity analysis, we were able to see how the change in investment cost may change the optimal solution regarding both costs and installed technologies. If the technologies were modeled as a function of time instead of constant, this would be taken into account when calculating the optimal solution.

- **Include more than the operational phase of the building in regard to ZEB.**
  As mentioned, this model is limited to the operational phase of the building in regard to ZEB. An estimate could be calculated for the emissions in other phases for different building types and standards. The emissions of the equipment for the technologies could also be included.

- **Expand the model to include more than one building.**
  The model is used for one building at the time. Now that different building types are included, it could be interesting to see if a neighbourhood of different buildings would give another solution to the optimisation problem.

- **Restrict the PV-solutions for each building type**
  In the optimal solution for this thesis, the available area for PV-production is not limited for each building type. For generic buildings, it is hard to know the available area. At the same time, the model should have an option for restriction if wanted. This will make the model more useful in optimisation of real-life cases.

- **Investigate the optimal value for subscribed power**
  For the analysis of the proposed grid tariff, power subscription, an optimal value of subscribed power is not investigated. In order to improve the results to be more close to reality, this value should be optimised for the different building types and building standards.

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A Point-source Model

```python
import pyomo.environ as pyo
from math import floor

# function that creates a dict, which maps each month (0-11) to a unique set of hours belonging to it
def createMonthSet():
    start = 0
    months = dict()
    for i in range(1,13):
        if i in (1,3,5,7,8,10):
            hours_in_month = list(range(start, start + 31*24)) # list of hours to be placed into dict if 31 days in month
        elif i in (4,6,9,11,12): # NB! removing last day of december to get exactly 52 weeks
            hours_in_month = list(range(start, start + 30*24)) # list of hours to be placed into dict if 30 days in month
        else:
            hours_in_month = list(range(start, start + 28*24)) # else february, disregard leap year
        months[i] = hours_in_month
        start += len(months[i])
    return months

def createHvector():
    start = 0
    months = dict()
    for i in range(1,13):
        if i in (1,3,5,7,8,10):
            hours_in_month = start + 31*24 # list of hours to be placed into dict if 31 days in month
            prev = 31*24
        elif i in (4,6,9,11,12): # NB! removing last day of december to get exactly 52 weeks
            hours_in_month = start + 30*24 # list of hours to be placed into dict if 30 days in month
            prev = 30*24
        else:
            hours_in_month = start + 28*24 # else february, disregard leap year
            prev = 28*24
```

```
        months[i] = hours_in_month
        start += prev
    return months

class ZEBModel():

    def __init__(self, M_const = 10000):
        """Create Abstract Pyomo model for ZEB"""
        # Deterministic two-stage model
        self.abstractmodel = self.createTWOSTAGEMODEL()

        self.M_const = M_const

    def disco(self, n, r):
        '''Discounting factor'''
        return 1/((1+r)••n)

    def annui(self, n, r):
        '''Annuity factor'''
        return r/(1-(1+r)••(-n))

    def capit(self, n, r): # Capitalization factor
        '''Capitalization factor'''
        return (1-(1+r)••(-n))/r

    def cost(self, Yn, cost, l, r):
        '''For the two-stage model: calculating forced reinvestment costs'''
        Kn = pyo.floor(Yn/(l•1))
        n = Yn-l•Kn
        Tn = Yn-n
        return cost•(self.annui(l,r)•self.capit(n,r)•self.disco(Tn, r) \
               + sum(self.disco(k•l,r) for k in range(0,Kn)))

    def npv_cost_Investments(self, m, st):
        investments = 0
        if st==1:
            for i in m.I:
                investments += (m.C_spe[i]•m.x[i]+ m.C_fxd[i]•m.a_i[i])
        else:
            investments = 0
        return investments
```

```python
def npv_cost_Operations(self, m, st):
    '''Operational costs for two-stage/deterministic
    Summation of yearly costs for all years in YRN'''
    techrun = 0
    runcosts = 0
    gridtariff = 0
    operations = 0
    if m.lastT == 4367:
        f = 2
    elif m.lastT == 23:
        f = 8736/24
    elif m.lastT == 95:
        f = 8736/96
    elif m.lastT == 287:
        f = 8736/288
    elif m.lastT == 671:
        '''multiplicationfactor will be 13 if reduced model'''
        f = 13
    elif m.lastT == 727:
        f = 12
    elif m.lastT == 8735:
        f = 1

    if st == 2:
        for i in m.I:
            techrun += m.C_run[i]*m.C_spe_0[i]*m.x[i]
        if m.A_ps + m.A_ep + m.A_pp > 1 or m.A_ps + m.A_ep + m.A_pp < 1:
            raise ValueError("Please select ONE AND ONLY ONE grid tariff
                type.")
        if m.A_ep: #Grid tariff model (includes VAT): Energy pricing
            ''' (inkluderer enova-avgift samt moms)'''
            gridtariff = 12*m.C_fxd_ep + m.C_spe_ep*sum(f*m.y_imp[t] for t in
                m.T)
            VAT = 1.25
            runcosts = sum(m.f_fp[t]*m.C_wo + VAT*m.y_imp[t]*m.P_spot[t] -
                m.y_exp[t]*m.P_spot[t]*m.A_exp for t in m.T)
        elif m.A_ps == 1: #Grid tariff model(includes VAT): Power subscription
            VAT = 1.25
            gridtariff = VAT*(12*(m.C_fxd_ps+(5.69*m.Y_max)) +
                m.C_pty_ps*sum(f*m.y_pty[t] for t in m.T) +
                m.C_spe_ps*sum(f*m.y_imp[t] for t in m.T))
            runcosts = sum(m.f_fp[t]*m.C_wo + VAT*m.y_imp[t]*m.P_spot[t] -
```

```
            m.y_exp[t]•m.P_spot[t]•m.A_exp for t in m.T)
        elif m.A_pp == 1: # Grid tariff model: Peak power charge
            month_set = createMonthSet()
            gridtariff = 0
            for month in m.M:
                if month in (0,1,11):
                    gridtariff += (m.C_fxd_pp + m.C_spe_pp_w1•sum(f•m.y_imp[t]
                        for t in month_set[month]) +
                        m.C_pty_pp_w1•m.y_max_imp[month])
                elif month in (2,10):
                    gridtariff += (m.C_fxd_pp + m.C_spe_pp_w2•sum(f•m.y_imp[t]
                        for t in month_set[month]) +
                        m.C_pty_pp_w2•m.y_max_imp[month])
                else:
                    gridtariff += (m.C_fxd_pp + m.C_spe_pp_s•sum(f•m.y_imp[t]
                        for t in month_set[month]) +
                        m.C_pty_pp_s•m.y_max_imp[month])
            VAT = 1.25
            runcosts = sum(m.f_fp[t]•m.C_wo/VAT + m.y_imp[t]•m.P_spot[t] -
                m.y_exp[t]•m.P_spot[t]•m.A_exp for t in m.T)
        operations = (f•runcosts + gridtariff + techrun)•self.capit(m.YRN,
            m.R)•self.disco(1, m.R)
    else:
        operations = 0
    return operations

def createTWOSTAGEMODEL(self):
    m = pyo.AbstractModel()
    m.name = 'ZEB stochastic two-stage model'

# SETS ##########################################################
    m.T = pyo.Set(doc = 'Set of all hours, full model: 8736, reduced model:
        672')
    m.M = pyo.Set(doc = 'Set of all months')
    m.I = pyo.Set(doc = 'Set of all technologies')
    m.ST = pyo.Set(initialize = [1, 2], doc='STAGE')

# PARAMETERS ####################################################

    m.lastT = pyo.Param(within=m.T, doc="Last time step")
    m.Area = pyo.Param(within=pyo.NonNegativeReals, doc="Building floor area")
```

```
#---Technology costs
    m.C_fxd_0 = pyo.Param(m.I,within=pyo.NonNegativeReals, default = 0,
        doc='Fixed investment cost for all techs, EUR in year t = 0')
    m.C_spe_0 = pyo.Param(m.I,within=pyo.NonNegativeReals, default =
        0,doc='Investment costs dependent on installed capacity, EUR/kW
        (EUR/kWh) in t= 0')
    m.C_run = pyo.Param(m.I,within=pyo.NonNegativeReals,default =
        0,doc='Yearly running cost of each tech, given from investment costs
        EUR/kW installed')

#---Grid Tariff pricing
    #Energy pricing
    m.A_ep = pyo.Param(within=pyo.Binary,default = 0,doc = 'Activation of
        energy pricing')
    m.C_fxd_ep = pyo.Param(within=pyo.NonNegativeReals,default = 0,doc='Fixed
        charge part of grid tariff for ep')
    m.C_spe_ep = pyo.Param(within=pyo.NonNegativeReals,default =
        0,doc='Specific energy charge part of grid tariff for ep')

    #Power Subscription pricing
    m.A_ps = pyo.Param(within = pyo.Binary, default = 0,doc = 'Activation of
        power subscription pricing')
    m.C_fxd_ps = pyo.Param(within=pyo.NonNegativeReals,default = 0,
        doc='Subscriptopn charge for pp')
    m.C_pty_ps = pyo.Param(within=pyo.NonNegativeReals,default =
        0,doc='Penalty charge for pp')
    m.C_spe_ps = pyo.Param(within=pyo.NonNegativeReals,default =
        0,doc='Energy charge charge for pp')
    m.Y_max = pyo.Param(within=pyo.NonNegativeReals,default = 0,doc =
        'Subscription limit')

    #Peak Power Pricing
    m.A_pp = pyo.Param(within=pyo.Binary)
    m.C_fxd_pp = pyo.Param(within=pyo.NonNegativeReals)
    m.C_spe_pp_w1 = pyo.Param(within=pyo.NonNegativeReals)
    m.C_spe_pp_w2 = pyo.Param(within=pyo.NonNegativeReals)
    m.C_spe_pp_s = pyo.Param(within=pyo.NonNegativeReals)
    m.C_pty_pp_w1 = pyo.Param(within=pyo.NonNegativeReals)
    m.C_pty_pp_w2 = pyo.Param(within=pyo.NonNegativeReals)
    m.C_pty_pp_s = pyo.Param(within=pyo.NonNegativeReals)

#---#Reference System
```

```
    #CO2-Factors
    m.A_co2 = pyo.Param(within=pyo.Binary,doc = 'Activation of co2 crediting
        system')
    m.G_ref = pyo.Param(within=pyo.NonNegativeReals,doc='CO2 reference
        emissions')
    m.G_el_imp = pyo.Param(within=pyo.NonNegativeReals,doc='gCO2 eq. per kWh
        imported/exported')
    m.G_el = pyo.Param(within=pyo.NonNegativeReals,doc='gCO2 eq. per kWh
        imported/exported')
    m.G_bf = pyo.Param(within=pyo.NonNegativeReals,doc='gCO2 eq. per kWh for
        technology i, i.e BB')
    m.G_wo = pyo.Param(within=pyo.NonNegativeReals,doc='gCO2 eq. per kWh for
        wood technology')
    m.G_tot = pyo.Param(within=pyo.NonNegativeReals,doc='gCO2 total for
        noZEB')

    #Primary Energy Factors
    m.A_pe = pyo.Param(within=pyo.Binary,doc = 'Activation of primary energy
        crediting system')
    m.PE_ref = pyo.Param(within=pyo.NonNegativeReals,doc='CO2 reference
        emissions')
    m.PE_imp = pyo.Param(within=pyo.NonNegativeReals,doc='PE per kWh imported
        electricity')
    m.PE_exp = pyo.Param(within=pyo.NonNegativeReals,doc='PE per kWh exported
        electricity')
    m.PE_bf = pyo.Param(within=pyo.NonNegativeReals,doc='PE per kWh for
        technology i, i.e BB')

#---Technologies
    m.A_i = pyo.Param(m.I, within=pyo.Binary,doc='Pre-activation of each
        tech')

    m.Eff = pyo.Param(m.I,within=pyo.NonNegativeReals, doc='Technology
        efficiency')
    m.Eff_ba_ch = pyo.Param(within=pyo.NonNegativeReals,doc='Battery charging
        efficiency')
    m.Eff_ba_dch = pyo.Param(initialize = 1, doc='Battery discharge
        efficiency')
    m.Beta_ba =
        pyo.Param(within=pyo.NonNegativeReals,doc='Charging/discharging rate')
    m.Beta_hs = pyo.Param(within=pyo.NonNegativeReals, doc='identical
```

```
    charging rate for heat storage')

m.L = pyo.Param(m.I, within=pyo.NonNegativeIntegers, doc='Lifetime of
    technology i')
m.X_min = pyo.Param(m.I, within=pyo.NonNegativeReals, doc='Max possible
    installed capacity of technology ')
m.X_max = pyo.Param(m.I, within=pyo.NonNegativeReals, doc='Min possible
    installed capacity of technology ')

m.Temp = pyo.Param(m.T, within=pyo.Reals, doc='Ambient temperature of
    certain hour')
m.Y_pv_f10 = pyo.Param(m.T, within=pyo.NonNegativeReals,doc='Possible PV
    output at time t')
m.Y_pv_S20 = pyo.Param(m.T, within=pyo.NonNegativeReals,doc='Possible PV
    output at time t')
m.Y_pv_S30 = pyo.Param(m.T, within=pyo.NonNegativeReals,doc='Possible PV
    output at time t')
m.Y_pv_E20 = pyo.Param(m.T, within=pyo.NonNegativeReals,doc='Possible PV
    output at time t')
m.Y_pv_E30 = pyo.Param(m.T, within=pyo.NonNegativeReals,doc='Possible PV
    output at time t')
m.Y_pv_W20 = pyo.Param(m.T, within=pyo.NonNegativeReals,doc='Possible PV
    output at time t')
m.Y_pv_W30 = pyo.Param(m.T, within=pyo.NonNegativeReals,doc='Possible PV
    output at time t')
m.Y_pv_S90 = pyo.Param(m.T, within=pyo.NonNegativeReals,doc='Possible PV
    output at time t')
m.Y_pv_E90 = pyo.Param(m.T, within=pyo.NonNegativeReals,doc='Possible PV
    output at time t')
m.Y_pv_W90 = pyo.Param(m.T, within=pyo.NonNegativeReals,doc='Possible PV
    output at time t')
m.COP_a2a = pyo.Param(m.T, within=pyo.NonNegativeReals, doc='Air-to-air
    heat pump performance at time t w/r SH')


#BITES-params
m.SS_cap = pyo.Param(within=pyo.NonNegativeReals, doc='Shallow storage
    capacity of house, fully determined by area, thus a parameter instead
    of a variable')
m.DS_cap = pyo.Param(within=pyo.NonNegativeReals, doc='Deep storage
    capacity of house, ---=---')
m.K_shallow = pyo.Param(doc='loss factor for BITES, shallow part')
```

```
    m.K_deep = pyo.Param(doc='loss factor for BITES, deep part')
    m.K_flow = pyo.Param(doc='flow factor for BITES, cross-node flow')

#---Energy Demand
    m.D_el = pyo.Param(m.T, within=pyo.NonNegativeReals, doc='Hourly building
        electricity demand')
    m.D_sh = pyo.Param(m.T, within=pyo.NonNegativeReals, doc='Hourly building
        space heating demand')
    m.D_dhw = pyo.Param(m.T, within=pyo.NonNegativeReals, doc='Hourly
        building domestic hot water demand')

#---Grid
    m.P_spot = pyo.Param(m.T, within=pyo.NonNegativeReals, doc='Hourly price
        of imported electricity EUR/kWh including certificates')
    m.X_max_imp = pyo.Param(within=pyo.NonNegativeReals, doc='Maximum grid
        import')
    m.X_max_exp = pyo.Param( within=pyo.NonNegativeReals,doc='Maximum grid
        export')
    m.A_imp = pyo.Param( within=pyo.Binary, doc='Binary: Import is activated,
        1/0')
    m.A_exp = pyo.Param( within=pyo.Binary,doc='Binary: Export is activated,
        1/0')
    m.C_bf = pyo.Param(within=pyo.NonNegativeReals, doc='Constant price of
        biofuel')
    m.C_wo = pyo.Param(within=pyo.NonNegativeReals, doc='Constant price of
        wood')

#---Control
    m.gamma = pyo.Param( within=pyo.NonNegativeReals, doc='=0 for strictly
        ZEB')
    m.R = pyo.Param(within=pyo.NonNegativeReals, doc='Chosen discount Rate')
    m.YRN = pyo.Param( within=pyo.NonNegativeIntegers, doc='Total years in
        modelling period')

    def npv_inv_spe(m, i):
        return self.cost(m.YRN, m.C_spe_0[i], m.L[i], m.R)
    m.C_spe = pyo.Param(m.I, rule = npv_inv_spe)

    def npv_inv_fxd(m, i):
        return self.cost(m.YRN, m.C_fxd_0[i], m.L[i], m.R)
    m.C_fxd = pyo.Param(m.I, rule = npv_inv_fxd)
```

```
#VARIABLES ##########################################################

    # 1 STAGE : STRATEGIC VARIABLES
    m.x = pyo.Var(m.I,within = pyo.NonNegativeReals,
        doc='Optimal installed capacity (storage size), semi-continous, kW
        (kWh)')
    m.a_i = pyo.Var(m.I, within = pyo.Binary,
        doc='Activation binary decision for technology i, 1/0')


    #2 STAGE : OPERATIONAL VARIABLES
    m.q_hwt = pyo.Var(m.T, domain = pyo.Reals,
        doc='Keeping track of HWT discharge')
    m.q_eb_dhw = pyo.Var(m.T,domain = pyo.NonNegativeReals,
        doc='Net heat supplied from (DHW) electric boiler at time t, kWh/h')
    m.q_po_sh = pyo.Var(m.T,domain = pyo.NonNegativeReals,
        doc='Net heat supplied from (SH) paneloven at time t, kWh/h')
    m.q_a2a_sh = pyo.Var(m.T, domain= pyo.NonNegativeReals,
        doc='Net heat supplied from air-to-air heat pump at time t, kWh/h')
    m.q_fp_sh = pyo.Var(m.T, domain=pyo.NonNegativeReals,
        doc='Net heat supplied from bio boiler at time t, kWh/h')
    m.f_fp = pyo.Var(m.T, domain= pyo.NonNegativeReals,
        doc='Wood input to the fireplace at time t kWh/h')

    m.z_hwt = pyo.Var(m.T, domain = pyo.NonNegativeReals,
        doc='Content in hot water tank (HWT) at the end of time t, kWh')
    m.z_ss = pyo.Var(m.T, domain = pyo.NonNegativeReals,
        doc='Content in shallow BITES at the end of time t, kWh')
    m.z_ds = pyo.Var(m.T, domain = pyo.NonNegativeReals,
        doc='Content in deep BITES at the end of time t, kWh')
    m.z_ba = pyo.Var(m.T, domain = pyo.NonNegativeReals,
        doc='Content of battery at the end of time t, kWh')

    #charging variables for BITES, shallow part
    m.q_ss = pyo.Var(m.T, domain = pyo.Reals,             doc='Energy
        released from shallow BITES at the end of time t, kWh')
    m.Flow = pyo.Var(m.T, domain = pyo.Reals,
        doc='Cross-node flow of two-node BITES model at time t, kWh')

    m.y_imp = pyo.Var(m.T, domain = pyo.NonNegativeReals,
        doc='Electricity imported from grid at time t, kWh')
    m.y_exp = pyo.Var(m.T, domain = pyo.NonNegativeReals,
```

```
    doc='Electricity exported to grid at time t, kWh')
m.y_pv_f10 = pyo.Var(m.T, domain = pyo.NonNegativeReals,
    doc='PV production at time t, kWh/h')
m.y_pv_S20 = pyo.Var(m.T, domain = pyo.NonNegativeReals,
    doc='PV production at time t, kWh/h')
m.y_pv_S30 = pyo.Var(m.T, domain = pyo.NonNegativeReals,
    doc='PV production at time t, kWh/h')
m.y_pv_E20 = pyo.Var(m.T, domain = pyo.NonNegativeReals,
    doc='PV production at time t, kWh/h')
m.y_pv_E30 = pyo.Var(m.T, domain = pyo.NonNegativeReals,
    doc='PV production at time t, kWh/h')
m.y_pv_W20 = pyo.Var(m.T, domain = pyo.NonNegativeReals,
    doc='PV production at time t, kWh/h')
m.y_pv_W30 = pyo.Var(m.T, domain = pyo.NonNegativeReals,
    doc='PV production at time t, kWh/h')
m.y_pv_S90 = pyo.Var(m.T, domain = pyo.NonNegativeReals,
    doc='PV production at time t, kWh/h')
m.y_pv_E90 = pyo.Var(m.T, domain = pyo.NonNegativeReals,
    doc='PV production at time t, kWh/h')
m.y_pv_W90 = pyo.Var(m.T, domain = pyo.NonNegativeReals,
    doc='PV production at time t, kWh/h')
m.y_eb_dhw = pyo.Var(m.T, domain = pyo.NonNegativeReals,
    doc='Electricity drawn from (DHW) electric boiler at time t, kWh/h')
m.y_po_sh = pyo.Var(m.T, domain = pyo.NonNegativeReals,
    doc='Electricity drawn for (SH) paneloven at time t, kWh/h')
m.y_a2a_sh = pyo.Var(m.T, domain=pyo.NonNegativeReals,
    doc='Electricity drawn for air-to-air heat pump at time t, kWh/h')
m.y_ch = pyo.Var(m.T, domain = pyo.NonNegativeReals,
    doc='Amount of electricity to battery (charging) at time t, kWh/h')
m.y_dch = pyo.Var(m.T, domain = pyo.NonNegativeReals,
    doc='Amount of electricity discharge from battery at time t, kWh/h')
m.y_pty = pyo.Var(m.T, domain = pyo.Reals,                      doc =
    'Penalty volume')
m.y_max_imp = pyo.Var(m.T, domain = pyo.Reals,                  doc =
    'Max import of every month, stored in list-like container (one value
    for each month)')

m.y_max = pyo.Var(m.M, domain = pyo.NonNegativeReals,           doc='max
    power for every month')

m.a_ch = pyo.Var(m.T, domain = pyo.Binary,                      doc =
    'Charging activation inward time t, 1 = activated')
```

```
    m.a_dch = pyo.Var(m.T, domain = pyo.Binary,                          doc =
        'Discharging activation inward time t, 1 = activated')
# CONSTRAINTS ##########################################################

# 1 STAGE : INVESTMENTS

    #---Activation and boundary constraints
    def Tech_active(m, i, st):
        return m.x[i] <= m.a_i[i]•self.M_const
    m.Tech_active = pyo.Constraint(m.I, m.ST, rule = Tech_active)

    def Tech_Min(m, i, st):
        return m.X_min[i]•m.a_i[i] <= m.x[i]
    m.Tech_Min = pyo.Constraint(m.I, m.ST, rule= Tech_Min)

    def Tech_Max(m, i, st):
        return m.x[i] <= m.X_max[i]•m.A_i[i]
    m.Tech_Max = pyo.Constraint(m.I, m.ST, rule= Tech_Max)

#2 STAGE : OPERATIONS

    #---Balacing constraints

    def El_Balance(m, t, st):
        return m.D_el[t] == m.y_imp[t] + m.y_pv_f10[t] +m.y_pv_S20[t]
            +m.y_pv_S30[t] +m.y_pv_E20[t] +m.y_pv_E30[t] +m.y_pv_W20[t]
            +m.y_pv_W30[t] +m.y_pv_S90[t] +m.y_pv_E90[t] +m.y_pv_W90[t] -
            m.y_exp[t] + m.y_dch[t] - m.y_ch[t] - m.y_a2a_sh[t] - m.y_po_sh[t]
            - m.y_eb_dhw[t]
    m.El_Balance = pyo.Constraint(m.T, m.ST, rule = El_Balance)

    def SH_balance(m, t, st):
        return m.D_sh[t] == m.q_ss[t] + m.q_po_sh[t] + m.q_a2a_sh[t] +
            m.q_fp_sh[t]
    m.SH_balance = pyo.Constraint(m.T, m.ST, rule = SH_balance)

    def DHW_balance(m, t, st):
        if t == 0:
            return m.D_dhw[t] + m.z_hwt[t] == m.z_hwt[m.lastT]•m.Eff['HWT'] +
                m.q_eb_dhw[t]
        else:
            return m.D_dhw[t] + m.z_hwt[t] == m.z_hwt[t-1]•m.Eff['HWT'] +
```

```
        m.q_eb_dhw[t]
m.DHW_balance = pyo.Constraint(m.T, m.ST, rule = DHW_balance)

#---Capacity
def PO_SH_Restriction(m,t, st):
    return m.q_po_sh[t] <= m.x['PO_SH']
m.PO_SH_Restriction = pyo.Constraint(m.T, m.ST, rule = PO_SH_Restriction)

def FP_SH_Restriction(m,t, st):
    i = t - floor(t/24)*24
    if i >= 16 and i <= 24:
        return m.q_fp_sh[t] <= m.x['FP_SH']
    else:
        return m.q_fp_sh[t] == 0
m.FP_SH_Restriction = pyo.Constraint(m.T, m.ST, rule = FP_SH_Restriction)

def A2A_SH_Restriction(m,t, st):
    return m.q_a2a_sh[t] <= m.x['A2A_SH']
m.A2A_SH_Restriction = pyo.Constraint(m.T, m.ST, rule =
    A2A_SH_Restriction)

def A2A_SH_Restriction_1(m,t, st):
    return m.q_a2a_sh[t] <= 0.5*m.D_sh[t]
m.A2A_SH_Restriction_1 = pyo.Constraint(m.T, m.ST, rule =
    A2A_SH_Restriction_1)

def EB_DHW_Restriction(m,t, st):
    return m.q_eb_dhw[t] <= m.x['EB_DHW']
m.EB_DHW_Restriction = pyo.Constraint(m.T, m.ST, rule =
    EB_DHW_Restriction)

#---Grid equations
def Grid_Import(m,t, st):
    return m.y_imp[t] <= m.X_max_imp
m.Grid_Import = pyo.Constraint(m.T, m.ST, rule=Grid_Import)

def Grid_Export(m,t, st):
    return m.y_exp[t] <= m.X_max_exp
m.Grid_Export = pyo.Constraint(m.T, m.ST, rule=Grid_Export)

#---Storage equations
```

```
def HWT_Restriction(m, t, st):
    return m.z_hwt[t] <= m.x['HWT']
m.HWT_Restriction = pyo.Constraint(m.T, m.ST, rule=HWT_Restriction)

def SS_Restriction(m, t, st):
    return m.z_ss[t] <= m.x['SS']*m.A_i['SS']
m.SS_Restriction = pyo.Constraint(m.T, m.ST, rule=SS_Restriction)

def DS_Restriction(m, t, st):
    return m.z_ss[t] <= m.x['DS']*m.A_i['DS']
m.DS_Restriction = pyo.Constraint(m.T, m.ST, rule=DS_Restriction)

def SS_charge_active(m,t, st):
    return m.q_ss[t] <= m.z_ss[t]
m.SS_charge_active = pyo.Constraint(m.T, m.ST, rule=SS_charge_active)

def SS_discharge_active(m,t, st):
    return - m.z_ss[t] <= m.q_ss[t]
m.SS_discharge_active = pyo.Constraint(m.T, m.ST,
    rule=SS_discharge_active)

def HWT_charge_active(m,t, st):
    return m.q_hwt[t] <= m.z_hwt[t]
m.HWT_charge_active = pyo.Constraint(m.T, m.ST, rule=HWT_charge_active)

def HWT_discharge_active(m,t, st):
    return - m.z_hwt[t] <= m.q_hwt[t]
m.HWT_discharge_active = pyo.Constraint(m.T, m.ST,
    rule=HWT_discharge_active)

def HWT_Balance_ch(m,t,st):
    if t == 0:
        return m.q_hwt[t] == m.z_hwt[m.lastT] - m.z_hwt[t]
    else:
        return m.q_hwt[t] == m.z_hwt[t-1] - m.z_hwt[t]
m.HWT_Balance_ch = pyo.Constraint(m.T, m.ST, rule = HWT_Balance_ch)

def Flow_Constraint(m,t,st):
    return m.Flow[t] == m.K_flow*((m.z_ss[t]/m.SS_cap) -
        (m.z_ds[t]/m.DS_cap))
m.Flow_Constraint = pyo.Constraint(m.T, m.ST, rule = Flow_Constraint)
```

```
def SS_balance_ch(m, t, st):
    if t == 0:
        return m.q_ss[t] == m.z_ss[m.lastT] - m.z_ss[t] - m.Flow[t] -
            m.z_ss[t]•(1 - m.K_shallow)
    else:
        return m.q_ss[t] == m.z_ss[t-1] - m.z_ss[t] - m.Flow[t] -
            m.z_ss[t]•(1 - m.K_shallow)
m.SS_balance_ch = pyo.Constraint(m.T, m.ST, rule = SS_balance_ch)

def DS_balance_ch(m, t, st):
    if t == 0:
        return m.z_ds[t] == m.z_ds[m.lastT] + m.Flow[t] - m.z_ds[t]•(1 -
            m.K_deep)
    else:
        return m.z_ds[t] == m.z_ds[t-1] + m.Flow[t] - m.z_ds[t]•(1 -
            m.K_deep)
m.DS_balance_ch = pyo.Constraint(m.T, m.ST, rule = DS_balance_ch)

def HWT_discharge_rate_min(m,t, st):
      return -m.x['HWT']•m.Beta_hs <= m.q_hwt[t]
m.HS_discharge_rate_min = pyo.Constraint(m.T, m.ST,
    rule=HWT_discharge_rate_min)

def HWT_discharge_rate_max(m,t, s):
    return m.q_hwt[t] <= m.x['HWT']•m.Beta_hs
m.HWT_discharge_rate_max = pyo.Constraint(m.T, m.ST,
    rule=HWT_discharge_rate_max)

def BA_Restriction(m,t, st):
    return m.z_ba[t] <= m.x['BA']
m.BA_restriction = pyo.Constraint(m.T, m.ST, rule=BA_Restriction)

def BA_Balance(m,t, st):
    if t == 0:
        return m.z_ba[t] == m.z_ba[m.lastT] - m.y_dch[t]•(1/m.Eff_ba_dch)
            + m.y_ch[t]•m.Eff_ba_ch
    else:
        return m.z_ba[t] == m.z_ba[t-1] - m.y_dch[t]•(1/m.Eff_ba_dch) +
            m.y_ch[t]•m.Eff_ba_ch
m.BA_Balance = pyo.Constraint(m.T, m.ST, rule=BA_Balance)

def BA_Charge_Balance(m, t, st):
```

```
    if t == 0:
        return m.y_ch[t] <= (m.x['BA'] -
            m.z_ba[m.lastT])*m.A_i['BA']*(1/m.Eff_ba_ch)
    else:
        return m.y_ch[t] <= (m.x['BA'] -
            m.z_ba[t-1])*m.A_i['BA']*(1/m.Eff_ba_ch)
m.BA_Charge_Balance = pyo.Constraint(m.T, m.ST, rule=BA_Charge_Balance)

def BA_Discharge_Balance(m,t, st):
    if t == 0:
        return m.y_dch[t] <= m.z_ba[m.lastT]*m.A_i['BA']*m.Eff_ba_dch
    else:
        return m.y_dch[t] <= m.z_ba[t-1]*m.A_i['BA']*m.Eff_ba_dch
m.BA_Discharge_Balance = pyo.Constraint(m.T, m.ST,
    rule=BA_Discharge_Balance)

def BA_charge_active(m,t, st):
    return m.y_ch[t] <= m.X_max_imp
m.BA_charge_active = pyo.Constraint(m.T, m.ST, rule=BA_charge_active)

def BA_discharge_active(m,t, st):
    return m.y_dch[t] <= m.X_max_imp
m.BA_discharge_active = pyo.Constraint(m.T, m.ST,
    rule=BA_discharge_active)

def BA_charge_rate(m,t, st):
    return m.y_ch[t] <= m.x['BA']*m.Beta_ba
m.BA_charge_rate = pyo.Constraint(m.T, m.ST, rule=BA_charge_rate)

def BA_discharge_rate(m,t, st):
    return m.y_dch[t] <= m.x['BA']*m.Beta_ba
m.BA_discharge_rate = pyo.Constraint(m.T, m.ST, rule=BA_discharge_rate)

#---Production constraints for generating technologies

def PV_f10_Balance(m,t, st):
    return m.y_pv_f10[t] == m.x['PV_f10']*m.Y_pv_f10[t]
m.PV_f10_Balance = pyo.Constraint(m.T, m.ST, rule=PV_f10_Balance)

def PV_S20_Balance(m,t, st):
    return m.y_pv_S20[t] == m.x['PV_S20']*m.Y_pv_S20[t]
m.PV_S20_Balance = pyo.Constraint(m.T, m.ST, rule=PV_S20_Balance)
```

```
def PV_S30_Balance(m,t, st):
    return m.y_pv_S30[t] == m.x['PV_S30']*m.Y_pv_S30[t]
m.PV_S30_Balance = pyo.Constraint(m.T, m.ST, rule=PV_S30_Balance)

def PV_E20_Balance(m,t, st):
    return m.y_pv_E20[t] == m.x['PV_E20']*m.Y_pv_E20[t]
m.PV_E20_Balance = pyo.Constraint(m.T, m.ST, rule=PV_E20_Balance)

def PV_E30_Balance(m,t, st):
    return m.y_pv_E30[t] == m.x['PV_E30']*m.Y_pv_E30[t]
m.PV_E30_Balance = pyo.Constraint(m.T, m.ST, rule=PV_E30_Balance)

def PV_W20_Balance(m,t, st):
    return m.y_pv_W20[t] == m.x['PV_W20']*m.Y_pv_W20[t]
m.PV_W20_Balance = pyo.Constraint(m.T, m.ST, rule=PV_W20_Balance)

def PV_W30_Balance(m,t, st):
    return m.y_pv_W30[t] == m.x['PV_W30']*m.Y_pv_W30[t]
m.PV_W30_Balance = pyo.Constraint(m.T, m.ST, rule=PV_W30_Balance)

def PV_S90_Balance(m,t, st):
    return m.y_pv_S90[t] == m.x['PV_S90']*m.Y_pv_S90[t]
m.PV_S90_Balance = pyo.Constraint(m.T, m.ST, rule=PV_S90_Balance)

def PV_E90_Balance(m,t, st):
    return m.y_pv_E90[t] == m.x['PV_E90']*m.Y_pv_E90[t]
m.PV_E90_Balance = pyo.Constraint(m.T, m.ST, rule=PV_E90_Balance)

def PV_W90_Balance(m,t, st):
    return m.y_pv_W90[t] == m.x['PV_W90']*m.Y_pv_W90[t]
m.PV_W90_Balance = pyo.Constraint(m.T, m.ST, rule=PV_W90_Balance)

def A2A_SH_Balance(m,t, st):
    return m.q_a2a_sh[t] == m.y_a2a_sh[t]*m.COP_a2a[t]
m.A2A_SH_Balance = pyo.Constraint(m.T, m.ST, rule = A2A_SH_Balance)

def PO_SH_Balance(m,t, st):
    return m.q_po_sh[t] == m.y_po_sh[t]*m.Eff['PO_SH']
m.PO_SH_Balance = pyo.Constraint(m.T, m.ST, rule = PO_SH_Balance)

def FP_SH_Balance(m,t, st):
```

```
    return m.q_fp_sh[t] == m.f_fp[t]*m.Eff['FP_SH']*m.A_i['FP_SH']
m.FP_SH_Balance = pyo.Constraint(m.T, m.ST, rule = FP_SH_Balance)

def EB_DHW_Balance(m,t, st):
    return m.q_eb_dhw[t] == m.y_eb_dhw[t]*m.Eff['EB_DHW']
m.EB_DHW_Balance = pyo.Constraint(m.T, m.ST, rule = EB_DHW_Balance)

#---Zero emission/energy constraints
def ZE_Balance(m):
    if m.A_co2==1:
        print('ACTIVE ZEB-carbon RESTRICTION')
        if m.lastT == 8735:
            return sum(m.y_imp[t]*m.G_el_imp + m.f_fp[t]*m.G_wo for t in
                m.T) <= sum(m.y_exp[t]*m.G_el for t in m.T)
        if m.lastT == 4367:
            return 2*sum(m.y_imp[t]*m.G_el - m.y_exp[t]*m.G_el +
                m.bf[t]*m.G_bf for t in m.T) <= m.G_ref*m.gamma
        elif m.lastT == 727:
            return 12*sum(m.y_imp[t]*m.G_el - m.y_exp[t]*m.G_el +
                m.bf[t]*m.G_bf for t in m.T) <= m.G_ref*m.gamma
        elif m.lastT == 671:
            return sum(m.y_imp[t]*m.G_el_imp + m.f_fp[t]*m.G_wo for t in
                m.T) <= sum(m.y_exp[t]*m.G_el for t in m.T)
        elif m.lastT == 287:
            return (8736/288)*sum(m.y_imp[t]*m.G_el - m.y_exp[t]*m.G_el +
                m.bf[t]*m.G_bf for t in m.T) <= m.G_ref*m.gamma
        elif m.lastT == 95:
            return sum(m.y_imp[t]*m.G_el - m.y_exp[t]*m.G_el +
                m.bf_sh[t]*m.G_bf + m.bf_dhw[t]*m.G_bf for t in m.T) <=
                sum(m.y_exp[t]*m.G_el for t in m.T)
        elif m.lastT == 23:
            return (8736/24)*sum(m.y_imp[t]*m.G_el - m.y_exp[t]*m.G_el +
                m.bf[t]*m.G_bf for t in m.T) <= m.G_ref*m.gamma
    elif m.A_pe == 1:
        print('ACTIVE ZEB-pef RESTRICTION')
        if m.lastT == 8735:
            return sum(m.y_imp[t]*m.PE_imp - m.y_exp[t]*m.PE_exp +
                m.bf[t]*m.PE_bf for t in m.T) <= m.PE_ref*m.gamma
        elif m.lastT == 671:
            return 13*sum(m.y_imp[t]*m.PE_imp - m.y_exp[t]*m.PE_exp +
                m.bf[t]*m.PE_bf for t in m.T) <= m.PE_ref*m.gamma
    else:
```

```
            print('NO ZEB RESTRICTION')
            return pyo.Constraint.Skip
    m.ZE_Balance = pyo.Constraint(rule=ZE_Balance)

#Subscription power pricing Constraint
    def pty_volume(m, t): #counting all power within one hour exceeding max
        limit
        if m.A_ps == 1:
            return m.y_imp[t] - m.Y_max <= m.y_pty[t]
        else:
            return m.y_pty[t] == 0
    m.pty_volume = pyo.Constraint(m.T, rule = pty_volume)

    def pty_volume2(m, t):
            return 0 <= m.y_pty[t]
    m.pty_volume2 = pyo.Constraint(m.T, rule = pty_volume2)

# Peak power restriction
    def peak_power(m, t):
        H = createHvector()
        for key in H.keys():
            if t <= H[key]:
                month = key
                break
        if t <= H[month]:
            return m.y_max_imp[month] >= m.y_imp[t]
        else:
            return pyo.Constraint.Skip
    m.peak_power = pyo.Constraint(m.T, rule = peak_power)

#   OBJECTIVE FUNCTION ##################################################

    def cost_Investments_rule(m, st):
        expr = self.npv_cost_Investments(m, st)
        return expr
    m.cost_Investments = pyo.Expression(m.ST, rule = cost_Investments_rule)

    def cost_Operation_rule(m, st):
        expr = self.npv_cost_Operations(m, st)
        return expr
    m.cost_Operations= pyo.Expression(m.ST, rule = cost_Operation_rule)
```

```
    def objective_TotalCost(m):
        expr = pyo.summation(m.cost_Investments) +
            pyo.summation(m.cost_Operations)
        return expr
    m.objective_TotalCosts = pyo.Objective(rule = objective_TotalCost, sense
        = pyo.minimize)

    return m

def createConcreteModeltwoStage(self, data):
        '''Function creating instance from input data'''
        concretemodel = self.abstractmodel.create_instance(data = {
            'mymodel':data}, namespace = 'mymodel')
        return concretemodel
```

B Waterborne Model

```
import pyomo.environ as pyo

#function that creates a dict, which maps each month (0-11) to a unique set of hours belonging to it
def createMonthSet():
    start = 0
    months = dict()
    for i in range(1,13):
        if i in (1,3,5,7,8,10):
            hours_in_month = list(range(start, start + 31•24)) # list of hours to be placed into dict if 31 days in month
        elif i in (4,6,9,11,12): # NB! removing last day of december to get exactly 52 weeks
            hours_in_month = list(range(start, start + 30•24)) # list of hours to be placed into dict if 30 days in month
        else:
            hours_in_month = list(range(start, start + 28•24)) # else february, disregard leap year
        months[i] = hours_in_month
        start += len(months[i])
    return months

def createHvector():
    start = 0
    months = dict()
    for i in range(1,13):
        if i in (1,3,5,7,8,10):
            hours_in_month = start + 31•24 # list of hours to be placed into dict if 31 days in month
            prev = 31•24
        elif i in (4,6,9,11,12): # NB! removing last day of december to get exactly 52 weeks
            hours_in_month = start + 30•24 # list of hours to be placed into dict if 30 days in month
            prev = 30•24
        else:
            hours_in_month = start + 28•24 # else february, disregard leap year
            prev = 28•24
        months[i] = hours_in_month
```

```
        start += prev
    return months

class ZEBModel():

    def __init__(self, M_const = 10000):
        """Create Abstract Pyomo model for ZEB """
        # Determenistic two-stage model
        self.abstractmodel = self.createTWOSTAGEMODEL()

        self.M_const = M_const

    def disco(self, n, r):
        '''Discounting factor'''
        return 1/((1+r)**n)

    def annui(self, n, r):
        '''Annuity factor'''
        return r/(1-(1+r)**(-n))

    def capit(self, n, r): # Capitalization factor
        '''Capitalization factor'''
        return (1-(1+r)**(-n))/r

    def cost(self, Yn, cost, l, r):
        '''For the two-stage model: calculating forced reinvestment costs'''
        Kn = pyo.floor(Yn/(l*1))
        n = Yn-l*Kn
        Tn = Yn-n
        return cost*(self.annui(l,r)*self.capit(n,r)*self.disco(Tn, r) \
               + sum(self.disco(k*l,r) for k in range(0,Kn)))

    def npv_cost_Investments(self, m, st):
        investments = 0
        if st==1:
            for i in m.I:
                investments += (m.C_spe[i]*m.x[i]+ m.C_fxd[i]*m.a_i[i])
        else:
            investments = 0
        return investments

    def npv_cost_Operations(self, m, st):
```

```
'''Operational costs for two-stage/deterministic
Summation of yearly costs for all years in YRN'''
techrun = 0
runcosts = 0
gridtariff = 0
operations = 0
if m.lastT == 4367:
    f = 2
elif m.lastT == 23:
    f = 8736/24
elif m.lastT == 95:
    f = 8736/96
elif m.lastT == 287:
    f = 8736/288
elif m.lastT == 671:
    '''multiplicationfactor will be 13 if reduced model'''
    f = 13
elif m.lastT == 727:
    f = 12
elif m.lastT == 8735:
    f = 1

if st == 2:
    for i in m.I:
        techrun += m.C_run[i]*m.C_spe_0[i]*m.x[i]
    if m.A_ps + m.A_ep + m.A_pp > 1 or m.A_ps + m.A_ep + m.A_pp < 1:
        raise ValueError("Please select ONE AND ONLY ONE grid tariff
            type.")
    if m.A_ep: #Grid tariff model: Energy pricing
        ''' inkluderer enova-avgift samt moms'''
        gridtariff = 12*m.C_fxd_ep + m.C_spe_ep*sum(f*m.y_imp[t] for t in
            m.T)
        VAT = 1.25
        runcosts = sum(VAT*m.y_imp[t]*m.P_spot[t] + (m.bf_sh[t] +
            m.bf_dhw[t])*m.C_bf - m.y_exp[t]*m.P_spot[t]*m.A_exp for t in
            m.T)
    elif m.A_ps == 1: #Grid tariff model: Power subscription
        gridtariff = 1.25*(12*(m.C_fxd_ps+(5.69*m.Y_max)) +
            m.C_pty_ps*sum(f*m.y_pty[t] for t in m.T) +
            m.C_spe_ps*sum(f*m.y_imp[t] for t in m.T))
        VAT = 1.25
        runcosts = sum(VAT*m.y_imp[t]*m.P_spot[t] + (m.bf_sh[t] +
```

```
            m.bf_dhw[t])•m.C_bf - m.y_exp[t]•m.P_spot[t]•m.A_exp for t in
            m.T)
        elif m.A_pp == 1: # Grid tariff model: Peak power charge
            month_set = createMonthSet()
            gridtariff = 0
            for month in m.M:
                if month in (0,1,11):
                    gridtariff += (m.C_fxd_pp + m.C_spe_pp_w1•sum(f•m.y_imp[t]
                        for t in month_set[month]) +
                        m.C_pty_pp_w1•m.y_max_imp[month])
                elif month in (2,10):
                    gridtariff += (m.C_fxd_pp + m.C_spe_pp_w2•sum(f•m.y_imp[t]
                        for t in month_set[month]) +
                        m.C_pty_pp_w2•m.y_max_imp[month])
                else:
                    gridtariff += (m.C_fxd_pp + m.C_spe_pp_s•sum(f•m.y_imp[t]
                        for t in month_set[month]) +
                        m.C_pty_pp_s•m.y_max_imp[month])
            VAT = 1.25
            runcosts = sum(m.y_imp[t]•m.P_spot[t] + (m.bf_sh[t] +
                m.bf_dhw[t])•m.C_bf/VAT - m.y_exp[t]•m.P_spot[t]•m.A_exp for t
                in m.T)
        operations = (f•runcosts + gridtariff + techrun)•self.capit(m.YRN,
            m.R)•self.disco(1, m.R)
    else:
        operations = 0
    return operations

def createTWOSTAGEMODEL(self):
    m = pyo.AbstractModel()
    m.name = 'ZEB stochastic two-stage model'

# SETS ##########################################################
    m.T  = pyo.Set(doc = 'Set of all hours, full model: 8736, reduced model:
        672')
    m.M = pyo.Set(doc = 'Set of all months')
    m.I = pyo.Set(doc = 'Set of all technologies')
    m.ST = pyo.Set(initialize = [1, 2], doc='STAGE')

# PARAMETERS ####################################################

    m.lastT = pyo.Param(within=m.T, doc="Last time step")
```

```
    m.Area = pyo.Param(within=pyo.NonNegativeReals, doc="Building floor area")

#---Technology costs
    m.C_fxd_0 = pyo.Param(m.I,within=pyo.NonNegativeReals, default = 0,
        doc='Fixed investment cost for all techs, EUR in year t = 0')
    m.C_spe_0 = pyo.Param(m.I,within=pyo.NonNegativeReals, default =
        0,doc='Investment costs dependent on installed capacity, EUR/kW
        (EUR/kWh) in t= 0')
    m.C_run = pyo.Param(m.I,within=pyo.NonNegativeReals,default =
        0,doc='Yearly running cost of each tech, given from investment costs
        EUR/kW installed')

#---Grid Tariff pricing
    #Energy pricing
    m.A_ep = pyo.Param(within=pyo.Binary,default = 0,doc = 'Activation of
        energy pricing')
    m.C_fxd_ep = pyo.Param(within=pyo.NonNegativeReals,default = 0,doc='Fixed
        charge part of grid tariff for ep')
    m.C_spe_ep = pyo.Param(within=pyo.NonNegativeReals,default =
        0,doc='Specific energy charge part of grid tariff for ep')

    #Power Subscription pricing
    m.A_ps = pyo.Param(within = pyo.Binary, default = 0,doc = 'Activation of
        power subscription pricing')
    m.C_fxd_ps = pyo.Param(within=pyo.NonNegativeReals,default = 0,
        doc='Subscriptopn charge for pp')
    m.C_pty_ps = pyo.Param(within=pyo.NonNegativeReals,default =
        0,doc='Penalty charge for pp')
    m.C_spe_ps = pyo.Param(within=pyo.NonNegativeReals,default =
        0,doc='Energy charge charge for pp')
    m.Y_max = pyo.Param(within=pyo.NonNegativeReals,default = 0,doc =
        'Subscription limit')

    #Peak Power Pricing
    m.A_pp = pyo.Param(within=pyo.Binary)
    m.C_fxd_pp = pyo.Param(within=pyo.NonNegativeReals)
    m.C_spe_pp_w1 = pyo.Param(within=pyo.NonNegativeReals)
    m.C_spe_pp_w2 = pyo.Param(within=pyo.NonNegativeReals)
    m.C_spe_pp_s = pyo.Param(within=pyo.NonNegativeReals)
    m.C_pty_pp_w1 = pyo.Param(within=pyo.NonNegativeReals)
    m.C_pty_pp_w2 = pyo.Param(within=pyo.NonNegativeReals)
    m.C_pty_pp_s = pyo.Param(within=pyo.NonNegativeReals)
```

```
#---#Reference System

    #CO2-Factors
    m.A_co2 = pyo.Param(within=pyo.Binary,doc = 'Activation of co2 crediting
        system')
    m.G_ref = pyo.Param(within=pyo.NonNegativeReals,doc='CO2 reference
        emissions')
    m.G_el = pyo.Param(within=pyo.NonNegativeReals,doc='gCO2 eq. per kWh
        imported/exported')
    m.G_bf = pyo.Param(within=pyo.NonNegativeReals,doc='gCO2 eq. per kWh for
        technology i, i.e BB')

    #Primary Energy Factors
    m.A_pe = pyo.Param(within=pyo.Binary,doc = 'Activation of primary energy
        crediting system')
    m.PE_ref = pyo.Param(within=pyo.NonNegativeReals,doc='CO2 reference
        emissions')
    m.PE_imp = pyo.Param(within=pyo.NonNegativeReals,doc='PE per kWh imported
        electricity')
    m.PE_exp = pyo.Param(within=pyo.NonNegativeReals,doc='PE per kWh exported
        electricity')
    m.PE_bf = pyo.Param(within=pyo.NonNegativeReals,doc='PE per kWh for
        technology i, i.e BB')

#---Technologies
    m.A_i = pyo.Param(m.I, within=pyo.Binary,doc='Pre-activation of each
        tech')

    m.Eff = pyo.Param(m.I,within=pyo.NonNegativeReals, doc='Technology
        efficiency')
    m.Eff_ba_ch = pyo.Param(within=pyo.NonNegativeReals,doc='Battery charging
        efficiency')
    m.Eff_ba_dch = pyo.Param(initialize = 1, doc='Battery discharge
        efficiency')
    m.Beta_ba =
        pyo.Param(within=pyo.NonNegativeReals,doc='Charging/discharging rate')
    m.Beta_hs = pyo.Param(within=pyo.NonNegativeReals, doc='identical
        charging rate for heat storage')

    m.L = pyo.Param(m.I, within=pyo.NonNegativeIntegers, doc='Lifetime of
        technology i')
```

```
m.X_min = pyo.Param(m.I, within=pyo.NonNegativeReals, doc='Max possible
    installed capacity of technology ')
m.X_max = pyo.Param(m.I, within=pyo.NonNegativeReals, doc='Min possible
    installed capacity of technology ')

m.Temp = pyo.Param(m.T, within=pyo.Reals, doc='Ambient temperature of
    certain hour')
m.Y_pv_f10 = pyo.Param(m.T, within=pyo.NonNegativeReals,doc='Possible PV
    output at time t')
m.Y_pv_S20 = pyo.Param(m.T, within=pyo.NonNegativeReals,doc='Possible PV
    output at time t')
m.Y_pv_S30 = pyo.Param(m.T, within=pyo.NonNegativeReals,doc='Possible PV
    output at time t')
m.Y_pv_E20 = pyo.Param(m.T, within=pyo.NonNegativeReals,doc='Possible PV
    output at time t')
m.Y_pv_E30 = pyo.Param(m.T, within=pyo.NonNegativeReals,doc='Possible PV
    output at time t')
m.Y_pv_W20 = pyo.Param(m.T, within=pyo.NonNegativeReals,doc='Possible PV
    output at time t')
m.Y_pv_W30 = pyo.Param(m.T, within=pyo.NonNegativeReals,doc='Possible PV
    output at time t')
m.Y_pv_S90 = pyo.Param(m.T, within=pyo.NonNegativeReals,doc='Possible PV
    output at time t')
m.Y_pv_E90 = pyo.Param(m.T, within=pyo.NonNegativeReals,doc='Possible PV
    output at time t')
m.Y_pv_W90 = pyo.Param(m.T, within=pyo.NonNegativeReals,doc='Possible PV
    output at time t')
m.COP_ashp_dhw = pyo.Param(m.T, within=pyo.NonNegativeReals, doc='Heat
    pump performance at time t w/r DHW')
m.COP_gshp_dhw = pyo.Param(m.T, within=pyo.NonNegativeReals, doc='Heat
    pump performance at time t w/r DHW')
m.COP_ashp_sh = pyo.Param(m.T, within=pyo.NonNegativeReals, doc='Heat
    pump performance at time t w/r SH')
m.COP_gshp_sh = pyo.Param(m.T, within=pyo.NonNegativeReals, doc='Heat
    pump performance at time t w/r SH')

#BITES-params
m.SS_cap = pyo.Param(within=pyo.NonNegativeReals, doc='Shallow storage
    capacity of house, fully determined by area, thus a parameter instead
    of a variable')
m.DS_cap = pyo.Param(within=pyo.NonNegativeReals, doc='Deep storage
    capacity of house, ---=---')
```

```
    m.K_shallow = pyo.Param(doc='loss factor for BITES, shallow part')
    m.K_deep = pyo.Param(doc='loss factor for BITES, deep part')
    m.K_flow = pyo.Param(doc='flow factor for BITES, cross-node flow')

#---Energy Demand
    m.D_el = pyo.Param(m.T, within=pyo.NonNegativeReals, doc='Hourly building
        electricity demand')
    m.D_sh = pyo.Param(m.T, within=pyo.NonNegativeReals, doc='Hourly building
        space heating demand')
    m.D_dhw = pyo.Param(m.T, within=pyo.NonNegativeReals, doc='Hourly
        building domestic hot water demand')

#---Grid
    m.P_spot = pyo.Param(m.T, within=pyo.NonNegativeReals, doc='Hourly price
        of imported electricity EUR/kWh including certificates')
    m.X_max_imp = pyo.Param(within=pyo.NonNegativeReals, doc='Maximum grid
        import')
    m.X_max_exp = pyo.Param( within=pyo.NonNegativeReals,doc='Maximum grid
        export')
    m.A_imp = pyo.Param( within=pyo.Binary, doc='Binary: Import is activated,
        1/0')
    m.A_exp = pyo.Param( within=pyo.Binary,doc='Binary: Export is activated,
        1/0')
    m.C_bf = pyo.Param(within=pyo.NonNegativeReals, doc='Constant price of
        biofuel')

#---Control
    m.gamma = pyo.Param( within=pyo.NonNegativeReals, doc='=0 for strictly
        ZEB')
    m.R = pyo.Param(within=pyo.NonNegativeReals, doc='Chosen discount Rate')
    m.YRN = pyo.Param( within=pyo.NonNegativeIntegers, doc='Total years in
        modelling period')

    def npv_inv_spe(m, i):
        return self.cost(m.YRN, m.C_spe_0[i], m.L[i], m.R)
    m.C_spe = pyo.Param(m.I, rule = npv_inv_spe)

    def npv_inv_fxd(m, i):
        return self.cost(m.YRN, m.C_fxd_0[i], m.L[i], m.R)
    m.C_fxd = pyo.Param(m.I, rule = npv_inv_fxd)

#VARIABLES ##########################################################
```

```
# 1 STAGE : STRATEGIC VARIABLES
m.x = pyo.Var(m.I,within = pyo.NonNegativeReals,
    doc='Optimal installed capacity (storage size), semi-continous, kW
    (kWh)')
m.a_i = pyo.Var(m.I, within = pyo.Binary,
    doc='Activation binary decision for technology i, 1/0')


#2 STAGE : OPERATIONAL VARIABLES
m.q_hs = pyo.Var(m.T, domain = pyo.Reals,
    doc='Keeping track of HS discharge')
m.q_eb_sh = pyo.Var(m.T,domain = pyo.NonNegativeReals,
    doc='Net heat supplied from (SH) electric boiler at time t, kWh/h')
m.q_eb_dhw = pyo.Var(m.T,domain = pyo.NonNegativeReals,
    doc='Net heat supplied from (DHW) electric boiler at time t, kWh/h')
m.q_bb_sh = pyo.Var(m.T,domain = pyo.NonNegativeReals,
    doc='Net heat supplied from (SH) bio boiler at time t, kWh/h')
m.q_bb_dhw = pyo.Var(m.T,domain = pyo.NonNegativeReals,
    doc='Net heat supplied from (DHW) bio boiler at time t, kWh/h')
m.bf_sh = pyo.Var(m.T, domain= pyo.NonNegativeReals,
    doc='Biofuel input to bio boiler at time t for SH kWh/h')
m.bf_dhw = pyo.Var(m.T, domain= pyo.NonNegativeReals,
    doc='Biofuel input to bio boiler at time t for DHW kWh/h')
m.q_ashp_sh = pyo.Var(m.T,domain=pyo.NonNegativeReals,
    doc='Net heat supplied from air source heat pump (SH) at time t,
    kWh/h')
m.q_gshp_sh = pyo.Var(m.T,domain=pyo.NonNegativeReals,
    doc='Net heat supplied from ground source heat pump (SH) at time t,
    kWh/h')
m.q_ashp_dhw = pyo.Var(m.T,domain=pyo.NonNegativeReals,
    doc='Net heat supplied from air source heat pump (DHW) at time t,
    kWh/h')
m.q_gshp_dhw = pyo.Var(m.T,domain=pyo.NonNegativeReals,
    doc='Net heat supplied from ground source heat pump (DHW) at time t,
    kWh/h')
m.q_ashp_eff = pyo.Var(m.T,domain=pyo.NonNegativeReals,
    doc='Net effective heat supplied from air source heat pump at time t,
    adjusted for source temperature, kWh/h')
m.q_ashp = pyo.Var(m.T,domain=pyo.NonNegativeReals,              doc='Net
    effective heat supplied from air source heat pump at time t, kWh/h')
```

```
m.z_hs = pyo.Var(m.T, domain = pyo.NonNegativeReals,
    doc='Content in heat storage (HS) at the end of time t, kWh')
m.z_hwt = pyo.Var(m.T, domain = pyo.NonNegativeReals,
    doc='Content in hot water tank (HWT) at the end of time t, kWh')
m.z_ss = pyo.Var(m.T, domain = pyo.NonNegativeReals,
    doc='Content in shallow BITES at the end of time t, kWh')
m.z_ds = pyo.Var(m.T, domain = pyo.NonNegativeReals,
    doc='Content in deep BITES at the end of time t, kWh')
m.z_ba = pyo.Var(m.T, domain = pyo.NonNegativeReals,
    doc='Content of battery at the end of time t, kWh')
m.Flow = pyo.Var(m.T, domain = pyo.Reals,
    doc='Cross-node flow of two-node BITES model at time t, kWh')

#charging variables for BITES, shallow part
m.q_ss = pyo.Var(m.T, domain = pyo.Reals,             doc='Energy
    released from shallow BITES at the end of time t, kWh')
m.q_hwt = pyo.Var(m.T, domain = pyo.Reals,             doc='Energy
    released from HWT at the end of time t, kWh')

m.y_imp = pyo.Var(m.T, domain = pyo.NonNegativeReals,
    doc='Electricity imported from grid at time t, kWh')
m.y_exp = pyo.Var(m.T, domain = pyo.NonNegativeReals,
    doc='Electricity exported to grid at time t, kWh')
m.y_pv_f10 = pyo.Var(m.T, domain = pyo.NonNegativeReals,
    doc='PV production at time t, kWh/h')
m.y_pv_S20 = pyo.Var(m.T, domain = pyo.NonNegativeReals,
    doc='PV production at time t, kWh/h')
m.y_pv_S30 = pyo.Var(m.T, domain = pyo.NonNegativeReals,
    doc='PV production at time t, kWh/h')
m.y_pv_E20 = pyo.Var(m.T, domain = pyo.NonNegativeReals,
    doc='PV production at time t, kWh/h')
m.y_pv_E30 = pyo.Var(m.T, domain = pyo.NonNegativeReals,
    doc='PV production at time t, kWh/h')
m.y_pv_W20 = pyo.Var(m.T, domain = pyo.NonNegativeReals,
    doc='PV production at time t, kWh/h')
m.y_pv_W30 = pyo.Var(m.T, domain = pyo.NonNegativeReals,
    doc='PV production at time t, kWh/h')
m.y_pv_S90 = pyo.Var(m.T, domain = pyo.NonNegativeReals,
    doc='PV production at time t, kWh/h')
m.y_pv_E90 = pyo.Var(m.T, domain = pyo.NonNegativeReals,
    doc='PV production at time t, kWh/h')
m.y_pv_W90 = pyo.Var(m.T, domain = pyo.NonNegativeReals,
```

```
        doc='PV production at time t, kWh/h')
    m.y_eb_sh = pyo.Var(m.T, domain = pyo.NonNegativeReals,
        doc='Electricity drawn from (SH) electric boiler at time t, kWh/h')
    m.y_eb_dhw = pyo.Var(m.T, domain = pyo.NonNegativeReals,
        doc='Electricity drawn from (DHW) electric boiler at time t, kWh/h')
    m.y_ashp_sh = pyo.Var(m.T, domain = pyo.NonNegativeReals,
        doc='Total electricity consumed by the AS heat pump (SH) at time t,
        kWh/h')
    m.y_gshp_sh = pyo.Var(m.T, domain = pyo.NonNegativeReals,
        doc='Total electricity consumed by the GS heat pump (SH) at time t,
        kWh/h')
    m.y_ashp_dhw = pyo.Var(m.T, domain = pyo.NonNegativeReals,
        doc='Total electricity consumed by the AS heat pump (DHW) at time t,
        kWh/h')
    m.y_gshp_dhw = pyo.Var(m.T, domain = pyo.NonNegativeReals,
        doc='Total electricity consumed by the GS heat pump (DHW) at time t,
        kWh/h')
    m.y_ch = pyo.Var(m.T, domain = pyo.NonNegativeReals,
        doc='Amount of electricity to battery (charging) at time t, kWh/h')
    m.y_dch = pyo.Var(m.T, domain = pyo.NonNegativeReals,
        doc='Amount of electricity discharge from battery at time t, kWh/h')
    m.y_pty = pyo.Var(m.T, domain = pyo.Reals,                      doc =
        'Penalty volume')
    m.y_max_imp = pyo.Var(m.T, domain = pyo.Reals,                  doc =
        'Max import of every month, stored in list-like container (one value
        for each month)')

    m.y_max = pyo.Var(m.M, domain = pyo.NonNegativeReals,           doc='max
        power for every month')

    m.a_ch = pyo.Var(m.T, domain = pyo.Binary,                      doc
        ='Charging activation inward time t, 1 = activated')
    m.a_dch = pyo.Var(m.T, domain= pyo.Binary,                      doc
        ='Discharging activation inward time t, 1=activated')

# CONSTRAINTS ##########################################################

# 1 STAGE : INVESTMENTS

    #---Activation and boundary constraints
    def Tech_active(m, i, st):
        return m.x[i] <= m.a_i[i]*self.M_const
```

```
    m.Tech_active = pyo.Constraint(m.I, m.ST, rule = Tech_active)

    def Tech_Min(m, i, st):
        return m.X_min[i]*m.a_i[i] <= m.x[i]
    m.Tech_Min = pyo.Constraint(m.I, m.ST, rule= Tech_Min)

    def Tech_Max(m, i, st):
        return m.x[i] <= m.X_max[i]*m.A_i[i]
    m.Tech_Max = pyo.Constraint(m.I, m.ST, rule= Tech_Max)

#2 STAGE : OPERATIONS

    #---Balacing constraints

    def El_Balance(m, t, st):
        return m.D_el[t] == m.y_imp[t] + m.y_pv_f10[t] + m.y_pv_S20[t] +
            m.y_pv_S30[t] + m.y_pv_E20[t] + m.y_pv_E30[t] + m.y_pv_W20[t] +
            m.y_pv_W30[t] + m.y_pv_S90[t] + m.y_pv_E90[t] + m.y_pv_W90[t]-
            m.y_exp[t] + m.y_dch[t] - m.y_ch[t] - m.y_ashp_sh[t] -
            m.y_gshp_sh[t] - m.y_ashp_dhw[t] - m.y_gshp_dhw[t] - m.y_eb_sh[t]
            - m.y_eb_dhw[t]
    m.El_Balance = pyo.Constraint(m.T, m.ST, rule = El_Balance)

    def SH_balance(m, t, st):
        if t == 0:
            return m.D_sh[t] + m.z_hs[t] == m.z_hs[m.lastT]*m.Eff['HS'] +
                m.q_ss[t] + m.q_ashp_sh[t] + m.q_gshp_sh[t] + m.q_eb_sh[t] +
                m.q_bb_sh[t]
        else:
            return m.D_sh[t] + m.z_hs[t] == m.z_hs[t-1]*m.Eff['HS'] +
                m.q_ss[t] + m.q_ashp_sh[t] + m.q_gshp_sh[t] + m.q_eb_sh[t] +
                m.q_bb_sh[t]
    m.SH_balance = pyo.Constraint(m.T, m.ST, rule = SH_balance)

    def DHW_balance(m, t, st):
        if t == 0:
            return m.D_dhw[t] + m.z_hwt[t] == m.z_hwt[m.lastT]*m.Eff['HWT'] +
                m.q_ashp_dhw[t] + m.q_gshp_dhw[t] + m.q_eb_dhw[t] +
                m.q_bb_dhw[t]
        else:
            return m.D_dhw[t] + m.z_hwt[t] == m.z_hwt[t-1]*m.Eff['HWT'] +
                m.q_ashp_dhw[t] + m.q_gshp_dhw[t] + m.q_eb_dhw[t] +
```

```
          m.q_bb_dhw[t]
m.DHW_balance = pyo.Constraint(m.T, m.ST, rule = DHW_balance)

#---Capacity

def ASHP_Restriction(m,t, st):
    return m.q_ashp_sh[t] + m.q_ashp_dhw[t] <= m.x['ASHP']
m.ASHP_Restriction = pyo.Constraint(m.T, m.ST, rule = ASHP_Restriction)

def GSHP_Restriction(m,t, st):
    return m.q_gshp_sh[t] + m.q_gshp_dhw[t] <= m.x['GSHP']
m.GSHP_Restriction = pyo.Constraint(m.T, m.ST, rule = GSHP_Restriction)

def EB_Restriction(m,t, st):
    return m.q_eb_sh[t] + m.q_eb_dhw[t] <= m.x['EB']
m.EB_Restriction = pyo.Constraint(m.T, m.ST, rule = EB_Restriction)

def BB_Restriction(m,t, st):
    return m.q_bb_sh[t] + m.q_bb_dhw[t] <= m.x['BB']
m.BB_Restriction = pyo.Constraint(m.T, m.ST, rule = BB_Restriction)

#---Grid equations

def Grid_Import(m,t, st):
    return m.y_imp[t] <= m.X_max_imp
m.Grid_Import = pyo.Constraint(m.T, m.ST, rule=Grid_Import)

def Grid_Export(m,t, st):
    return m.y_exp[t] <= m.X_max_exp
m.Grid_Export = pyo.Constraint(m.T, m.ST, rule=Grid_Export)

#---Storage equations

def HS_Restriction(m, t, st):
    return m.z_hs[t] <= m.x['HS']
m.HS_Restriction = pyo.Constraint(m.T, m.ST, rule=HS_Restriction)

def HWT_Restriction(m, t, st):
    return m.z_hwt[t] <= m.x['HWT']
m.HWT_Restriction = pyo.Constraint(m.T, m.ST, rule=HWT_Restriction)

def SS_Restriction(m, t, st):
```

```
    return m.z_ss[t] <= m.x['SS']•m.A_i['SS']
m.SS_Restriction = pyo.Constraint(m.T, m.ST, rule=SS_Restriction)

def DS_Restriction(m, t, st):
    return m.z_ds[t] <= m.x['DS']•m.A_i['DS']
m.DS_Restriction = pyo.Constraint(m.T, m.ST, rule=DS_Restriction)

def SS_charge_active(m,t, st):
    return m.q_ss[t] <= m.z_ss[t]
m.SS_charge_active = pyo.Constraint(m.T, m.ST, rule=SS_charge_active)

def SS_discharge_active(m,t, st):
    return - m.z_ss[t] <= m.q_ss[t]
m.SS_discharge_active = pyo.Constraint(m.T, m.ST,
    rule=SS_discharge_active)

def HS_charge_active(m,t, st):
    return m.q_hs[t] <= m.z_hs[t]
m.HS_charge_active = pyo.Constraint(m.T, m.ST, rule=HS_charge_active)

def HS_discharge_active(m,t, st):
    return - m.z_hs[t] <= m.q_hs[t]
m.HS_discharge_active = pyo.Constraint(m.T, m.ST,
    rule=HS_discharge_active)

def HWT_charge_active(m,t, st):
    return m.q_hwt[t] <= m.z_hwt[t]
m.HWT_charge_active = pyo.Constraint(m.T, m.ST, rule=HWT_charge_active)

def HWT_discharge_active(m,t, st):
    return - m.z_hwt[t] <= m.q_hwt[t]
m.HWT_discharge_active = pyo.Constraint(m.T, m.ST,
    rule=HWT_discharge_active)

def HS_Balance_ch(m,t,st):
    if t == 0:
        return m.q_hs[t] == m.z_hs[m.lastT] - m.z_hs[t]
    else:
        return m.q_hs[t] == m.z_hs[t-1] - m.z_hs[t]
m.HS_Balance_ch = pyo.Constraint(m.T, m.ST, rule = HS_Balance_ch)

def HWT_Balance_ch(m,t,st):
```

```
    if t == 0:
        return m.q_hwt[t] == m.z_hwt[m.lastT] - m.z_hwt[t]
    else:
        return m.q_hwt[t] == m.z_hwt[t-1] - m.z_hwt[t]
m.HWT_Balance_ch = pyo.Constraint(m.T, m.ST, rule = HWT_Balance_ch)

def Flow_Constraint(m,t,st):
    return m.Flow[t] == m.K_flow*((m.z_ss[t]/m.SS_cap) -
        (m.z_ds[t]/m.DS_cap))
m.Flow_Constraint = pyo.Constraint(m.T, m.ST, rule = Flow_Constraint)

def SS_balance_ch(m, t, st):
    if t == 0:
        return m.q_ss[t] == m.z_ss[m.lastT] - m.z_ss[t] - m.Flow[t] -
            m.z_ss[t]*(1 - m.K_shallow)
    else:
        return m.q_ss[t] == m.z_ss[t-1] - m.z_ss[t] - m.Flow[t] -
            m.z_ss[t]*(1 - m.K_shallow)
m.SS_balance_ch = pyo.Constraint(m.T, m.ST, rule = SS_balance_ch)

def DS_balance_ch(m, t, st):
    if t == 0:
        return m.z_ds[t] == m.z_ds[m.lastT] + m.Flow[t] - m.z_ds[t]*(1 -
            m.K_deep)
    else:
        return m.z_ds[t] == m.z_ds[t-1] + m.Flow[t] - m.z_ds[t]*(1 -
            m.K_deep)
m.DS_balance_ch = pyo.Constraint(m.T, m.ST, rule = DS_balance_ch)

def HS_discharge_rate_min(m,t, st):
      return -m.x['HS']*m.Beta_hs <= m.q_hs[t]
m.HS_discharge_rate_min = pyo.Constraint(m.T, m.ST,
    rule=HS_discharge_rate_min)

def HS_discharge_rate_max(m,t, s):
    return m.q_hs[t] <= m.x['HS']*m.Beta_hs
m.HS_discharge_rate_max = pyo.Constraint(m.T, m.ST,
    rule=HS_discharge_rate_max)

def HWT_discharge_rate_min(m,t, st):
      return -m.x['HWT']*m.Beta_hs <= m.q_hwt[t]
m.HWT_discharge_rate_min = pyo.Constraint(m.T, m.ST,
```

```
    rule=HWT_discharge_rate_min)

def HWT_discharge_rate_max(m,t, s):
    return m.q_hwt[t] <= m.x['HWT']*m.Beta_hs
m.HWT_discharge_rate_max = pyo.Constraint(m.T, m.ST,
    rule=HWT_discharge_rate_max)

def BA_Restriction(m,t, st):
    return m.z_ba[t] <= m.x['BA']
m.BA_restriction = pyo.Constraint(m.T, m.ST, rule=BA_Restriction)

def BA_Balance(m,t, st):
    if t == 0:
        return m.z_ba[t] == m.z_ba[m.lastT] - m.y_dch[t]*(1/m.Eff_ba_dch)
            + m.y_ch[t]*m.Eff_ba_ch
    else:
        return m.z_ba[t] == m.z_ba[t-1] - m.y_dch[t]*(1/m.Eff_ba_dch) +
            m.y_ch[t]*m.Eff_ba_ch
m.BA_Balance = pyo.Constraint(m.T, m.ST, rule=BA_Balance)

def BA_Charge_Balance(m, t, st):
    if t == 0:
        return m.y_ch[t] <= (m.x['BA'] -
            m.z_ba[m.lastT])*m.A_i['BA']*(1/m.Eff_ba_ch)
    else:
        return m.y_ch[t] <= (m.x['BA'] -
            m.z_ba[t-1])*m.A_i['BA']*(1/m.Eff_ba_ch)
m.BA_Charge_Balance = pyo.Constraint(m.T, m.ST, rule=BA_Charge_Balance)

def BA_Discharge_Balance(m,t, st):
    if t == 0:
        return m.y_dch[t] <= m.z_ba[m.lastT]*m.A_i['BA']*m.Eff_ba_dch
    else:
        return m.y_dch[t] <= m.z_ba[t-1]*m.A_i['BA']*m.Eff_ba_dch
m.BA_Discharge_Balance = pyo.Constraint(m.T, m.ST,
    rule=BA_Discharge_Balance)

def BA_charge_active(m,t, st):
    return m.y_ch[t] <= m.X_max_imp*m.a_ch[t]
m.BA_charge_active = pyo.Constraint(m.T, m.ST, rule=BA_charge_active)

def BA_discharge_active(m,t, st):
```

```
    return m.y_dch[t] <= m.X_max_imp*m.a_dch[t]
m.BA_discharge_active = pyo.Constraint(m.T, m.ST,
    rule=BA_discharge_active)

def Battery_Balance(m,t, st):
    return m.a_ch[t] + m.a_dch[t] <= 1
m.Battery_Balance = pyo.Constraint(m.T, m.ST, rule=Battery_Balance)

def BA_charge_rate(m,t, st):
    return m.y_ch[t] <= m.x['BA']*m.Beta_ba
m.BA_charge_rate = pyo.Constraint(m.T, m.ST, rule=BA_charge_rate)

def BA_discharge_rate(m,t, st):
    return m.y_dch[t] <= m.x['BA']*m.Beta_ba
m.BA_discharge_rate = pyo.Constraint(m.T, m.ST, rule=BA_discharge_rate)

#---Production constraints for generating technologies

def PV_f10_Balance(m,t, st):
    return m.y_pv_f10[t] == m.x['PV_f10']*m.Y_pv_f10[t]
m.PV_f10_Balance = pyo.Constraint(m.T, m.ST, rule=PV_f10_Balance)

def PV_S20_Balance(m,t, st):
    return m.y_pv_S20[t] == m.x['PV_S20']*m.Y_pv_S20[t]
m.PV_S20_Balance = pyo.Constraint(m.T, m.ST, rule=PV_S20_Balance)

def PV_S30_Balance(m,t, st):
    return m.y_pv_S30[t] == m.x['PV_S30']*m.Y_pv_S30[t]
m.PV_S30_Balance = pyo.Constraint(m.T, m.ST, rule=PV_S30_Balance)

def PV_E20_Balance(m,t, st):
    return m.y_pv_E20[t] == m.x['PV_E20']*m.Y_pv_E20[t]
m.PV_E20_Balance = pyo.Constraint(m.T, m.ST, rule=PV_E20_Balance)

def PV_E30_Balance(m,t, st):
    return m.y_pv_E30[t] == m.x['PV_E30']*m.Y_pv_E30[t]
m.PV_E30_Balance = pyo.Constraint(m.T, m.ST, rule=PV_E30_Balance)

def PV_W20_Balance(m,t, st):
    return m.y_pv_W20[t] == m.x['PV_W20']*m.Y_pv_W20[t]
m.PV_W20_Balance = pyo.Constraint(m.T, m.ST, rule=PV_W20_Balance)
```

```
def PV_W30_Balance(m,t, st):
    return m.y_pv_W30[t] == m.x['PV_W30']*m.Y_pv_W30[t]
m.PV_W30_Balance = pyo.Constraint(m.T, m.ST, rule=PV_W30_Balance)

def PV_S90_Balance(m,t, st):
    return m.y_pv_S90[t] == m.x['PV_S90']*m.Y_pv_S90[t]
m.PV_S90_Balance = pyo.Constraint(m.T, m.ST, rule=PV_S90_Balance)

def PV_E90_Balance(m,t, st):
    return m.y_pv_E90[t] == m.x['PV_E90']*m.Y_pv_E90[t]
m.PV_E90_Balance = pyo.Constraint(m.T, m.ST, rule=PV_E90_Balance)

def PV_W90_Balance(m,t, st):
    return m.y_pv_W90[t] == m.x['PV_W90']*m.Y_pv_W90[t]
m.PV_W90_Balance = pyo.Constraint(m.T, m.ST, rule=PV_W90_Balance)

def ASHP_SH_Balance(m,t, st):
    return m.q_ashp_sh[t] == m.y_ashp_sh[t]*m.COP_ashp_sh[t]
m.ASHP_SH_Balance = pyo.Constraint(m.T, m.ST, rule = ASHP_SH_Balance)

def ASHP_DHW_Balance(m,t, st):
    return m.q_ashp_dhw[t] == m.y_ashp_dhw[t]*m.COP_ashp_dhw[t]
m.ASHP_DHW_Balance = pyo.Constraint(m.T, m.ST, rule = ASHP_DHW_Balance)

def GSHP_SH_Balance(m,t, st):
    return m.q_gshp_sh[t] == m.y_gshp_sh[t]*m.COP_gshp_sh[t]
m.GSHP_SH_Balance = pyo.Constraint(m.T, m.ST, rule = GSHP_SH_Balance)

def GSHP_DHW_Balance(m,t, st):
    return m.q_gshp_dhw[t] == m.y_gshp_dhw[t]*m.COP_gshp_dhw[t]
m.GSHP_DHW_Balance = pyo.Constraint(m.T, m.ST, rule = GSHP_DHW_Balance)

def EB_SH_Balance(m,t, st):
    return m.q_eb_sh[t] == m.y_eb_sh[t]*m.Eff['EB']
m.EB_SH_Balance = pyo.Constraint(m.T, m.ST, rule = EB_SH_Balance)

def EB_DHW_Balance(m,t, st):
    return m.q_eb_dhw[t] == m.y_eb_dhw[t]*m.Eff['EB']
m.EB_DHW_Balance = pyo.Constraint(m.T, m.ST, rule = EB_DHW_Balance)

def BB_SH_Balance(m,t, st):
    return m.q_bb_sh[t] == m.bf_sh[t]*m.A_i['BB']*m.Eff['BB']
```

```
m.BB_SH_Balance = pyo.Constraint(m.T, m.ST, rule=BB_SH_Balance)

def BB_DHW_Balance(m,t, st):
    return m.q_bb_dhw[t] == m.bf_dhw[t]*m.A_i['BB']*m.Eff['BB']
m.BB_DHW_Balance = pyo.Constraint(m.T, m.ST, rule=BB_DHW_Balance)

#---Zero emission/energy constraints
def ZE_Balance(m):
    if m.A_co2==1:
        print('ACTIVE ZEB-carbon RESTRICTION')
        if m.lastT == 8735:
            return sum(m.y_imp[t]*m.G_el + m.bf_sh[t]*m.G_bf +
                m.bf_dhw[t]*m.G_bf for t in m.T) <= sum(m.y_exp[t]*m.G_el
                for t in m.T)
        if m.lastT == 4367:
            return 2*sum(m.y_imp[t]*m.G_el - m.y_exp[t]*m.G_el +
                m.bf[t]*m.G_bf for t in m.T) <= m.G_ref*m.gamma
        elif m.lastT == 727:
            return 12*sum(m.y_imp[t]*m.G_el - m.y_exp[t]*m.G_el +
                m.bf[t]*m.G_bf for t in m.T) <= m.G_ref*m.gamma
        elif m.lastT == 671:
            return sum(m.y_imp[t]*m.G_el + m.bf_sh[t]*m.G_bf +
                m.bf_dhw[t]*m.G_bf for t in m.T) <= sum(m.y_exp[t]*m.G_el
                for t in m.T)
        elif m.lastT == 287:
            return (8736/288)*sum(m.y_imp[t]*m.G_el - m.y_exp[t]*m.G_el +
                m.bf[t]*m.G_bf for t in m.T) <= m.G_ref*m.gamma
        elif m.lastT == 95:
            return sum(m.y_imp[t]*m.G_el - m.y_exp[t]*m.G_el +
                m.bf_sh[t]*m.G_bf + m.bf_dhw[t]*m.G_bf for t in m.T) <=
                sum(m.y_exp[t]*m.G_el for t in m.T)
        elif m.lastT == 23:
            return (8736/24)*sum(m.y_imp[t]*m.G_el - m.y_exp[t]*m.G_el +
                m.bf[t]*m.G_bf for t in m.T) <= m.G_ref*m.gamma
    elif m.A_pe == 1:
        print('ACTIVE ZEB-pef RESTRICTION')
        if m.lastT == 8735:
            return sum(m.y_imp[t]*m.PE_imp - m.y_exp[t]*m.PE_exp +
                m.bf[t]*m.PE_bf for t in m.T) <= m.PE_ref*m.gamma
        elif m.lastT == 671:
            return 13*sum(m.y_imp[t]*m.PE_imp - m.y_exp[t]*m.PE_exp +
                m.bf[t]*m.PE_bf for t in m.T) <= m.PE_ref*m.gamma
```

```python
        else:
            print('NO ZEB RESTRICTION')
            return pyo.Constraint.Skip
    m.ZE_Balance = pyo.Constraint(rule=ZE_Balance)

#Subscription power pricing Constraint
    def pty_volume(m, t): #counting all power within one hour exceeding max
        limit
        if m.A_ps == 1:
            return m.y_imp[t] - m.Y_max <= m.y_pty[t]
        else:
            return m.y_pty[t] ==0
    m.pty_volume = pyo.Constraint(m.T, rule = pty_volume)

    def pty_volume2(m, t):
            return 0 <= m.y_pty[t]
    m.pty_volume2 = pyo.Constraint(m.T, rule = pty_volume2)

# Peak power restriction
    def peak_power(m, t):
        H = createHvector()
        for key in H.keys():
            if t <= H[key]:
                month = key
                break
        if t <= H[month]:
            return m.y_max_imp[month] >= m.y_imp[t]
        else:
            return pyo.Constraint.Skip
    m.peak_power = pyo.Constraint(m.T, rule = peak_power)

#   OBJECTIVE FUNCTION #################################################

    def cost_Investments_rule(m, st):
        expr = self.npv_cost_Investments(m, st)
        return expr
    m.cost_Investments = pyo.Expression(m.ST, rule = cost_Investments_rule)

    def cost_Operation_rule(m, st):
        expr = self.npv_cost_Operations(m, st)
        return expr
    m.cost_Operations= pyo.Expression(m.ST, rule = cost_Operation_rule)
```

```
    def objective_TotalCost(m):
        expr = pyo.summation(m.cost_Investments) +
            pyo.summation(m.cost_Operations)
        return expr
    m.objective_TotalCosts = pyo.Objective(rule = objective_TotalCost, sense
        = pyo.minimize)

    return m

def createConcreteModeltwoStage(self, data):
        '''Function creating instance from input data'''
        concretemodel = self.abstractmodel.create_instance(data = {
            'mymodel':data}, namespace = 'mymodel')
        return concretemodel
```

C Load Profiles

C.1 Regular building SFH

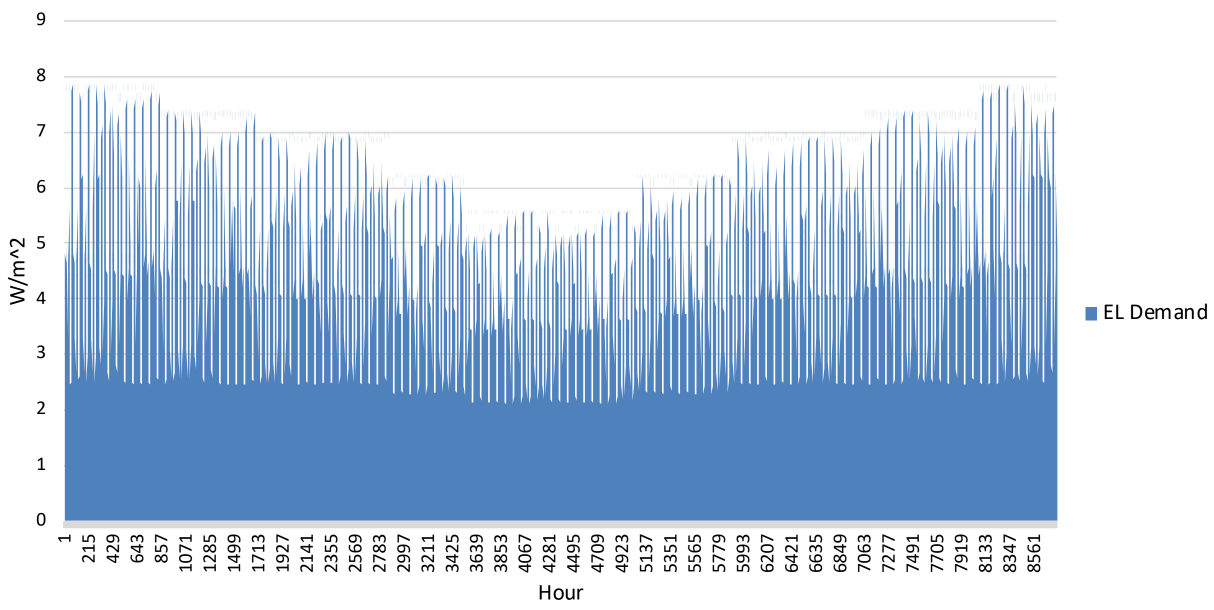

Figure C.1: Electricity Demand for Regular SFH

C.2 Post-insulated building SFH

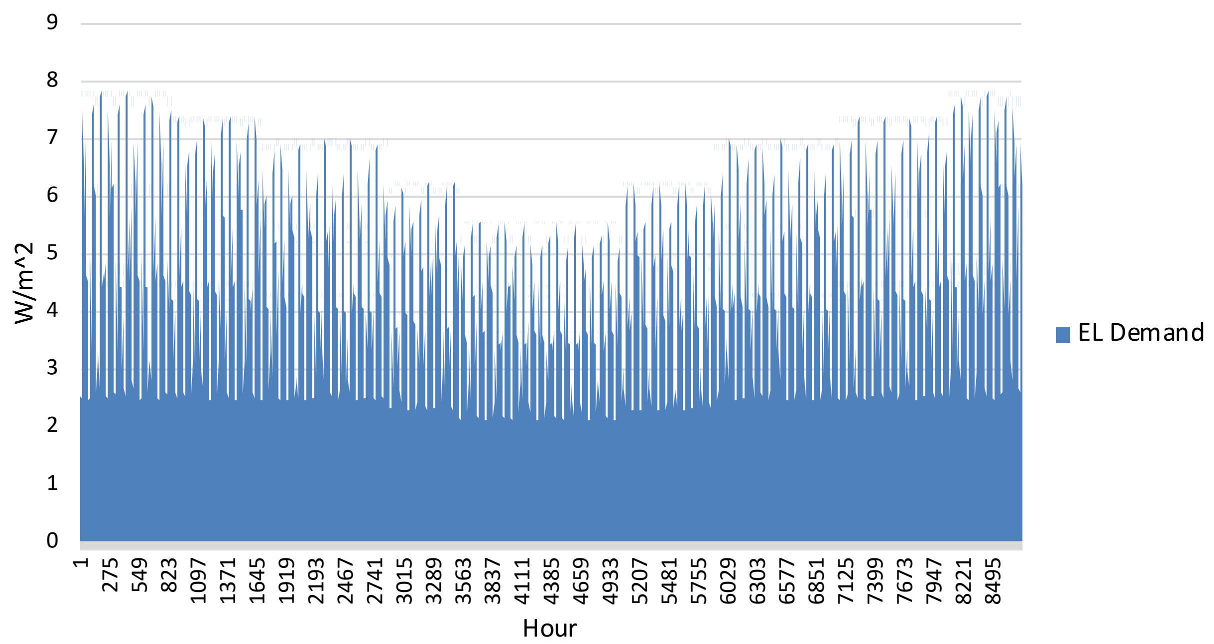

Figure C.2: Electricity Demand for Post-insulated SFH

C.3 Regular building Apartment Block

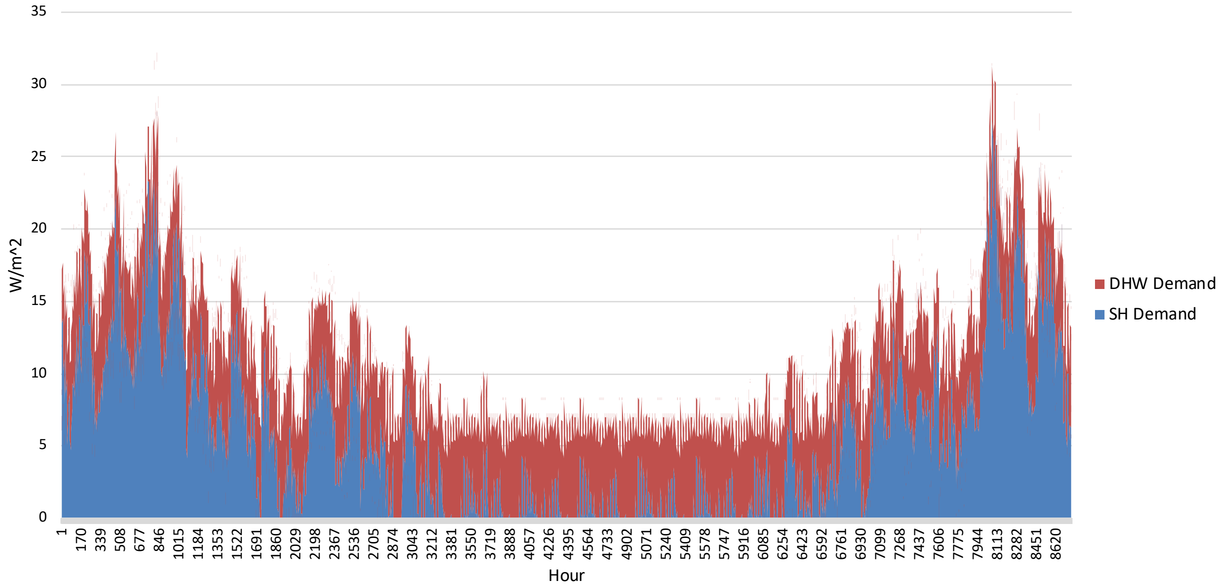

Figure C.3: Heat Demand for Regular Apartment Block

C.4 Post-insulated building Apartment Block

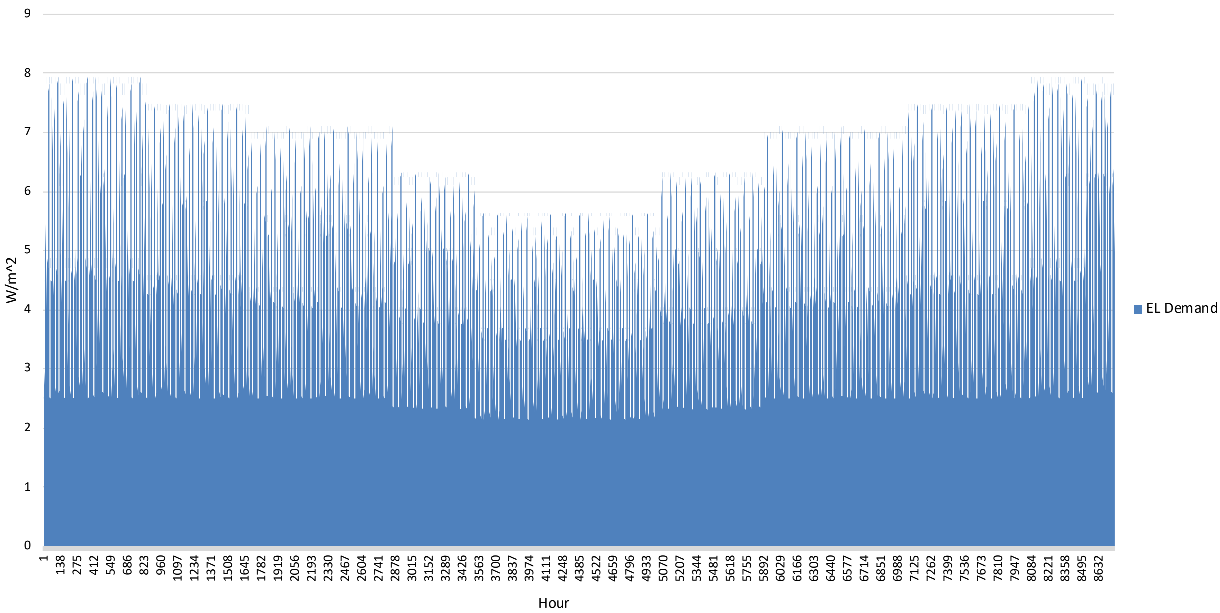

Figure C.4: Electricity Demand for Post-insulated Apartment Block

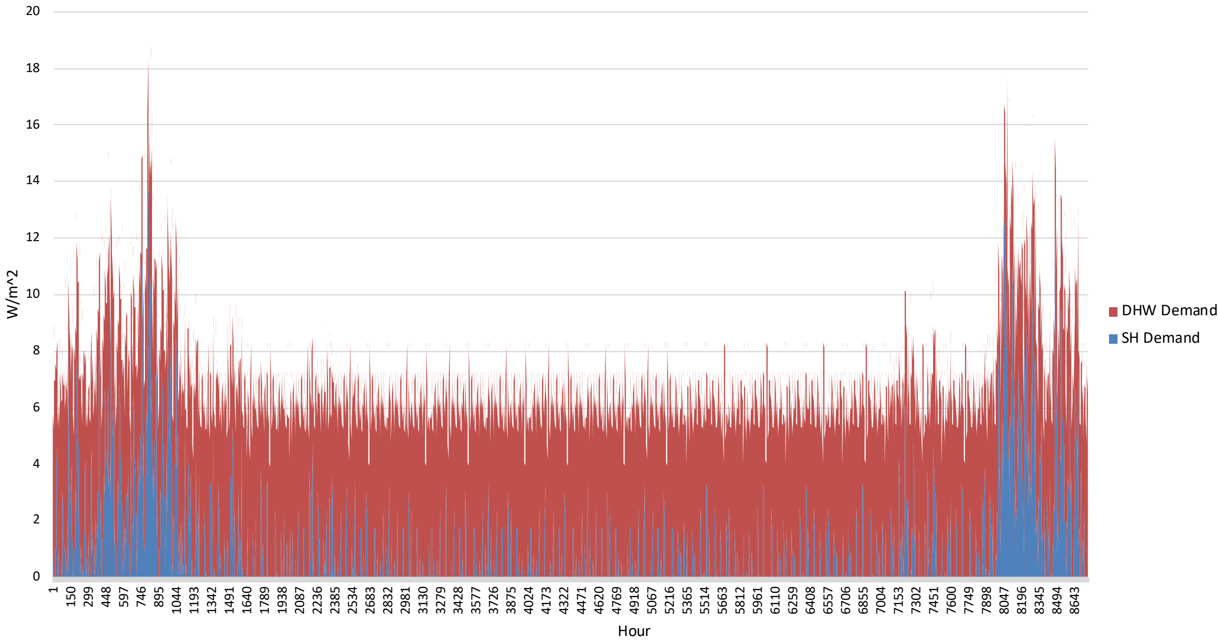

Figure C.5: Heat Demand for Post-insulated Apartment

C.5 Regular building Office

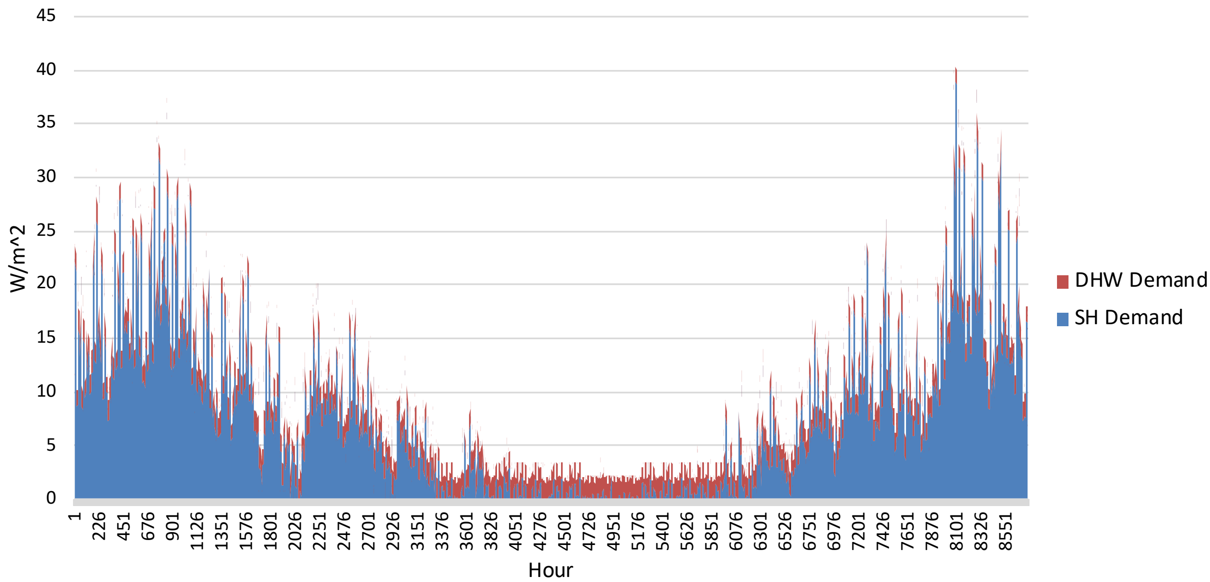

Figure C.6: Heat Demand for Regular Office

C.6 Post-insulated building Office

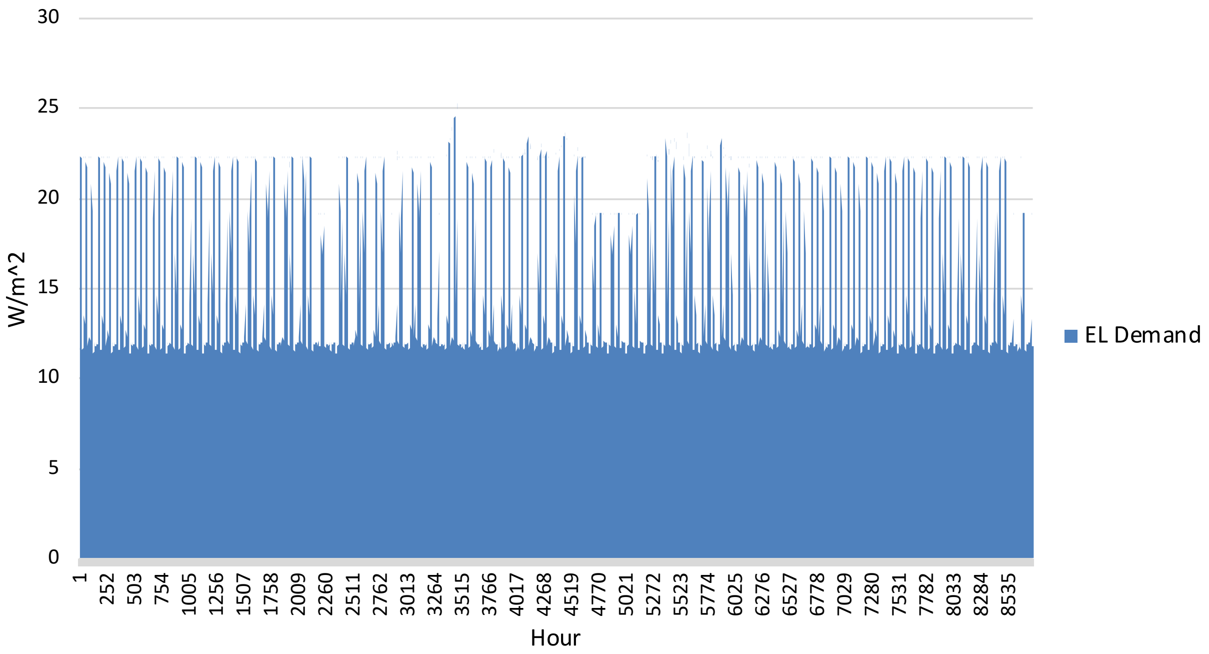

Figure C.7: Electricity Demand for Post-insulated Office

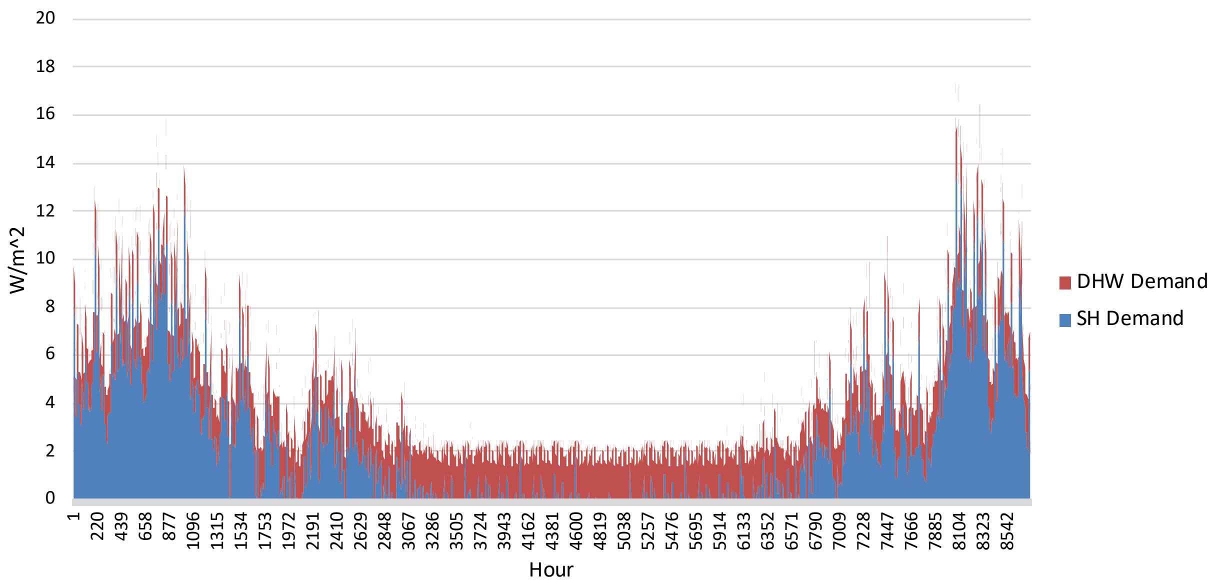

Figure C.8: Heat Demand for Post-insulated Office

Camilla Hengebøl

A study on optimal utilization of electric heating for buildings

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