NTNU – Trondheim
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Net electricity load profiles of Zero Emission buildings

A Cost Optimization Investment Model for Investigating Zero Balances, Operational Strategies and Grid Restrictions

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Problem Description

Net electricity load profiles of Zero Emission buildings

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The optimization model developed in the student's project thesis, "Optimal investments in Zero Emission Buildings" is to be further developed in the master thesis.

The optimization model developed in the project thesis finds the optimal capital investments when minimizing total costs, given that the annual net electricity consumption is to be zero. In the master thesis, a feature of choosing different zero-balance restrictions should be made possible, including the option of zero CO_2-emissions, zero energy or zero primary energy (PEI) consumption. Further, the model is expected to include the following enhancements:

- Investment possibility for bioenergy boiler
- Improved modelling of the heat storage and solar thermal system

The model will be used for investigating investments in ZEB school buildings in Norway. Technical equipment to be included in the model is heat pump, solar thermal, heat storage, electric boiler, bio boiler and PV panels. Operational and investment costs (EUR/MW and/or EUR/kWh) are to be found for each technology based on search in literature and on the web. Costs and conversion factors with appurtenant sources shall be documented in the report. The model is to be run with the following operational strategies:

A No storage available. "Independent" production and consumption patterns
B Cost minimization
C Minimizing grid load (or "burden")
D CO_2 minimization

Within each of the strategies, the student should reflect over the following results:

- Optimal size of heat storage (daily or seasonal storage size)
- Optimal size of PV panels and ST modules
- Net electricity load profile for 1 year (with the optimal capital investment)

If time, the model is to be made stochastic by having a spread of the load profiles and/or electricity price. The load profiles and electricity price forecasts will be provided by PhD student. In this case, the value of stochastic solution, VSS, shall also be considered within each strategy.

Preface

This thesis completes my master's degree in Energy and Environmental Engineering at the Norwegian University of Science and Technology (NTNU). It was written in the spring 2014 at the department of Department of Electric Power Engineering, in coordination with the The Research Centre on Zero Emission Buildings (ZEB) organized by NTNU and SINTEF.

I would like to express my appreciation for my co-supervisor Karen Byskov Lindberg's guidance and encouragement, in addition to profitable discussions I enjoyed through regular Skype meetings with her. They have been indispensable for the work. I would also like to thank her for reading and giving feedback on the report, and my supervisor, Ole Morten Midtgård, for always having an open door.

I would further thank the Fraunhofer-Institut für Solare Energisysteme (ISE) in Freiburg, Germany for warmly hosting me one week and for giving very useful insight into optimizing model applications for multi-energy carrier systems.

Moreover, I would like to thank Professors Magnus Korpås and Gerard L. Doorman, who have provided comments on key elements of the model. For help with effective implementation of the Mosel code, I would thank Carl Fredrik Tjeransen, Mari Holmen and Christian Skar.

Finally, I would like to show gratitude to my research assistant colleagues at the Department of Energy and Process Engineering for encouragement in periods with heavy work loads, as well as my fellow students at F311 for valuable advice, discussions and coffee breaks.

Astrid Ånestad

Trondheim, August 2014

Abstract

On the way to meet the internationally sanctioned climate targets, zero emission buildings / zero energy buildings (ZEB) will be an important step. Research is ongoing on what a reasonable definition of ZEB will contain. In Norway, it is decided that the building code should be nearly zero energy buildings from the year 2020.

In this master's thesis, an optimization model for finding cost-optimal investment and operational strategies for ZEB is developed. The building modelled, is a passive school with a hydronic heat distribution system. Possible investments include photovoltaic solar cells (PV), solar collectors, heat pumps, biomass boilers, electric boiler, heat storage and connection to the district heating grid. The model is designed as a dynamic mixed integer programming model, and implemented in Mosel Xpress. The model minimizes the total discounted costs of operations and investments over the lifetime of the building. Different restrictions of zero CO_2 emissions, zero primary energy consumption and level of grid burden can be applied.

The analysis shows that if a zero CO_2 restriction with Norwegian CO_2 factors are applied, the least expensive way to reach ZEB is by investing in PV in combination with pellet biomass boiler as base load and district heating to cover peak demand. To reach the zero balance for the school with Norwegian CO_2 factors, the highest hourly value for export of electricity per hour exceeds the maximum hourly value of imports by about 120%. If European factors for CO_2 is applied, it will be more reasonable to reach ZEB than with Norwegian factors. If asymmetric primary energy factors are used instead of symmetric factors, investment in PV becomes higher, and the peak export values increases.

The model is developed as a deterministic model, and does not take into account uncertainties in input data. To compensate for this, various sensitivity analyses are conducted. Future work includes testing the model with load profiles for other types of buildings.

Sammendrag

På veien til å nå de internasjonalt satte klimamålene, vil nullutslippsbygg/nullenergibygg (ZEB) være et viktig steg på veien. Mye forskning pågår for å finne ut hva en fornuftig definisjon av ZEB vil innebære. I Norge er det vedtatt at bygningsstandarden skal være nesten nullenergibygg fra 2020.

I denne masteroppgaven er det utviklet en optimeringsmodell for å finne kostnadsoptimale investeringer og driftsstrategier for ZEB. Bygningen som er modellert er en passivskole med vannbårent oppvarmingssystem. Mulige investeringsalternativer er solceller (PV), solfangere, varmepumper, biokjeler, elkjel, varmelager og tilknytning til fjernvarmenett. Modellen er utviklet som en dynamisk blandet heltallsmodell (MIP), og implementert i Mosel Xpress. Modellen minimerer de totale diskonterte kostnadene for driften og investeringer over levetiden til bygget. Ulike restriksjoner for CO_2-utslipp, primærenergibruk og nettbelastning kan inkluderes.

Analysen viser at dersom en null CO_2-restriksjon med norske CO_2-faktorer legges til grunn, vil den rimeligste måten å nå ZEB være ved å investere i PV, kombinert med pelletskjel som grunnlast og fjernvarmetilknytning for å dekke topplasten. For å nå nullbalansen for skolen med norske CO_2-faktorer, vil maksverdiene for eksport av elektrisitet per time overgå maksverdiene for import med ca 120%. Dersom europeiske faktorer for CO_2 legges til grunn vil det bli rimeligere å nå ZEB enn med norske faktorer. Dersom asymmetriske primærenergifaktorer benyttes i stedet for symmetriske faktorer, vil investeringene i PV bli høyere, og belastningen på nettet dermed øke.

Modellen er utviklet som en deterministisk modell, og tar ikke inn usikkerheter i inputdataene. For kompensere for dette er ulike sensitivitetsanalyser gjennomført. Videre arbeid inkluderer blant annet å teste ut modellen på lastprofiler fra andre typer bygg.

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Abbreviations

COP	Coefficient of Performance
EQ.	Equivalents
GM	Generation Multiple
IEA	The International Energy Agency
IP	Integer Programming
MIP	Mixed Integer Programming
NVE	Norwegian Water Resources and Energy Directorate
N.R.	Non-renewable
OM	Operation and Maintenance
PE	Primary Energy
P.V.	Present Value
PV	Photovoltaic
LP	Linear Programming
VAT	Value Added Tax
ZEB	Zero Emission Buildings / Zero Energy Buildings

asym	Asymmetrical
a-w	Air-to-water
bb	Biomass Boiler
c	Chips
dh	District heating
eb	Electric boiler
hp	Heat pump
p	Pellets
pv	PV-panels
w-w	Water-to-water
S	Storage
sym	Symmetrical

Chapter 1

Introduction

1.1 Energy Use in Buildings

The building sector is according to The International Energy Agency (IEA) the sector that consumes most energy. The sector represents about one third of all energy consumption, and about half of the electricity use globally [1]. In the Nordic region, the building sector is accountable for close to one third of the final energy consumption in the region [2].

The international community has agreed that global warming is one of the largest challenges we face and recognizes that the temperature increase should not exceed the threshold of 2°C. This requires global co-operation. Developed countries are to make, according to the UN sanctioned agreement Convention on Climate Change (UNFCC), "low carbon development strategies or plans" to enhance this mitigation [3].

In the context of energy efficiency and the building sector, Zero Emission Buildings/Zero Energy Buildings (ZEB) have got more and more attention. The EU Energy Performance of Buildings Directive of 2010 says:

> "*1. Member States shall ensure that: (a) by 31 December 2020, all new buildings are nearly zero- energy buildings; and (b) after 31 December 2018, new buildings occupied and owned by public authorities are nearly zero-energy buildings. Member States shall draw up national plans for increasing the number of nearly zero-energy buildings. These national plans may include targets differentiated according to the category of building*" [4].

The white paper on Norwegian Climate Policy of 2012 says the technical building code from 2020 should be “nearly zero energy level” [5]).

1.2 Objective

The objective of this master thesis is to further develop an optimizing model to investigate investments in ZEB school buildings in Norway. The improved model should be used to investigate how different definitions of zero energy building influence the investments, operational strategies and grid burden of the building.

1.3 Outline

The report starts with a brief introduction to the relevant background and theory of the elements included in the model shall be given. Thereafter, in chapter 3, system boundaries, assumptions and choices made in the modelling phase will be presented. The chapter will further present a schematic overview of the structure of the model. The input data used in the optimization will be presented, before the mathematical formulation of the problem will be presented in detail in chapter 5. The results will be presented and analysed in chapter 6, followed by a conclusion of the findings. Details and data from the analysis will be presented in appendix A. Calculations and conversions performed on the input data will be presented in appendix B and C. Screen-dumps of the control parameter files for the model is presented in appendixD.

Chapter 2

Theory and Background

This chapter will give a short introduction to the theory and relevant background for the key elements of the model developed. It is not the intention to give a complete picture of the theory behind the fields included, but to give a short background behind methods and equations used in the developed model framework.

First, a short briefing of the energy use in buildings and the ZEB concept will be given, second optimizing terms and methods used in the model will be explained. The third section contains a brief description of the factors used to analyse the building performance. In the fourth section a short presentation of the equations used for the discounting of costs will be given. In the fifth section there is a trivial technical description of the available energy technologies for investments, while the last section will provide a short structure for how the energy prices are calculated.

2.1 ZEB

ZEB could either refer to a Zero Emission Building, Zero Energy Building or Zero Primary Energy Building, depending on which zero-balance and crediting system chosen [6].

The overall ZEB expression include buildings that is stand-alone, not-grid connected and produce sufficiently energy to meet its own energy demand at all times. However, most buildings are connected to the energy infrastructure, and the term *net ZEB* is thereby more relevant. With a grid connected building, the possibility of interacting with the energy infrastructure, such as the power grid or district heating systems, will make it possible to optimize the capacity of the energy sources, utilize energy in other parts of the power system in periods with surplus, and reduce the need of back-up systems [6]. The net ZEB balance is presented in equation 2.1, and adopted from [7].

$$\text{Net ZEB:} \qquad |export| - |import| \ \geq 0 \tag{2.1}$$

Conceptually a net ZEB is a building where the energy demand is greatly reduced, and where there are on-site renewable generation that can produce and deliver enough energy to the grid to achieve a carbon or energy neutral balance [8]. Figure 2.1 shows the main concept of first reducing the energy demand of the building to a low energy building, or passive building, and then increase on site-energy generation for export in order to compensate for imported energy.

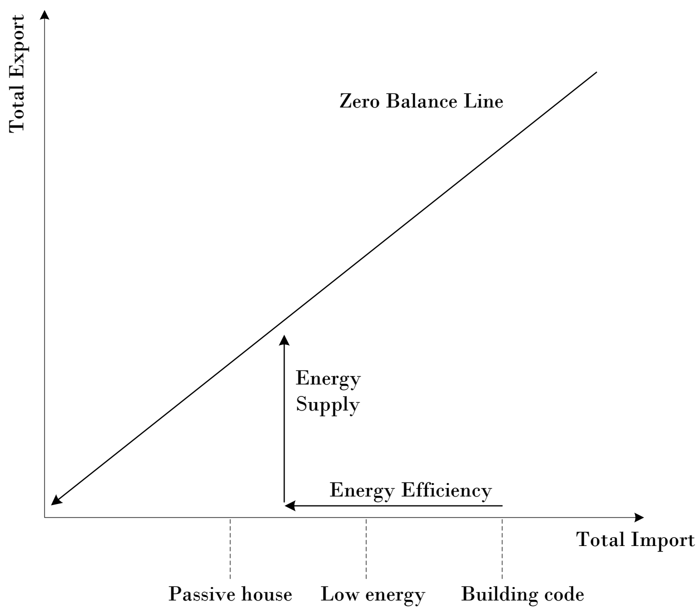

FIGURE 2.1: Pathway to ZEB, reduced energy demand and increased on-site energy supply. Figure obtained from [8]

Research on net ZEBs is ongoing widely. However, still there does not exist a common definition of net ZEB. With the implementation of the concept of net ZEB within the building codes [4], it will becomes even more important to agree upon a clear common understanding of the net ZEB concept. Satori et al. [8] summarizes the level of common understanding of net ZEB:

> "*Conceptually, it is understood that a Net ZEB is a building with greatly reduced energy demand that can be balanced by an equivalent on-site generation of electricity, or other energy carriers, from renewable*

> *sources. It is also understood that the definition may affect significantly the way buildings are designed to achieve the goal.”* [9]

The way to calculate *net zero* is in other word not decided, and the way one define zero might be more favorable toward some technologies. The emphasis in the definition of a ZEB building might vary with different stakeholder’s motivation of ZEBs. Energy institutions might be more concerned with source energy, the building owners will be interested in the energy cost, while environmental concerned institutions might emphasize the emission balance [6].

Figure 2.2 visualize the interaction between the building and the infrastructure. To achieve the zero balance, the amount of delivered (imported) energy needs to be larger or equal to the feed-in energy (energy exported), given the weighing factors for the crediting system chosen.

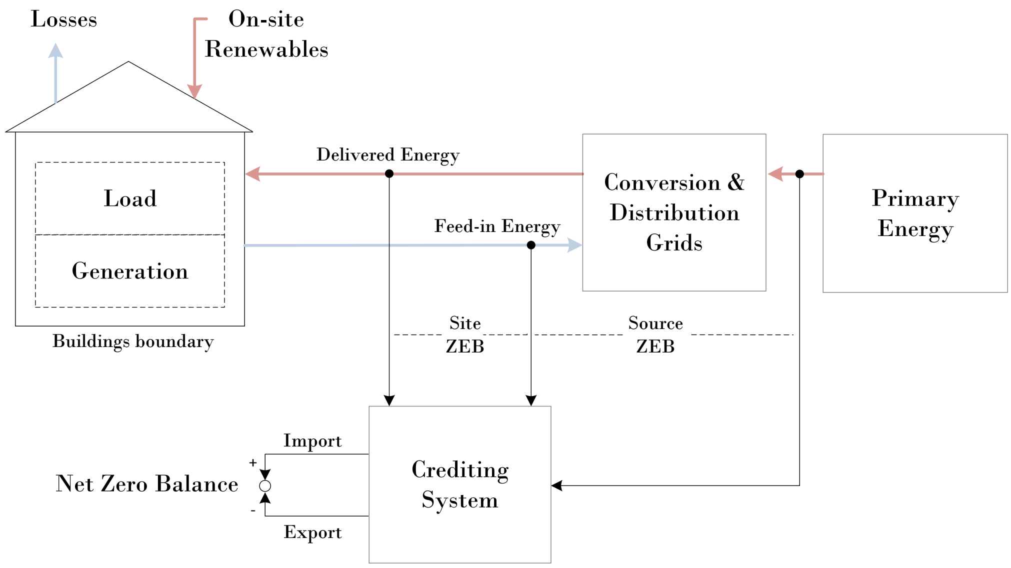

FIGURE 2.2: Visualization of the connection between building and energy grids. The net zero balance will be when the import equalizes the export for the chosen crediting system. The figure is obtained from [9].

Marszal et al [10] sums up the most important issues to consider in terms of a ZEB definition. These include choices related to the evaluation of the zero balance: metric, time period, type of energy sources and type of energy balance used. Important factors of the physical parameters of the properties of the building evaluated will constitute the basis for the energy sources accepted, the energy infrastructure connected to the building, level of energy efficiency, the building’s indoor climate and interaction between the building and the power grid.

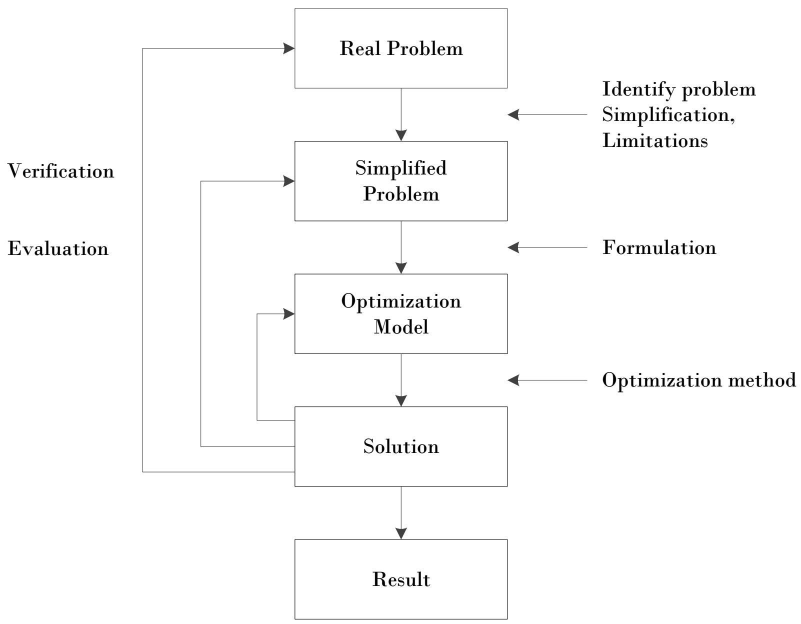

FIGURE 2.3: View of the optimization process [13]

2.2 Optimization

When an optimization problem is to be developed, usually a standardized method is used. The basic principles of operational programming is described in [11], [12] and [13]. There are some basic steps that usually are followed, which is presented in [13]. The steps of the optimization process is visualized in figure 2.3.

The problem as it appears in the real world needs be analysed, before it can be described in an optimization model. The real problem will in most cases be intricate, and the significant factors for the problem needs to be identified. When the key factors of the real problem is identified, the simplified problem is formulated as an optimization model in mathematical form [13].

When the model is in mathematical form, the problem is described by sets of mathematical equations that will aim to describe the structure of the real problem [12]. The complexity of the formulation of the simplified problem, and how much effort required to solve the problem, needs to be weighed against the contribution to the wanted quality of the result.

Thereafter the model is implemented in a suitable problem solver, and solved using a suitable algorithm. Throughout the modelling phase evaluation of the model and verification of the results, needs to be performed to see if it describes the real problem as intended [13].

2.2.1 Dynamic vs. Static Programming

In a dynamic programming model time differences are included, contrary a static model. A dynamic model is a model where the problem is divided into different stages. For each stage decisions has to be made. The optimal solution will be dependent on decisions made in the series of stages, and thus influence the state of the model in that time step [11]. This is typical for economical programming [12]. A dynamic programming model can thus be used to describe problems running over longer time periods.

2.2.2 Deterministic vs. Stochastic Programming

In deterministic programming the system can only be in one state at a given time, while in stochastic programming, the system may achieve several possible states of the system [11]. Thus, for stochastic programming, probability distributions can be included in the model, to account for expected or predicted variations in the input parameters. In the deterministic programming models, the input parameters are fixed to one single estimated value, and does not include uncertainties of input data.

2.2.3 Linearity

In linear programming (LP), all constraints of the formulation of the model needs to be linear. When only linear constraints are used for modelling, solving the problem demands less computations. On the other hand, linearisation of the constraints may oversimplify the problem, and reduce the utility of the results.

Figure 2.4 presents the principle of a geometrical presentation of the solution space for a two variable mixed integer model. The linear constraints, frames the feasible region for a linear programming solution. Only solutions within this feasible region will meet the restrictions of the mathematical modeling of the problem. For a simple minimizing problem, the equation that is minimized, i.e. the objective function, could be visualized as in figure 2.4. The optimal solution will always be in the intersection of two linear constraints [12].

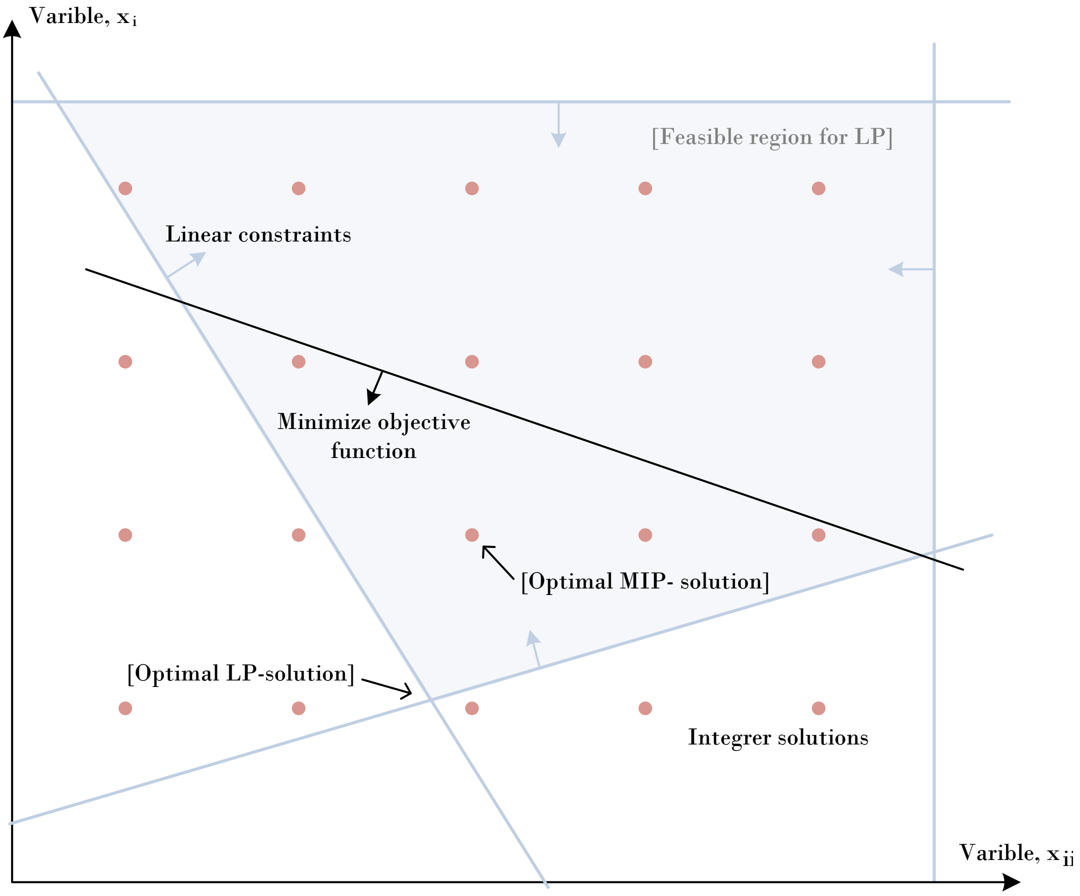

FIGURE 2.4: Geometrical representation of the solution space of a MIP with two variables. The feasible region is presented by the shaded region. The linear constraints have the color of light blue, and the objective function is marked by the black line. The concept of optimal solution of the LP model and the MIP-model is presented. The figure is loosely based on [12] and [13]

.

2.2.4 Mixed Integer Programming

If the number of integer variables in a pure integer programming (IP) model, exceeds a few hundreds, the cost of calculating will most likely overrun the benefit of the integer solution[12]. When both integers (discrete variables) and continuous variables are present in the model, the optimization problem is a mixed integer programming (MIP) model. The most common application of MIP is to include logical variables, or indicator variables, that can either take the value 0 or 1 [12].

When including integer variables the necessary number of operations needed for solving the problem increases dramatically, and the time to achieve optimal solution will expand.

The optimal LP-solution of the IP-problem is known as the LP-relaxation of the IP problem [13]. When mixed integer programming is used, the optimal solution will usually not be close to the boundary of the feasible solution space of the LP-problem. It is not given that the model will find an optimal solution at all. The most effective way of solving the MIP is then by using the branch and bound method [12].

2.2.5 Indicator Variables

For variables that are semi-continuous, indicator variables are used in the modelling of the problem. It could be that a variable either is zero, or above a certain limit, or the case were we want to distinguish between when a variable is zero and when the variable has a positive value. This is done by introducing the expression for the indicator variable in equation (2.2).

$$x - M \cdot \delta <= 0 \tag{2.2}$$

x is a variable linked to the binary variable (δ). M is a fixed input parameter, representing the upper bound of the variable x. If x is zero, δ could be anything, but if x has a value larger than zero, and smaller than the upper bound of x, δ has to take the value of 1.

2.3 Crediting Systems

As seen in section 2.1, the crediting factors are used to weight import and export of energy in the ZEB balance. The crediting factors could have great impact on which technologies that becomes favourable when net zero constraints are applied. The factors are conceptually technology based, but the national crediting factors will to some extend be influenced by political priorities. Specially the crediting of biomass varies between the European countries [14]. The values used for crediting factors in this work is presented in section 4.8 and 4.9.

2.3.1 CO_2 Factors

The CO_2 emission factors are specified values that describes how much CO_2 emissions, or CO_2 equivalents greenhouse gasses that has been emitted per unit of energy delivered. The CO_2 emission coefficients are given values for each energy carrier [15]. In this work the Norwegian and the proposed standard European CO_2 factors will be investigated.

2.3.2 Primary Energy Indicators

Primary energy is "*energy that has not been subjected to any conversion or transformation process*" [15]. The total primary energy factor is the ratio of all the primary energy used for processing, transporting, extracting and distribution of the delivered energy, divided by the amount of actually delivered energy.

The primary energy factor of an energy carrier could be either based on all non-renewable energy used in the process of the energy conversion or the total energy used. If both non-renewable and renewable primary energy is included in the primary energy factor, the primary energy factor is called *total primary energy factor*, while primary energy factor only based on non-renewable energy is called *non-renewable primary energy factor*. Renewable energy is in this setting defined as energy that is not being extracted [15].

2.4 Grid Burden

A report by the IEA Solar Heating & Cooling Programme [16], presents potentially useful indicators for analysing the load match and grid interaction of net ZEBs. One indicator presented is the generation multiple (GM) [16].

The generation multiple is defined as seen in equation [16],

$$GM_{export/import} = \frac{max[export(t)]}{max[import(t)]} \tag{2.3}$$

Where $GM_{export/import}$ is the generation multiple with respect to exported- and imported energy. *max[export(t)]* is the maximum export at time t, and *max[import(t)]* is the max delivered electricity to the building at time t [16].

The GM factor visualizes the relationship between the export of on-site generation and the load of the building, by comparing the peak values of export and import of electricity from the grid [16].

2.5 Economic Theory

2.5.1 Net Present Value Analysis

Investment projects are often evaluated by performing a net present value analysis. A net present value analysis is a discounted cash flow technique that includes the time value of money. Different investment options may be compared if the total cost of the investments are discounted back to the same year. An expression for the present value P, of a single cash flow, based on [17], [18] and [19] is presented in equation 2.4 below,

$$P = F \cdot \left[\frac{1}{(1+r)^n} \right] = F(P/V, r, n) \tag{2.4}$$

where r is the discount rate, n the lifetime of the investment and F, the net cash flow at the end of period n. The term $(P/V, r, n)$ represents the single-payment present worth factor, or the discount factor. The net present value of a project is the sum of the present value of the investments included in the project.

The annuity of an investment represents the investment cost as a series of equal annual amounts over the lifetime of the investment. The annuity A based on [18] and [19], of an investment P over the period n, and with the discount rate r, is given in equation 2.5 as following,

$$A = P \cdot \left[\frac{r}{1-(1+r)^{-n}} \right] = P(A/P, r, n) \tag{2.5}$$

where $(A/P, r, n)$ represents the capital recovery factor. It follows that the present value of the capitalized annuity might be found by equation 2.6 following, [18] and [19].

$$P = A \cdot \left[\frac{1-(1+r)^{-n}}{r} \right] = A(P/A, r, n) \tag{2.6}$$

where $(P/A, r, n)$ represents the uniform-series present worth, A the annuity, r the discount rate and n the service life of the investment.

The discount rate r disperse the relative value of a cost today against a cost in the future. The discount rate used in financial analysis of investment project could have a great impact on the probability of projects. The discount rate could be the real interest rate adjusted for expected rise of energy cost, general inflation or taxation rates [20]. The discount rate will present the required rate of return of the specific investment, and therefore may vary [21].

2.6 Technology Description

This chapter will give a brief description of the different technologies included as possible investments in the model.

2.6.1 Photovoltaics (PV)

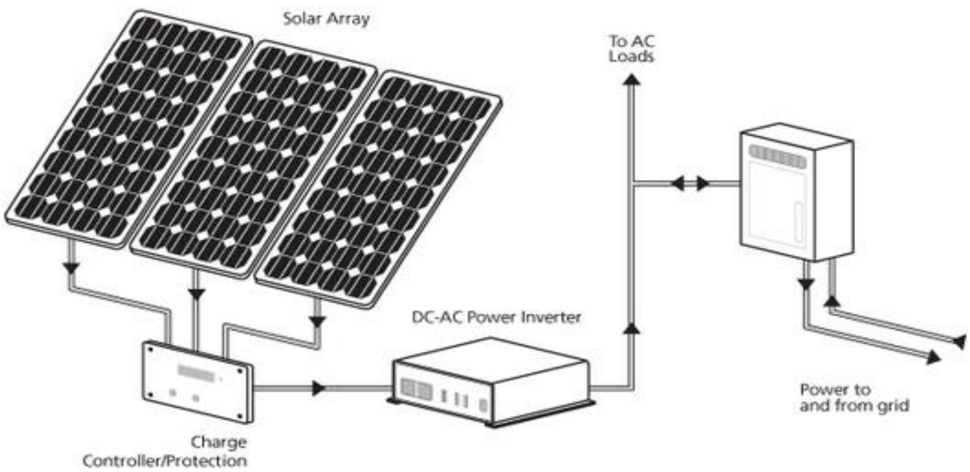

FIGURE 2.5: Principal sketch of a PV panel, with inverter. Obtained from [22]

Photovoltaic modules (PV) utilize photovoltaic solar cells to transform energy from solar irradiation to electrical energy. A photovoltaic solar cell consist of a semiconductor, with doped front- and backsides, giving an electrical potential between the front- and backsides. When the solar rays hit the front side of the semiconductor, the electrons becomes free, and generate an electrical current going to the backside of the semiconductor [23]. A converter is needed to convert the direct current (DC) from the PV cells to alternating current (AC) for use in the building or exported to the grid. A basic sketch of the key elements in typical PV module used in buildings is shown in figure 2.5. The development of PV generation in the Norwegian marked can be found in [24] and [25].

2.6.2 Solar Thermal Collector

The technology behind solar thermal collectors are described in [23] and [26] amongst others. Solar collectors used as heat source in passive buildings are described in [27] and [28]. The potential of solar thermal energy in Norway is discussed in [24].

There are several ways a solar collector modules can be designed. The solar collector transforms the solar irradiation to heat, when solar rays are absorbed by the collector. To heat up the water, water is circulated through the collectors in channels. The two most common types of solar collectors are the plane solar collector and evacuated tube collectors. Evacuated collectors give lower heat losses to the surroundings, but are more expensive to produce [23]. A sketch of the principles of plane solar collector system is shown in figure 2.5.

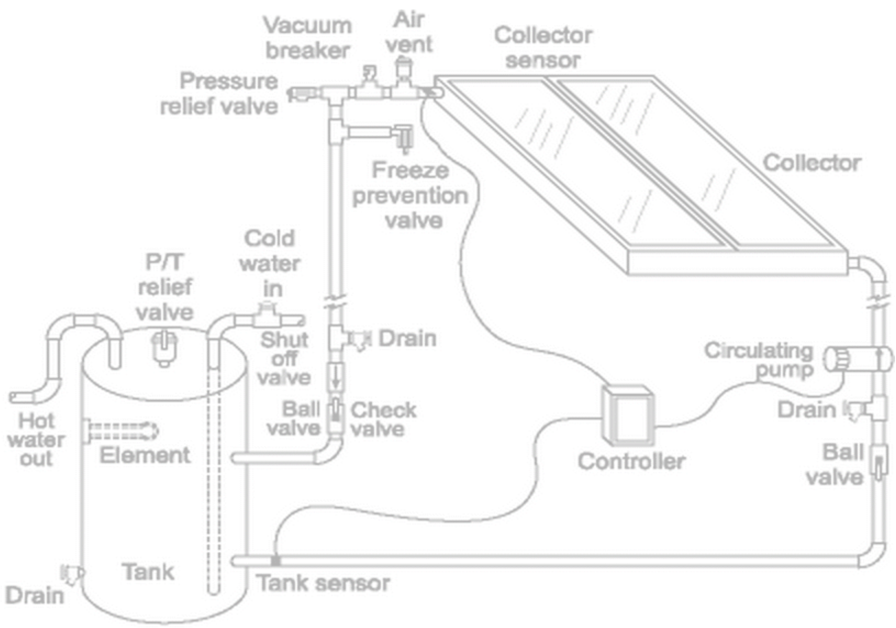

FIGURE 2.6: Principal sketch of a flat plate thermal solar collector, when connected to an accumulator tank. Control systems, valves and circulation pumps included. Obtained from [29].

The energy produced by the solar collector will vary with the seasons. At the summer months the production will be larger, but the demand lower [30]. Globally, solar collectors are commonly used for heating of hot water [24]. Norway has a longer dark period in the winter, but also a colder spring and fall, which makes the heating season longer. Hence, it might be possible to utilize more of the solar energy to meet the heating demand [20].

2.6.3 Ground Source Heat Pump

Ground source heat pump systems and heat sources are described in [28] [31] [23] [20] and [32]. A heat pump transfers energy from a cold region to a warm region by the use of a working fluid. The main components in a heat pump is a condenser, an evaporator, a compressor and an expansion valve. The working fluid circulates in a closed loop. At the compressor, the pressure of the working fluid increases. From the compressor the fluid moves to the condenser where the surplus heat transfers to the warm region. From the compressor the fluid runs though the expansion valve, and the pressure decreases, and the working fluid enters the evaporator with a lower temperature than at the starting point. Heat is thus extracted from the cold region, before the working fluid flows to the compressor again.

Heat pumps are a mature and widely used technology. Different heat sources and working fluids may be used for a heat pump, depending on what is available, and what temperature lift is wanted. Typical energy sources for a ground source heat pumps are sea water, ground water or ground heat [26].

2.6.4 Air Source Heat Pump

The principle behind an air source heat pump is the same as for a ground source heat pump. An air source heat pump uses the ambient air as a heat source, and thus is more effected by temperature changes, compared to a ground source heat pump, where the temperature in the energy source is more stable [26]. The coefficient of performance (COP)for an air-source heat pump has to be calculated on the basis of the temperature of the surrounding air.

The carnot efficiency of an ideal heat pump cycle is presented in equation (2.7).

$$COP_{carnot} = \frac{T_H}{T_H - T_C} \tag{2.7}$$

The carnot efficiency is the theoretical maximum heat delivery by the heat pump. However, the heat delivered by the heat pump will be lower than the theoretical maximum, and thus, the carnot efficiency has to be multiplied with the *goodness* *factor* of the heat pump to see the real heat delivered by the heat pump. The *goodness factor* for heat pump are described in [33].

2.6.5 Electric Boiler

The electric boiler uses electricity to directly heat water. There are different types of electric boilers, the main types being element boiler and electrode heater. In an element boiler, heating elements usually in the form of u-tubes, heat up the water in a tank. The heating elements contains isolated spiral wires that leads electricity, and thus heats up the elements. In an electrode heater, the electricity is transmitted directly in the water. The technology behind electric boilers are further explored in [20].

2.6.6 Biomass Boiler

Biomass boilers are generally used to burn biomass for heat generation. Biomass boilers can be of a range of capacities, from heating dwellings to large district heating systems [23]. The properties of biomass can vary widely, depended on the gathering and the conversion of the biomass.

In the model two types of biomass fuels, pellets and moist chips are included. Pellets can be used for all sizes of boilers. Biomass pellets are a biomass product with a high level of conversion. Pellets can be transported from the storage to the furnace by the use of a screw feeder. The other biomass fuel in the model is chips with a moisture content of about 50%. The properties of chips depend highly on the types of trees used, harvesting method and moisture content [23].

Biomass systems for heating, and the potential of biomass as an energy source is further described in [23] and [34].

2.6.7 District Heating

District heating is an energy distribution system where heat is transported from a heating central to the end users. By centralizing the heat production, it enables more effective use of different energy sources, and the energy technologies may run with more optimal loads, which can increase the utilization of the energy content in the fuel. At the same time, losses in the district heating system needs to be accounted for [35]. Commonly, the consumer will be indirectly connected to the district heating grid through a heat exchanger. The heat exchanger is a part of the district heating interface for the consumer, and here, the energy use will be measured as well [35].

Detailed description of a district heating system is found in [20] and [36].

2.6.8 Heat Storage

The main task for an accumulator tank, or a heat storage, is to close the gap between the energy produced and the energy demand of the building, to ensure more stable and effective energy production. To make sure the heat in the water do not get degraded, the water heating storage needs to be partitioned [37]. Most renewable energy carriers need a accumulator tank to secure stable operation [38]. General description of heat storage is provided in [39].

2.7 Electricity and District Heating Charges

2.7.1 Electricity Price

In Norway electricity prices consist of both the energy price, and renting of the power grid [40]. Generally the electricity price to the consumer is calculated according to equation (2.8).

$$\begin{aligned} Energy\ price \ =\ & El\ spot\ price \\ & +\ Fixed\ charge\ +\ Variable\ charge \\ & +\ El\ certificate\ charge\ +\ VAT \end{aligned} \tag{2.8}$$

The *el spot price* is the hourly spot price for electricity. The fixed and variable charge are charges the energy company can choose to add to the cost. All energy suppliers and some energy consumers are decreed to buy electricity certificates, and this cost is added to the energy bill to the consumer [41]. The electricity certificate charge is set by the marked, and the monthly average electricity certificate prices are presented by Statnett [42]. The value added tax(VAT), is added to the energy price for the costumers. However, for service, industry and public administration the VAT is tax-deductable [43].

The grid rental charge is calculated according to equation (2.9) [44].

$$
\begin{aligned}
\textit{Grid charge} &= \textit{Energy charge} \\
&+ \textit{Fixed charge} + \textit{Power charge} \\
&+ \textit{Electricty consumption tax} \\
&+ \textit{Payment to the Energy Fund}
\end{aligned}
\tag{2.9}
$$

Where the energy charge is intended to compensate for costumer specific cost for the grid company. The fixed charge is an annual charge from the grid companies. A power charge calculated based on given time periods, could additionally apply. The fixed charge and power charge is together meant to cover the fixed cost of the grid companies [44]. For energy supplied a consumption tax of electricity applies [45], in addition to payment to the Energy Fund [46].

For costumers that want to sell on-site production of electricity to the grid, an optional agreement between the grid company and the costumers can be made [47].

2.7.2 District Heating Price

The regulations of the price of district heating states that price of district heating is regulated to not exceed the electricity price in the same supply area. The price elements for district heating can be different between the different district heating suppliers, and the price of district heating could consist of annual charge, heating price and connection fee. These regulations apply to costumers with compulsory connection to the district heating grid [48].

Chapter 3

Method

3.1 System Description

3.1.1 Buildling Outline

The properties of the model is general, and not specific to a certain type of building. The input data on the heat and electricity demand is obtained from an ongoing PhD work by Karen Byskov Lundberg, and is data from a passive house school in Drammen in south-eastern Norway [49]. In the model, optimization is performed on a fictional building with a floor area of 10 000 m^2. This is not the same size as the passive house building in Drammen, but represents a decent sized school building.

The options of additional energy installations in the building is photovoltaic solar cells (PV), solar thermal collector (ST), ground source heat pump with water-to-water as energy mediums (HP$_{ww}$), air source heat pump with air-to-water as energy mediums (HP$_{aw}$), biomass boiler with biomass pellets (BB$_p$), and chips(BB$_c$) as fuel, respectively. Additionally an electric boiler (EB), connection to the district heating grid (DH) and a heat storage (S) is included as possible investments. The installed technologies and the interconnections within the building modelled is shown in 3.1.

3.1.2 Assumptions

For all the optional technologies to invest in, the technologies are modelled on a highly generalized level. Within the hourly time steps all properties are assumed to

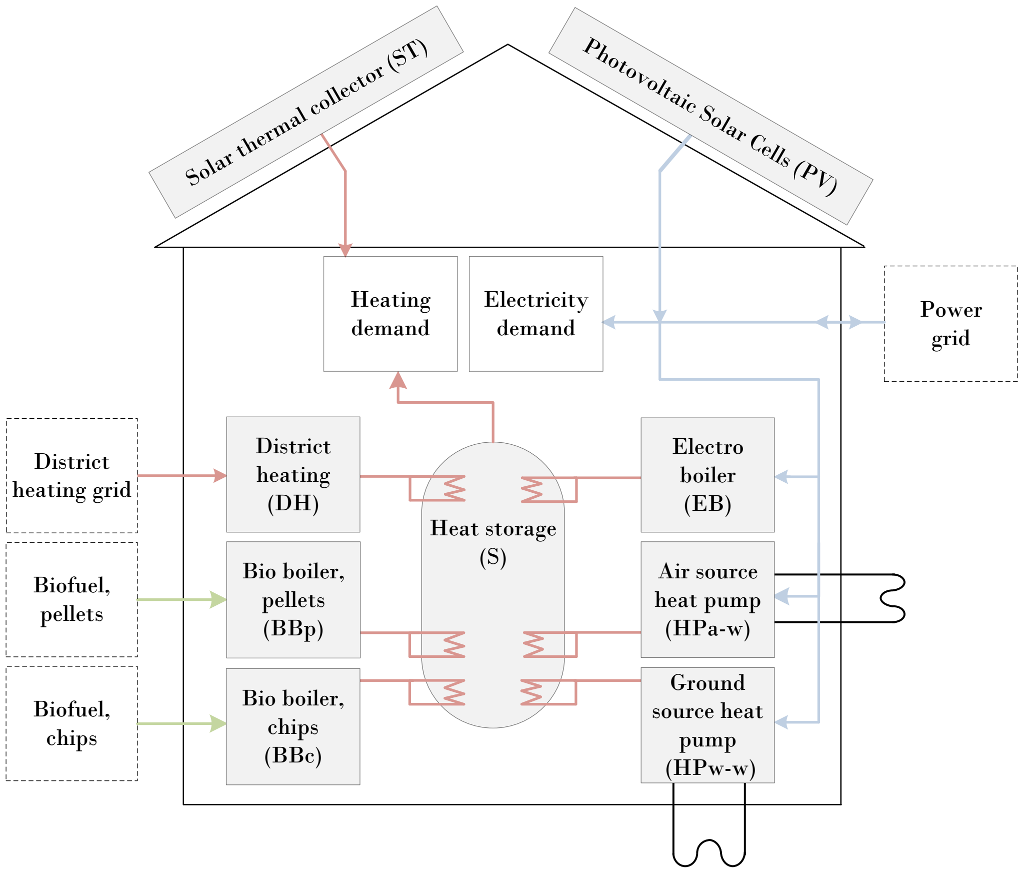

FIGURE 3.1: Overview of energy technologies available for investment in the model. Technologies is marked by shaded boxes. The demand of the building is marked by solid line boxes, while the fuel supply and connection to infrastructure is marked by dotted line boxes.

be steady state. In the model, it is assumed that the building does not affect any of its surroundings, and that any of the energy technologies installed will influence the energy use in the building. It is further assumed that the building has an hydronic heat distribution system, and that the installation cost of this is included in the cost of the building. The cost of the building is included in the modelling framework, however, these costs are set to zero, and not included in the analysis of the results of the model.

Costs of the installation of the electrical system are not included. The building is assumed to have installed electric installations within the building, and an additional strengthening of this system is not included. In the model, the cost of electric power is defined as the costs of buying power only.

The heat storage is assumed to have a temperature differential of 45°C. There are assumed no charging or discharging restrictions of the storage, though this is developed as an optional feature in the model. The model is running on an hourly resolution, and it is supposed that it is realistically that the storage could be emptied within one hour if wanted. Further there is no separation of different heat levels within the heat storage. For delivering heat to the decried temperature, accumulator tanks are usually divided into differ temperature levels. By leaving out the temperature gradients in the heat storage the model gets simplified. However, when optimizing the size of heating storages, the changes in the heating demand will be the deciding factor for the optimal solution of the storage. Temperature division of storages may play a larger role when deciding the size of the storage [37].

Intentionally no constraints of the area available for the PV modules or solar collectors is included. Nor are grid limitations included. This is done to compare the technologies based on their profitability, without limitations that are building specific. Limitations to the grid is analysed by including an optional restriction of the grid. This will be further elaborated in section 5.5.

The biomass boiler is modelled with the restriction of a minimum production of 50 kWh/h. This is a general assumption made to prevent the biomass boiler from running with too low a capacity, as discussed in section 2.6.

In the model two different types of biomass boilers are included, one biomass boiler using pellets as fuel, and one biomass boiler using wood chips as fuel. The two biomass boilers are modelled identically, but their input data is different. However in the analysis only the pellet boiler is set to be a possible investment. This was done to reduce the number of available technologies, and thus the complexity of the analysis. Taking to account the uncertainties by variations of cost due to local variations for biomass systems, the pellet biomass boiler is assumed to cover the general option of a biomass boiler.

3.2 Optimization Method

The model developed is a deterministic dynamic mixed integer programming model, and will analyse energy supply to a building over the full lifetime of 60 years. A deterministic model implies, as discussed in section 2.2, that the input parameters only has static values, and no uncertainties of the input parameters are included. Uncertainties in key input parameters are however still considered by including sensitivity analysis, presented in section 6.8. The model is dynamic by including time steps of one hour, for a given number of periods within the lifetime of the building. Thus the optimal operation strategy of the building will be achieved in hourly resolution, as further discussed in section 6.3. The model will include binary decisions for running of the biomass boiler, solar collector and semi-linear investment cost.

3.2.1 Multiple Objective Functions

Initially the intention was to develop an optimization model with multiple objective functions. This strategy was pursued for a while. There are several options to how multiple goal functions can be handled, but no flawless way of doing it. In [12] two strategies are presented. One strategy is to run the model with several objectives after each other, and then analyse the different solutions to find an optimal combined solution. The second option is to minimize a weighted sum of the objectives of interest [12].

The latter alternative has been tested out for this model. The results of optimization run with multiple objective functionsis presented in appendix E. When an objective is the weighted sum of different linear constraints, the weighting factor could play a large impact on the finished optimal solution. In this model the goal is to minimize the emissions and the costs. By using the weighted sum of emissions and costs, proper relations between the benefit of the emissions and cost needs to be considered. One possible option could be to place a carbon cost on emissions, to minimize a goal function in monetary terms only.

However, as seen by the results in table E.1 in appendix E, minimizing emissions and costs gave results that is little use of, and a more accurate and deliberate weighing factors would need to be developed. Consequently, it was decided to further develop a model with a single objective of minimizing costs only, and at the same time add zero-constraints to CO_2 emissions and primary energy use.

To limit the solution space, as discussed in section 2.2 and to avoid unbounded solutions, a maximum value of installed capacity of all technologies is set to 1000 kW.

3.2.2 Mosel Xpress

The optimization problem was developed in the Mosel modelling environment, and solved with the FICO®Xpress Optimization Suite platform. Further details of the

Mosel language, can be found in [50]. Details of the FICO®Xpress Optimization Suite can be found in [50].

3.3 Model Outline

In figure 3.2 the outline of the model is presented. The input variables will be presented in chapter 4, the mathematical framework representing the optimization model will be treated in detail in chapter 5, while the results of the model will be analysed in chapter 6.

FIGURE 3.2: Outline of the model showing the input data to the model (further discussed in chapter 4), the modelling framework (further discussed in chapter 5), and the structure of the results as output from the model (further discussed in chapter 6).

Chapter 4

Input data

This chapter presents the input data used in the optimization model, as well as assumptions and simplifications made in the collection phase. Public charges and relevant public guidelines will be presented where relevant. Input data are in general taken from public cost analysis reports and provided from energy companies or suppliers.

Information of the technical installations are mainly gathered from the *ZEB Cost Database* developed in the project work by Løtveit (2013) [51], and the periodical report 'Kostnader ved produksjon av kraft og varme' (2011) [52] given out by NVE, where specific costs of heat and power generation is summarized.

Prices for heat and power is provided from the producers and grid companies in Oslo [53], [54] and [55], whereas bio fuel cost is gathered from NVE's report [52].

Load profiles for the building, thermal solar heat production series and PV generation are provided by Karen Byskov Lindberg [49], Fraunhofer Institute for Solar Energy Systems (ISE)[56] and Multiconsult [57] respectively.

Input data for the constant crediting factors, carbon emission factors, and primary energy factors are obtained from Dokka et al. [58] and the draft report by CEN [15].

The costs in this report are presented exclusive value added tax (VAT). No subsidies are included in the cost data for the technologies. The cost are representative for the Norwegian market. Where the input data that might vary regionally within Norway, data for Oslo or central eastern Norway, are used.

4.1 Load Profiles

For every hour, the energy demand need to be meet by energy supplied from the grid or from installations in the building. The building analysed is a 10,000 m^2 passive house school building. The energy demand profiles used in this work, are predicted heat- and electricity load for a passive school building in the Drammen area [49]

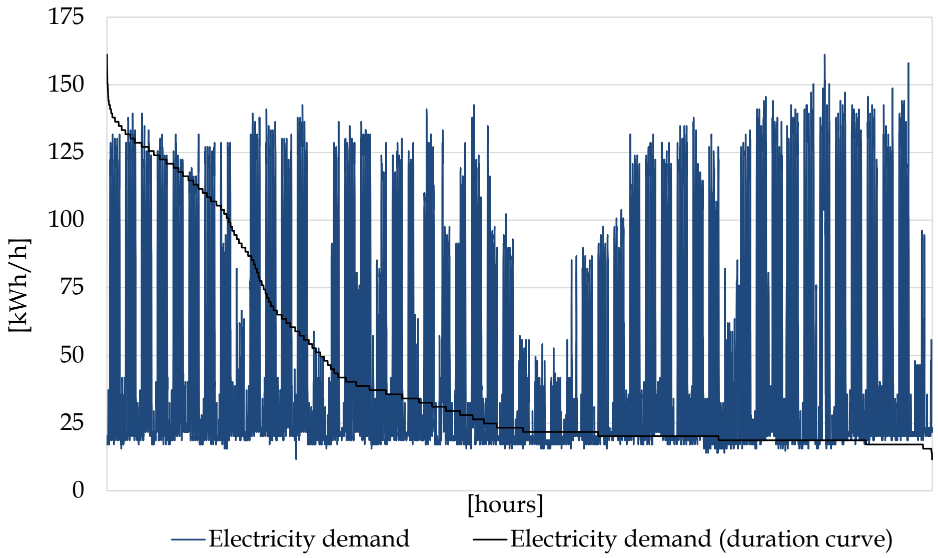

FIGURE 4.1: Electricity demand profile for a 10,000 m^2 passive school in south-eastern Norway for 2012.

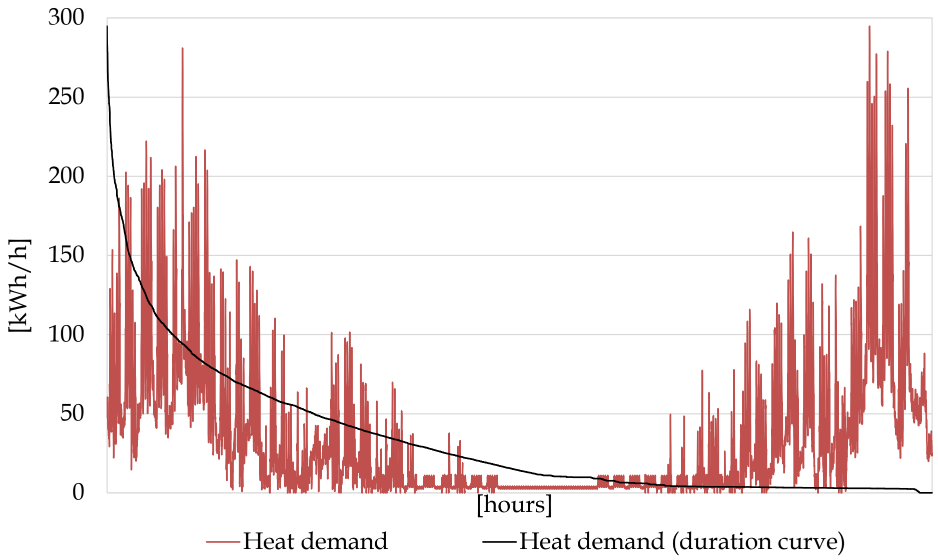

FIGURE 4.2: Heat demand profile for a 10,000 m^2 passive school in south-eastern Norway for 2012.

The total energy demand of the 10,000 m^2 building is 677 MWh. The energy input data is in time steps of one hour. In the analysis, the energy demand of the year 2012 is applied. 2012 was a leap year, thus for compliance with other production data series, the demand data of February 29th is excluded in the analysis. This is also the case for the spot price of electricity for the leap day of years with a leap day.

The maximum peak electricity demand during one hour was 161 kWh/h, and the lowest electricity demand was 11.6 kWh/h. The total annual electricity demand of the school is higher than the heating demand, with 381 MWh in 2012. The electricity demand per hour over the whole year of 2012, as well as the duration curve for electricity is visualized in figure 4.1.

The total heat demand for hot water and room heating is 296 MWh, or 29.6 kWh/m^2. 295 kWh/h is the highest heat demand during one hour of the year, while the lowest heat demand is 0 kWh/h. During 131 hours of the year, there is no heat demand in the building. The duration curve of the heat demand and the hourly heat demand values of 2012 is shown in Figure 4.2.

4.2 Investment Cost

The accuracy of an optimization model will be no better than the input data to the model. However, to make a generic model, simplifications in the modelling, and in the gathering of input data needs to be performed. The applicability to different building types, is a core aim for this model, hence the input-data needs to be generalized. The costs and efficiency of the technologies, together with the environmental properties, will be the basis of how the different technologies are compared in the model.

Several assumptions has been done in the gathering stage of investment costs. In this model, all investment costs are assumed to have linear or semi linear behavior. This is a simplification performed, due to the nature of the optimizing problem, as discussed in 2.2. Linear installation costs without a fixed element implies that the marginal cost of installing the first kW is the same as the last. In reality, this will not be the case. Generally, larger producing units will have lower specific cost of energy than smaller units. In real life, technologies are produced in limited options of sizes [26]. However, in the model it is assumed that all technologies are available in a infinite number of possible sizes.

TABLE 4.1: Investment Costs of Technologies

Tech.	Investment cost		Source	
	[Euro/kW]	[NOK/kW]		
PV	2,170	18,000	Multiconsult (2013)	[25]
ST	$275^{(1)}$	$2280^{(1)}$	Løtveit, NVE (2012,-11)	[51, 52]
HP_{w-w}	$325+675^{(2)}$	$2.700+5,600^{(2)}$	Løtveit (2012)	[51]
HP_{a-w}	512	4,250	SGP (2014)	[59]
$BB_{pellets}$	482	4,000	NVE (2011)	[52]
BB_{chips}	542	4,500	NVE (2011)	[52]
EB	145	1,200	SGP (2005)	[60]
DH	$6,024 + 60^{(3)}$	$50,000 + 500^{(3)}$	Hafslund (2014)	[55]
S	$90^{(4)}$	$750^{(5)}$	Lotveit (2012)	[51]

(1) Specific cost solar collector of $70m^2$. (2) Energy well for ground source heat pump. (3) District heating connection fee (fixed) [Euro] + District heating connection fee (specific). (4) Euro/kWh. (5) NOK/kWh. Exchange rate: 8.3 (20/06/14)

Several factors will play a role in the cost of installing and operating the different technologies, and what is included in the cost estimates of the different energy alternatives presented, may vary. Where mounting cost is available, as for the investment costs gathered from [51], this is included. Additional piping cost within the building is not included. If mounting cost are not specified, the system cost is used if provided.

No VAT or specific subsidies is included in the input cost. The investment cost of the available technologies are presented in table . For life time adjusted investment cost, see appendix B.

The investment cost of PV is from the report "Kostnadsstudie Solkraft i Norge 2013" [25] by Multiconsult for Enova. The specific investment cost of 2170 Euro/kWp (18,000 NOK/kWp), is the system price for a 100 kWp system of a commercial building.

For solar thermal collectors, the heating cost database by NVE [52] is used as source for the investment cost. The cost of a tap water heating system of an area between 50 to 50,000 m^2, is said to be in the range of 1500 to 2500 NOK/m^2 or 180 to 300 Euro/ m^2. The cost used in the analysis is 2000 NOK/m^2 or 240

Euro/m^2 [52]. For mounting costs the database by Løtveit is used. For flat plate collectors, the average mounting cost is 21,000 NOK or 2530 Euro [51]. The investment decision of the solar thermal collector is a binary investment decision, as the energy production of a ST-system will be highly dependent on the size of the solar thermal collector installed. The ratio of energy delivered and collector area installed will not be linear in the same way as can be assumed for the PV or heat pump technologies. Thus, the fixed investment cost of ST will be 240 Euro/m^2 multiplied by the collector area of the ST-collector simulated (70 m^2), in addition to the mounting cost of 2530 Euro [51]. No specific cost is used, and it is assumed that no other capacity than the one stated could be invested.

The investment cost of a ground source water-to-water heat pump used, consist of one fixed part and one specific part. The price is found by the assumption that the heat pump invested would be in the range of 100 kW. The specific investment cost is thus the average investment costs of water-to-water heat pumps in the range of 90kw to 110kW. From the cost database from Løtveit, the average cost of heat pumps from the supplier SGP is 2700 NOK/kW or 325 Euro/kW without an energy well, but including mounting and other equipments [51]. The price of an energy well is for the same capacities 5600 NOK/kW or 675 Euro/kW. The lifetime of the heat pump and the energy well is assumed not to be equal as further described in 4.4. When the investment cost is discounted, the prices of the heat pump and the energy well is allocated together in one specific investment cost, as seen in table B.2.

For the air source air-to-water heat pump, only specific investment cost is used. An estimate by SGP for specific price of a 100 kW air-to-water heat pump is 301 Euro/kW or 2500 NOK/kW [59]. This price is not including heat exchangers, circulation pumps, control systems or mounting cost. However, due to lack of more specific data, this is the specific cost used.

Only one of the biomass boilers is chosen to be active in the analysis. Still, in the model two types of biomass boilers are included and input data is collected. The two types of biomass boilers of which data is collected, is a pellets boiler and a boiler for moist chips. The heating cost report by NVE presents investment costs of a 1MW pellets boiler, with the total specific investment costs of 482 Euro/kW or 4000 NOK/kW [52]. For a biomass boiler using biomass chips with the water content of 50%, the total specific investment costs is 542 Euro/kW or 4500 NOK/kW. 1MW biomass boiler is about ten times larger than the expected capacity of a biomass investment for the passive house school. Still due to lack of accurate data for smaller units of biomass boilers, this cost data is used.

The cost of connecting with the district heating grid for the costumer, usually covers the real cost of connection [61]. The investment cost and district heating charges used in the simulations, are based on the district heating supplier in Oslo, Hafslund's costs. The district heating investment costs for Hafslund's costumers is an one-time fee. The one-time fee is calculated by a formula with a fixed charge, and a specific charge. For a connection to Hafslund's grid, the fixed charge is 50000 NOK/kW or 6024 Euro/kW, and the specific charge 500 NOK or 60 Euro [55]. The one-time fee covers all costs concerning connection to the district heating grid for the consumer. Heat exchangers, which must be exchanged regularly, is under normal conditions covered by the annual charge that applies for Hafslund's costumers. It is assumed that the building will be within the area for the district heating grid, if district heating gird is chosen as an investment. Further details on how the costs of connection to district heating are decided can be found in [48].

The accumulator tank used for a heat storage could be installed in a wide range of capacities. The investment cost is gathered from the database by Løtveit [51], as the average price of accumulator tanks in the range of 600-5000 liters. The average specific investment cost in the analysis is 90 Euro/kWh, or 750 NOK/kWh. Details on the calculation of specific investment cost of electric boiler is found in appendix C.

4.3 Operational Costs

The operational costs of the technologies are given as a percentage of the total investment cost. The operational cost used in the analysis is presented in table 4.2. The specific investments costs are being adjusted for lifetime differences. The operation costs have been adjusted for lifetime in the same way. The operational costs used as input to the model in D.2 is the same operational costs as presented in table 4.2, but modified for the differences in life times of the technologies.

Variations in operational costs is likely. For the biomass boilers, the operation and infrastructure for the operation of the boilers may be important. For the district heating system no other operational cost than what is included in the annual charge is included. The heat storage is assumed to have negligible operational costs.

Table 4.2: Yearly Operational and Maintenance(OM) Costs and Lifetime of Technologies

Technology	**OM cost**$^{(1)}$		**Lifetime**	
	[%]	Source	[Years]	Source
PV	2.0	Multiconsult [25]	25	Multiconsult [25]
ST	1.0	SINTEF [26]	20$^{(3)}$	
HP_{w-w}	3.0	Statsbygg [31]	15,40$^{(2)}$	ENOVA[62], Novema [63]
HP_{a-w}	3.0	Statsbygg [31]	15	ENOVA[64]
BB_{chips}	5.5	Hohle [34]	20	Hohle [34]
$BB_{pellets}$	3.0	Hohle [34]	20	Hohle [34]
EB	2.0	SINTEF [26]	20	NVE [52]
DH	0$^{(3)}$		60$^{(4)}$	
S	0$^{(3)}$		20$^{(5)}$	

(1) Operational and Maintenance cost given as % of investment cost. (2) Lifetime of energy well. (3) Assumed value. (4) Life time of pipes and substation, changes included in energy cost from district heat supplier. (5) Assumed equal lifetime as the electric boiler.

4.4 Lifetimes

With some minor variations, the expected lifetimes in table 4.2 are corresponding to life times used in analysis by [26, 52, 65, 66], amongst others. Life time for district heating is set to 60 years which is the same lifetime as the building, as the connection-fee is a one time fee. The life time of the energy well of the ground source heat pump is assumed to have 40 year life time, while the heat pump is assumed to have a life time of 15 years, only.

4.5 Efficiencies

The efficiencies of the technologies used in the analysis is presented in table 4.3. The COP of the air-to-water heat pump is calculated by hourly values based on equation (2.7) in section 2.6. The ambient temperature of the building is provided in correspondence to the heat demand load profiles by [49]. The temperature from the heat pump to the heat storage is set to be 45°C. The goodness factor, for calculating the COP_{aw} is based on the report by Fraunhofer ISE [33]. The goodness-factor used is the value of 0.4.

The ground source heat pump is assumed to have a COP of 3.2, based on the input data for ground source heat pump provided by [51].

The efficiencies of the biomass boilers are based on the report by NVE, and corresponding to the investment cost data for the biomass boilers. There are assumed no losses from the district heating on the consumer side of the heat use metering. For the heat storage, one percentage losses is used in the analysis. The effect of higher losses in the storage is investigated in section 6.8.

TABLE 4.3: Efficiencies of Technologies

Technology	Definition	Value	Source
HP_{w-w}	Coefficient of performance, COP_{w-w} (from supplier)	(3.2)	Løtveit [51]
HP_{a-w}	Coefficient of performance, COP_{a-w} (calculated from hourly ambient temperature)	average: (3.5)	(1)
BB_{chips}	Efficiency of boiler	85%	NVE [52]
$BB_{pellets}$	Efficiency of boiler	90%	NVE [52]
EB	Efficiency of boiler	98%	SINTEF [26]
DH	Efficiency of heat exchanger	100%(2)	
S	Efficiency of storage	99%	

(1) See section 2.6. (2) Assumed value.

4.6 Solar Irradiation Data

Inputs of solar data were provided by Multiconsult [57]. The solar data is from the solar simulation program PVsyst V6.11 with data from Meteonorm7, and represents the PV generation data from an industrial building in Oslo. The total direct electricity output to the grid was given in hour-resolution.

The production series of the thermal solar collectors were provided by Fraunhofer ISE [56]. The production series is from simulation run with ColSim 0.63 with data from Meteonorm7, and is specific to a plane solar collector of the size of 70 m^2. The attainable energy production from ST will be specific to the heat demand of the building. In the simulations, solar irradiation data for southern Norway is used.

4.7 Energy Cost

4.7.1 Electricity Bought

The energy price of buying is calculated according to equation (2.8). The grid rental charges of buying electricity from the grid is calculated accordingly to equation (2.9).

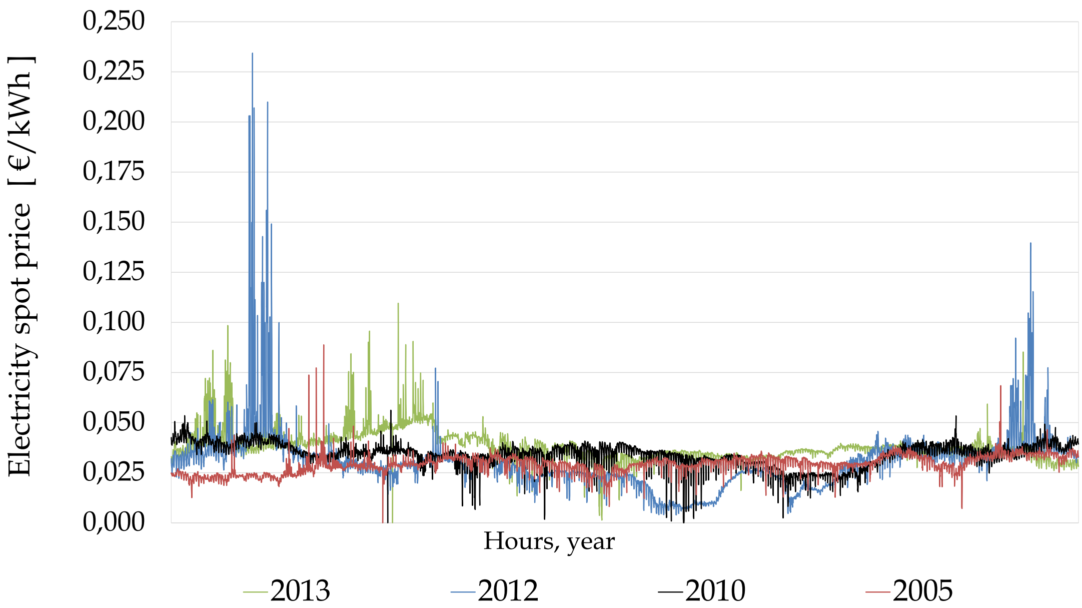

FIGURE 4.3: Electricity spot price profiles for 2013, 2012, 2010 and 2005. 2012 is the reference spot price profile. 2005 represents a low price level year, 2010 a medium price level year, while 2013 was a high price level year.

The spot price of electricity is obtained from Nord Pool Spot [67]. In figure 4.3 the electricity price profiles of 2013, 2012, 2010 and 2005 are shown. 2012 is the reference price profile. 2012 had a low annual average electricity price level, but with high peaks during winter, and low prices during summer. 2005 represents a low price level year, 2010 a medium price level year, while 2013 was a high price level year. 2012 is the basis year used in the analysis if not specified otherwise, while the spot price profiles for 2013, 2010 and 2005 is used when the results are tested for changes in the spot price levels in the sensitivity analysis, discussed in 6.8.

The electricity certificate charge used is 0.20 Euro cent/kW, and is obtained form Norwegian Energy Certificate System [42]. The electricity consumption tax was revised in 2014, and the value used is 1,49 Euro cent (0.1239 NOK) [45].

A summary of the grid charges for the companies providing electricity and district heating in the region is presented in appendix C. The variable charges on the energy price is from Hafslund Strøm. The grid charges used are based on Hafslund Nett's grid rental charges [53].

4.7.2 Electricity Sold

The price for electricity sold to the grid is based on Hafslund Nett's plus-costumer agreement, where the price for electricity sold equals the spot electricity price from hour to hour [68]. This is in line with the plus-costumer guidelines provided by NVE [47].

4.7.3 District Heating

The district heating prices used is the district heating charges applied by Hafslund Varme. The district heating charges are following the grid rental charges in structure, and the energy price is based on the spot price profiles from NordPoolSpot. Hafslund Varme operates with a price structure of district heating, where the cost of district heating, gets a 2% reduction to the price of electricity [55]. The prices of district heating, together with the district heating prices for the comparable district heating companies are provided in appendix C.

4.7.4 Biofuel

The biofuel prices are the prices provided in 'Kostnader ved produksjon av kraft og varme' [52]. For pellets, the cost is for bulk supplies is 0.33 NOK/kWh or 0.04 Euro/kWh. For wood chips, the price is 0.25 NOK/kWh or 0.03 Euro/kWh [52]. The prices are from 2010.

4.8 Primary Energy Factors

The primary energy factors are presented in table 4.4. The primary energy factors for electricity and biomass are obtained form the proposed European standard values in [15].

TABLE 4.4: Primary Energy Factors

Energy carrier	**Primary Energy Factor [kWh$_p$/kWh$_s$]**			
	Total		Non-renewable	
	Asymmetrical	Symmetrical	Asymmetrical	Symmetrical
Electricity import [15]	2.50	2.00	2.50	2.00
Electricity export [15]	2.00	2.00	2.00	2.00
Biomass pellets [15]	1.05	1.05	0.05	0.05
Biomass chips [15]	1.05	1.05	0.05	0.05
District heating (1)	0.70	0.70	0.70	0.70

(1) Calculated, based on local district heating supplier.

For electricity the PE factors are equal for total primary energy factors and non-renewable primary energy factors. Thus all primary energy used to bring electricity to the grid is based on non-renewable energy. For biomass, however, the total primary energy factor is higher than the non-renewable primary energy factor. This implies that in the processing of the biomass, most of the primary energy used is from the basis of renewable energy.

For both total and non-renewable primary energy factors, symmetrical and asymmetrical factors are presented. For symmetrical primary energy factors the primary energy factor of export and import of electricity are equal. The electricity sold to the grid is valued equally with the electricity bought from the grid. Contrary, for asymmetrical primary energy factors, the electricity imported has a higher primary energy factor than the electricity exported to the grid. Thus, to achieve a zero balance of primary energy use, more electricity needs to be exported than has been imported.

For the district heating, the factors for primary energy and CO_2 emissions will vary based on how the heat to the local district heating system is supplied. The

Primary energy factors used in this work is based on the district heating system in Drammen, the same place as the school where the heating demand profiles used is estimated. The energy supply for the district heating is based a 15 MW sea-heat pump and 8 MW biomass boiler for base load [69]. By using the same primary energy factors for biomass and electricity as presented in table 4.4, and a COP of 3.2, the corresponding primary energy factor of district heating will be 0.7 [kWh_p/kWh_s].

4.9 CO_2 Emission Factors

Table 4.5 shows the CO_2 factors used in the analysis. The European CO_2 factors for European and Norwegian conditions are gathered from the proposed European standard values, [15] and proposed values for Norway by Dokka et al. [58].

TABLE 4.5: CO_2 Factors

Energy carrier	**CO_2 factor [g CO_2-eq/kWh]**	
	Norwegian factors *(NOR)*	European factors *(EN)*
Electricity import	130 [58]	350 [15]
Electricity export	130 [58]	350 [15]
Biomass pellets	7 [58]	14 [15]
Biomass chips	4 [58]	14 [15]
District heating (1)	40	40

(1) Calculated, based on local district heating supplier.

The largest difference between the European and Norwegian CO_2 factors, are that the CO_2 factor for electricity is 2.7 times larger for European than Norwegian values. Also biomass has double, or more than double the value for CO_2 factors of biomass with European values. The Norwegian CO_2 factors are thus favouring the use of electricity and biomass for energy supply, in comparison with European factors. This could be based of the national energy resources, as well as political decisions.

The CO_2 factors for district heating is calculated on basis of the district heating system in Drammen, in the same fashion as the primary energy factions in section 4.8.

4.10 Economic Parameters

The exchange rate used throughout the work is 8.3 NOK/Euro. This was the exchange rate between Euros and Norwegian kroner the 20th June 2014 [70]. The discount rate used is 6%.

Chapter 5

Mathematical formulation

This chapter presents the mathematical framework of the model for optimal investments of energy technologies in ZEBs, developed in this thesis. The optimizing model is a deterministic dynamic mixed integer programming model as discussed in section 2.2. The formulation of the model is based on the principles introduced in section 2.2. The goal function of the model is to minimize the total discounted cost subjected to constraints framing the behavior of a zero emission building, in addition to available energy supply technologies as well as alternative constraints on the performance of the building.

This mathematical formulation show in detail how the physical constraints of the building is modelled in terms of the optimization performed.

The first part of this chapter defines and describes sets, indexes, variables and parameters as the dimensions of the model. Following are the equations restricting the model. The constraints concerning the performance of the building; cost, CO_2 emissions, primary energy use and electricity export will be presented first. Subsequently the constraints of electricity balance, heat balance and energy balances of the technologies are described. The full code written in Mosel can be found in appendix F. Screen dump of input files for alternative constraints and input parameters is in appendix D.

5.1 Sets and Indexes

This optimization model is designed to optimize the energy production for different energy sources that could be utilized in a ZEB. To describe the dimensions of the model compactly, data is organized within indexed sets. Sets are finite, given by the choice of how large the model should be in terms of technologies and periods analysed.

TABLE 5.1: Declaration of Indexes

Description	Index
Technology	i
Energy carrier	e
Hour	t
Month	mth
Year	yr
Period	p

The dimensions of the model is shown in table5.1, where the indexes are displayed. The index i, represents possible energy supply technologies. Properties corresponding to the energy carrier utilized is indexed by e. The time steps within one year are indexed by t. Time dimensions of month, year and period of analysis are represented by the indexes mth, yr and p respectively.

TABLE 5.2: Description of Sets and Subsets

Description	Set	Index
Set of energy technologies	I	i
Subset of I, heat technologies	I_{heat}	i
Set of energy carriers	E	e
Set of time steps during one year, starting from t=0	TT	t
Subset of TT, time steps, starting from t=1	T	t
Set of months within each year	MTH	mth
Subset of MTH, set of winter months	MTH_w	mth
Subset of MTH, set of summer months	MTH_s	mth
Set of years within each period	YR	yr
Set of periods within the optimizing period	P	p

The indexes in table 5.1 are corresponding to the sets presented in table 5.2. The sets classifies the data input of the model. I is the set containing all the technologies modelled, and the sub-set of I_{heat} are those technologies in I that has a demand of energy to produce heat. The number of periods, P, within the total optimizing period determines the time frame of the optimizing. Each period consist of a set of years, YR. Within each year, there is a set of time steps T, and a set of months M. The time steps T is equal every year, representing the consecutive hours within a year. The set of months M has two sub-sets MTH_w and MTH_s. This is to include parameters with different input data for summer- and winter months. Similarly, TT contains the sub-set of T to be able to include initial values for variables, at t = 0.

The reason for dividing the model into years and periods is to be able to analyse results several years ahead, without having to run the optimizing for every consecutive year. However, for discounting of operational costs, the dimension of years needs to be included. The periods allow for stepwise changes in input parameters over the whole period of analysis.

Table 5.3: Description of Elements in the Sets and Subsets

Set / Subset	Elements	
Energy technologies	$I = \{PV, ST, HP_{w-w}, HP_{a-w}, BB_p, BB_c, EB, DH, S\}$	
Heat technologies	$I_{heat} = \{HP_{w-w}, HP_{a-w}, BB_p, BB_c, EB, DH\}$	
Energy carriers	$E = \{EL_{imp}, EL_{exp}, BIO_p, BIO_c, HEAT_{dh}\}$	
Time steps, from t=0	$TT = \{0, ..., TN\}$	where $TN = 8760$
Time steps, from t=1	$T = \{1, ..., TN\}$	where $TN = 8760$
Months	$MTH = \{1, ..., MTHN\}$	where $MTHN = 12$
Winter months	$MTH_w = \{1, 2, 3, 11, 12\}$	
Summer months	$MTH_s = \{4, 5, 6, 7, 8, 9, 10\}$	
Years	$YR = \{1, ..., YRN\}$	
Periods	$P = \{1, ..., PN\}$	

In table 5.2 the sets are defined as used in the simulations. All the sets are created based on input data.

The technologies available for investment are photovoltaic solar cells (PV), thermal solar collectors (ST), ground source water to water heat pump (HP_{w-w}), air to water heat pump with ambient air as heat source (HP_{a-w}) and biomass boilers with pellets (BB_p) or wood chips (BB_c), respectively as fuel. Additionally electric boiler (EB), connection to the district heating grid (DH) and a heat storage unit (S) is included in the set of (I). The technologies are discussed in detail in section 2.6. For the energy balances, (PV), (ST) and (S) are treated differently due to their nature or input data. The rest of the heat producing technologies are modelled in a comparable manner, and are therefore gathered in the sub-set I_{heat}.

The crediting factors of energy are linked to energy carriers, as seen in figure 2.2. The energy carriers utilized by the technologies in set I are electricity imported from the grid (EL_{imp}), electricity exported to the grid (EL_{exp}), biomass as pellets (BIO_p), biomass as wood chips (BIO_c) and heat from the district heating grid($HEAT_{dh}$).

For a standard year except leap year, the total numbers of hours are 8760. The major part of the constraints is defined within the subset TT, starting from hour 1. For the energy storage however, the state before the first hour needs to be known. Thus, for initial conditions of the heat storage, the full set of TT, staring from hour 0 is used.

The set M contains all the twelve months of the year, whereas the subset M_s contains the months of April through October, and M_w the months November to March. The sub sets are used for calculating peak power charges on electricity and heat district heating. The peak power charges are decided by the grid companies as discussed in section 2.7. The elements of M_s and M_w presented here is corresponding to the input data in section 2.7.

5.2 Variables

The values of the variables is the optimal solutions to be found by the model. In the model, small letters are used for variables, and large letters for parameters. All of the variables are continuous and non-negative, except if otherwise specified. Binary variables are denoted by the Greek letter δ. The variables are presented in table 5.4.

In the model the letter x represents installed capacities for the respective technologies or maximum values for the grid. $x\,(i,p)$ has only one dimension, and thus are the main decision variables. In the case of the heat pumps, electric boiler, biomass boilers and district heating the $x\,(\text{"}HP_{w-w}\text{"},p)$ represents the installed capacity.

Table 5.4: Declaration of Variables

Description	Variable	Unit
Installed capacity of technology i	$x\,(i)$	kW
Binary variable, if investing in technology $i = 1$	$\delta_{x,inv}\,(i)$	$\in \{0,1\}$
Grid, peak value import	$x_{imp,max}$	kWh/h
Grid, peak value export	$x_{exp,max}$	kWh/h
Electricity imported from grid at time t	$y_{imp}\,(p,t)$	kWh/h
Binary variable, if importing from grid $i = 1$	$\delta_{imp}\,(p,t)$	$\in \{0,1\}$
Electricity exported to grid at time t	$y_{exp}\,(p,t)$	kWh/h
Binary variable, if exporting to grid $i = 1$	$\delta_{exp}\,(p,t)$	$\in \{0,1\}$
Electricity produced by PV, at time t	$y_{PV}\,(p,t)$	kWh/h
Peak electricity import, highest t per month m	$ppm_{imp}\,(p,m)$	kWh/h
Heat provided by heat technology i, at time t	$q\,(i,p,t)$	kWh/h
Heat injected to heat storage S at time t	$u\,(p,t)$	kWh/h
Heat stored in the heat storage tank at time t	$s\,(p,t)$	kWh/h
Electricity consumed by HP_{ww} at time t	$d_{HP_{ww}}\,(p,t)$	kWh/h
Electricity consumed by HP_{aw} at time t	$d_{HP_{aw}}\,(p,t)$	kWh/h
Electricity consumed by EB at time t	$d_{EB}\,(p,t)$	kWh/h
Bio fuel, pellets, consumed by BB_p at time t	$b_{BB_p}\,(p,t)$	kWh/h
Bio fuel, chips, consumed by BB_c at time t	$b_{BB_c}\,(p,t)$	kWh/h
Heat taken from DH grid at time t	$h_{DH}\,(p,t)$	kWh/h
Peak DH import, highest t per month m	$ppm_{DH}\,(p,m)$	kWh/h
Emissions, total	g_{tot}	$g\ CO_2\ eq$
Primary energy use, total	pe_{tot}	kWh_p
El exported, total	$export_{tot}$	kWh
Total cost, total	$cost^{TOT}$	Euro
Investment cost, total	$cost^{INV}_{tot}$	Euro
Running cost, annual	$cost^{RUN}_{tot}\,(p)$	Euro/yr

To handle the semi-continuous modelling of the investment cost, a binary variable, $\delta_{x,inv}(i)$, correlating to the investment of a technology, $x(i)(p)$ is needed for all technologies. In the case of photovoltaic solar system, $x("PV", p)$ represents the nominal installed capacity.

Heat production data for the thermal solar collector is for a given size of $70m^2$, as discussed in section 4.6. Investment of ST is therefore a binary decision variable. $\delta_{x,inv}(i)$ equals one if ST is chosen to be invested, and zero otherwise. $x_{imp,max}$ and $x_{exp,max}$ are the highest effect of import and export of electricity of one hour during the period of analysis.

The letter y represents hourly values of electricity supplied or exported. $y_{imp}(p,t)$ is the import of electricity from the grid to the building at hour t in period p. $y_{exp}(p,t)$ is the electricity sold to the grid. To prevent the building form buying and selling electricity to the grid at the same time binary variables for import and export is introduced. This is further explained in constraints (5.17), (5.18) and (5.19). Electricity production from the PV-panels at every time step is stored in $y_{PV}(p,t)$. $ppm_{imp}(p,m)$ is the electricity bought from the grid at the hour with the highest peak power per month.

q represents hourly values of heat flows in the building. $q(i,p,t)$ is the supply of heat from technology i in hour t in period p. q_{ST} is the heat provided from the thermal solar collector ST, if ST is chosen as an optimal investment. q_{ST} is denoted differently than the other heat producing technologies, in $q(i,p,t)$, due to the binary decision of ST.

$u(p,t)$ represents the net energy flow to the storage, S, and can be both negative and positive. $s(p,t)$ is the accumulated heat in the storage at the given time t and period p.

The technologies in I_{heat} need energy fuel or electricity to produce heat. For the heat pumps and the electric boiler, electricity consumption at a given time are the variables $d_{HP_{w-w}}(p,t)$, $d_{HP_{a-w}}(p,t)$ and $d_{EB}(p,t)$. Biomass consumption of the biomass boilers are $b_{BB_p}(p,t)$ and $b_{BB_c}(p,t)$. For the district heating system, the heat delivered by the district heating grid is $h_{DH}(p,t)$. Equivalent to the monthly highest peak power of the grid, $ppm_{imp}(p,m)$ the highest peak demand from the district heating grid per month is denoted $ppm_{DH}(p,m)$.

g_{tot}, pe_{tot} and $export_{tot}$ are the total emissions of CO_2 equivalents, primary energy use and total electricity exported over the whole period of analysis.

The total operational and investment cost discounted to year zero is the variable $cost^{TOT}$, while the total investment cost is $cost_{tot}^{INV}$. The operational cost is defined for each period, and represented by $cost_{tot}^{RUN}(p)$.

5.3 Parameters

The parameters are the input values to the model. The parameters in table 5.5 are presented in chapter 4. In table 5.5, $H_{acc,t,m}(mth)$ is an array containing the number of accumulated hours at the end of every month, and is used for computing the peak power price of electricity and district heating. R is the discount rate.

$Min_{prod,BBp}$ and $Min_{prod,BBp}$ are cut-off limits for heat production by the biomass boilers. The value decides how low the production of the biomass boiler can go, before it turns off.

While running the model in different modes, limits to the size of the storage could be useful. A restriction to how quickly the heat storage could be charged and discharged implemented by $Max_{charge,S}$. If no restriction to discharging, this is set to one, or to 100%. A limit to the highest capacity of storage that could be installed can be introduced in $Max_{inv,S}$.

As discussed in section 2.2, a restriction on the maximum values for the variables eases the solving of the optimizing problem. Thus the maximum investment range, $M_{inv,x}$ is a value set higher than a realistic value of $x(i)$ for all i excluding the storage, to limit the solution space of the optimizing problem. Consequently $Max_{inv,S}$ has the same function if the model is run by default.

Max grid connection Max_{grid} is a maximum reference for grid burden used for restricting the grid burden. This is further explained in equations (5.10) and (5.11). $\alpha_{exp,imp}$ and α_{exp} are coefficients for the grid burden restriction, while $\lambda_{\text{Grid Burden}_{exp,imp}}$ and $\lambda_{\text{Grid Burden}_{exp}}$ are control parameters for turning on and off the restriction on the grid burden.

G_{tot}^{REF} is a reference for CO_2 emissions, when relaxing the zero emission restriction. β is the relaxation coefficient. λ_{ZeroG} is a binary control parameter for the zero CO_2 emission restriction. Similar λ_{ZeroPE} is the reference and $gamma$ the relaxation coefficient for the zero primary energy restriction. λ_{ZeroPE} the binary control parameter. Restriction of the grid burden as well as relaxation of the zero emission- and the zero energy restrictions are further elaborated at the end of the chapter.

Table 5.5: Declaration of Parameters

Description	Parameter	Unit
Electricity demand of building	$D_{el}(p,t)$	kWh/h
Heat demand of building	$D_{heat}(p,t)$	kWh/h
Investment costs, specific	$C^{INV,spesific}(i)$	Euro/kW
Investment costs, fixed	$C^{INV,fixed}(i)$	Euro
Operational costs	$C^{RUN}(i)$	% of $C^{INV,tot}$
Power output of PV per kW_{PV} installed	$Y_{PV}(p,t)$	$(kWh/h)/kWp_{PV,inv}$
Heat output of ST if installed	$Q_{ST}(p,t)$	kWh/h
Coefficient of performance HP water-water	COP_{w-w}	$-$
Coefficient of performance HP air-water	$COP_{a-w}(p,t)$	$-$
Efficiency of BB, pellets	η_{BB_p}	%
Efficiency of BB, chips	η_{BB_c}	%
Efficiency of EB	η_{EB}	%
Efficiency of DH	η_{DH}	%
Efficiency of heat storage tank	η_S	%
Price of electricity bought from grid	$P_{EL_{imp}}(p,t)$	Euro/kWh
Price of electricity sold to grid	$P_{EL_{exp}}(p,t)$	Euro/kWh
Grid annual fixed charge	$GRYFCH$	Euro
Grid peak power charge summer	$GRPPCH_s$	Euro/$kWh_{h_{max,MTH_s}}$
Grid peak power charge winter	$GRPPCH_w$	Euro/$kWh_{h_{max,MTH_w}}$
Price of biofuel, pellets	P_{BIO_p}	Euro/kWh
Price of biofuel, chips	P_{BIO_c}	Euro/kWh
Price of district heating	$P_{DH}(p,t)$	Euro/kWh
District heating annual fixed charge	$DHYFCH$	Euro
DH peak power charge summer	$DHPPCH_s$	Euro/$kWh_{h_{max,MTH_s}}$
DH peak power charge winter	$DHPPCH_w$	Euro/$kWh_{h_{max,MTH_w}}$
Primary energy factors	$PE(e)$	kWh_{PE}/kWh_s
CO_2 emissions factor, grid hourly	$G_{EL_{imp}}(t)$	gCO_{2-eq}/kWh
CO_2 emissions factors, constant	$G(e)$	gCO_{2-eq}/kWh_s

Table 5.6: Declaration of Parameters continued

Description	Parameter	Unit
Investment cost of building	$INV_{cost,building}$	Euro
Embodied emissions in the building	$G_{embodied}$	gCO_2-eq
Embodied energy in the building	$PE_{embodied}$	kWh_p
Discount rate	R	%
Accumulated hours at end of month, mth	$H_{acc,t,m}\,(mth)$	h
Min production biomass boiler pellets	$Min_{prod,BBp}$	kW
Min production biomass boiler chips	$Min_{prod,BBc}$	kW
Max storage size	$Max_{inv,S}$	kW
Max storage charging rate	$Max_{charge,S}$	%
Max investment range	$M_{inv,x}$	kW
Max grid connection	M_{grid}	kW
Emissions, total reference	G_{tot}^{REF}	gCO_2-eq/yr
Primary Energy use, total	PE_{tot}^{REF}	kWh_p/yr
Max grid burden restriction, export+import	$\alpha_{exp,imp}$	$-$
Max grid burden restriction, export	α_{exp}	$-$
Relaxing of zero emission constraint	β	$-$
Relaxing of zero primary energy constraint	γ	$-$
If technologies are available	$\lambda\,(i)$	$\in \{0,1\}$
If zero emissions constraint is applied	λ_{ZeroG}	$\in \{0,1\}$
If zero primary energy constraint is applied	λ_{ZeroPE}	$\in \{0,1\}$
If grid burden restriction, export + import	$\lambda_{\text{Grid Burden}_{exp,imp}}$	$\in \{0,1\}$
If grid burden restriction, export	$\lambda_{\text{Grid Burden}_{exp}}$	$\in \{0,1\}$

5.4 Objective Function

The objective function of this dynamic model is to minimize the total cost, $cost^{TOT}$ over the full period of analysis. The goal function is presented in equation (5.1). Further elaboration on the modelling of the goal function is found in section 3.2.

Objective function:

$$Minimize \ \{ \ cost^{TOT} \ \} \tag{5.1}$$

5.5 Performance Constraints

5.5.1 Total Costs

The total cost is the sum of the total investment cost of all the selected technologies to invest in, and the running cost throughout the analysis period. The total cost is presented in equation (5.2). Investment costs are adjusted for the lifetime of the respective technology, and discounted to year 0. This is further described in detail in appendix B.

The running cost ($cost^{RUN}_{tot}\,(p)$) are calculated for a year, thus the needs to be discounted, first to the beginning of the period (p), then to year zero. This is done according to equation (2.4) in section 2.5.

Total Costs:

$$cost^{TOT} = \ cost^{INV}_{tot} + \sum_{p \in P} \frac{1}{(1+R)^{YRN \cdot (p-1)}} \left(cost^{RUN}_{tot}\,(p) \cdot \frac{1}{(1+R)^{yr}} \right) \tag{5.2}$$

$cost^{RUN}_{tot}\,(p)$ is defined for every period, but is the annual running cost. I.e.the input parameters are set to be equal within each period, but might change between consecutive periods. Since the input parameters are constant every year of a period, the annual running cost will be equal for every year within the same period as well. This is visualized in Figure 5.1.

5.5.2 Investment Costs

All investments are implemented at the start of the period of analysis. If a technology is chosen, it is implicit that the same technology is reinvested throughout the lifetime of the building. The input values of investment costs are adjusted for lifetimes and the input values are the present net worth of the sum of investments of each technology through the full period of analysis. Details of the discounting of investment costs are summarized in appendix B.

The investment costs consists of two parts for each technology; a parameter for specific costs and a parameter for initial fixed costs. The specific costs are the investment costs of the technologies per unit kW installed. As discussed in section 4.2, ST only has a fixed investment cost, the investment cost of DH has a fixed and a specific investment cost and the remaining technologies has specific investment cost only. However, fixed and specific investment costs are declared for all technologies to increase flexibility and simplicity in the structure of the model. Investment cost of the building is included, though set to zero in the simulations in this thesis. The investment costs are presented in equation (5.3).

Investment cost(yr):

$$cost_{tot}^{INV} = INV_{cost,building} + \sum_{i \in I} \left(C_{spesific}^{INV}(i) \cdot x(i) \; + \; C_{fixed}^{INV}(i) \cdot \delta_{x,inv}(i) \right) \quad (5.3)$$

$$\forall \; p \in P$$

5.5.3 Operational Costs

The periodical operational costs are the net sum of income and running expenses for a year, and is expressed in equation (5.4).

The sum of operation and maintenance cost of the technologies for energy supply are modelled as an annual percentage of the total initial investment cost. For all technologies except solar thermal collectors this is modelled as a percentage of the specific investment cost, as discussed in section 4.3. If the solution is to invest in ST, if $\delta_{x,inv}$("ST") equals one, the running cost is set to be a percentage of the total fixed investment cost of a 70 m^2 collector.

Yearly Running cost:

$$
\begin{aligned}
& cost_{tot}^{RUN}(p) = \\
& \sum_{i \in I | i \neq ST} \Big(C^{RUN}(i) \cdot C_{spesific}^{INV}(i) \cdot x(i) \Big) \\
& \qquad + \; C^{RUN}(\text{"}ST\text{"}) \cdot C_{fixed}^{INV}(\text{"}ST\text{"}) \cdot \delta_{x,inv}(\text{"}ST\text{"}) \\
& + \sum_{t \in T} \Big(y_{imp}(p,t) \cdot P_{EL_{imp}}(p,t) \; - \; y_{exp}(p,t) \cdot P_{EL_{exp}}(p,t) \\
& \qquad + \; b_{BB_p}(p,t) \cdot P_{BIO_p} + b_{BB_c}(p,t) \cdot P_{BIO_c} \\
& \qquad + \; h_{dh}(p,t) \cdot P_{DH}(p,t) \Big) \\
& + \sum_{mth \in MTH_s} \Big(ppm_{imp}(p,m) \cdot GRPPCH_s + ppm_{DH}(p,m) \cdot DHPPCH_s \Big) \\
& + \sum_{mth \in MTH_w} \Big(ppm_{imp}(p,m) \cdot GRPPCH_w + ppm_{DH}(p,m) \cdot DHPPCH_w \Big) \\
& \qquad + \; GRYFCH + DHYFCH \\
& \qquad \qquad \qquad \qquad \qquad \forall \, p \in P
\end{aligned}
\tag{5.4}
$$

The net energy costs are summarized over all hours of the year. The income is the amount of electricity sold to the grid ($y_{imp}(p,t)$) times the price of selling electricity to the grid ($P_{EL_{imp}}$). For every hour (t), the energy costs are the amount of electricity, biomass or heat bought times the price of electricity, biomass or heat form the district heating grid.

For every month, a peak power charge of grid rental for electricity and district heating applies. The cost is given by the hour with the highest consumption of electricity ($ppm_{imp}(p,m)$), or heat ($ppm_{DH}(p,m)$) times the charge for monthly peak power, ($GRPPCH$) and ($DHPPCH$) respectively. This charge varies between the winter and summer.

Finally, an annual fixed charge for electricity ($GRYFCH$) and district heating ($DHYFCH$) applies if invested.

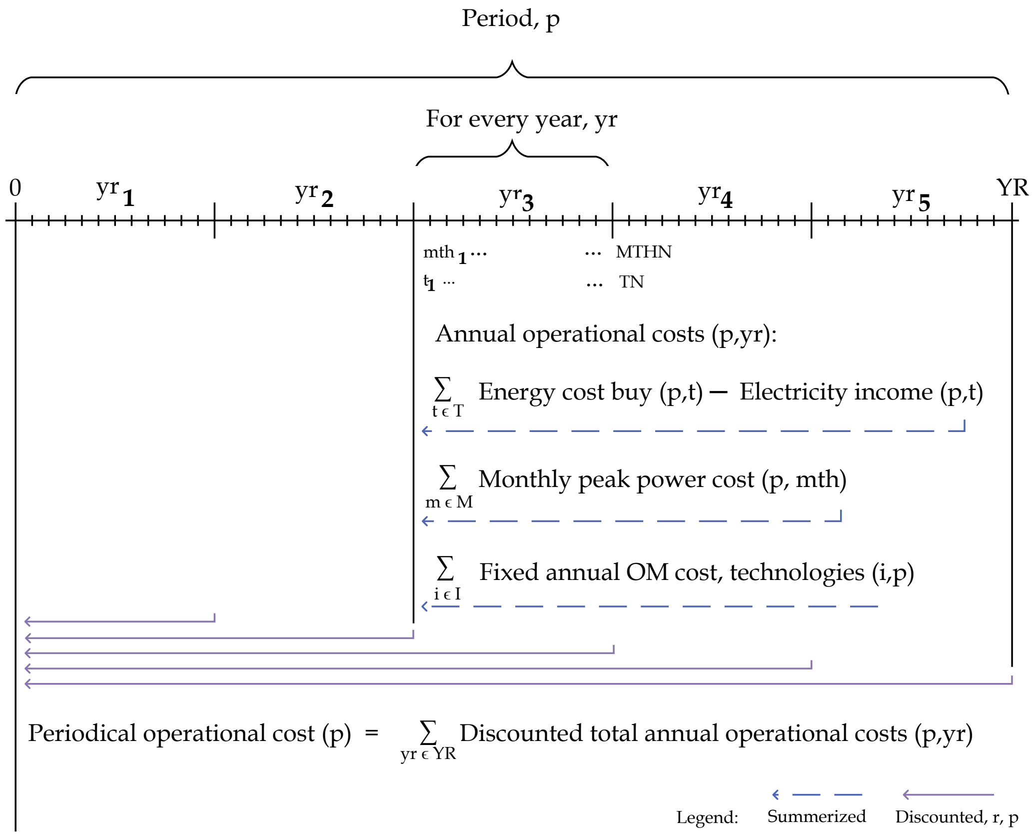

FIGURE 5.1: Discounting of operational cost within a period (p). For every year the annual costs are summarized, and discounted to the beginning of each period. For each period the sum of all discounted annual running costs within the period is discounted back to year zero.

5.5.4 Emissions

Equation (5.5) is the emission balance for the building in this model. Total emissions from the building is the sum of emission from energy fuel consumed by the heat technologies and emissions form electricity bought from the grid minus CO_2 emissions from electricity equal to the total export of electricity from the building. The electricity from PV generation are assumed to have no emissions during the analysis period. The electricity exported is assumed to displace CO_2 emissions in the grid, thus having negative contribution to the emission balance of the building, as stated in figure 2.2.

The emission factors ($G(e)$) for all of the energy carriers except EL_{imp} are constant throughout the period. In the model the input of $G("EL_{imp}")$ has a possibility of hourly time series.

Total Emissions:

$$
\begin{aligned}
g_{tot} = \sum_{p \in P} \sum_{t \in T} \; YRN \cdot \Bigg(& h_{DH}(p,t) \cdot G(\text{"}HEAT_{DH}\text{"}) \\
& + \; y_{imp}(p,t) \cdot G(\text{"}EL_{imp}\text{"}) \; - \; y_{exp}(p,t) \cdot G(\text{"}EL_{exp}\text{"}) \\
& + \; b_{BB_c}(p,t) \cdot G(\text{"}BB_c\text{"}) \; + \; b_{BB_p}(p,t) \cdot G(\text{"}BB_p\text{"}) \Bigg)
\end{aligned}
\tag{5.5}
$$

For the zero emission balance, the sum of all emissions over the years needs to equalize CO_2 emissions displaced in the grid by the PV production exported. If emissions embodied in the building envelope is included, the embodied emissions in the building needs to be offset by the export of PV production as well. This balance is presented in equation (5.6).

Zero Emission balance:

$$
(g_{tot} + G_{embodied}) \cdot \; \lambda_{\text{ZeroG}} \; = \; G_{tot}^{REF} \; \cdot \; YRN \; \cdot \; PN \; \cdot \; \beta \tag{5.6}
$$

In the analysis a relaxation of the zero emission balance could be of interest. A possibility to relax the zero emission constraint is included in equation (5.6), where β is the relaxation coefficient, and λ_{ZeroG} a binary parameter given as input, deciding weather the constraint is active or not. The product of a reference value of total annual emissions (G_{tot}^{REF}) and the number of years for the whole optimizing period represents a maximum value for the relaxation. G_{tot}^{REF} is given as an input parameter. In the analysis performed, the reference value G_{tot}^{REF} is the annual emissions with no zero restrictions applied.

The relaxation coefficient β is a continuous variable, taking values between zero and one. $\beta = 0$ equals a strictly zero emission restriction, while $\beta = 1$ represents no restriction, corresponding to G_{tot}^{REF}.

5.5.5 Primary Energy Use

Corresponding to the CO_2 emission balance in equation (5.5), the sum of primary energy used throughout the whole period of analysis needs to be equalized by the primary energy of the electricity exported form the building to the grid. In equation (5.7) the total primary energy consumption is the sum of the energy consumed of the different energy carriers, $h_{DH}(p,t)$, b_{BB_p} and b_{BB_c} multiplied with their respective primary energy factors $PE\,(\text{"}HEAT_{DH}\text{"})$, $PE\,(\text{"}BB_c\text{"})$ and $PE\,(\text{"}BB_c\text{"})$. The electricity imported and exported might have different primary energy coefficients ($PE\,(\text{"}EL_{imp}\text{"})$ and $PE\,(\text{"}EL_{exp}\text{"})$, if asymmetrical primary energy indicators are used. Of this reason, primary energy use of electricity imported form the grid ($y_{imp}\,(p,t)$) is presented in the balance as a positive term, and electricity exported to the grid ($y_{exp}\,(p,t)$) a negative term.

Total Primary Energy Use:

$$\begin{aligned} pe_{tot} = \sum_{p\in P}\sum_{t\in T} YRN \cdot \Bigg(& h_{DH}\,(p,t)\cdot PE\,(\text{"}HEAT_{DH}\text{"}) \\ & +\ y_{imp}\,(p,t)\cdot PE\,(\text{"}EL_{imp}\text{"})\ -\ y_{exp}\,(p,t)\cdot PE\,(\text{"}EL_{exp}\text{"}) \\ & +\ b_{BB_c}\,(p,t)\cdot PE\,(\text{"}BB_c\text{"})\ +\ b_{BB_p}\,(p,t)\cdot PE\,(\text{"}BB_p\text{"})\ \Bigg) \\ & \forall\ p\in P, t\in T \end{aligned} \tag{5.7}$$

Parallel to the zero emission balance, a zero primary energy balance is applied in equation (5.8).

Zero Primary Energy balance:

$$(pe_{tot} + PE_{embodied})\cdot\ \lambda_{\text{ZeroPE}}\ =\ PE_{tot}^{REF}\ \cdot\ YRN\ \cdot\ PN\ \cdot\ \gamma \tag{5.8}$$

γ is the continuous relaxation coefficient and λ_{ZeroPE} the binary parameter to turn on or off the constraint. PE_{tot}^{REF} is the maximum reference value for reference to the relaxation, given as input in the 'Model Input Parameter File' in appendix D.

5.5.6 Grid Restrictions

The total export of electricity is the sum of all electricity exported at each hour of the period of analysis. This is presented in equation (5.9).

Total export:

$$export_{tot}\ =\ \sum_{p\in P}\sum_{t\in T} YRN\cdot\ y_{exp}\,(p,t) \tag{5.9}$$

To analyse the effect ZEB-buildings have on the power grid, it could be interesting to restrict the grid burden. Ways of evaluating the grid burden is discussed in section 2.4. In equation (5.10) the peak export and import is restricted, while the constraint in equation (5.11) is limiting the peak export only. In equations (5.10) and (5.11),

Restrictions of grid burden, export and import:

$$\big(y_{imp}\left(p,t\right) + y_{exp}\left(p,t\right)\big) \cdot \lambda_{\text{Grid Burden}_{exp,imp}} \;\leq\; \alpha_{exp,imp} \;\cdot\; M_{grid} \qquad \forall\ p \in P, t \in T \tag{5.10}$$

Restrictions of grid burden, export:

$$y_{exp}\left(p,t\right) \cdot \lambda_{\text{Grid Burden}_{exp}} \;\leq\; \alpha_{exp} \;\cdot M_{grid} \qquad \forall\ p \in P, t \in T \tag{5.11}$$

$y_{imp}\left(p,t\right)$ and $y_{exp}\left(p,t\right)$ represents the import and export at each hour. $\lambda_{\text{Grid Burden}_{exp,imp}}$ and $\lambda_{\text{Grid Burden}_{exp}}$ are control parameters to turn on and off the grid restrictions, while α_{exp} is the grid restriction coefficient. M_{grid} is a maximum reference value to the restriction, given as input. In the analysis M_{grid} is set to be equal to the sum of the highest peak demand of electricity and heat in the building.

5.6 Technical Constraints

5.6.1 Electricity Balance

The electricity balance in constraint (5.12) contains the electricity bought from the grid, electricity production at the site, the electricity used by the other energy sources, as well as the building demand. A overview of the variables in the electricity balance of the building is presented in figure 5.2. In figure 3.1 all of the elements of the building modelled is presented. For every hour of the analysis period, the hourly electricity demand of the building ($D_{el}\left(p,t\right)$) must be covered. The total electricity demand is the hourly electricity demand of the building in addition to electricity demand of the electric boiler ($d_{EB}\left(p,t\right)$), air-to-water heat pump ($d_{HP_{a-w}}\left(p,t\right)$) and ground source water-to-water heat pump ($d_{HP_{a-w}}\left(p,t\right)$). In the electricity balance in equation (5.12),

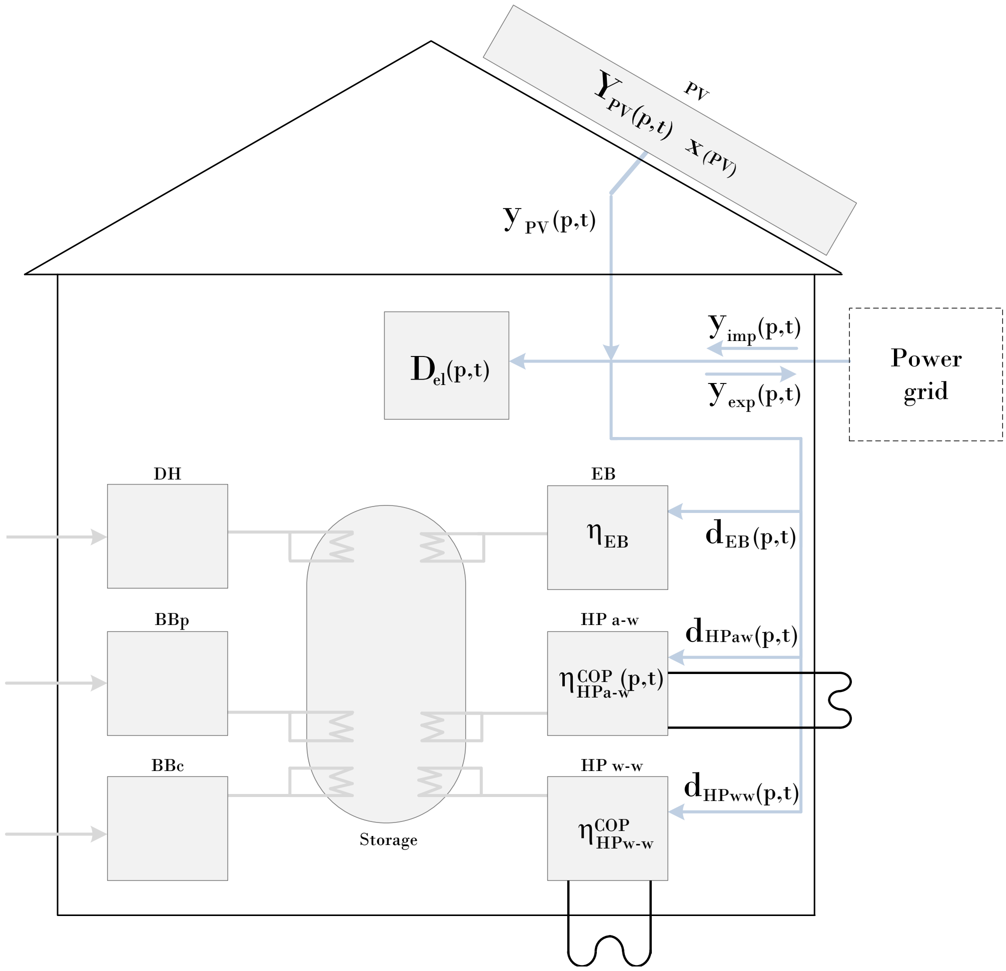

FIGURE 5.2: The electricity balance visualized by flows in the building. The electrical system consist of on site PV generation, demand of electricity by heat generating units, electricity specific demand and interaction with the power grid. y is representing electricity supplied or exported, d represents electricity demanded and η the respective efficiency of the technologies.

Electricity balance:

$$D_{el}(p,t) = \quad y_{imp}(p,t) \ + \ y_{PV}(p,t) \ - \ y_{exp}(p,t) \tag{5.12}$$

$$- \, d_{HP_{w-w}}(p,t) \ - \ d_{HP_{a-w}}(p,t) \ - \ d_{EB}(p,t)$$

$$\forall \ p \in P, t \in T$$

the sources of electricity are on site PV generation ($y_{PV}(p,t)$) and electricity import from the power grid ($y_{imp}(p,t)$) if shortage of electricity. Excess electricity can be exported to the grid ($y_{exp}(p,t)$).

5.6.2 Grid Constraints

Grid companies operate with a monthly peak power charge. In order to include the peak charge in the optimizing model, the monthly peak power needs to be found. In equations (5.13) and (5.13), the highest monthly peak value of $y_{imp}\left(p,t\right)$ and $d_{DH}\left(p,t\right)$ is found.

Monthly Peak power charge:

$$for \quad t \leq H_{acc,t,m}\left(mth\right) \quad \longrightarrow \quad ppm_{imp}\left(p,mth\right) \; \geq \; y_{imp}\left(p,t\right) \tag{5.13}$$

$$for \quad t \leq H_{acc,t,m}\left(mth\right) \quad \longrightarrow \quad ppm_{DH}\left(p,mth\right) \; \geq \; d_{DH}\left(p,t\right) \tag{5.14}$$

$$\forall\, p \in P, t \in T$$

$h_{acc,t,m}\left(mth\right)$ is a counting array containing for every month the time step number of the last hour of the last day in the month. The first month January $\left(H_{acc,t,m}\left(1\right)\right)$ will have the value 744, while the last month, December $\left(H_{acc,t,m}\left(12\right)\right)$ will have the value 8760. For every month, the peak value will be stored in the variables $ppm_{imp}\left(p,mth\right)$ and $ppm_{DH}\left(p,mth\right)$.

As discussed in section 2.7, the grid charges and district heating charges are calculated equally. Of this reason, the peak power district heat charges are presented in this section together with the monthly peak electricity charges.

Equations (5.15) and (5.16) find the highest peak value of import$\left(y_{imp}\left(p,t\right)\right)$ and export$\left(y_{exp}\left(p,t\right)\right)$, and assign it to the peak value variables for maximum export $\left(x_{exp,max}\right)$ and maximum import $\left(x_{imp,max}\right)$.

Grid load, max export / max import:

$$\text{Max electricity import:} \qquad y_{imp}\left(p,t\right) \; \geq \; x_{imp,max} \tag{5.15}$$

$$\text{Max electricity export:} \qquad y_{exp}\left(p,t\right) \; \geq \; x_{exp,max} \tag{5.16}$$

$$\forall\, p \in P, t \in T$$

$x_{exp,max}$ and $x_{imp,max}$ are the peak values for the whole period of analysis, and hence only contains one value each.

In the model, electricity imported from the grid and electricity exported to the grid are modelled as two different arrays of variables. This allows for the use of asymmetrical crediting factors for primary energy and CO_2. However, to make sure that the building does not export and import electricity in the same hour a logic constant on interaction with the power grid is included, in equations (5.17), (5.18) and (5.19).

Grid logic constraint:

$$\begin{aligned}
&\text{If import:} && y_{imp}\,(p,t) &&\leq \delta_{imp}\,(p,t)\cdot M_{grid} && (5.17)\\
&\text{If export:} && y_{exp}\,(p,t) &&\leq \delta_{exp}\,(p,t)\cdot M_{grid} && (5.18)\\
&\text{Either export or import:} && \delta_{imp}+\delta_{exp} &&\leq 1 && (5.19)\\
&&&&& \forall p\ \in P, t\in T
\end{aligned}$$

δ_{imp} and δ_{exp} are indicator variables that get the value one if $y_{imp}\,(p,t)$ and $y_{exp}\,(p,t)$ respective are positive. δ_{imp} and δ_{exp} are found by the indicator variable method presented in section 2.2. The upper bound M_{grid} is input parameter, the same as used in equations (5.10) and (5.11).

5.6.3 Heat Balance

Similar to the electricity balance, the heat demand of the building needs to be met from energy produced or stored at all times. The heat variables with all options of technologies in the building is visualized in figure 5.3. In figure 3.1 all of the elements of the building modelled is presented.

There are no option to export heat to surrounding district heat infrastructure, but a heat storage introduces flexibility in the heat system. The heat balance for the building is presented in equation (5.20),

Heat balance:

$$D_{heat}\,(p,t) \;+\; s\,(p,t) \;=\; \sum_{i\in I_{heat}} \big[q\,(i,p,t)\big] \;+\; q_{ST}\,(p,t) \;+\; s\,(p,(t-1))\cdot\eta_S \quad (5.20)$$

$$\forall p\in P, t\in T$$

where $D_{heat}\,(p,t)$ is the heat demand of the building at each hour. $q\,(i,p,t)$ is the heat generated by the heat technologies in I_{heat}, and $q_{ST}\,(p,t)$ the heat delivered form the solar collector(ST) if ST is chosen as an optimal investement. $s\,(p,t)$ is the heat stored in the heat storage at a given time step, while $s\,(p,(t-1))$ is the heat in the storage from the previous hour. If the model find it optimal to shift the

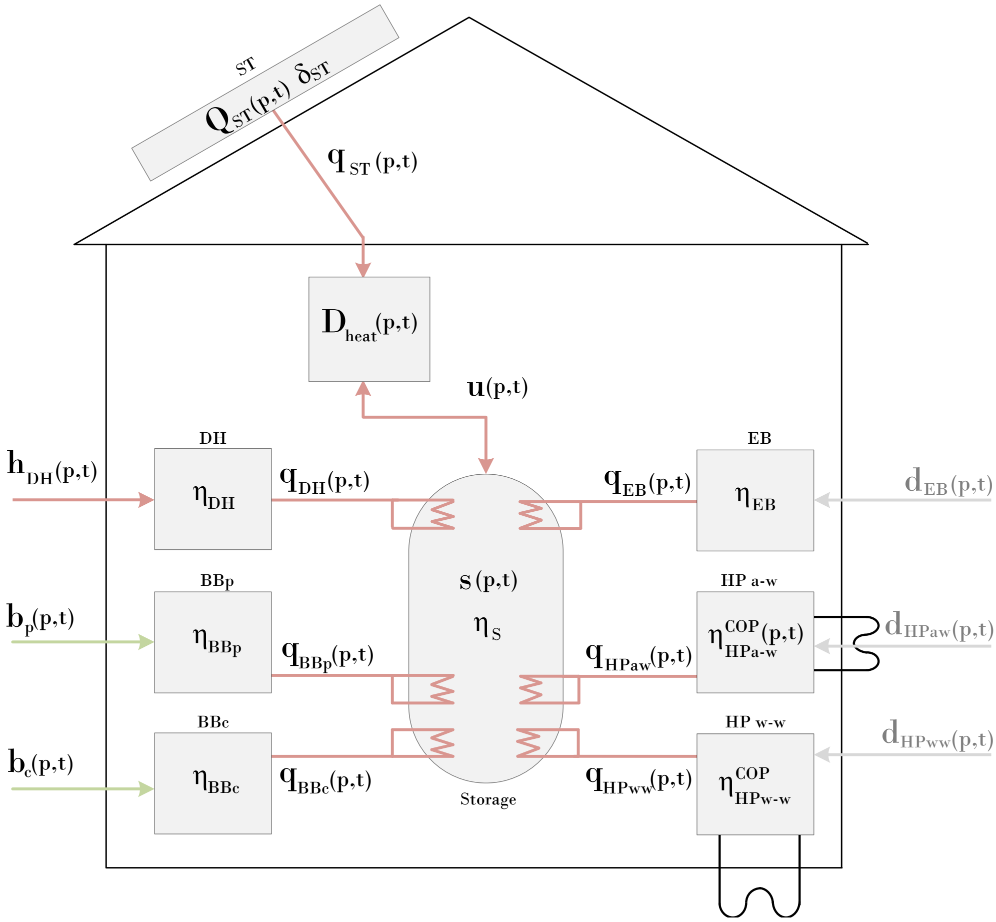

FIGURE 5.3: The heat balance visualized by flows in the building. The heating system consist of on site solar collectors, heat pumps, boilers and connection to the district heating grid. η represents the efficiency of the technologies, q heat supplied, s heat stored in storage, d energy demanded, h heat demanded from district heating grid and b biomass consumption.

heat production from the fixed heat demand of the building ($D_{heat}(p,t)$), to later or earlier hours, this can be done by utilizing the storage. If the heat production in one hour excess heat demand at the same hour, the surplus heat is stored to the storage, increasing the value of s. There are losses in the storage, and the efficiency is η_S.

5.6.4 Heat Storage Balances

To register the heat balance in the heat storage, the variable $u(p,t)$ is included. For every hour, $u(p,t)$ equals the difference between the heat level in the storage from the previous hour to the current hour. If $u(p,t)$ has a positive value, heat is extracted from the storage, if $u(p,t)$ is negative, heat in injected into the heat storage. The heat storage balance is expressed in equation (5.21).

Heat storage balance:

$$s(p,t) - s(p,(t-1)) = u(p,t) \qquad \forall\, p \in P, t \in T \tag{5.21}$$

Boundary conditions for the heat storage is included to prevent the heat storage from behaving like a heat sink or heat source at the first or last time step each year. Thus, the amount of heat in the storage at first and last time step is set to be equal. Optionally the heat in the storage could have been set to zero to limit the solution space, however, this is not done, to keep the flexibility in the size of the storage. The contraint for the boundary condition is presented in equation (5.22).

Heat Storage, Boundary Condition:

$$s(p,0) = s(p,TN) \qquad \forall\, p \in P \tag{5.22}$$

To find the optimal size of installed capacity of the storage, the variable $x\,("S")$ is introduced. For all time steps the heat stored in the storage $s(p,t)$ cannot exceed the installed capacity of the storage ($x\,("S")$). Additionally $\lambda\,("S")$ is a binary control parameter, deciding if the storage is active or not. $\lambda\,("S")$ is given as input in 'Control Pramater File' in appendix D. If $\lambda\,("S")$ equals zero, $s(p,t)$ is zero at all timesteps. The heat capacity constant is expressed in equation (5.23).

Capacity heat storage:

$$s(p,t) \;\leq\; x\,("S") \cdot \lambda\,("S") \qquad \forall\, p \in P,\ t \in TT \tag{5.23}$$

For analysis of the effect of the heat storage on the optimal solution for installed energy technologies, it can be of interest to put a maximum value on installed capacity of the storage ($Max_{storage}$). This parameter is given as input in the 'Model Input Parameter File' in appendix D. The constant for maximum installed storage is given in equation (5.24). When the model is run without restrictions to the heat storage, $Max_{storage}$ is given a large value, and working as a restriction to the solution space.

Maxiumum capacity heat storage:

$$x\,(\text{"}S\text{"}) \quad \leq \quad Max_{storage} \tag{5.24}$$

Another aspect with the heat storage is the charging and discharging rate of the storage, as elaborated on in section 3.1. The constants for maximum charging- and discharging rate are given in equation (5.25) and (5.26).

Charging constraint heat storage:

$$\text{Max charging:} \qquad u\,(p,t) \cdot \lambda_{charge} \; \leq Max_{charge\ rate} \cdot x\,(\text{"}S\text{"}) \tag{5.25}$$

$$\text{Max discharging:} \qquad -u\,(p,t) \cdot \lambda_{charge} \; \leq Max_{charge\ rate} \cdot x\,(\text{"}S\text{"}) \tag{5.26}$$

$$\forall\ p \in P, t \in T$$

λ_{charge} is a binary control parameter, turning on and off the charging constraint. $Max_{charge\ rate}$ is the charging rate, and is given as the percentage value of installed capacity of the storage. $u\,(p,t)$ is the heat storage balance variable defined in equation (5.21).

5.6.5 Logical Investment Constraints

For all of the heat generating technologies in I_{heat}, the energy production can not exceed the installed capacity variable ($x\,(i)$) of the technology. A binary decision variable to be able to turn on and off the technologies ($\lambda\,(i)$) are also included. This is expressed in equation (5.27).

Capacity Technologies:

$$q\,(i,p,t) \;\leq\; x\,(i) \cdot \lambda\,(i) \tag{5.27}$$

$$\forall\ p \in P, t \in T, i \in I_{heat}$$

The investment costs consist of a fixed and a specific part. To be able to include this fixed part of the investment cost, a binary indicator variable is included ($\delta_{x,inv}\,(i)$) in the logic investment constraint. If technology i is invested, ($\delta_{x,inv}\,(i)$) is assigned the value 1, else it takes the value 0. M_{inv} is a maximum value, set to limit the solution space, but not influencing the optimal solution, as discussed in section 2.2.

Logic capacity investment:

$$x(i) \leq \delta_{x,inv}(i) \cdot M_{inv} \qquad \forall\, i \in I | i \neq \text{"}S\text{"} \tag{5.28}$$

5.6.6 Energy Balances, Technologies

The energy output of each technology is modelled by restrictions in the model, transforming energy input to desired electricity or heat to the building. $\lambda(i)$ is the binary control parameter deciding if the technology is available for investment or not. In equation (5.29), the energy balance of PV panels is presented.

Energy balance PV:

$$y_{PV}(p,t) = x(\text{"}PV\text{"}) \cdot Y_{PV}(p,t) \cdot \lambda(\text{"}PV\text{"}) \qquad \forall\, p \in P, t \in T \tag{5.29}$$

$y_{PV}(p,t)$ is the electricity output of the PV panels, $x(\text{"}PV\text{"})$ the installed capacity, and $Y_{PV}(p,t)$ the specific power output per kWp PV panles invested. $y_{PV}(p,t)$ and $x(\text{"}PV\text{"})$ are variables decided by the model, and $Y_{PV}(p,t)$ is given as input as a data series with hourly resolution.

Similar to PV, the solar collectors are modelled as an input production series for solar heat production. However, ST is modelled as a binary decision as discussed in section 2.6.

Energy balance ST:

$$q(\text{"}ST\text{"},p,t) = \delta_{x,inv}(\text{"}ST\text{"}) \cdot Q_{ST}(p,t) \cdot \lambda(\text{"}ST\text{"}) \qquad \forall\, p \in P, t \in T \tag{5.30}$$

In equation (5.30), the energy balance for the solar thermal collectors is presented. $q(\text{"}ST\text{"},p,t)$ is the heat output of the collectors given that the binary decision $\delta_{x,inv}(\text{"}ST\text{"})$ is one and the collectors are active $(\lambda(\text{"}ST\text{"}))$. $Q_{ST}(p,t)$ is a data series with the absolute heat output of a solar collector with a given size. In the simulations run in this thesis, the solar collector area was 70 m^2.

There are two heat pumps available for investment, an air source air-to-water heat pump (HP_{aw}) and a ground source water-to-water heat pump (HP_{ww}). The energy balances for the two heat pumps, equations (5.32) and (5.31), therefore take the same shape.

Energy balance HP$_{w-w}$:

$$q\left("HP_{w-w}", p, t\right) = d_{HP_{w-w}}\left(p, t\right) \cdot COP_{w-w} \qquad \forall\ p \in P, t \in T \tag{5.31}$$

Energy balance HP$_{a-w}$:

$$q\left("HP_{a-w}", p, t\right) = d_{HP_{a-w}}\left(p, t\right) \cdot COP_{a-w}\left(p, t\right) \qquad \forall\ p \in P, t \in T \tag{5.32}$$

The heat output $q\left("HP_{w-w}", p, t\right)$ and $q\left("HP_{a-w}", p, t\right)$ equals the electricity input, or demand ($d_{HP_{w-w}}\left(p, t\right)$ and $d_{HP_{a-w}}\left(p, t\right)$) times the coefficient of performance of the heat pumps (COP_{w-w} and $COP_{a-w}\left(p, t\right)$). The coefficient of performance of the ground source heat pump is assumed constant throughout the year, while the COP of an air source heat pump is dependent on the ambient air, and has hourly resolution.

Similar to the heat pumps the two biomass boilers are modelled equally, in equations (5.33) and (5.34).

Energy balance BB$_p$:

$$q\left("BB_p", p, t\right) = b_{BB_p}\left(p, t\right) \cdot \eta_{BB_p} \qquad \forall\ p \in P, t \in T \tag{5.33}$$

Energy balance BB$_c$:

$$q\left("BB_c", p, t\right) = b_{BB_c}\left(p, t\right) \cdot \eta_{BB_c} \qquad \forall\ p \in P, t \in T \tag{5.34}$$

The heat outputs ($q\left("BB_p", p, t\right)$ and $q\left("BB_c", p, t\right)$) are the product of the amount of biomass fuel consumed ($b_{BB_p}\left(p, t\right)$ and $b_{BB_c}\left(p, t\right)$) and the respective efficiency of the biomass boilers (η_{BB_p} and η_{BB_c}).

The energy balance for district heating is seen in equation (5.35)

Energy balance DH:

$$q\,(\text{"}DH\text{"}, p, t) \; = \; h_{DH}\,(p, t) \cdot \eta_{DH} \qquad \forall\, p \in P, t \in T \tag{5.35}$$

where $q\,(\text{"}DH\text{"}, p, t)$ is the heat input to the heat balance of the building, and $h_{DH}\,(p, t)$ the measured demand from the district heating grid at the consumer interfase and η_{DH} the efficiency of the components inside the building. Since the system border is set at the building walls, no losses prior to the consumer interfase for the district heating is included in this balance.

The heat supplied by the electric boiler ($q\,(\text{"}EB\text{"}, p, t)$) equals the product of the electricity demanded by the electric boiler ($d_{EB}\,(p, t)$) and the boiler efficiency (η_{EB}). This is expressed in equation (5.36).

Energy balance EB:

$$q\,(\text{"}EB\text{"}, p, t) \; = \; d_{EB}\,(p, t) \cdot \eta_{EB} \qquad \forall\, p \in P, t \in T \tag{5.36}$$

Chapter 6

Results

In this chapter the results of the analysis of the model is presented. The model is run with different input factors and constraints, to analyse the impact of different parameters on the optimal investment and operation of a ZEB-building. For structural reasons the results and analysis of the results are both included in this chapter. Tables with details of the analysis are found in appendix A.

In the first section, investment decisions of the model given different zero-criteria, when all technologies are available, are analysed. The emphasis in the analysis has been to show which factors is decisive for the optimal solution. Additionally, the impact on costs, grid interaction and export of electricity, given choices of crediting factors has been analysed. In the second section the investment analysis of the zero-constraints is continued, by excluding selected technology options.

In the third and fourth section, operation strategies of the building are studied. Annual electricity and heating balances are displayed, as well as weekly operation of the building for winter, autumn and summer season.

In the fifth section the dynamical dimension of the model has been tested, by running the model for two periods. During the two periods, the CO_2 factors are reduced. In the sixth section, restrictions to the peak export of electricity is applied, and it is investigated how grid restrictions changes the self-consumption of PV-generation. In the seventh section a relaxation of the zero CO_2 emission constraint is performed.

The eight section presents sensitivity analysis of the optimal solution of the model in general, when changing the input parameters. Particular attention was given the PV investments, finding the level where PV becomes profitable.

Thoroughout the result chapter seven different cases studies are performed. The different zero constraints of the model is presented in 5.5, and the different crediting factors in 4.8 and 4.9. In the *NoZero* case, no zero restrictions are applied. Thus, the solutions of *NoZero* case represents the purely cost optimal solution. The *zeroCO_2-NOR* case and *zeroCO_2-EN* case is the model run with the zero CO_2 emission constraint active when Norwegian and European CO_2 emission factors is applied. The *zeroPE n.r.-sym* case and the *zeroPE n.r.-sym* case are the results when the zero primary energy constraint is applied with non-renewable primary energy factors. The *zeroPE n.r.-sym* case is run with symmetrical electricity factors, while the *zeroPE n.r.-asym* case differentiates between factors for electricity exported and electricity imported. Likewise, the *zeroPE total-sym* and *zeroPE total-asym* cases are the model run with the zero primary energy constraint, and symmetrical and asymmetrical total primary energy factors. If not specified otherwise Norwegian CO_2 factors and symmetrical total primary energy factors are applied. The different criteria factors for CO_2 emissions and primary energy are discussed in section 2.3.

The optimization model, and the results from some of the analysis presented in this chapter is also used in the ongoing PhD work by Karen Byskov Lindberg. One paper is to be published in this context. The zero balances and grid restrictions are further investigated in "Optimal Investments in Zero Carbon Buildings" by Lindberg et al. [71], for the Zero Carbon Buildling Conference (ZCB) in Birmingham 11-12 September 2014. Additionally in the conference contribution at the Renewable Energy Research Conference (RERC) 16-18 June 2014 in Oslo, "Impact of Zero Energy Buildings on the electricity grid: Net electricity load profiles with optimal investments" [72], the optimal investments in ZEB and net electricity load profiles are further investigated.

Some of the findings and arguments for the results presented here may of this reason overlap with the papers cited.

6.1 Investments: All technologies Available

Figure 6.1 illustrate the optimal cost minimizing investments of the energy technologies, for the seven main zero balance cases.

The installed capacity for the different cases show that the model chooses to invest in a base load technology and a peak load technology.

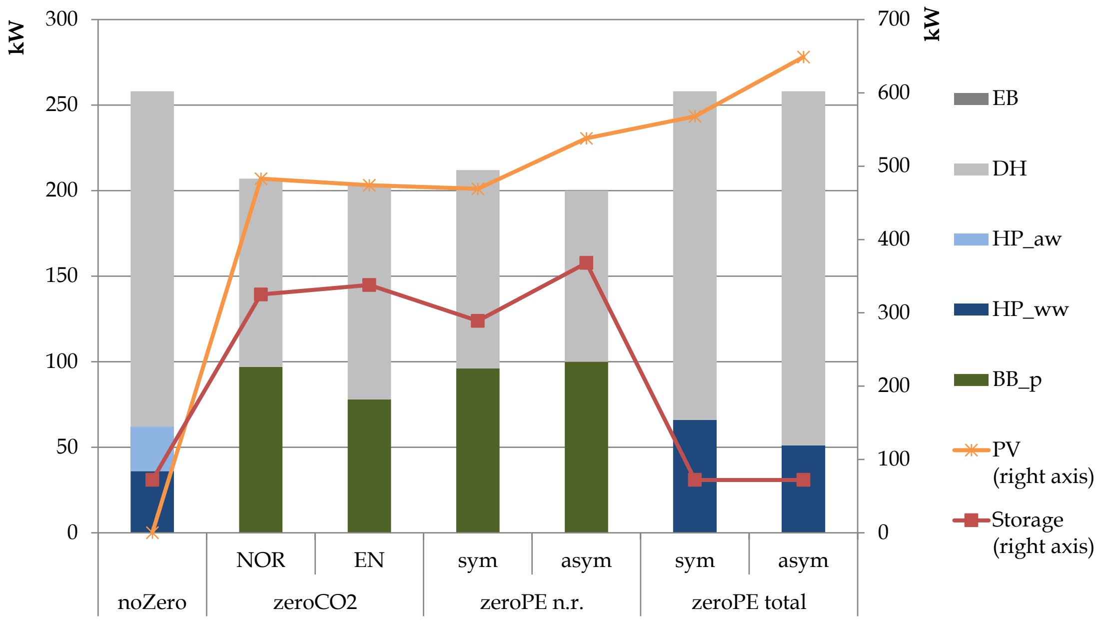

FIGURE 6.1: Installed capacity for the different zero cases. All technologies available, min production of biomass boiler 50 kWh/h, no restriction on storage charging.

6.1.1 Peak Load

District heating (DH) is preferred over electric boiler (EB) as peak load for all cases. The specific investment cost of EB (204 Euro/kW) is higher than the specific investment cost of DH, which is 60 Euro/kW, based on the input data presented in section 4.2. The investment cost of district heat has additionally a fixed cost of 6,024 Euro. Thus, if the installed capacity of district heating is larger than 42 kW, DH has lower specific investment cost than electric boiler.

As discussed in section 2.7 the energy price for both DH and EB are linked to the electricity spot price. From section 4.7 the price of DH from the grid is fixed to be 2% lower than the electricity bought from grid. Both the investment cost and the operational cost are thus favouring DH as a peak load source, compared to EB when the installed capacity of the energy source for peak load is in the size of 100 kW.

In terms of CO_2 emissions and primary energy use, district heating has a clear advantage over electric boiler. Since DH is cheaper, and has both a lower primary energy-factor and a lower CO_2 factor compared to EB, the solution of district heating as peak load source is a robust solution for all seven cases.

6.1.2 Base Load

The technologies for base load is varying between heat pumps (HP_{ww} and HP_{aw}) and biomass boiler (BB_p).

For the case of cost minimizing only, *noZero*, a 36 kW water-to-water heat pump (HP_{ww}) and a 26 kW air-to-water heat pump (HP_{aw}) are installed. HP_{ww} has higher COP than HP_{aw} during the peak heating season but a lower COP during the summer, as discussed in section 4.5. This makes the HP_{ww} favorable compared to HP_{aw} in terms of energy output, for the largest part of the heating season. However, the specific investment cost of HP_{ww} including energy well, is 1,297 Euro/kW, while HP_{aw} has a specific investment costs of 852 Euro/kW. The type and size of heat pump chosen as optimal investment is thus a tradeoff between the higher COP of HP_{ww}, and lower investment cost of HP_{aw}. With no zero-constraint applied biomass boiler is disfavoured, though the investment cost of biomass boiler is 679 Euro/kW, which is lower than the investment cost of both HP_{ww} and HP_{aw}. The bio pellets as energy fuel, is on average cheaper than the net electricity price. However, the thermal efficiency of heat pumps surpasses the biomass boiler, making the heat pumps cheaper compared to the biomass boiler in relative terms.

When the zero CO_2 emission criteria is applied, the base load shifts from heat pumps to biomass boiler. For bio energy from wood pellets, the CO_2 emission factors are 7 g CO_2 eq/kW with Norwegian factors and 14 g CO_2 eq/kW for the proposed European norm. For heat delivered from a water-to-water heat pump with COP = 3.2, the equivalent CO_2 emission factors will be 109 g CO_2 eq/kW for Norwegian- and 40.6 g CO_2 eq/kW for European figures. All CO_2 emissions from the building needs to be accounted for by energy generation on-site, as discussed in 2.1. With the zero CO_2 criteria, the use of biomass boiler compared to heat pumps will generate less CO_2 emissions to the zero CO_2 balance of the building, and hence reduce the cost related to investment of on-site power production.

By comparing the size of base load investments in the case of *noZero*, to the size of base load investments in the *zeroCO2-NOR* case and *zeroCO2-EN* case, the investments of DH is lower for both cases. The CO_2 factor for district heating is dependent on local variations, as discussed in section 4.9. In this analysis the CO_2 factor for DH is 40 g CO_2 eq/kW for both Norwegian and European factors. DH has higher CO_2 factor than BB_p, which explains the reduced size of district heating investment with zero CO_2 constraints.

When the non-renewable primary energy constraints are applied, *zeroPE n.r.-sym* and *zeroPE n.r.-asym*, the base load shifts from heat pumps to pellets biomass boiler in the same manner as for the zero CO_2 cases. The PE factors for the heat sources DH and BB_p are the same in the case of *zeroPE n.r.-sym* and *zeroPE n.r.-asym*, still there are variations in both installed capacity of DH and BB_p. For the *zeroPE n.r.-asym* case the installed capacities are 100 kW BB_p and 100 kW DH. For the symmetrical case the district heating capacity is reduced by 14%, while the biomass boiler is increased by 4%. The *zeroPE n.r.-asym* case has in total 12 kW higher installed capacity in heat generation, when disregarding the heat storage. BB_p has considerable lower primary energy factor (0.05 kWh_p/kWh_s) when only looking at the non-renewable fragment, compared to district heating (0.70 kWh_p/kWh_s).

6.1.3 Norwegian vs. European CO_2 Factors

The Norwegian- and European CO_2 factors are presented in table 4.5. The difference in the installed capacity for the two different sets of CO_2 factors are seen in figure 6.1. The installed capacity of BB_p as base load is larger with Norwegian factors, than with European factors. For Norwegian factor the ratio of CO_2 emissions per kWh for biomass boiler to district heating will be 1 : 5.7, compared to 1 : 2.9 for European factors. This could explain why a larger pellets boiler is invested with Norwegian factors than with European. With Norwegian factors the gained reduction in CO_2 emissions, and thus in the total CO_2 emissions of the building, by shifting away from the optimal size of installed capacity of district heating will be larger, compared to European factors. Consequently, the larger the difference between the CO_2 factors for DH and BB_p are, the more favorable is it to reduce the installed capacity and energy production of DH.

6.1.4 Total vs. Non-renewable Primary Energy Factors

The difference between total and non-renewable primary energy factors are explained in section 2.3. As seen in section 4.8 the total primary energy factors affects BB_p primarily, which is 1.05 kWh_p/kWh_s. This value is still lower than the primary energy factor of electricity imported from the grid (2.5 kWh_p/kWh_s). With a water-to-water heat pump, the primary energy factor will be more favorable for investment in HP_{ww} than in BB_p. This is seen in figure 6.1, when zero primary energy restrictions are active with total primary energy factors, the base load shifts from BB_p to heat pump.

An interesting observation is that the installed capacity of heat pumps in combination with district heating, is very similar for the *zeroPE total* cases and the *noZero* reference case, when looking at the sum of the heat pump installations. As stated earlier, the effective primary energy factor for heat delivered by a heat pump will be lower than the electricity imported from the grid. With a COP of 3.2 the primary energy use of one kWh heat from HP_{ww} will be approximately 0.78 kWh_p/kWh_s). This is only 12% higher than the primary energy factor of DH. When the difference in primary energy factor values are small, the investment and operational cost ratio will be the leading condition for finding the optimal solution, and hence the optimal solution will be close to the cost optimal solution in the *noZero* case.

6.1.5 Symmetrical vs. Asymmetrical Primary Energy factors

Zero-constraints are stricter when asymmetrical factors are applied than when symmetrical factors are utilized. This reflects why the installed capacity of district heat is replaced by BB_p in the *zeroPE n.r.-asym* case relative to the *zeroPE n.r.-sym* case.

With symmetric PE factors for electricity, both purchase and sale of electricity is treated equally with a PE factor of 2.5. In the case of asymmetric factors, the export of electricity is less valued (PE factor 2.0) than import in order to favor self-consumption of on-site electricity production. However, when the optimization problem with the zero-PE requirement is active, the optimal solution leads to an increase in PV installed in order to reach the level of export that is required to level out the electricity import occurring during wintertime. Thus, even though self-consumption is increasing, the zero requirement with asymmetric factors increases the installed PV area and consequently, increasing total exports. For both of the asymmetrical zero-PE cases the annual CO_2 emissions are lower than for the corresponding symmetrical zero-PE cases. This is due to the CO_2 factors used in the analysis are symmetrical for all cases analysed, thus an asymmetrical zeroPE restriction will lead to negative CO_2 emissions.

6.1.6 Storage

For all of the seven cases considered, an investment in heat storage is made. For the cases where heat pumps in combination with district heat is chosen, in the *noZero*-, *zeroPE total-sym-* and *zeroPE total-asym* cases, the installed storage capacity is 72 kW, or 1,392 liters of water with a heat differential of 45. The installed capacity of the heat storage increases by a factor of 3-4 when a biomass boiler is used as base load instead of a water-to-water heat pump. This large change in installed capacity is most probably caused by the minimum production restriction of 50 kWh/h, that is applied to the biomass boiler, as discussed in section 2.6. During the summer, the heating demand load series of 2012 has heating demands that is far below 50 kWh/h, and this could increase the use of heat storage when combined with a biomass boiler.

Within the four cases with BB_p as optimal solution for base load coverage, there are still large variations in the size of the storage. This seems to be related to the relation between the installed capacity of peak and base load for the zeroPE cases.

6.1.7 ST Investments

None of the cases investigated chooses to invest in solar thermal collectors (ST). This is most probably due to the heat load profile used. A passive school building has close to no heating demand during the summer, when the heat generation from ST is highest. The building will not be able to make use of large amounts of the heat from the ST, and thus an investment in ST will be too expensive. However, the profitability of solar collectors could change for building types with higher heat demand during summer.

6.1.8 Cost and PV Investments

In figure 6.2 the total investment cost and total discounted operational cost are presented. In the reference case of *noZero*, the investment cost accounts for 15% of the total cost of 653 thousand Euro. When applying the zero CO_2 restriction with Norwegian factors the total cost increases to over 2 million Euro. For the six different zero-constraints the investment cost increases by 14 to 19 times, while the operational cost is changed in the range of 2,5% increase to a decrease of 10%.

There is a clear link between the installed capacity of PV-panels and the total discounted cost. For the case of *zero*CO_2*-NOR*, installations of PV accounts for 92% of the total investment cost. This can also be seen by comparing the investments of heat technologies and heat storage in figure 6.1, where the investments for the *noZero-* and *zeroPEtotal-sym* were close to the same, while the investment cost in

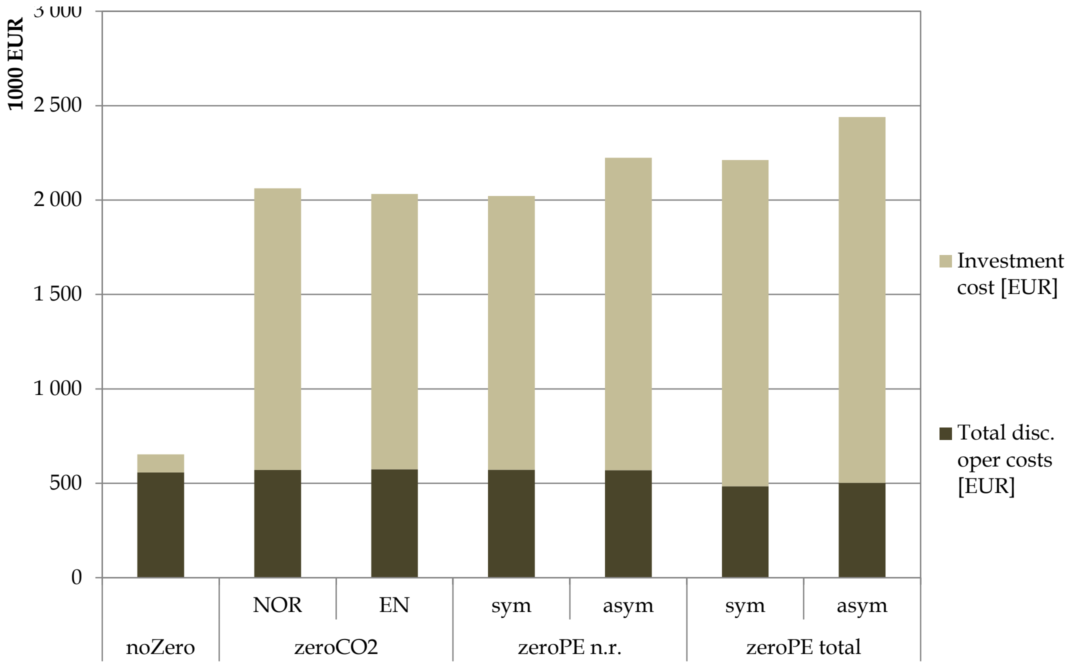

FIGURE 6.2: Investment cost and total discounted operational cost for the different zero cases. All technologies available, minimum production of biomass boiler 50 kWh/h, no restriction on storage charging.

figure 6.2 are 17 times higher of the *zeroPEtotal-sym* case compared to the *noZero* case.

Electricity exported is proportional to PV installed, as long as the self-consumption of PV generation is low. The amount of self consumption will be further investigated in section 6.7.

The total investment costs, and electricity exported is greater for *zeroCO2-NOR* than for *zeroCO2-EN*, even though the biomass has lower CO_2 factors with Norwegian number, and thus will have lower CO_2 emissions from the heat generation. This is due to the zero-constraint where PV needs to displace the same amount of CO_2 from the grid as emissions generated from the building.

Electricity exported and imported from the grid has CO_2 emissions of 350 g CO_2-eq/kW for European norm, and 130 g CO_2-eq/kW for Norwegian norm. With Norwegian CO_2 factors a building will have lower CO_2 emissions, but it will at the same time need to export lager amounts of electricity to the grid to achieve the zero CO_2 balance, making the necessary investment in PV larger.

6.1.9 Grid Interaction

Figure 6.3 presents the peak export and import values for electricity sold and bought from the grid. The values are the hourly peak values in kWh/h.

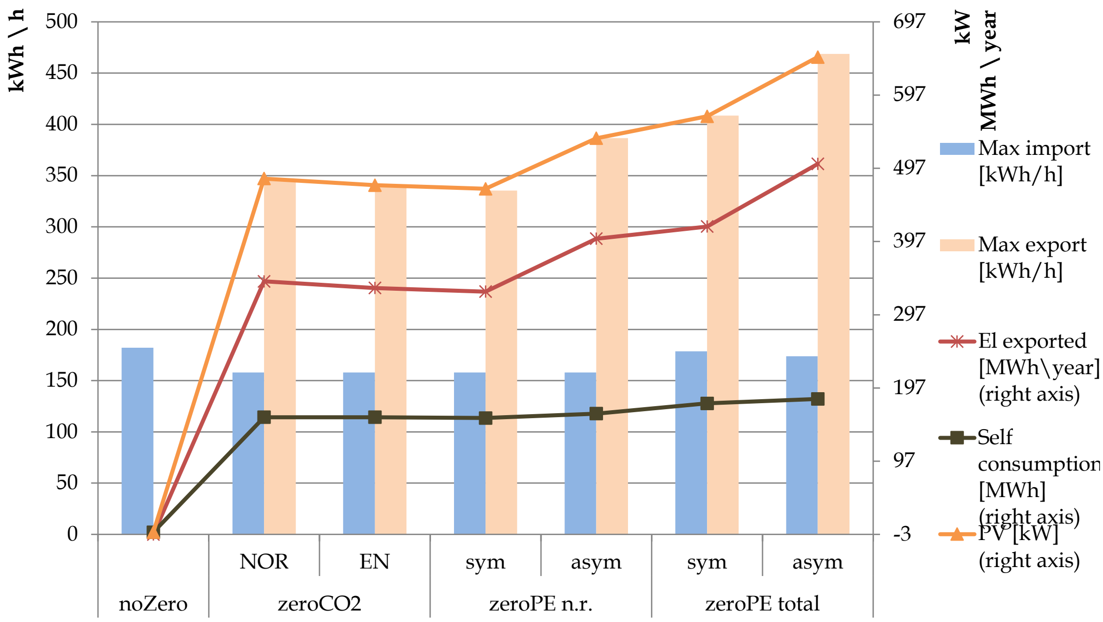

FIGURE 6.3: Peak export and import values, total export of electricity and PV capacity invested for the different zero cases. All technologies available, minimum production of biomass boiler of 50 kWh/h, no restriction on storage charging.

When the zero-constraints are applied the installed capacity of PV and thus the export of electricity is increasing in order to achieve the zero-balance.

The peak import values is decreasing when the heat sources are shifted from heat pumps to biomass boiler. For the case of *zeroPE total-asym*, the peak import is reduced from 179 kWh/h to 174 kWh/h, implying that asymmetrical crediting factors of electricity might have a small influence on self-consumption of electricity. For the case of *zeroPE total-sym* the amount of electricity generated by PV used for own consumption equals 175 MWh/year, and 182 MWh/year for *zeroPE total-asym*.

The self-consumption is calculated for every hour. If PV is producing one hour, the self-consumption equals the difference between the electricity generated by PV and the electricity bought from the grid in the same hour. The installed capacity of PV is increasing as the asymmetrical PE factors are applied. Still, the self-consumption as a percentage value of the total PV generation is decreasing with asymmetrical PE factors. For *zeroPE total-sym* the self-consumption is 37% of the total PV generation, while the self-consumption of *zeroPE total-asym* is only 33%. Most of the increase in electricity generated by the PV is exported, and of this reason, the electricity export is increasing parallel to the increase in installed capacity of the PV.

Furthermore, figure 6.3 shows that the increase in PV generation do not necessarily increase the self-consumption, because most of the electricity is generated during the summer, when the electricity production is much larger than the specific electricity demand. Additionally, when biomass boiler and district heating are chosen as heat source, the possibilities of self-consuming the large amounts of PV generated electricity gets poorer.

6.1.10 Zero Constraints

Annual CO_2 emissions and primary energy use for the seven different cases are presented in figure 6.4. For all cases except *zeroPE tot-sym* total CO_2 emissions have a less strict binding than primary energy.

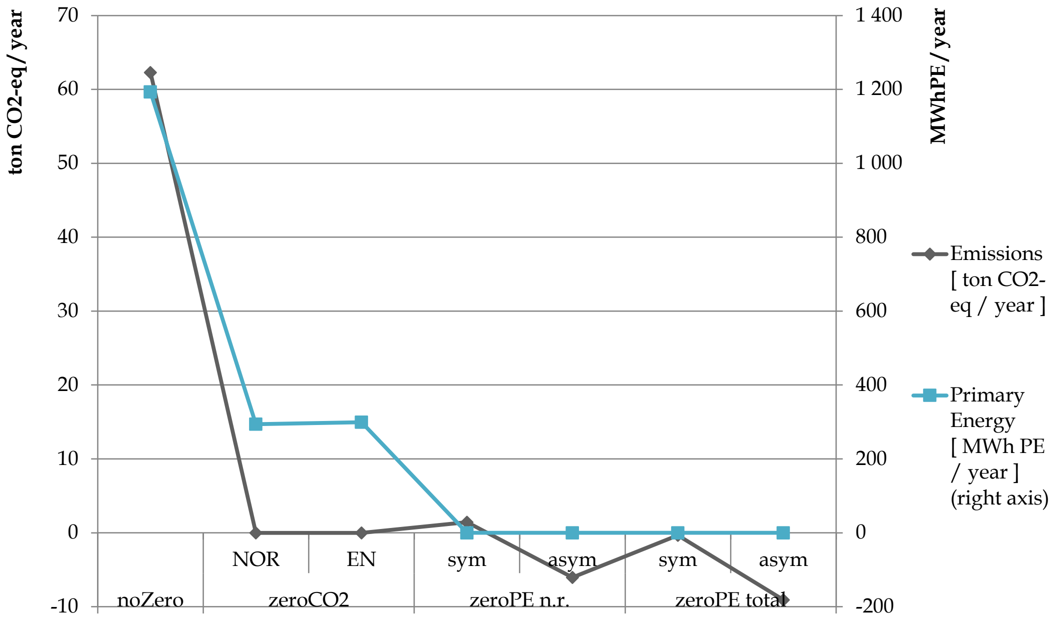

FIGURE 6.4: Net CO_2 emissions and primary energy use for the different zero cases. All technologies available, min production of biomass boiler 50 kWh/h, no restriction on storage charging.

When comparing the *zeroCO2-NOR* case which is run with total symmetrical primary energy factors to the case of *zeroPEtotal-sym* which is run with Norwegian CO_2 factors, the zeroPE restriction seems stricter, though both the CO_2 emissions and primary energy use is close to zero in the *zeroPEtotal-sym* case. This is due to the shift in optimal technologies. The PE factor of DH is 0.70, total PE factors for BB_p is 1.05, and PE factor of HP_{ww} is 0.63 kWh_p/kWh_s. The equivalent CO_2 factors of HP_{ww} and DH are 41 and 40 g CO_2 eq/kW respectively, compared to only 7 g CO_2 eq/kW for BB_p. This implies that the biomass boiler will be cheap in terms of CO_2 emissions, but contribute to a large use of primary energy, as seen in the zero CO_2 cases in figure 6.4. In the *zeroPE total-sym* case, BB_p will be exchanged by HP_{ww}. The ratio between the PE factors and CO_2 factors of HP_{ww} and DH is almost equal, making the zero total primary energy restriction in *zeroPE total-sym* in figure 6.4 give almost zero annual CO_2 emissions.

The strictest zero-constraint would be the case that is hardest to reach, i.e. the case with the highest investment costs. Higher PV installation is caused by a stronger zero PE or zero CO_2 constraint. Thus, the most expensive and strictest zero requirement is observed with the highest installation of PV. From figure 6.2 it is clear that zero primary energy restriction with total asymmetrical primary energy factors is the strictest constraint, followed by *zeroPE n.r.-asym* and *zeroPE tot-sym*.

6.1.11 Main Findings

The main observations of investment decisions for the zero cases are the following:

- District heating is preferred over electric boiler as peak load for all cases.
- When no restriction is applied, or when the total zero-PE constraint is applied, heat pumps are used for base load.
- When zero CO_2 constraints or non-renewable factors zero-PE constraints are applied, biomass pellets boiler is favored as base load.
- PV investment cost accounts for more than 90% of the investment cost when the zero CO_2 or zero PE constraints are applied.
- Asymmetrical PE factors generate larger investments in PV, and higher peak values of electricity exported to the grid.
- When asymmetrical PE factors are used, the self-consumption of on-site electricity generation seems to increase in absolute value, but the share of PV electricity used by self consumption is decreasing.

- *zeroPE total-asym* is the strictest zero-constraint, with the largest PV investments.
- Norwegian CO_2 factors make it more expensive to reach ZEB-building compared to European factors, due to the increased need of PV investments.
- The COP of the heat pumps affects the installation ratio between HP_{ww} and HP_{aw} when zero-restrictions are applied.

6.2 Investments: Reduction of Technologies Available

In section 6.1 the influence of the different factors for CO_2 and primary energy with zero-restrictions to the optimal investment decisions were analysed. However, usually not all technologies are available at all sites. In this section the influence of CO_2 and primary energy factors with zero-restrictions to the optimal results, when there are limitations in available technologies, are analysed.

With all technologies available, the model make the decision to invest in biomass boiler for base load, and district heating for peak load for the *zeroCO$_2$-NOR* case. Figure 6.5 presents optimal investments with reductions in available technologies, while figure 6.6 show the corresponding costs and electricity exported. Details and numbers of the analysis are found in table A.1, A.3, A.4 and A.5 in appendix A

As seen in figure 6.5, when no biomass boiler is available, the installed capacity of DH is increased with 83% compared to the *zeroCO$_2$-NOR* case with all technologies available. The increase is only 2.5% compared to the optimal solution of all technologies when no zero restriction is applied. Likewise, installed capacity of HP_{ww} is 58 kW with no biomass boiler, while HP_{ww} and HP_{aw} together are 62 kW for the *noZero case* with all technologies available.

No HP_{aw} is installed for the *zeroCO$_2$-NOR* case, and no biomass boiler available. The total cost increases by 7% compared to the *zeroCO$_2$-NOR* case with all technologies available, as seen in figure 6.6. As stated in section 6.1, the total cost is highly dependent on the investments of PV-panels, as these cost accounts for the major part of the total investment costs. When no biomass boiler is available, the installed capacity of PV-panels increases by 17% compared to if all technologies are available.

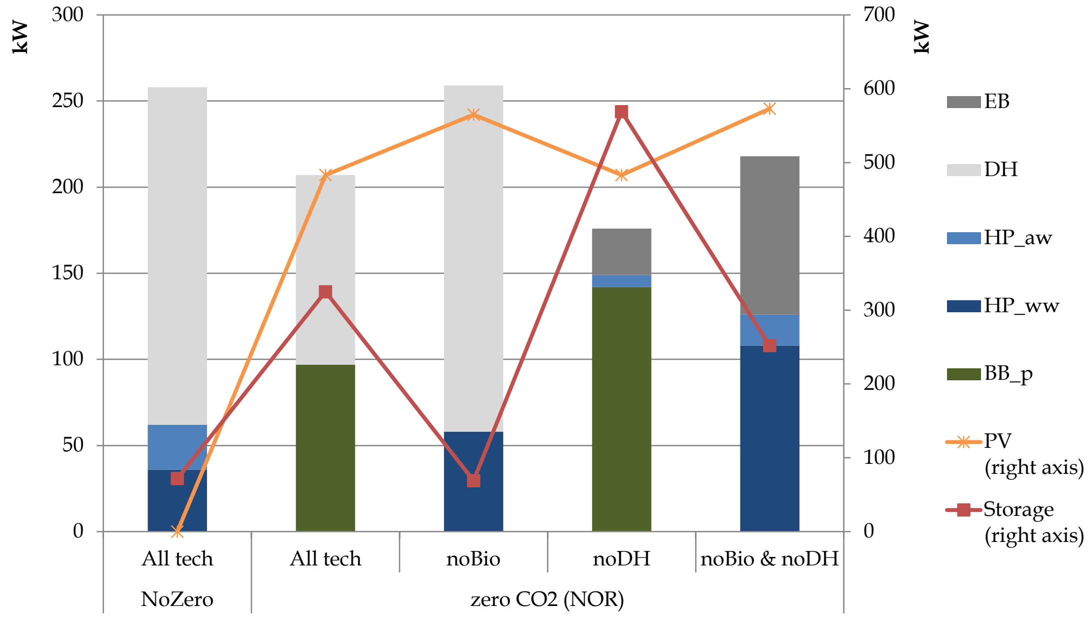

FIGURE 6.5: Installed capacity for the *zero*CO_2-*NOR* case. Cases with reduction in available technologies, min production of biomass boiler 50 kWh/h, no restriction on storage charging.

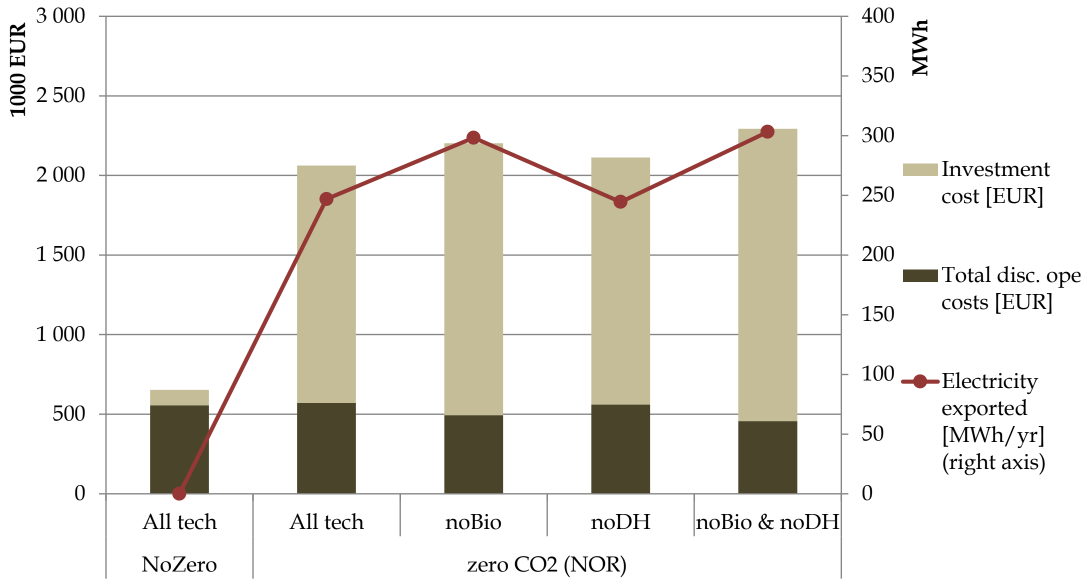

FIGURE 6.6: Investment cost, total discounted operational cost and electricity exported for the *zero*CO_2-*NOR* case. Cases with reduction in available technologies, min production of biomass boiler 50 kWh/h, no restriction on storage charging.

When no district heating is available the installed capacity in biomass boiler increases by 46% compared to when all technologies are available. Peak load is then covered by electric boiler and air-to-water heat pump. The total discounted costs increases by 2.5%, while there is no increase in the PV capacity installed in reference to all technologies available.

When no biomass boiler and no district heating is available a water-to-water heat pump is covering base load, and air-to-water heat pump and electric boiler is covering the peak load. HP_{aw} has lower COP than HP_{ww}, but has lower specific investment cost, thus HP_{aw} is used for peak load to a higher extent than HP_{ww}. This is the most expensive combination, investment costs increases by $12_{\%}$, and PV installations by 19%. The total discounted costs are increased by 11%.

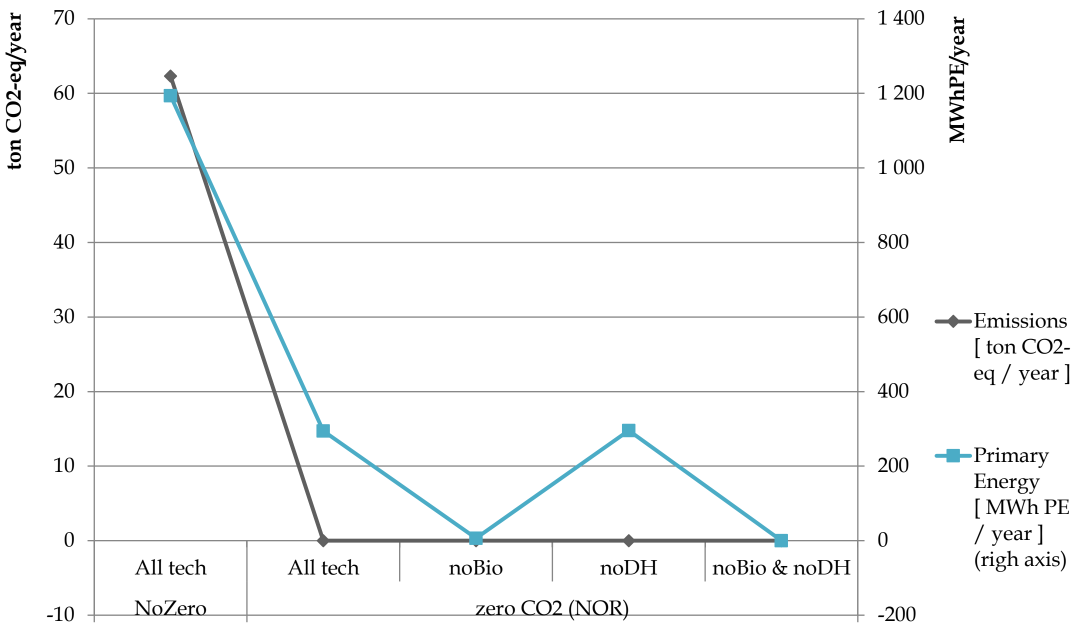

FIGURE 6.7: Net CO_2 emissions and PE use for the zeroCO_2 NOR case. Cases with reduction in available technologies,min production of biomass boiler 50 kWh/h, no restriction on storage charging.

In figure 6.7 annual CO_2 emissions and primary energy use are displayed. The figure show the same trend that biomass is lucrative in terms of CO_2 emissions, but disfavorable in use of primary energy, as seen in figure 6.4. For the relation between district heating and electricity the CO_2 emission-factors and district heating factors are close to equal.

6.2.1 No Biomass Boiler

Figure 6.8 shows the investments for the seven different cases when no biomass boiler is available.

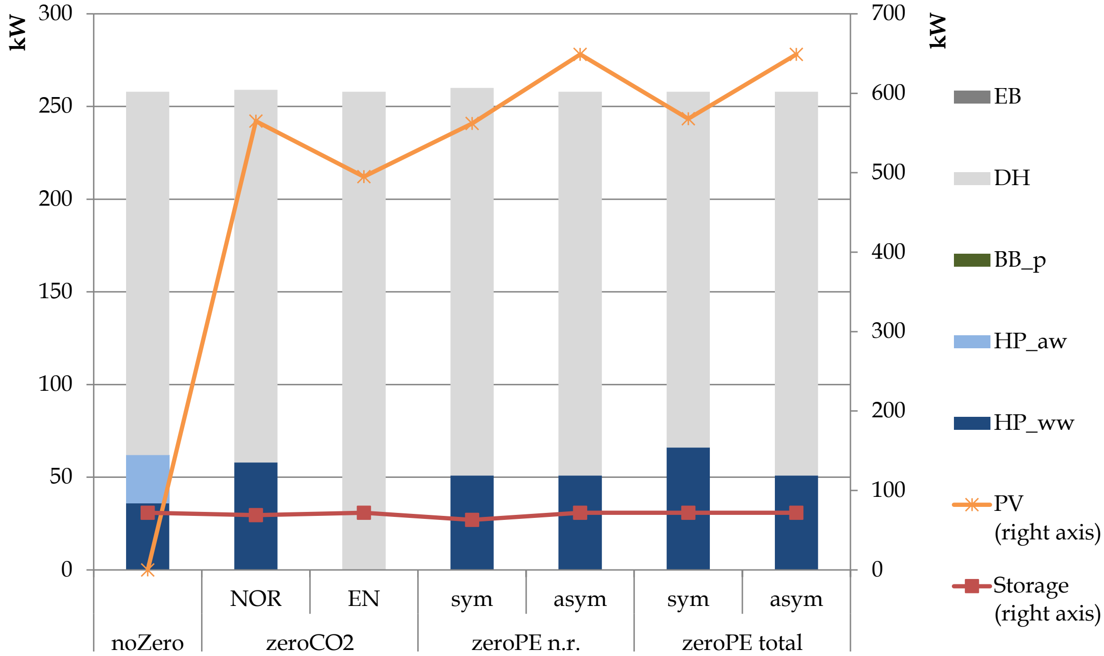

FIGURE 6.8: Installed capacity for the different zero cases. No biomass available, min production of biomass boiler 50 kWh/h, no restriction on storage charging.

The combination of a water-to-water heat pump and district heating for peak load stays as a robust solution, with the exception of the *zeroCO_2-EN* case. With European factors and zero CO_2 restriction only DH and storage is installed, using DH for both peak and base load. Since the European CO_2 factors has higher values for electricity than district heat, no heat pump is installed. This also reflects the lower PV installed for the *zeroCO_2-EN* case with no BB_p. For all crediting factors except *zeroCO_2 EN* the installed capacity of HP_{ww} is varying between 51-66 kW, and 191-209 kW for DH. Air-to-water heat pump is disfavored for all cases with zero-criteria applied.

6.2.2 No District Heating

The results of optimal investments decisions when no district heating is available is presented in figure 6.9.

When district heating no longer is available, HP_{aw} in combination with electric boiler is installed to cover the peak load. For the cases with net zero CO_2 emissions

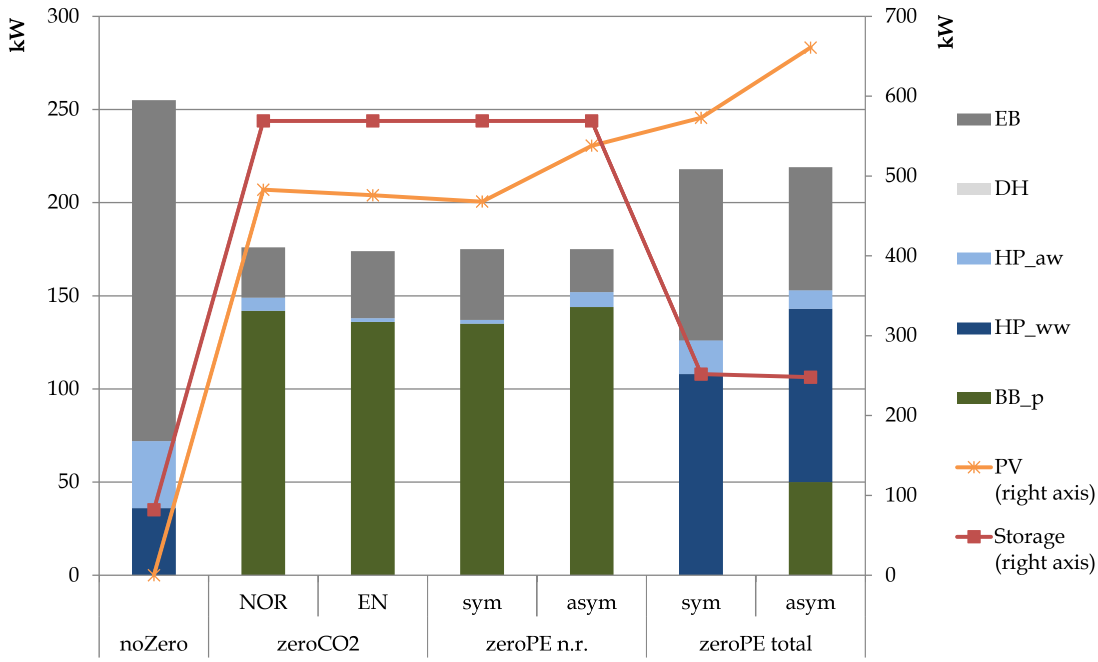

FIGURE 6.9: Installed capacity for the different zero cases. No district heating available, min production of biomass boiler 50 kWh/h, no restriction on storage charging.

and net zero PE use there is a shift from HP_{ww} as base load to BB_p as base load, which is corresponding to the results from section 6.1. The size of the installed storage is increased with more than 100 kWh compared to the zero CO_2 cases and zero PE n.r. cases when all technologies were available. The increase of installed capacity of heat storage is corresponding to the increase in installed capacity of BB_p.

For the *zeroPEtotal-sym* case, HP_{ww} and HP_{aw} is replacing BB_p due to higher total PE factors, as discussed in section 6.1. However with the *zeroPEtotal-asym* case, the base load is no longer only HP_{ww}, as was the case when DH was available. When electric boiler is used for peak load, the stricter asymmetrical PE factors for electricity forces the model to invest in BB_p as well as HP_{ww} in order to reduce the electricity consumption.

6.2.3 No District Heating and no Biomass Boiler

Figure 6.10 shows optimal investments of the seven cases, given only electricity based technologies available.

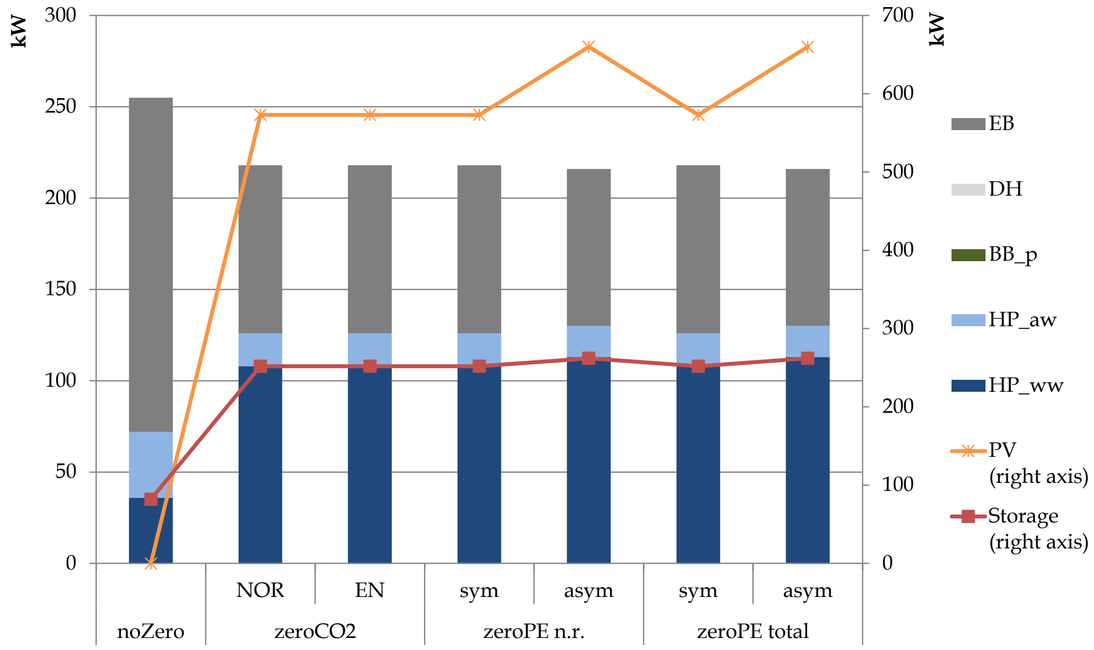

FIGURE 6.10: Installed capacity for the different zero cases. No district heating of biomass boiler available, min production of biomass boiler 50 kWh/h, no restriction on storage charging.

For all zero cases a combination of HP_{ww} as base load, and HP_{aw} and EB as peak loads is invested. This combination seems truly robust for all the factors and zero-constraints applied. The largest shift in going from the *noZero* case to the zero-restricted cases is that it is invested in a larger HP_{ww} and storage for base load and smaller EB investment.

An all electric system will inevitably lead to a net zero electricity building when zero-constraints are applied, regardless of the CO_2 og PE factors as long as they are symmetrical. With symmetrical factors, the crediting factors are equal for electricity imported and exported, and thus the net electricity consumption will be net zero. When asymmetrical PE factors are applied, electricity imported has a higher PE factor value than electricity exported. Thus, more electricity needs to be exported than what is imported to achieve the net zero-PE balance. This is reflected by the increased installations in PV for the *zeroPE n.r.-asym-* and *zeroPE total-asym* case in figure 6.10.

When heat pumps and electric boiler is used for heating, the self-consumption increases by 13% when compared to when all technologies were available. The tendency of higher self-consumption in absolute values when asymmetrical factors are applied, as seen in section 6.1, is even more visible when the heating is electricity based. For asymmetrical factors of non-renewable primary energy factors the increase in self-consumption is 3.9% compared to symmetrical factors, while the increase is 3.4% for total primary energy factors.

6.2.4 Main Findings

The main observations of investment decisions with reduction in available technologies when the zero cases are applied are as follows:

- When the $zeroCO_2$-*NOR* case is applied with restrictions in available technologies, the total discounted costs increase by between 2.5% to 11%.
- The value of the PE n.r. factor for biomass boiler is corresponding closer to the CO_2 factor for biomass boiler than the PE tot-factor, giving large values of primary energy use when zero-CO_2 restrictions are applied.
- With no biomass boiler is available a water-to-water heat pump in combination with district heating and storage stays as the optimal solution for all zero cases except $zeroCO_2$ *EN*, where district heating is chosen as the only heat generating technology in combination with storage.
- With no district heating available, larger capacity of BB_p to cover base load is invested, and smaller peak load capacities. An electric boiler and an air to water heat pump are installed as peak load technologies.
- With only electricity based technologies available, the installed capacity for heating and storage is equal for all zero-constraints. When asymmetrical primary energy factors are applied the PV installations are increased.

6.3 Hourly Operation: Annual

In this section, the results of optimal operation strategies for a possible zero emission school is analysed. Thus the $zeroCO_2$-*NOR* case is further investigated.

6.3.1 Electricty Balance

The hourly electricity balance for 2012 is presented in figure 6.11. The figure shows the electricity specific demand, electricity bought from the grid and electricity exported to the grid. The optimal heating solution for the $zeroCO_2$-*NOR* case with all technologies available do not include any electricity based technologies, hence the electricity specific demand of the building forms the total electricity demand.

From figure 6.11 it is seen that the on-site production of PV contributes to reduce the electricity bought from the grid from approximately week 12 to week 40, which is about half of the year. Further, the peak export exceeds the peak import by about 120%. During winter, the on-site production contributes marginally to reducing the electricity bought from the grid.

6.3.2 Heat Balance

In figure 6.12 the annual heat balance for the storage is presented. The highest heat content of the storage, 325 kWh, is only 40 kW(kWh/h) larger than the highest peak heat demand of the building. Thus, the storage is not used as seasonal storage, but in general used as a daily and weekly storage. There is a tendency that the storage is charged with a lower power input of heat, and discharged with a higher power output, during the period with a high heating demand. During summer, the charging is done with higher power input, and discharged with lower power output over a longer time period.

6.3.3 Annual Energy Production

Figure 6.13 is the corresponding annual energy production to the installed capacities from figure 6.5, for the *zero*CO_2*-NOR* case with reduction in available technologies. As expected the base load investments is responsible for the largest part of the energy production. However, in general the peak load sources have the highest installed capacity. Additionally there seems to be a strong correlation between the ratio of installed peak- and base load capacity, and the ratio of heat provided by the peak load technology, and the heat provided by the base load technology. The heat losses from the storage is marginal compared to the total energy provided.

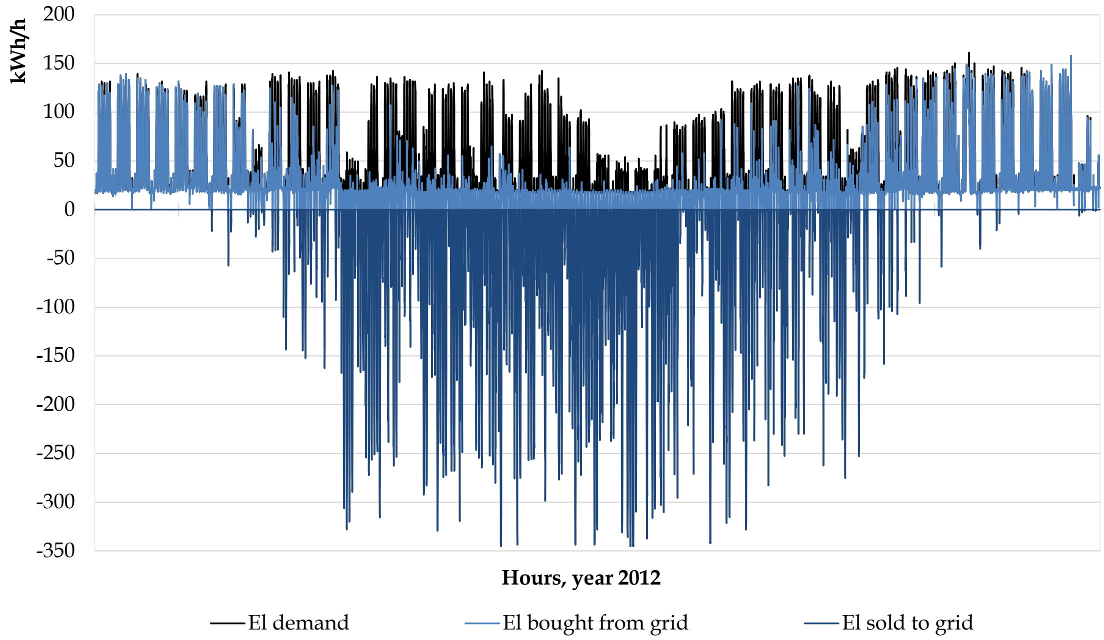

FIGURE 6.11: Hourly electricity balance for the zeroCO_2 NOR case, during one year. All technologies available, min production of biomass boiler 50 kWh/h.

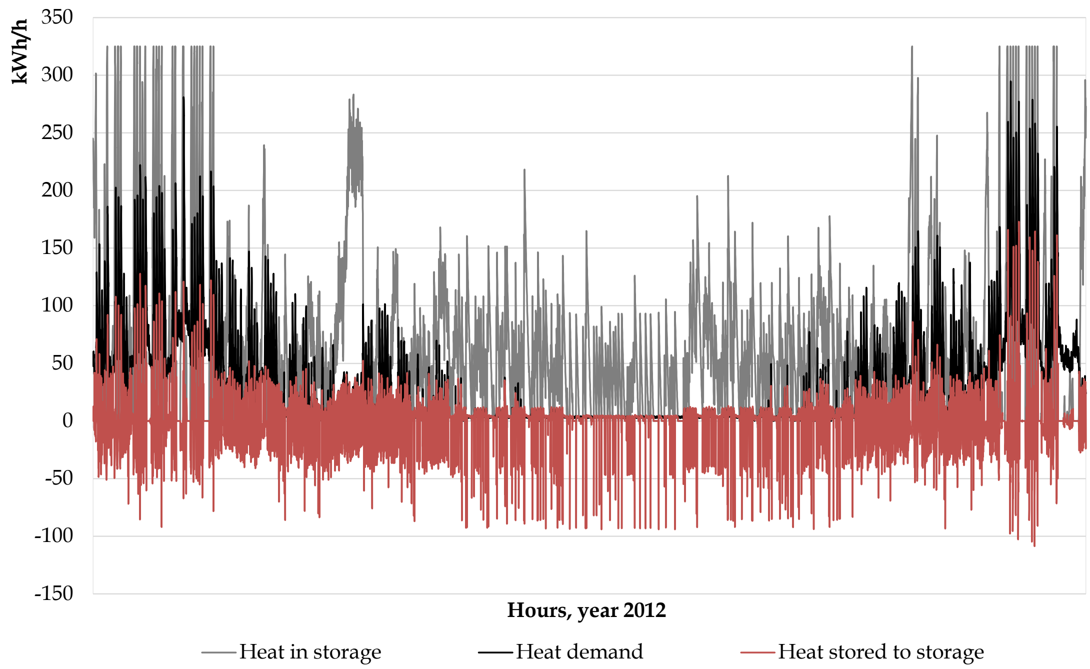

FIGURE 6.12: Hourly heat balance for the zeroCO_2 NOR case, during one year. All technologies available, min production of biomass boiler 50 kWh/h.

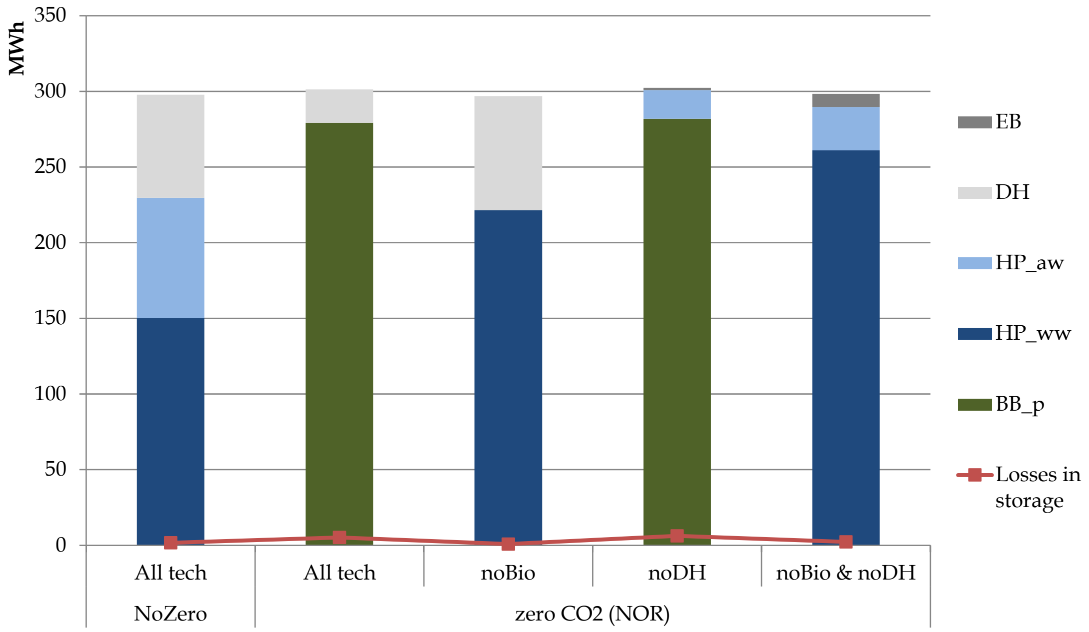

FIGURE 6.13: Energy production zero CO_2 NOR case. Cases with reduction in available technologies, min production of biomass boiler 50 kWh/h, no restriction on storage charging.

6.4 Hourly Operation: Weekly

6.4.1 All Technologies

The following graphs show the hourly operation of the heat technologies during one winter week in January. This week is selected because it contains high peak heat demand values. The heat production series are presented together with the electricity price and ambient temperature, to visualize how these parameters are affecting the optimal operation of the technologies.

Figure 6.14 represents the case of *zero*CO_2-*NOR* with all technologies available. *Heat to storage* represents energy extraction from the storage, where positive values represents heat taken out of the storage, while the negative values represents the heat stored to the storage. Recall that the price of district heat is linked to the electricity price, as discussed in section 4.7.

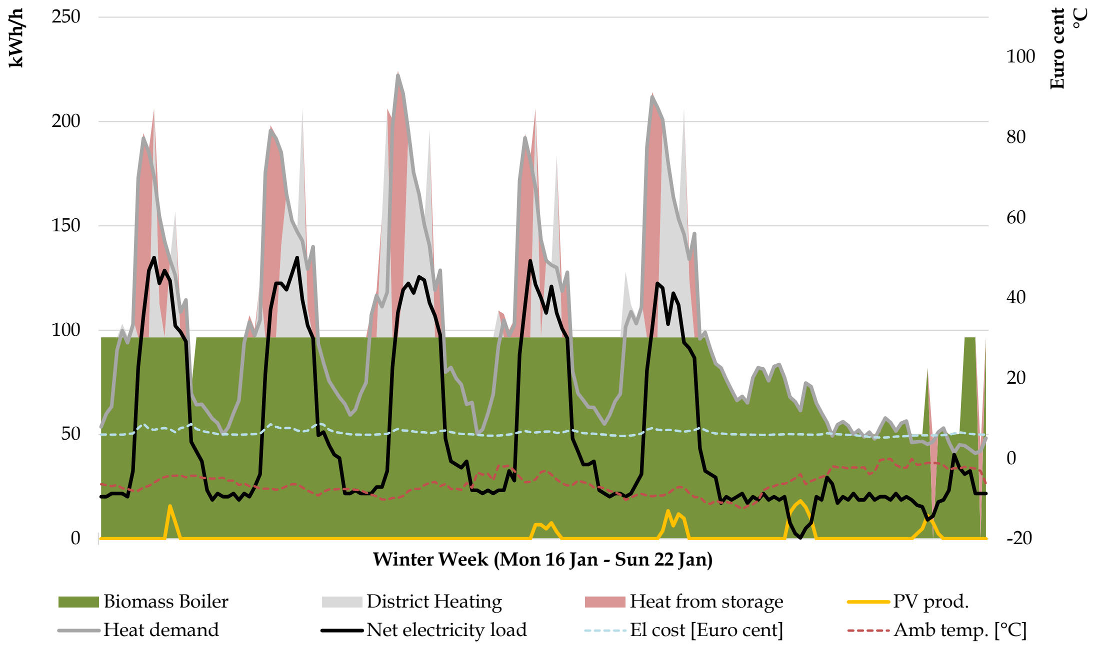

FIGURE 6.14: Operation of heat technologies during one winter week (Mon 16 Jan - Sun 22 Jan) for the zeroCO_2 NOR case. All technologies available, min production of biomass boiler 50 kWh/h.

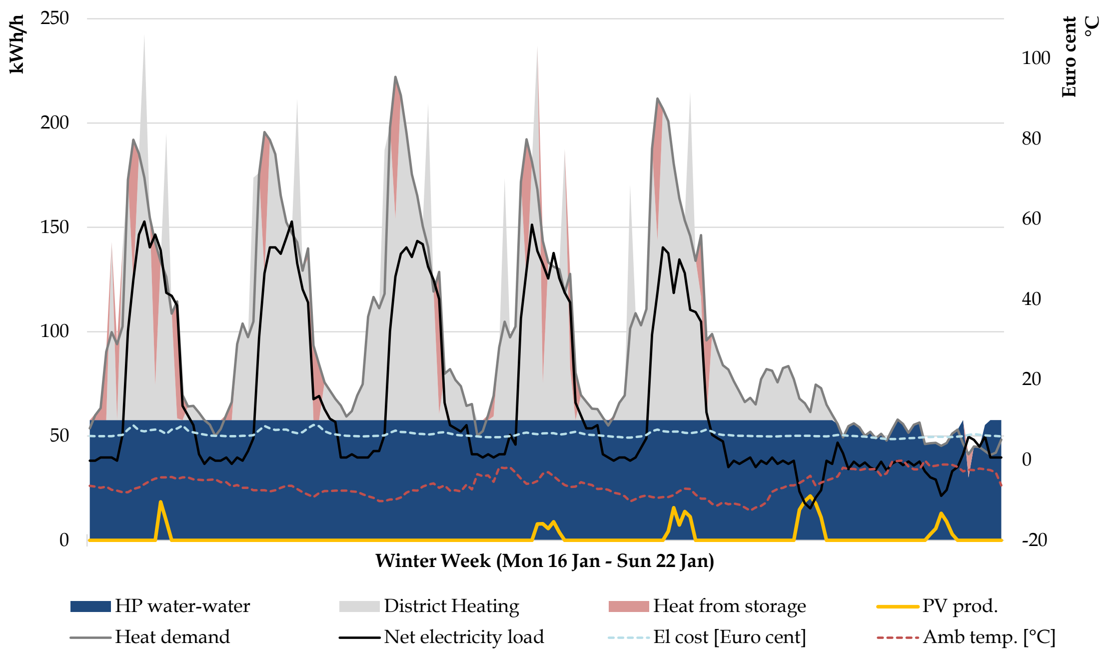

FIGURE 6.15: Operation of heat technologies during one winter week (Mon 16 Jan - Sun 22 Jan) for the zeroCO_2 NOR case. No biomass boiler available

BB_p is used as base load, and DH as peak load. BB_p is covering up to 97 kW, and running on maximum capacity in the weekdays. When the heating demand gets lower than 50 kWh/h, BB_p is turned off, and the storage is covering the heat demand. BB_p is run nearly constant on maximum capacity in the weekdays, using the lower demands at night to charge the heat storage. However, the BB_p installed capacity and storage is not large enough to save heat for the whole peak at mid-day. The district heat is used partly to meet the demand at day and partly to fill the storage in the hours of the day when the price of district heating is lower.

6.4.2 No Biomass Boiler

The operation strategy for a typical winter week for the same case of zero CO_2 emissions with Norwegian CO_2 factors but without biomass boiler, is seen i figure 6.15. The electricity generation from the installed PV is not large enough to influence the operation of the heat pump, as seen on the last day, when the water-to-water heat pump reduces the production at the same time as PV is producing. However, the PV production is reducing the net electricity bought from the grid, when sun is present.

The water-to-water heat pump is running on maximum capacity in the weekdays, and covering the full heat demand in the weekends. The district heating is covering a larger part of the peak load, than in the case where all technologies were available. The district heating is operated in the same way as for all technologies, and show a clear tendency of avoiding operation during times with peaks in the district heating cost.

6.4.3 No District Heating

When no district heating technology is available, seen in figure 6.16, only the biomass boiler and the heat storage are used to meet the heat demand. The storage is charged in the early morning, and discharged to meet peak demand of heat at mid-day. In the weekends, the heating demand is less than the minimum production of BB_p, and the storage is being filled in the hours where the heat demand is lower than 50 kWh/h. The installed air-to-water heat pump is used together with the storage as heat source in the summer, when the heat demand is far less than the minimum production of the biomass boiler.

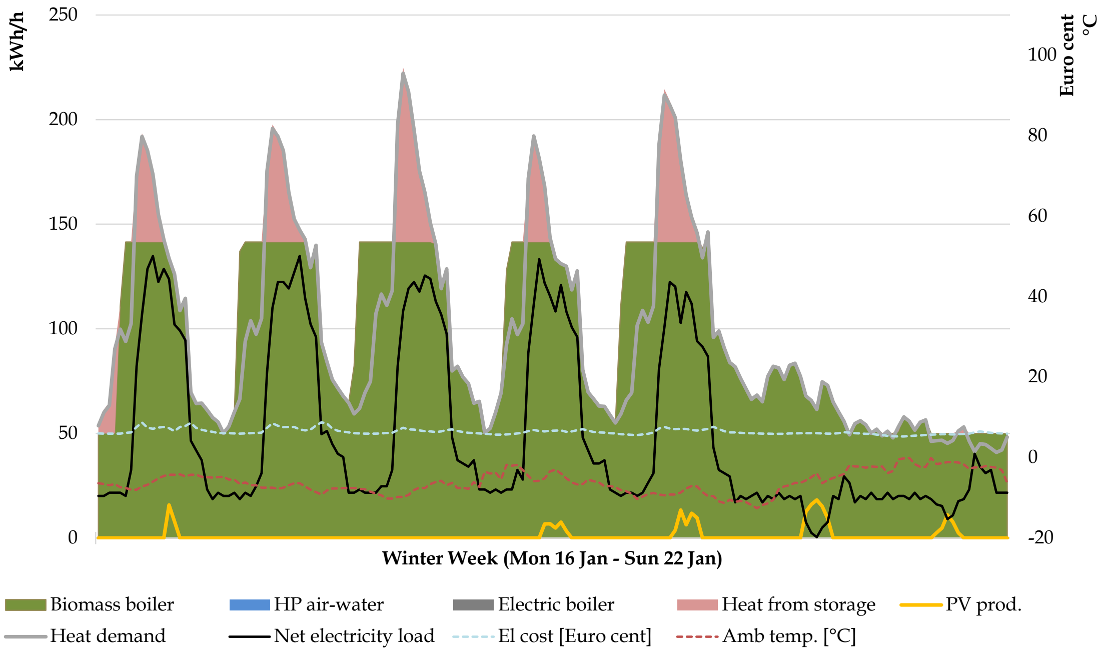

FIGURE 6.16: Operation of heat technologies during one winter week (Mon 16 Jan - Sun 22 Jan) for the zeroCO_2 NOR case. No district heating available, min production of biomass boiler 50 kWh/h.

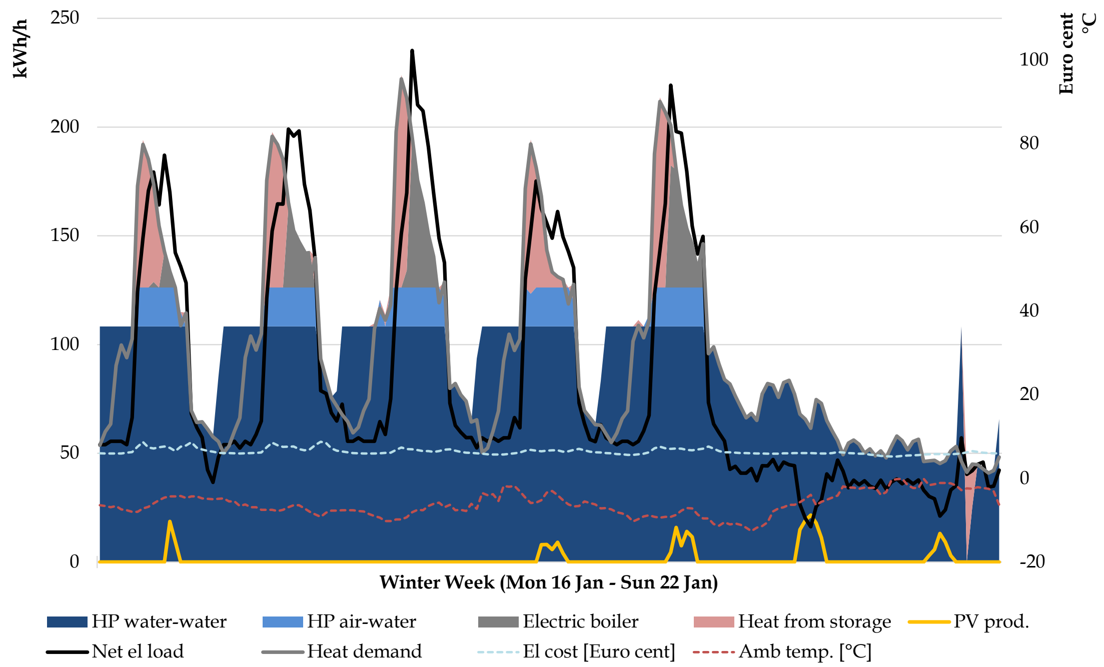

FIGURE 6.17: Operation of heat technologies during one winter week (Mon 16 Jan - Sun 22 Jan) for the zeroCO_2 NOR case. No district heat or biomass boiler available, min production of biomass boiler 50 kWh/h.

6.4.4 All Seasons, no Biomass Boiler and no District Heating

For the case where neither district heating or biomass boiler is available, all technologies will be based on electricity as energy carrier. To have a deeper look at how hourly variations in the electricity price influences the operation of the heating technologies, operation curves for one typical week during winter, autumn and summer will be presented for this specific case.

In figure 6.17 it is apparent that the peaks of the net electricity bought from the grid increases. This is coherent with the findings in section 6.2. The peak values of electricity imported per hour increases by 70% compared to the case of all technologies but DH available.

HP_{ww} is used as base load, and running on maximum load all but the afternoon hours during the weekdays. During the weekends, the heat pump is covering the whole load. In the weekdays the heat pump chooses to reduce the production of heat instead of filling up the storage. The changes in the power price cannot be said to have a noticeable influence of the operation of the heat pump, as the magnitude of the effect is seen in the case of all technologies available in figure 6.14.

Instead of installing a larger heat storage, and running the heat pump at maximum during the whole heating season, a small air-to-water heat pump is installed. The HP_{aw} is covering the base of the peak load, while the storage and an additional electric boiler is covering the remaining peak load. The cost of installing an air-to-water heat pump and an electric boiler will be a trade off with the cost of installing a larger storage, as seen in combination with a biomass boiler in figure 6.16.

In figure 6.18 and 6.19 the weekly operation during a typical week in the autumn and summer is shown. District heating and biomass boiler is still non-available.

During the autumn, only HP_{ww} and the heat storage is being used. The storage is used to cover the peak demand, but also for responding to peaks in the electricity price, as seen on the Monday. In comparison to BB_p, no min production restriction is applied to heat pump, thus when the demand is low, HP_{ww} is covering the demand, with no use of storage.

During the summer months, HP_{aw} has a higher COP than HP_{ww}, and is covering the whole heat demand together with the storage. The electricity price has almost no variations in price during the hours of the day.

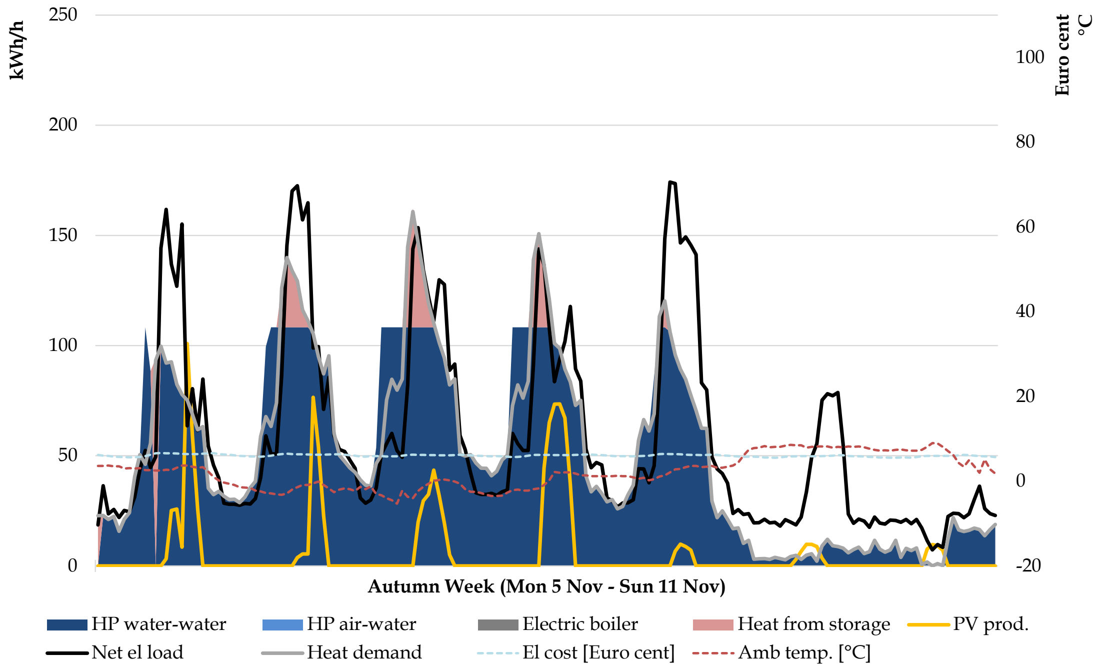

FIGURE 6.18: Operation during one autumn week (Mon 5 Nov - Sun 11 Nov) for the zeroCO_2 NOR case. No district heat or biomass boiler available.

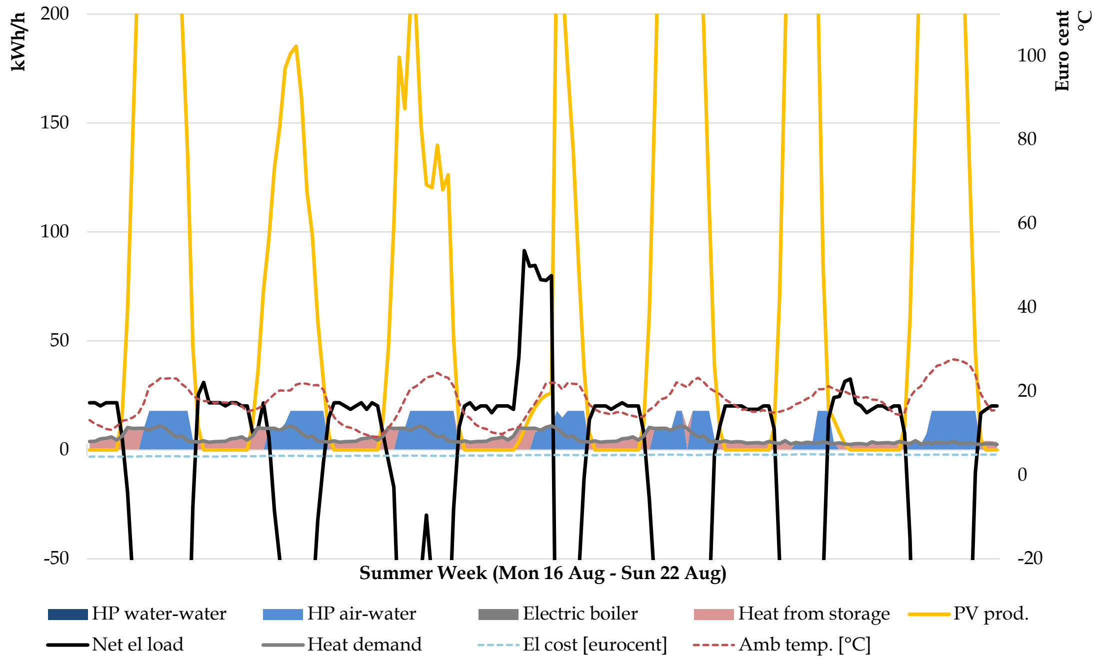

FIGURE 6.19: Operation during one summer week (Mon 16 Aug - Sun 22 Aug) for the zeroCO_2 NOR case. No district heat or biomass boiler available. The peak values for PV generation and net electricity profile are cut to see how the operation of the heat technologies react to surplus on-site electricity generation.

HP_{aw} is using the storage to cover the night demand for heat, while the HP_{aw} is producing max during the day. This is because asymmetrical electricity pricing makes it more profitable to selfconsume PV electricity, during the day, by use of the HP_{aw}.

6.4.5 Main Findings

The main observations of optimal operation strategy are as follows:

- When the biomass boiler is used as base load heating, the storage is used to limit the installed capacity of BB_p. Additionally the storage is used to supply heat when the heat demand is lower than the minimum production of the biomass boiler.
- When district heating is used as peak load in combination with biomass boiler as base load, the storage is used to avoid peak energy cost of the district heating.
- For water-to-water heat pump based heating, the storage is used to limit the installed capacity of HP_{ww}.
- In the winter week, the all-electricity-based heating utilize both a water-to-water heat pump for base load and air-to-water heat pump and electric boiler in combination with a heat storage for peak load coverage.
- In an autumn week, the all-electricity-based heating utilize water-to-water heat pump for base load, and heat storage only, as peak load.
- In a summer week, the all electricity based heating utilize air-to-water heat pump only. The air-to-water is run when there is on-site PV generated electricity available, using storage to cover night load.
- There is no tendency of reducing the heat production from the heat pump based on variations in the electricity price.

6.5 2 periods: Decreasing CO_2 Factors

The model is developed to be able to take in different input data in subsequent periods within the period of analysis. There is no restriction to how many periods the model can handle. However in this simulation the model is tested for two periods with a decrease in the CO_2 factors of electricity. For the first period of 30 years a CO_2 factor of 130 g CO_2 eq/kW is used, while a CO_2 factor of 10 g CO_2 eq/kW is applied for the second period of 30 years. The model is run with multiple periods for tree different technology combinations, and with zero CO_2 emissions with Norwegian factors. The total results of the analysis with two periods is compared to the results with one period and fixed CO_2 factor of 130 g CO_2 eq/kW for electricity. The details of the analysis is found in table A.6 in appendix A.

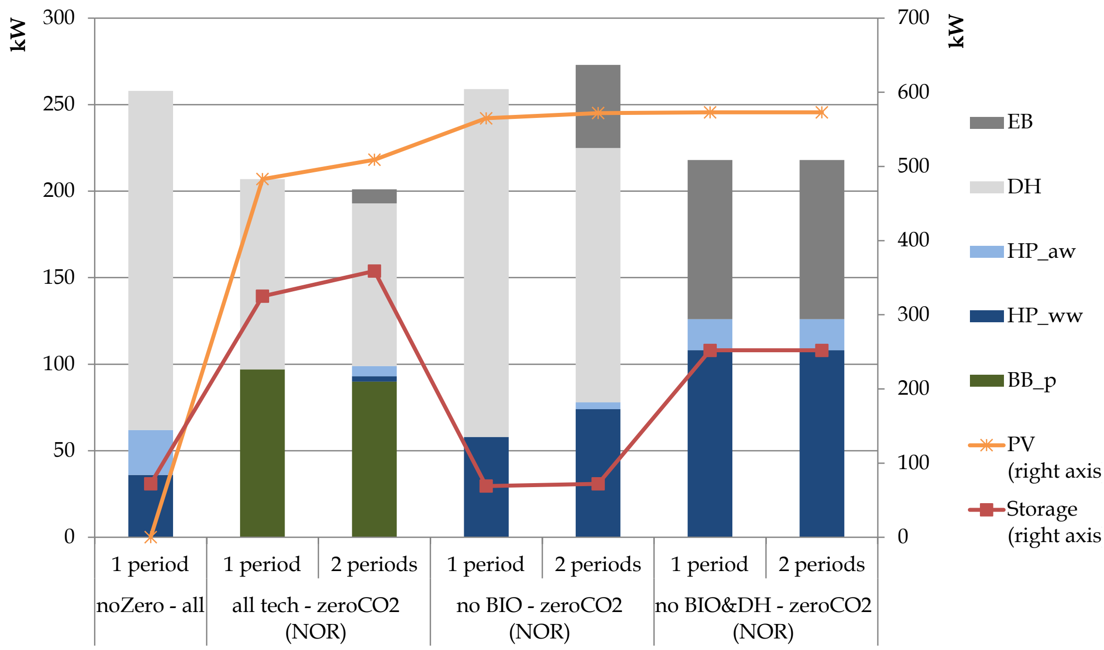

FIGURE 6.20: Installed capacity of for multiple periods. The model is run in *1 period* and *2 periods*. For *1 period*, the analysis is of one period with 60 years, and symmetrical CO_2 factor for electricity of 130 $gCO2-eq/kWh$. For *2 periods* the model is run with two periods of 30 years each, where the symmetrical CO_2 factor for electricity is 130 $gCO2-eq/kWh$ in the first period, and 10 $gCO2-eq/kWh$ in the second. Cases with reduction in available technologies, min production of biomass boiler 50 kWh/h.

When all technologies are available the optimal solution for one period is district heating and biomass boiler, as seen in section 6.1. For the analysis over two periods and decreasing CO_2 factors, the optimal investments shift to include both electric boiler, air-to-water heat pump and water-to-water heat pump. During the first period, the biomass boiler is used to cover the full load during winter load, while in the second period, parts of the base load during the winter is covered by the heat pumps, reducing the heat generation from the biomass boiler. In the second period the CO_2 factors of the biomass boiler will be higher than the equivalent

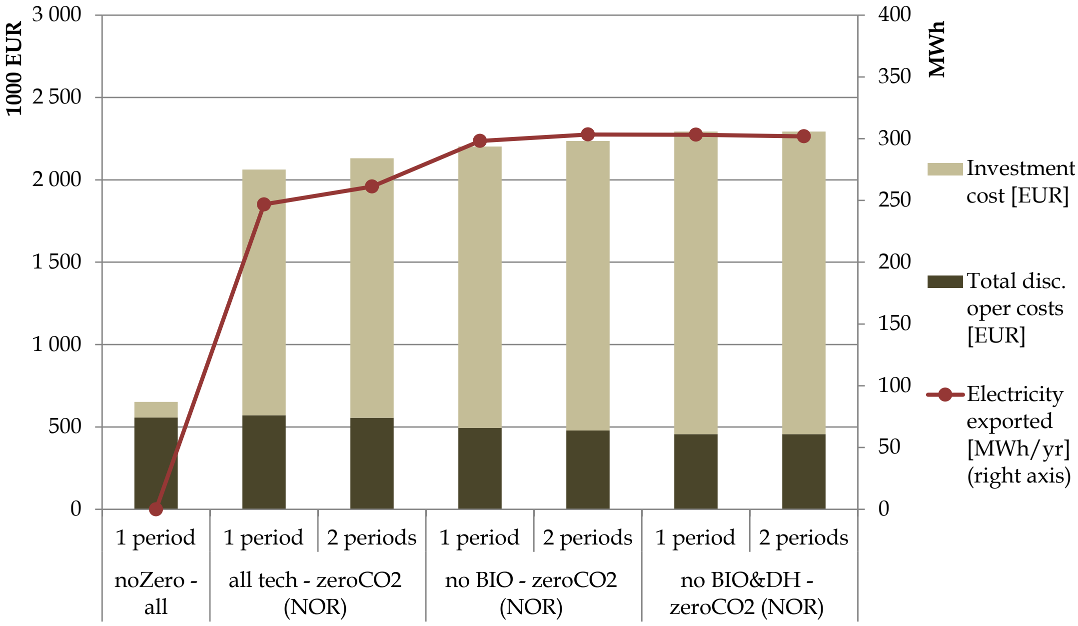

FIGURE 6.21: Investment cost, total discounted operational cost and electricity exported for multiple periods. CO_2 factor for electricity is 130 g CO_2 eq/kW in the first period, and 10 g CO_2 eq/kW in the second. Cases with reduction in available technologies, min production of biomass boiler 50 kWh/h.

CO_2 factor of a heat from a heat pump, causing larger investments in heat pumps. Within the two periods the annual heat production of the HP_{ww} is 9 MWh in the first period and 19.7 MWh in the second.

This tendency of more lucrative investments in heat pumps with decreasing CO_2 factors is even more clear for the case where no biomass is available.

For the case of only technologies based on electricity, there are no difference when analysis over two periods with decreasing CO_2 factors. This is again caused by the principle that a building based on electricity as the only energy carrier needs to be net zero in import of electricity to achieve the zero-constraints. This means that the solution will be the same for all symmetrical zero restrictions applied.

There seems to be only small changes in the installed capacity of PV, even though the CO_2 factors are decreasing quite dramatically in the second period. This is also reflected by the total discounted costs presented in figure 6.21. For the case of all technologies available the installed capacity of PV is increased to 509 kW, which is 5% higher than the case all technologies and *zeroCO$_2$-NOR*-constraint of one period only. For the analysis with no BB_p available, is the increase in PV investments 1.2 %.

6.5.1 Main Findings

The main observations of the results of the analysis run with two periods and decreasing CO_2 factors:

- Reduction in CO_2 factors for electricity tend to shift the investment and energy production towards more use of heat pumps and electric boiler.
- Reduction in CO_2 factors for electricity has no influence of the optimal investment in an all electricity based heating system.

6.6 Grid Restriction

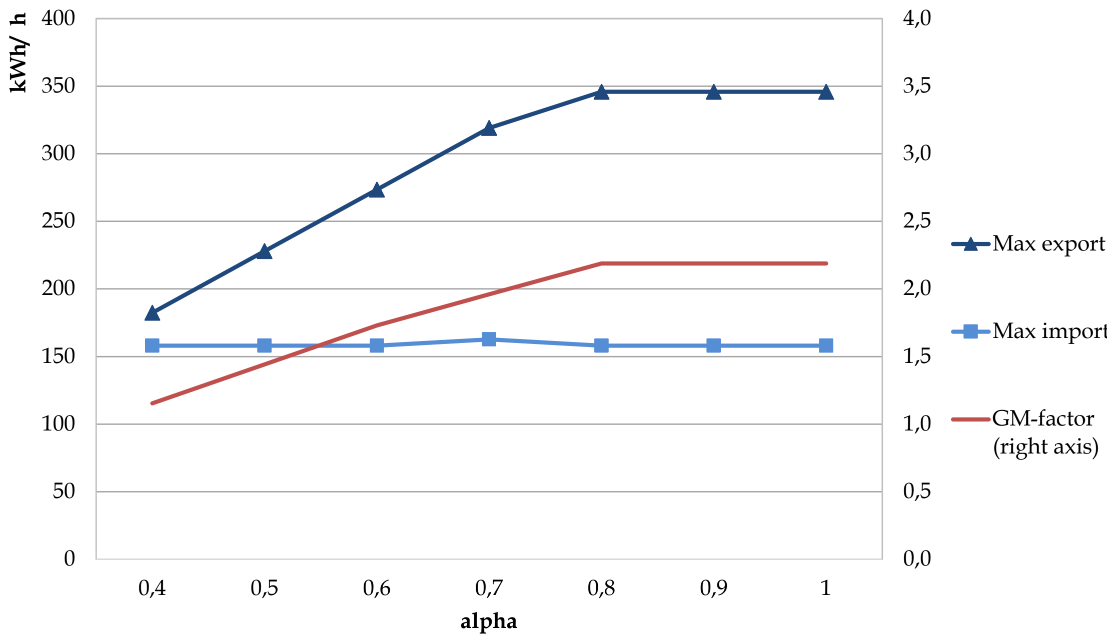

FIGURE 6.22: Grid restriction, grid burden. α is the restriction on the sum of peak import and export, in reference to the *noZero* case. In the *noZero* case there are no PV-installation, and $\alpha = 1$ will this be the peak net import of electricity. Max export and import are the highest values of export and import during the analysis-period. GM is the generation multiple, describing the grid burden in terms of the ration of electricity production compared to the design load of the building (see section 2.4). All technologies available, no min production of biomass boiler, no restriction on storage charging.

For analysing the effect of limiting the maximum export and import from of the building to the grid, the possibility of introducing grid burden-restrictions is included, as elaborated in section 5.5. In this sections the results of analysis of the *zero*CO_2-*NOR* case, where the maximum export and import were restricted through the α-value, are presented. The analysis is performed with α-values going from 1 to 0.4. At α=1, the maximum power exchange through the grid equals M_{grid}, which is the sum of the highest hourly import of the *noZero* case. At approximately α=0.35 the restriction has reached the lowest possible value of α where the specific electricity demand still can be met. When α is less than 0.35 no possible solutions is obtainable with the input data used.

In figure 6.23 the highest values of export and of import of electricity within one hour is presented, along with the generation multiple. It is evident that the export of electricity to the grid exceed the peak export values when the zeroCO_2 restriction is applied. When the heating is based on biomass boiler and district heating, the peak values of electricity will be caused by the specific electricity demand only. Thus there are only marginal changes in the max values of electricity import when the α-restriction is tightened.

The generation multiple (GM) represents the ratio of peak export to the peak import. From the graphs presented it can be seen that the restriction of the grid burden has a negligible effect on the peak export values before α is reaching values below 0.8. At α equal 0.8 the peak value of hourly export is 119% higher than the peak import. From α equal 0.8 to 0.4 the decrease in peak export is close to linear with decreasing α-values. At α equal 0.4 the peak export value is 15% higher than the peak import.

The PV investments show little influence of the peak export restriction. The production of electricity is fixed to the installed capacity of PV, since there is no battery available for storage of electricity. However, from α equal 0.4 to 0.5 the installed capacity of PV is increasing by 7%, at the same time as the total electricity export is reduced by 2%, as seen in 6.22. Then the heat storage is increasing, consequently the heat losses in the storage will increase. To meet the zero-restriction, the PV generation needs to be increased.

In figure 6.23, the optimal investments when the grid restriction is active, are shown. As the peak export value is being limited, the model chooses to shift the investments towards electric boiler, at the same time as a larger heat storage is invested. When investing in electric boiler in combination with a heat storage, more electricity can be used for self-consumption, reducing the import of electricity, however.

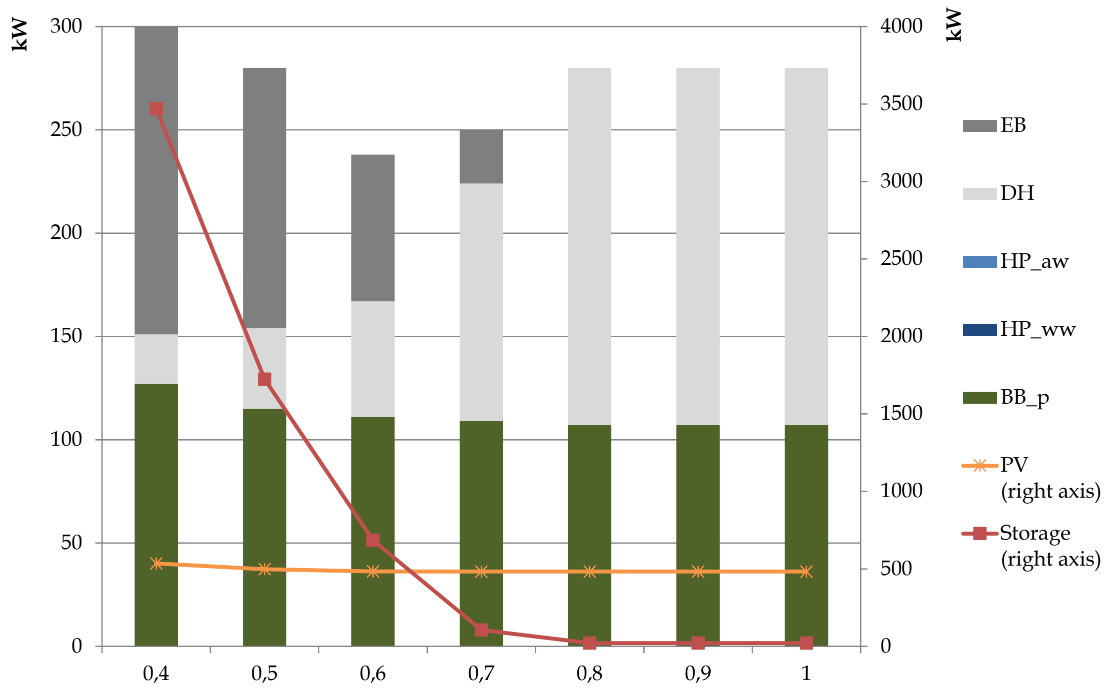

FIGURE 6.23: Grid restriction. Installed capacities for *zeroCO*$_2$*-NOR*, and decreasing grid restriction (α). α is the restriction on the sum of peak import and export, in reference to the *noZero* case. All technologies available, no min production of biomass boiler.

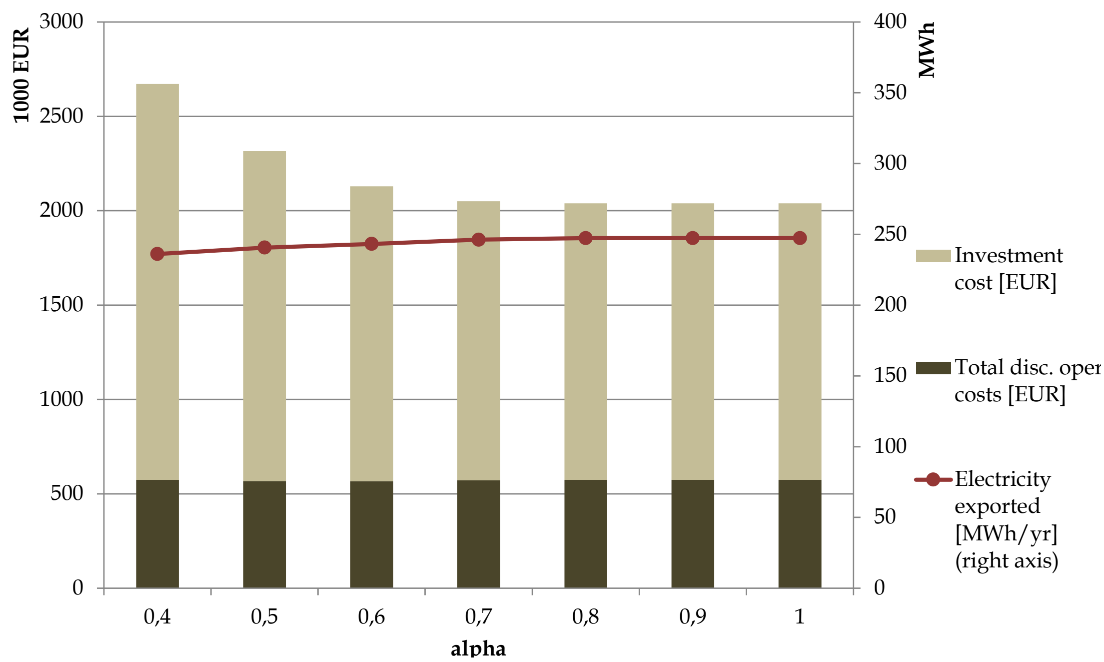

FIGURE 6.24: Grid restriction. Investment cost, total discounted operational cost and electricity exported for *zeroCO*$_2$*-NOR*, and decreasing grid restriction (α). α is the restriction on the sum of peak import and export, in reference to the *noZero* case. All technologies available, no min production of biomass boiler.

With stricter α-values, the installed capacity of electric boiler is increasing, and the investments in district heating is consequently reduced. The investments in heat storage has close to exponential growth from α equal 0.7 to 0.4. At α equal 0.8 the installed capacity of heat storage is 21 kWh, or 405 liters with a temperature differential of 40 °C. At α equal to 0.4, the size of heat storage has increased to 67,000 liters with the same temperature differential.

The increase in the total costs in figure 6.24, seems to be corresponding to the shift from district heating to electric boiler and increased storage. However, the growth in investment cost is not reflecting the exponential growth in the heat storage, as seen in table A.7. This indicate that the investment costs of PV panels drowns out the investment costs of heating, as also seen in section 6.1.

6.6.1 Main Findings

Main observations of the results of grid restrictions:

- With zeroCO_2 constraints and BB_p as base load, the hourly peak export values exceed the peak values of electricity import.
- From α equals 0.6 to 0.4 the PV investments increases, while the total export of electricity is slightly reduced.
- Grid restrictions shows negligible influence of the installed capacity of base load, and peak electricity import values.
- To reduce peak export values, the peak load shifts from district heating to electric boiler in combination with storage to increase self-consumption of on-site PV electricity.
- The investments in heat storage increases exponentially from α equals 0.8 to 0.4.

6.7 Relaxation of the Zero CO_2 Constraint

In the results so far, the analysis has been performed either with a strict zero-constraint, or with no constraint at all. In this section the zero CO_2 constraint will be relaxed, to see how investment decisions and self-consumption are altered on the way to a zero-emission-system. The overall details of the analysis are written in table A.8 in appendix A.

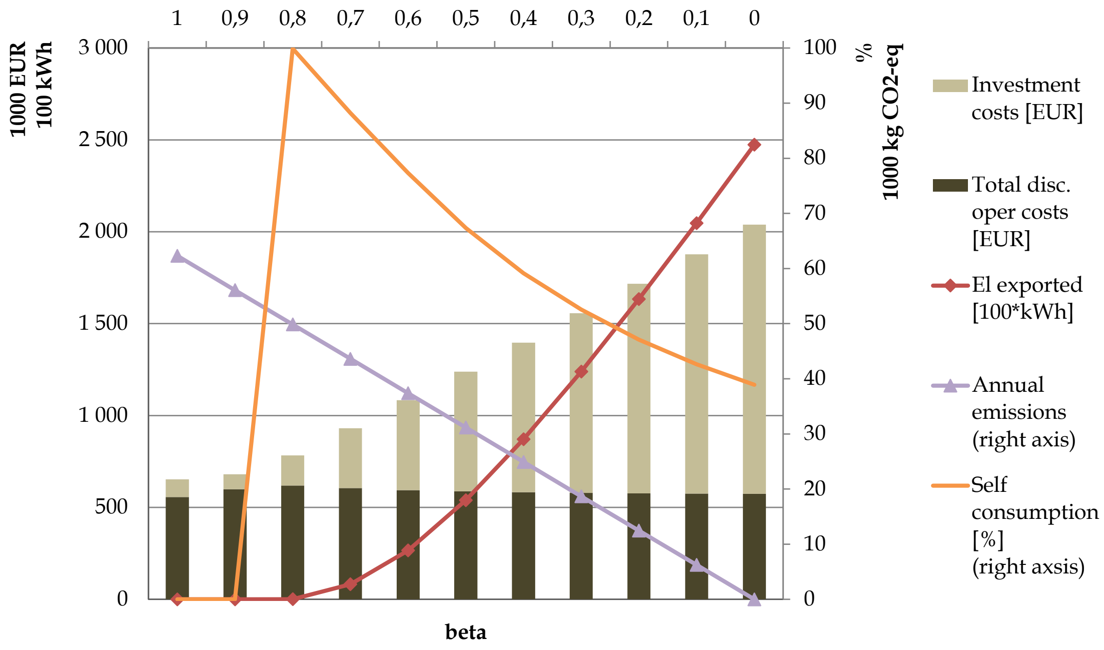

FIGURE 6.25: zeroCO_2 relaxation: Self consumption, investment cost, total discounted operational cost, annual emissions and electricity exported. Beta is running from 1 to 0, where 1 represents *noZero* case, and 1 equals the *zeroCO_2-NOR* case. Self-consumption is defined as the difference of electricity generated by PV, and the electricity exported within the same hour. The percentage value of self-consumption is the total amount of self-consumption divided by the total amount of electricity provided by PV. All technologies available, no min production of biomass boiler.

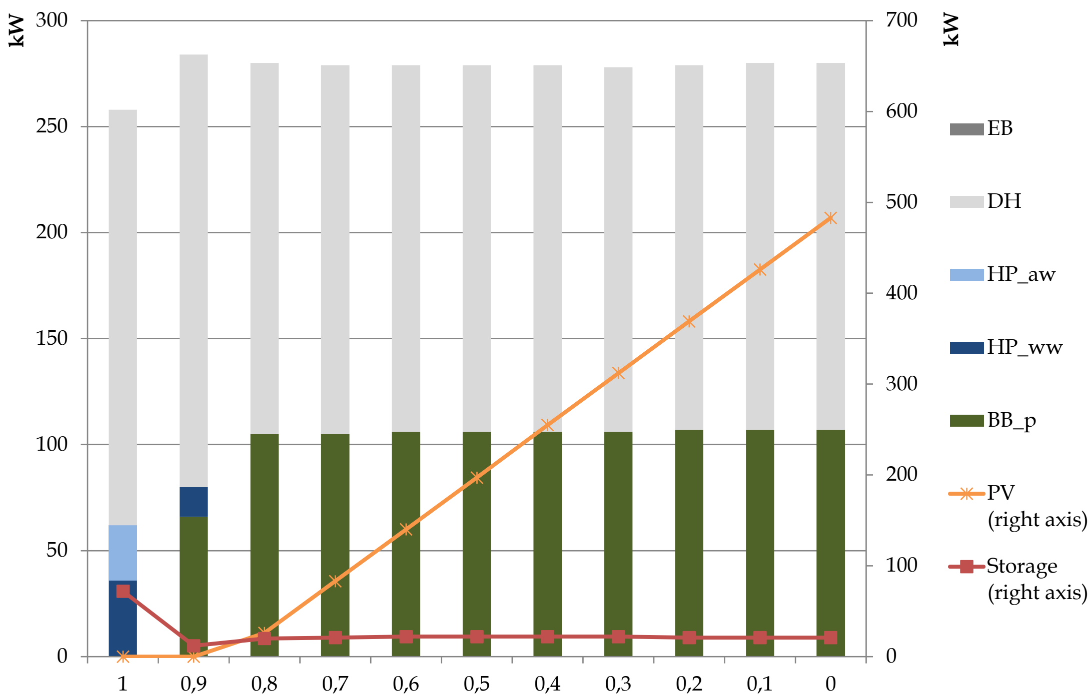

FIGURE 6.26: zeroCO_2 relaxation: Installed capacities. Beta is running from 1 to 0, where 1 represents *noZero* case, and 1 equals the *zeroCO_2-NOR* case. All technologies available, no min production of biomass boiler.

In figure 6.25 the total discounted investment cost, the total discounted operational cost, total export of electricity, annual emissions as well as self-consumption is presented. The β values varies form 0 to 1, where β equal to 1 represents the *noZero* case, and β equal to 0 is the *zeroCO$_2$-NOR* case. Thus, the annual emissions are by definition decreasing linearly by the decrease of β.

In figure 6.25, the self-consumption is given as a percentage value of the total PV production.

When no zero-constraint is applied, the total discounted operational cost constitute the major part of the total costs. Between β equal 0.6 and 0.5 the ratio shift, and the investment cost is larger than the operational costs. From the *noZero* case to the *zeroCO$_2$-NOR* case the investment cost increases by 1.37 million Euro, while the total discounted operational costs decreases by 17 thousand Euro due to export of PV electricity.

When the zero-constraint is strengthened to β equal 0.9, the investment cost decreases by 14%, while the operational costs increases by 7.5%. This implies that the model first tries to reduce the emissions from the building, by choosing a mix of technologies that gives lower emissions than the case of no CO_2 restriction, before it applies the PV panels. As seen in figure 6.26. The base load is shifted from water-to-water heat pump to biomass boiler as main base load.

The peak load is shifted from an air-to-water heat pump combined with district heating, to a water-to-water heat pump with district heating. This could be explained by the higher COP of the HP_{ww} during winter, and thus investments in HP_{ww} will allocate less CO_2 emissions than the HP_{aw}.

From β equal to 0.8 the least polluting mix of technologies for heat generation is chosen, and the increase in investment cost is from installation of PV only, confer figure 6.25 and 6.26.

The self-consumption of electricity generated by PV is inversely corresponding to the increase in electricity exported. The price for electricity sold to the grid is lower than the price of buying electricity from the grid. Hence, the model will try to use as much as possible of the electricity for self-consumption. However, the optimal heating combination is Bio and DH, so no electricity will be used for heating purposes. The self-consumption needs to be when the PV is generating, and the building has electricity demand within the same hour. When the PV generation is small, the building is able to utilize all of the electricity generated on-site to meet the specific electricity demand. As the electricity generated by the PV increases, the production exceed the electricity demand of the building, and

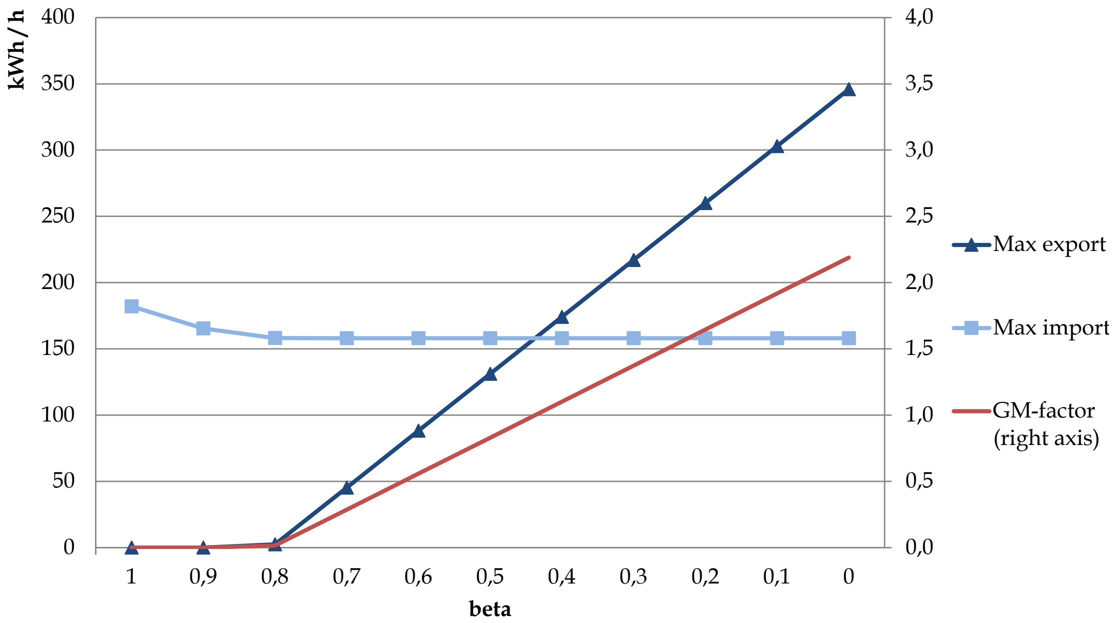

FIGURE 6.27: zeroCO_2 relaxation: Grid burden. Beta is running from 1 to 0, where 1 represents *noZero* case, and 1 equals the *zeroCO_2-NOR* case. Max export and import are the highest values of export and import during the analysis-period. GM is the generation multiple, describing the grid burden in terms of the ration of electricity production compared to the design load of the building (see section 2.4. All technologies available, no min production of biomass boiler, no restriction on storage charging.

the level of self-consumption is decreasing. At β equal 0.8, 26 kWp PV is invested, and the self-consumption share is 99.9%. At the zero CO_2 constraint at β equal 0 the installed capacity of PV is 483 kWp, while the self-consumption share only is 38.9%.

The model does not choose to invest in technologies that could increase the self-consumption. This could be explained by the large difference in CO_2 factors of biomass and electricity as discussed in section 6.1. If asymmetrical factors were to be included in the zero-constraint it is possible that the investments would shift more towards self-consumption.

In figure 6.27 the hourly maximum export- and import values of electricity is seen with the tightening of the zeroCO_2 restriction. By the nature of the model, the peak generation by PV is proportional with the installed capacity of PV. From β equal to 0.8 the hourly peak value of the export is increasing linearly. The peak values of the import is in total reduced by 13%, all of the reduction is from the shift away from heat pump to biomass boiler as base load source.

The peak values of the electricity export is overtaking the peak import for values of β less than to 0.5.

6.7.1 Main Findings

The main observations of the results of grid restrictions are as follows:

- When the zero CO_2 restriction is applied (β=0), the investment costs increases by 1,37 million Euro, and the operational costs decreases by 17 thousand Euro, compared to no restrictions (β=1).
- The model chooses first to reduce emissions form heat generation. When the least polluting heat technologies is obtained, on site PV is invested.
- Self-consumption of electricity generated by PV is used to meet electricity specific demand of the building only, and the model does not make a shift in the invested heat technology to increase self-consumption.
- At β equal to or less than 0.4 the hourly peak export values is higher than the hourly peak import values.

6.8 Sensitivity Analysis

To see how the results from the model respond to changes in the input data, and how robust the results are, four different sensitivity analysis are performed. Special areas of interest are the size of the changes in the investments cost of PV, and how large increase in electricity spot price level is needed to make PV panels a profitable investment without zero-restrictions.

6.8.1 Different Electricity Profiles

To see how dependent the installed capacity of the heat technologies and PV is of the electricity price level, three additional electricity spot price profiles is analysed. The electricity spot price profiles are presented in section 4.7, and are the spot price profiles of Oslo in the years 2013, 2005 and 2010, in addition to 2012, which is used as basis in the rest of the chapter. For the *zero*CO_2*-NOR* case, the optimal solution is without any technology using electricity as prime source. However, the price profile of district heating is directly linked to the spot price of electricity, and hence, the district heating could react to the variations in the price profiles.

The installed capacities for the *zeroCO_2-NOR* case with the four different electricity spot price profiles are seen in figure 6.28.

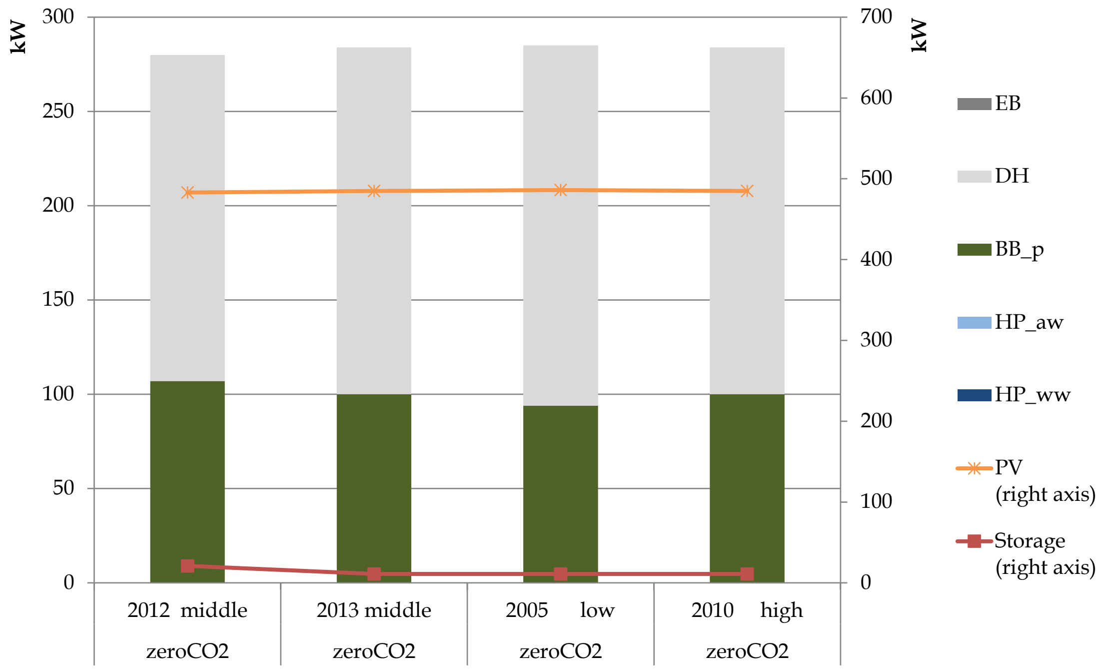

FIGURE 6.28: Sensitivity analysis. Installed capacities for the *zeroCO_2-NOR* case and different electricity price-profiles. All technologies available.

None of the price levels are changing the types of technologies installed, but the ratio between the size of the biomass boiler as base load and the district heat as peak load varies slightly. The size of the biomass boiler varies with a difference of 13 kW between the largest to smallest. The variations in PV investments varies from 486 kWp for 2005 prices which is the year with the lowest price level, to 483 kWp which is the largest value of the PV investment with 2012 series. The largest variations is found for the district heat, which varies from 191 kW for the low 2005 price profile, to 173 kW for the price profile of 2012.

Though there are some variations of the installed capacity of district heating, the influence of different electricity spot price profiles is relatively low.

6.8.2 Reduction in PV Installation Cost

To see how the investment cost of PV-panels influences the installed capacity in PV, a sensitivity analysis where the PV investment cost is reduced is performed, as all the zero cases forces PV installations to be made. No zero-restriction is applied. For the optimizing model to be able to find a possible solution, a restriction on possible installed capacity was necessary to include, as discussed in section 2.2. This restriction was set to 1000 kW. When the technologies reaches this limit of installed capacity, the optimal solution is unlimited capacity.

The result of the sensitivity analysis is presented in figure 6.29.

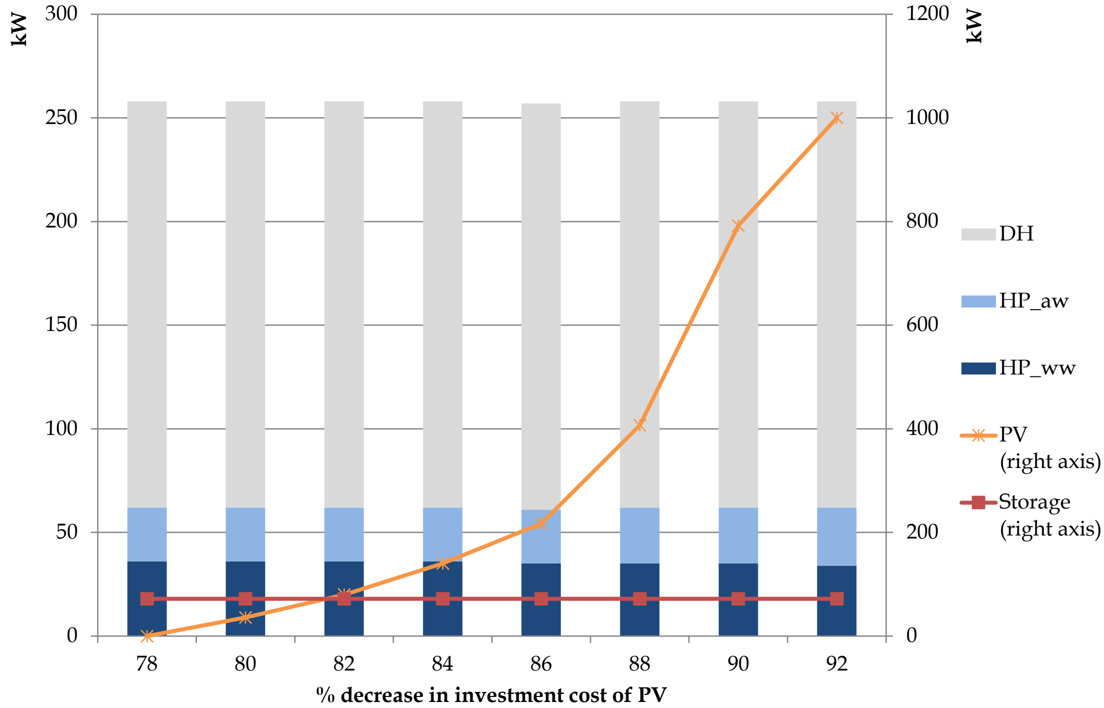

FIGURE 6.29: Sensitivity analysis: PV investment cost. Installed capacity of technologies, when the PV investment cost is reduced with the *noZero* case. All technologies available, no min production of biomass boiler, no restriction on storage charging. Restriction on maximum allowed installed capacity of technologies of 1000 kW.

Until the installation cost of PV is reduced by 78%, no PV is being installed. When the investment cost reduction is larger than 78% the investment in PV is economic even without any restrictions to CO_2 emissions or primary energy use. At a reduction of the investment cost of 80%, 36 kWp of PV is being installed. At a price reduction larger than 92% the PV investment reaches the maximum of 1000 kW. Thus the optimal solution of PV investments is unlimited in this simplified model.

For the optimal solution of the model to change, the investment cost of PV panels needs to be reduced by at least 78%. Up to 78% reduction, the solution of the *noZero* case seems fairly robust.

6.8.3 Electricity Price Level Increase

The optimal solution could change not only due to altered electricity profiles, but also due to the general price level of the electricity. In this section the general price level for both electricity sold to the grid, electricity bought from the grid and the price of district heating is increased, and analysed with the no-Zero case. The price level is increased in steps of 0.42 Eurocent or 0.05 NOK. The result of the price increase from 0.181 to 0.241 Euro (or 1.50 to 2.00 NOK) is presented in figure 6.30.

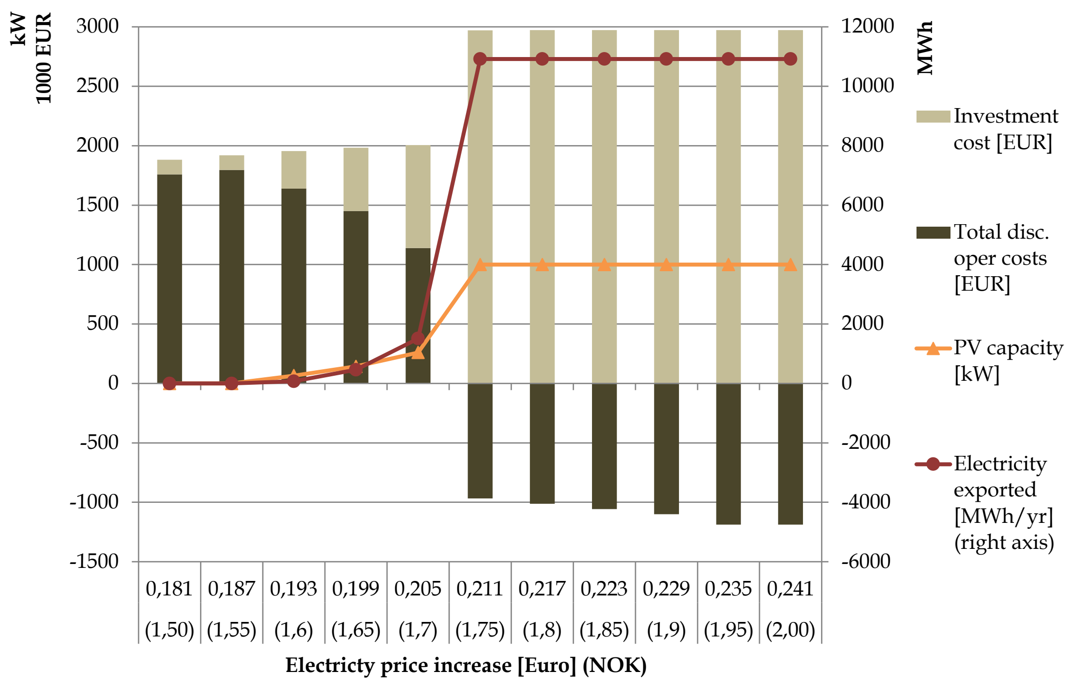

FIGURE 6.30: Sensitivity Analysis: Electricity Price Level. Investment Cost, Total Discounted Operational cost, electricity exported and capacity of PV when both the price for importing and exporting electricity from the grid is increased stepwise, for the *noZero* case. No BB_p, DH or $HP_a w$ available, no min production of biomass boiler. Maximum allowed installed capacity of technologies of 1000 kW.

The base load shifts from heat pumps to biomass boiler. PV investments turns profitable when the total price level is increased by 0.19 Euro. After the price level is increased by 0.21 Euro, the investments in PV goes unlimited, and the operational costs becomes negative. The income of selling electricity to the grid is large enough to cover the operational cost of the building with heat technologies, and gives a surplus income.

6.8.4 Heat Storage Efficiency

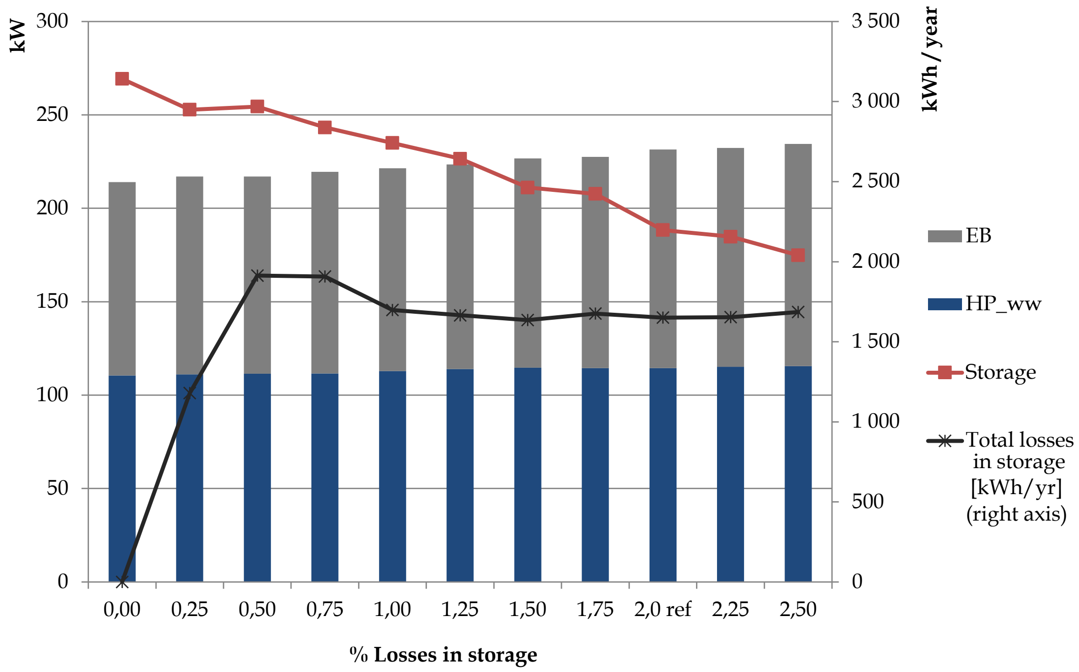

FIGURE 6.31: Sensitivity analysis. Efficiency of heat storage decreasing from 0 to 2.50. Installed capacities and total losses with the *zero*CO_2*-NOR* case. All technologies available, no min production of biomass boiler, no restriction on storage charging.

In figure 6.31 the effect of how the efficiency influences the installed capacity of the storage, is investigated. The *zero*CO_2*-NOR* case is applied. Only water-to-water heat pump and electric boiler are available, for the reason of having fewer variables that could influence the size of the installed capacity of the heat storage.

From the results presented, it can be seen that the reduction in efficiency of the storage has only a small influence on the installed capacity of the peak load. The capacity of the electric boiler is increased by 7.7%, and the installed capacity of the water-to-water heat pump is increased by 1.4 % when the losses of the storage increased by one percent from 1.0 % to 2.0 %. The influence of the efficiency of the storage seem to have a great influence of the installed capacity of the storage, however. The reduction in installed capacity of the storage is decreasing linearly when the efficiency of the storage decreases. From 1.0% to 2.0% losses in the storage, the installed capacity drops by 20%.

By looking at the heat losses in the storage, the total losses stabilizes around 1.67 MWh per year when the losses in the storage drops below 1.0%. It appear as the model chooses to invest in a manner where the losses in the storage is levelized.

When the losses increases, the capacity is reduced, making less heat stored in the accumulator tank. Though less heat is stored in the tank, the efficiency is lower, making the losses stabilizing.

The investments in PV show no influence by the storage efficiency, but the electricity export is increasing by 2.0%. This could imply that with increasing storage losses the self consumption is reduced.

6.8.5 Main Findings

The main observations of the sensitivity analysis are as follows:

- When running the model with different electricity spot price profiles, there are only negligible changes in PV investments, but there could be negligible alternation of the size of peak load energy technologies installed.
- When the PV installation cost is reduced by more than 78%, PV investments turn profitable with no zero-restriction applied. Decreased installation cost of PV show no influence of capacity in installed heat technologies.
- If the total price level of electricity is increased by 0.19 Euro, it becomes favorable to invest in PV. After an increase of 0.21 Euro, the optimal capacity of PV becomes unbound.
- With reduced efficiency of the heat storage the installed capacity of the storage is reduced linearly. Total losses in the heat storage tend to stabilize at 1.67 MWh per year with reduced efficiency.

Chapter 7

Discussion

The model developed is a mixed integer model. Thus, for the largest part, the model consist of linear constraints. The investment prices of the energy technologies are assumed linear or semi-linear, as presented in section 4.2. No lower limit of installed capacity of the technologies are applied. When using linear investment cost in this way, the model can choose to invest in unrealistically small units. This is seen in the results of the zero cases with no storage or district heating available. For instance for the $zeroCO_2$-NOR case with no district heating available, the model chooses to invest in a 27 kW electric boiler, and a 7 kW air-to-water heat pump. This makes sense for the optimization model, but would not be a realistic choice in a real investment decision. On the other hand, did the results show that the by far largest investment cost was due to PV investments. Therefore, limitations to the minimum investments of the heating technologies would most likely have a small influence on the total costs or investments.

For the biomass boiler a minimum production of 50 kW was included to prevent the biomass boiler from operating on too low capacities. This value was set as a fixed vale, and not a percentage value. This limitation has proven to have a large influence on the installed capacity of the storage. This is seen by comparing the the $zeroCO_2$-NOR case with with all technologies available, for the cases where the minimum production constraint on the biomass boiler active, and when the constraint is not active, respectively. In table A.8 at $\beta = 0$, the minimum production restriction of the biomass boiler is not active, and the installed storage capacity is 21 kWh. In table A.1, the storage capacity is 325 kWh, for the same case and technologies available, but with the minimum production constraint applied. Since the minimum production is set to be a constant value, and has been proven to have a great impact on the installed capacity of the storage, it is to be assumed that the level of the cut off level for the biomass boiler could influence the overall solution of the analysis.

The input data will introduce uncertainty. The input data are collected from different sources, and differ to some extent in what year the data are from and what is included in the specific cost. Variations of the prices available could influence the optimal solution. When comparing the results of total cost of the cases with reductions in available technologies, the total discounted costs increase up to 11% from the solution with all technologies available. The variations in investment prices could conceivable be larger than 11%. This implies that if one technology for a specific setting is available at a reduced cost, the whole solution could change. However, to see how variations in the PV investment cost, would influence the installed capacity of PV, a sensitivity analysis of the PV investment cost was performed.

In this simulation load profiles for one school only has been analysed. The model has not been tested out on other types of buildings than this school. The investment decisions will probably change if another building were to be analysed. In none of the cases analysed, solar thermal collectors were invested. ST might be favored for a building with higher heating demands during the summer season.

The values of crediting factors, for primary energy and CO_2-emissions also show a great influence of the solution chosen, for the cases with all technologies available. As discussed in section 2.3 the choice of crediting factors will be politically decided, to some extent. Thus the choice of primary energy factors that are used, will affect the solution.

When all technologies available, the optimal solution was a combination of biomass boiler and district heating. When the sensitivity analysis with different electricity profiles was applied, close to no variations in the solutions were seen. However, the sensitivity analysis was not run with only electricity based technologies available. If a case with only electricity based technologies available were investigated, the sensitivity analysis might have given different results for the operational strategies.

Throughout the whole model, the MIP-model has been set to have a cut off value of 1.5%, for the gap between the best bound and best found solution. This means that if the difference between the solution of the LP-relaxation and the best bound is less than 1.5%, the model accepts the current solution and ends running the model. This value is set as a tradeoff between a wish for an accurate solution, and limitations to to the available time for calculations. When using bound-and-break to find the optimal solution, this introduces a risk of finding local min and max values as optimal solutions. From the result tables in appendix A, it is seen that it is only in the cases where biomass boiler is invested, and the restrictions to minimum biomass production is applied, that the gap is in the range above 1.0%. Thus, it is assumed that a cut-off value of 1.5% will not have a large impact on the optimal solution.

Chapter 8

Conclusion

In this work a deterministic, dynamic optimisation model for optimal investments of a ZEB has been developed. The ZEB is assumed to be grid connected, and has a hydronic heat distribution system, and the possibility of investing in nine different energy technologies. The model minimizes total discounted cost of investments and operations over the lifetime of the building. The following main crediting factors are implemented in the model in order to reach the net zero balance: Net zero CO_2 emissions with Norwegian (*zero*CO_2*-NOR*) or European factors (*zero*CO_2*-EN*), and net zero primary energy use with total or non-renewable, symmetric (*zeroPEtot-asym*, *zeroPEnr-asym*) or asymmetric (*zeroPEtot-sym*, *zeroPEnr-sym*) PE factors.

The input data consist of investment cost, operational cost and energy cost amongst others. Cost data is based on Norwegian marked values, and no subsidies are included. For simplification, most of the specific investment costs, in EUR/kW installed, are assumed constant and determined for sizes in the range of 50-100 kW. This could be an important source of error as no lower limit to installed capacity is made, hence the model may choose to invest in smaller units which in reality have higher costs, which to some extend is reflected in the results. For the analysis performed, the load demand of a passive school building based on of 10,000 m^2 is used.

In the analysis, the installed heating capacity and operation of the different options of crediting factors have been studied. Additionally through sensitivity analysis, some parameters have been studied in more detail.

Investments

For the case of net zero CO_2 emissions with Norwegian CO_2 factors, the amount of PV needed to reach the zero balance is 483 kW_p, or approximately $3190m^2$ PV panels. For the same case, a 97 kW biomass boiler, 110 kW district heating capacity and a heat storage of 6175 liters is invested. The base area of the school analysed is 10,000 m^2. If the school would have two stories only, the roof area would be 5,000 m^2, and 3,190 m^2 PV panels would not be unrealistic.

For all combinations of zero-constraints and no constraint, district heating is preferred over electric boiler as peak load. Biomass boiler is chosen as base load technology in the zeroCO_2 cases and in the *zeroPEn.r.-sym* and *asym* cases, while heat pumps are chosen when no zero constraints are active, or when *zeroPEtot-sym* and *asym*constraints are applied.

With the zero CO_2 criteria, the use of biomass boiler compared to heat pumps will generate less CO_2 emissions to the zero CO_2 balance of the building, and hence reduce the cost related to investment of on-site power production.

Thermal solar collectors are not invested in any of the cases analysed. This is most probably due to the demand profile of a school building, being very low in the summer when the solar collector produces heat. PV panels is not profitable without zero-constraints applied. The sensitivity analysis performed shows that the PV investment cost needs to be reduced by about 78% for this specific case to be profitable without any zero-constraints.

Operation

When PV panels are installed, the on-site production of PV contributes to reduce the electricity bought from the grid about half of the year. The heat storage is not used as seasonal storage, but used as a daily and weekly storage.

The storage is used to cover daily peak demands, and to reduce the installed capacity of the base load energy sources. When district heating is used as peak load in combination with biomass boiler as base load, the storage is used to avoid peak energy cost of the district heating. There is no tendency of reducing the heat production from the heat pump based on variations in the electricity price.

CO_2 factors

The Norwegian CO_2 factors have lower values for CO_2 emissions from electricity in the grid, than the European factors. Thus, the invested capacity in PV needed be able to replace the same amount of CO_2 emissions from the grid will be higher for Norwegian factors. Consequently it is more expensive to reach the zero CO_2 balance when using Norwegian factors, than European factors.

When the CO_2 factors are reduced during the last half of the 60 years of analysis, the results show a tendency to shift the investment, and the energy production, towards more use of heat pumps and electric boilers. However, for an all electricity based heating system, reductions in CO_2 factors for electricity has no influence of the optimal investments, compared to no reduction.

When the zero CO_2 constraint is tightened from no restriction in CO_2 emissions to complete zero CO_2 restriction, the model chooses first to reduce emissions from heat generation. When the least polluted heat technologies are obtained, on site PV is invested to compensate for the emissions emitted by the building.

Primary Energy factors

Asymmetrical primary energy factors has lower PE factor values of electricity exported, than for electricity imported. This is in order to enhance self-consumption. However, to be able to reach the zero-constraint when asymmetrical PE factors are applied, larger investments of PV are needed. This is reflected by higher peak values of electricity exported, as seen in the results. When asymmetrical PE factors are used, the self-consumption of on-site electricity generation seems to increase in absolute value, but the share of PV electricity used in self consumption is decreasing.

Grid burden

The peak export exceeds the peak import by about 120% for the case of zero CO_2 with Norwegian factors. When grid restrictions are applied to reduce peak export values, the peak load technology shifts from district heating to electric boiler in combination with storage to increase self-consumption of on-site PV electricity.

Cost

PV investment cost accounts for more than 90% of the investment cost when the zero-constraints are applied. When going from no constraints to zero CO_2 with Norwegian factors the investment cost increases by 1.37 million euro, while the total discounted operational costs decreases by 17 thousand euro due to export of PV electricity. When restrictions to available technologies are applied, the total discounted costs increases by between 2.5% to 11%.

Chapter 9

Further Work

Throughout the analysis the energy profiles of a passive school building has been used. A school typically has close to no heating demand during the summer, because of summer holidays. Further work will be to test out the model on demand profiles of other typical building types, to see if the optimal investments shift with higher energy demand in the summer.

In the model, reduction of CO_2 factors for electricity from the grid over two periods were tested, and showed a tendency of increased investments in technologies based on electricity. However, the multi-period analysis of reduction in CO_2 emissions in the grid could be further analysed, to get a more accurate comprehension on the effect of reduced CO_2 factors for electricity in terms of investments in ZEB. Additionally, the effect of increasing electricity price levels over several periods could be investigated.

The model is a deterministic model, but modelling a building 60 years ahead includes a large degree of uncertainties. To get more robust results the model could be expanded to a stochastic model including uncertainties in the key parameters.

In the report by the IEA Solar heating & cooling programme [16], several indicators for analysing the load match and grid interaction indicators were proposed, though only the generation multiple (GM) has been included in this analysis. More factors could be analysed to get a wider impression of how the grid interaction factors reflect the burden to the grid.

One of the necessary weaknesses of the model as it is in this report, is the linearity of the investments costs. By including non-linear investment costs the model could better grasp the real price profiles of technologies. This could for instance be done as a stepwise linear approach.

Bibliography

[1] International Energy Agency (IEA), "Technology Roadmap - Energy efficient building envelopes," , The Organisation for Econ. Co-operation and Develop. (OECD), 2013.

[2] International Energy Agency (IEA) and Nordic Energy Research, "Nordic Energy Technology Perspectives - Pathway to a Carbon Neutral Energy Future," , The Organisation for Econ. Co-operation and Develop. (OECD), 2013.

[3] Conference of the Parties (COP), "Report of the Conference of the Parties on its sixteenth session, held in Cancun from 29 November to 10 December 2010," FCCC/CP/2010/7/Add.1, United Nations Framework Conv. on Climate Change (UNFCCC), 2011.

[4] Council of the European Union (EU), "Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the Energy Performance of Buildings," Directive Directive 2010/31/EU, European Parliament, 2010.

[5] Norwegian Ministry of the Environment, "Report no. 21 (2011-2012) Report to the Storting - Norwegian Climate Policy Summary," white paper, Stoltenberg II Government, 2012. (in Norwegian).

[6] P. Torcellini and S. Pless and M. Deru, "Zero Energy Buildings: A Critical Look at the Definition," , National Renewable Energy Laboratory (NREL); U.S. Department of Energy, 2006.

[7] I. Sartori, T.H. Dokka and I. Andersen, "Proposal of a Norwegian ZEB definition: Assessing the Implications for Design," in *zero emission buildings - proceedings of Renewable Energy Conference 2010, Oslo, Norway*, 2010.

[8] I. Sartori et al., "Net Zero Energy Buildings: A Consistent Definition Framework," *Energy and Buildings*, vol. 48, pp. 220–232, 2012.

[9] I. Sartori et al., "Criteria for Definition of Net Zero Energy Buildings," in *EuroSun 2010 - Conference Papers, Graz, Austria*, 2010.

[10] A.J. Marszal et al., "Zero Energy Building – A review of definitions and calculation methodologies," *Energy and Buildings*, vol. 43, pp. 971–979, 2011.

[11] F.S. Hiller and G.J. Lieberman, *Introduction to Operations Research.* Singapore: Mc Graw-Hill, 2010.

[12] H.P. Williams, *Model Building in Mathematical Programming.* West Sussex, UK: John Wiley and Sons, LTD, 1999.

[13] J. Lundgren, M. Rönnquist and P. Värbrand, *Optimization.* Malmö, Sweden: Studentlitteratur, 2012.

[14] F. Noris et al., "Implications of weighting factors on technology preference in net zero energy buildings," *Energy and Buildings*, vol. 82, pp. 250–262, 2014.

[15] European Committee for Standardization (CEN), "Energy Performance of Buildings (EPBD) - DRAFT Overarching Standard," DRAFT-prEN 15603, 2013.

[16] Salom et. al. Solar Heating & Cooling Programme, "Analysis Of Load Match and Grid Interaction Indicators in NZEB with High-Resolution Data - A report of Subtask A IEA Task 40/Annex 52 Towards Net Zero Energy Solar Buildings," , International Energy Agency (IEA), 2013.

[17] S.P. Park, *Fundamentals of Engineering Economics.* Endinburgh, UK: Pearson Education Limited, 3 ed., 2013.

[18] L. Blank, *Basis of Engineering Economy.* Boston, USA: McGraw-Hill Higher Education, 2008.

[19] A.E. Boardman et al., *Cost-Benefit Analysis: Concepts and Practice.* New Jersey, USA: Pearson Education, Inc, 2006.

[20] NTNU and SINTEF, *ENØK i bygninger: effektiv energibruk [Energy Efficiency in Buildings: Effective Energy Use]*, vol. 3. Oslo, Norway: Gyldendal Undervisning, 2007. (in Norwegian).

[21] S.P. Park, *Contemporary Engineering Economics.* New Jersey, USA: Pearson Education Inc., 2007.

[22] Samplex Solar, "Off-grid Solar Power System Basic." (Picture)[Online], 2014. Available: http://samlexsolar.com/learning-center/solar-systems-basics.aspx [June 23, 2014].

[23] Sweco, "Fornybar energi 2007 [Renewable Energy 2007]," , for NVE et al., 2007. (in Norwegian).

[24] KanEnergi and SINTEF, "Mulighetsstudie - solenergi i Norge [Feasibility Study: Solar Energy in Norway]," , for Enova, 2011. (in Norwegian).

[25] Multiconsult, "Kostnadsstudie, Solkraft Norge 2013 [Cost study, Solar power in Norway 2013]," , for Enova, Oslo, 2013. (in Norwegian).

[26] M. Grønli et. al, "KLIMATEK: Varmeproduksjon i bygninger [KLIMATEK: Heat Prod. in Buildings," , SINTEF Energiforskning AS, Norsk forskningsråd, Oslo, 1999. (in Norwegian).

[27] I. Andersen(SINTEF), "Planlegging av solvarmeanlegg for lavenergiboliger og passivhus. En introduskjon: [Planning of solar thermal systems for low-energy buildings and passive houses. An introduction]," , SINTEF Byggforsk AS, Enova, 2008. (in Norwegian).

[28] J. Stene, "Oppvarmingssystemer for lavenergiboliger: [Heating systems for low energy buildings]," , SINTEF Energiforskning AS, 2006. (in Norwegian).

[29] Missouri Dep. of Economic development. US, "Passive Solar Water Heating." (Picture)[Online], 2014. Available: http://ded.mo.gov/division-of-energy/renewables/missouri-s-solar-energy-resource/passive-solar-water-heating [June 23, 2014].

[30] L.B. Rindal, F. Salvesen and KanEnergi, "Solenergi for varmeformål - snart lønnsomt? [Solar Energy for heating - soon profitable?]," , for NVE, 2008. Available at: http://www.nve.no/Global/Publikasjoner/Publikasjoner[June 15, 2014] (in Norwegian).

[31] H. Rustad et al. (Statsbygg), "Varmepumpeveileder [Heat Pump Guidelines]." [Online], 2003. Available: http://statsbygg.no/en/Miljo/miljopublikasjonar/ [April 14, 2014] (in Norwegian).

[32] M.J. Moran and H. S. Shapiro, *Fundamentals of Engineering Thermodynamics*. West Sussex, UK: John Wiley & Sons, Ltd, 5 ed., 2006.

[33] Russ, C. et al. Fraunhofer-Institut für Solare Energiesysteme (ISE), "Feldmessung Wärmepumpen im Gebäudebestand[field measurements of heat pumps in the building stock]," , for E.ON Energie AG, 2010. (in German).

[34] E.E. Hohle (editor, ed., *Bioenergi: Miljø, teknikk og marked [Bioenergy: Environment, technology and market]*. Brandbu, Norway: Energigården, 2001. (in Norwegian).

[35] R. Ulseth et al., *Energisystemer [Energy systems].* Trondheim, Norway: Tapir Aksademiske Forlag, 2010. (in Norwegian).

[36] M. Rosenberg, "Kostnader for fjernvarmeutbygging [Cost of district heating development]," , Bioen AS, Nittedal, Norway, 2010. (in Norwegian).

[37] J. Dahl, *Short term water heat storage.* Ph.D dissertation / LuleåUniv. of Technology, LuleåTekniska Universitet, 1993.

[38] J.H. Gilje (SGP Varmeteknikk AS), "Akvaterm akkumulatortanker [Akvaterm accumulator tanks]." [Online], 2014. Available: http://www.sgp.no/Akkumulatortanker/akkumulatortanker.asp?meny=1,6,71&act=readRecNo=10 [July 29, 2014] (in Norwegian).

[39] İ. Dinçer and M. A. Rosen, *Thermal Energy Storage: Systems and applications.* West Sussex, UK: John Wiley & Sons, Ltd, 2 ed., 2011.

[40] I.M. Clausen (Adviser. Norwegian Water Resources and Energy Directorate (NVE)). private communication, 18th Dec. 2013.

[41] Norwegian Water Resources and Energy Directorate (NVE), "Hva er elsertifikater [What is electricity certificates]." [Online], 2014. Available: http://www.nve.no/no/Kraftmarked/Elsertifikater/Hva-er-elsertifikater/ [July 29, 2014] (in Norwegian).

[42] Norwegian Energy Certificate System (NECS), "Statistics El-certificates: Average Price per month," 2014. Available: http://necs.statnett.no/WebPartPages/AveragePricePage.aspx [June 22, 2014].

[43] Skattetaten (Norwegian Tax Administration, "Merverdiavgift – veiledning til næringsdrivende. [Value Added Tax - guide for commercial business]," 2014. Available: http://www.skatteetaten.no/no/Bedrift-og-organisasjon/Merverdiavgift/Merverdiavgift–veiledning-til-naringsdrivende-/?chapter=3728# kapitteltekst [July 29, 2014] (in Norwegian).

[44] Norwegian Water Resources and Energy Directorate (NVE), "Komponenter i nettleien [Components of the grid rental price]." [Online], 2014. Available: http://www.nve.no/no/Kraftmarked/Nettleie1/Om-nettleie-/ [July 29, 2014] (in Norwegian).

[45] Norwegian Customs and Excise, "Avgft påelektrisk kraft 2014: Rundskriv nr.10/2014 S, Avgiftskode EL [Tax on electrical power 2014: Directive no. 10/2014 S, Tax code EL]," , 2014. Available:

http://www.toll.no/upload/aarsrundskriv/2014/2014_ % 20Elektrisk_ kraft.pdf (in Norwegian).

[46] Norwegian Ministry of Petroleum and Energy, "Forskrift om innbetaling av påslag på nettariffen til Energifondet (forskrift om Energifondet) [Regulations of payment of charge on the grid tariff to the Energy Fund (Regulation of the Energy Fund]," , 2001. (in Norwegian).

[47] Norwegian Water Resources and Energy Directorate (NVE), "Plusskunder [Plus costumers]." [Online], 2014. Available: http://www.nve.no/no/Kraftmarked/Nettleie1/Beregning-av-tariffer-for-innmating-fra-produksjon/Plusskunder/ [July 29, 2014] (in Norwegian).

[48] Norwegian Water Resources and Energy Directorate (NVE), "Veileder nr 3/2011 Veileder - rammer for utbygging og drift av fjernvarmeanlegg [Guideline nr 3/2011 Guideline for developement and operation of district heating systems]," , 2011. (in Norwegian).

[49] K.B Lindberg and G. Doorman, "Hourly load modelling of non-residential building stock," in *Powertech 2013, Grenoble, France*, 2013.

[50] FICO^{TM}, "FICO^{TM} Xpress - Xpress-Mosel - Reference manual." [Online], 2013. Available: http://www.maths.ed.ac.uk/hall/Xpress/FICO_ Docs/-mosel/mosel_ lang/dhtml/moselref.html [Feb 1, 2014].

[51] S.V. Løtveit, "Cost Optimality of Energy Systems in Zero Emission Buildings in Early Design Phase," Master's thesis, Norwegian Univ. of Science and Technology (NTNU), 2013.

[52] K. Hofstad (editor), "Håndbok nr 1-11: Kostnader ved produksjon av kraft og varme [Handbook nr 1-11: Costs of production of power and heat]," , Norwegian Water Resources and Energy Directorate (NVE), 2009. (in Norwegian).

[53] Hafslund Nett AS, "Grid rental prices for commercial consumers." [Online], 2014. Available: http://hafslundnett.no/english/customer_ services/artikler/les_ artikkel.asp?artikkelid=1983 [June 12, 2014] (in Norwegian).

[54] M.L. Sagbakken (Customer service. Hafslund Strøm AS). private communication, 12th July. 2014.

[55] Hafslund Varme AS, "Fjernvarmepriser og vilkår [District heating costs and conditions], howpublished = [Online]," 12th June. 2014. Available: http://http://www.hafslund.no/fjernvarme/priser_ og_ vilkaar/2069 [June 12, 2014] (in Norwegian).

[56] C. Witter, “Simulations in ColSim0.63 - with data from Meteonorm7.m,” , Dept. of Smart Grids, Fraunhofer Institute for Solar Energy Systems (ISE), Freiburg, Germany, 2014.

[57] S. Merlet, “Simulations in PVSyst V6.11 with data from Meteonorm7,” , Multiconsult AS, Oslo, Norway, 2013.

[58] T.H Dokka et al., “A Norwegian Zero Emission Building Definition.” In Passivhus Norden, The 6th Passive House Conference in the Nordic countries, Göteborg, Sweden, 2013.

[59] H. Hjelmstad (SGP Varmeteknikk AS). private communication, 26th July. 2014.

[60] J.H. Gilje (SGP Varmeteknikk AS), “Fremtidens oppvarmingsløsning - Valg av energibærer til grunnlast, spisslast og backup innenfor og utenfor fjernvarmenett [Heating solutions of the future - Choice of energy carrier for base load, peak load and back up within and outside the district heating grid].” Presentation, Fjernvarmedagene 2013, Fornebu, Norway, 2013. (in Norwegian).

[61] J.A. Carsten (Sales consultant. Agder Energi Varme AS). private communication, 11th June. 2014.

[62] Enova SF, “Kjøpsveileder: væske-vann varmepumpe [Purchase Guide: liquid-water heat pump].” Purchase Guide, 2012. Available: http://www.enova.no/radgivning/privat/rad-om-produkter-og-losninger/oppvarmingsalternativ/vaskevann-varmepumpe/117/0/ [April 14, 2014] (in Norwegian).

[63] Novema kulde as, “Varmepumpe brukt mot energibrønn [heat pump used with energy well].” [Online]. Available: http://www.novemakulde.no/01/dot03_01.pdf [June 29, 2014].

[64] Enova SF, “Kjøpsveileder: luft-vann varmepumpe [Purchase Guide: air-water heat pump].” Purchase Guide, 2012. Available: http://www.enova.no/radgivning/privat/rad-om-produkter-og-losninger/oppvarmingsalternativ/luftvann-varmepumpe/113/0/ [April 14, 2014] (in Norwegian).

[65] Pöyry Energy (Oxford) Ltd, “The potental and cost of district heating networks,” , A report to the Department of Energy and Climate Change, 2009. Available: http://www.poyrycapital.com/assets/files/downloads/Technical% 20Analysis% 20& % 20Costing% 20of% 20DH% 20networks% 200904.pdf.

[66] Euroheat & Power: Task Force Customer Installations, "District Heating in Buildings," , Brussels, 2011. Available at: http://www.euroheat.org/Files/Filer/documents/Publications/District% 20Heating% 20in% 20buildings_ final.pdf.

[67] NordPoolSpot, "Historical Market Data," 2014. Available: Available: http://www.nordpoolspot.com/Market-data1/Downloads/Historical-Data-Download1/Data-Download-Page/ [Jan 15, 2014].

[68] Hafslund Nett AS, "Spørsmål og svar om plusskunde-ordningen [Questions and answer about the plus-costumer arrangement]." [Online], 2014. Available: Available: http://hafslundnett.no/omoss/artikkelarkiv/les_ artikkel.asp?artikkelid=2155 [June 12, 2014] (in Norwegian).

[69] Drammen Fjernvarme, "Produksjonsanlegg [Production plants]." [Online], 2014. Available: http://df.no/om_ oss/produksjonsanlegg/ [July 31, 2014] (in Norwegian).

[70] DNB, "Daily updated foreign exchange rates." [Online], 2014. Available: https://www.dnb.no/en/currencylist?la=EN& site=DNB_ NO [June 20, 2014].

[71] K.B Lindberg et al., "Optimal Iinvestments in Zero Carbon Buildings," in *Zero Carbon Building Conference(ZCB) 2014, Birmingham, UK*, 2014. to be published.

[72] K.B Lindberg et al., "Impact of Zero Energy Buildings on the electricity grid: Net electricity load profiles with optimal investments." Presentation, Renewable Energy Research Conference (RERC) 2014, Oslo, Norway, 2014.

[73] EB Nett, "Nettleie pr 1.1.2014 - Forbruk over 100.000 kWh/ år [Grid rental per 1.1.2014 - Consumption over 100,000 kWh/year]." [Online], 2014. Available: https://www.eb-nett.no/wp-content/uploads/2014/01/Ark-Nettleieinfo-OVER-100000_ 2014-ny.pdf [Jan 15, 2014] (in Norwegian).

[74] Agder Energi Nett, "Nettleiepriser 2013: Bedriftskunder [Grid rental prices 2013: Commercial consumers], howpublished = [Online]," 2014. Available: http://www.aenett.no/PageFiles/623/Nettleiepriser_ bedri_ 33062a.pdf?epslanguage=no [June 15, 2014] (in Norwegian).

[75] Norwegian Ministry of Petroleum and Energy, "Forskrift om Energifondet, [Energy Fund Regulations]," , 2001. (in Norwegian).

[76] R. Johnsen (Marketing manager. EB Strøm). private communication, 15th Jan. 2014.

[77] Drammen Fjernvarme, "Priser og vilkår: Tariffbeskrivelse Drammen Fjernvarme [Costs and conditions: Tariff description Drammen District heating]." [Online], 2014. Available: http://df.no/priser_og_vilk_r/ [Jan 15, 2014] (in Norwegian).

[78] Agder Energi Varme, "Pris påfjernvarme [Price of district heating]." [Online], 12th June. 2014. Available: http://www.ae.no/AEVarme/Kundeinformasjon/Pris/ [June 12, 2014] (in Norwegian).

Appendix A

Result Tables

Table A.1: Result table, All Zero Cases, All technologies

Zero-constraint:	**noZero**	**zeroCO2**		**zeroPE**		**zeroPE**	
PE-factor:	*PE tot asym*	*PE tot sym*	*PE tot sym*	*PE n-r sym*	*PE n-r asym*	*PE tot sym*	*PE tot asym*
CO2-factor:	*CO2-NOR*	*CO2-NOR*	*CO2-EUR*	*CO2-NOR*	*CO2-NOR*	*CO2-NOR*	*CO2-NOR*
Objective:				*minCost*			
Cost:							
Total cost [1000 EUR]	653	2 063	2 032	2 021	2 224	2 212	2 439
Investment cost [1000 EUR]	96	1 492	1 457	1 450	1 655	1 728	1 937
Tot. Disc. Op.costs [1000 EUR]	557	571	574	571	569	485	502
Crediting:							
Emissions [kg CO2-eq/yr]	62 306	0	0	1 443	-6 053	-339	-9 075
Primary Energy [MWhPE/yr]	1 193	294	299	0	0	0	0
Electricity exported [MWh/yr]	0	247	240	237	289	300	361
Installed capacity [kW]							
PV	0	483	474	469	538	568	649
ST (1/0)	0	0	0	0	0	0	0
HP_ww	36	0	0	0	0	66	51
HP_aw	26	0	0	0	0	0	0
BB_p	0	97	78	96	100	0	0
BB_c	NA	NA	NA	NA	NA	NA	NA
EB	0	0	0	0	0	0	0
DH	196	110	126	116	100	192	207
S	72	325	338	289	368	72	72
Energy production [MWh/y]:							
PV	0	404	397	393	450	476	543
ST	0	0	0	0	0	0	0
HP_water-water	150	0	0	0	0	235	208
HP_air-water	80	0	0	0	0	0	0
BB_pellets	0	279	259	279	282	0	0
BB_chips	0	0	0	0	0	0	0
EB	0	0	0	0	0	0	0
DH	68	22	42	22	20	62	89
Losses in Storage	2	5	5	5	5	1	1
Self consumption (of PV gen.)	0	157	157	156	162	176	182
Sum heat produced -losses	296	296	296	296	296	296	296
Grid							
Max el import [kWh/h]	182	158	158	158	158	179	174
Max el export [kWh/h]	0	345	339	335	387	409	469
GM-factor	0	2,19	2,14	2,12	2,45	2,29	2,70
Optimizing							
Gap (%):	0,75	1,21	1,45	1,00	1,25	0,22	0,20
Optimizing time (sec)	81	685	508	605	412	63	41

Comment: 1 % losses in storage. ST is a binary decision. Min production Bio boiler: 50kW. No storage restrictions. MIP gap cut-off = 1,5 %

TABLE A.2: Result table, All zero cases, All technologies - no Storage

Zero-constraint:	**noZero**	**zeroCO2**		**zeroPE**		**zeroPE**	
PE-factor:	*PE tot sym*	*PE tot sym*	*PE tot sym*	*PE n-r sym*	*PE n-r asym*	*PE tot sym*	*PE tot asym*
CO2-factor:	*CO2-NOR*	*CO2-NOR*	*CO2-EUR*	*CO2-NOR*	*CO2-NOR*	*CO2-NOR*	*CO2-NOR*
Objective:				*minCost*			
Cost:							
Total cost [1000 EUR]	663	2 117	2 059	2 092	2 303	2 222	2 452
Investment cost [1000 EUR]	95	1 574	1 443	1 545	1 756	1 724	1 937
Tot. Disc. Op.costs [1000 EUR]	568	543	615	547	547	498	515
Crediting:							
Emissions [kg CO2-eq/yr]	62 096	0	0	985	-7 108	-334	-9 199
Primary Energy [MWhPE/yr]	961	183	235	0	0	0	0
Electricity exported [MWh/yr]	0	264	246	257	312	303	366
Installed capacity [kW]							
PV	0	513	482	503	576	568	649
ST (1/0)	0	0	0	0	0	0	0
HP_ww	43	24	0	22	21	68	55
HP_aw	23	3	0	3	3	3	0
BB_p	0	96	79	100	109	0	0
BB_c	NA	NA	NA	NA	NA	NA	NA
EB	0	0	0	0	0	0	0
DH	229	172	216	170	162	224	240
S	NA	NA	NA	NA	NA	NA	NA
Energy production [MWh/y]:							
PV	0	430	404	421	482	476	544
ST	0	0	0	0	0	0	0
HP_water-water	166	75	0	70	67	222	209
HP_air-water	63	16	0	16	14	13	0
BB_pellets	0	172	157	175	181	0	0
BB_chips	0	0	0	0	0	0	0
EB	0	0	0	0	0	0	0
DH	67	33	140	36	35	61	87
Losses in Storage	0	0	0	0	0	0	0
Sum heat produced -losses	296	296	296	296	296	296	296
Grid							
Max el import [kWh/h]	183	165	158	165	165	181	175
Max el export [kWh/h]	0	367	345	360	414	408	469
GM-factor	0	2,22	2,18	2,18	2,52	2,26	2,68
Optimizing							
Gap (%):	0,23	0,24	0,23	0,24	0,22	0,21	0,19
Optimizing time (sec)	24	57	70	38	28	31	28

Comment: 1 % losses in storage. ST is a binary decision. Min production Bio boiler: 50kW. No storage restrictions. MIP gap cut-off = 1,5 %

TABLE A.3: Result table, All zero cases, no BB_p

Zero-constraint:	**noZero**	**zeroCO2**		**zeroPE**		**zeroPE**	
PE-factor:	*PE tot sym*	*PE tot sym*	*PE tot sym*	*PE n-r sym*	*PE n-r asym*	*PE tot sym*	*PE tot asym*
CO2-factor:	*CO2-NOR*	*CO2-NOR*	*CO2-EUR*	*CO2-NOR*	*CO2-NOR*	*CO2-NOR*	*CO2-NOR*
Objective:				*minCost*			
Cost:							
Total cost [1000 EUR]	653	2 202	2 081	2 195	2 439	2 212	2 439
Investment cost [1000 EUR]	96	1 708	1 439	1 691	1 937	1 728	1 937
Tot. Disc. Op.costs [1000 EUR]	557	494	642	504	502	485	502
Crediting:							
Emissions [kg CO2-eq/yr]	62 306	0	0	321	-9 075	-339	-9 075
Primary Energy [MWhPE/yr]	964	6	140	0	0	0	0
Electricity exported [MWh/yr]	0	298	256	296	361	300	361
Installed capacity [kW]							
PV	0	565	495	562	649	568	649
ST (1/0)	0	0	0	0	0	0	0
HP_ww	36	58	0	51	51	66	51
HP_aw	26	0	0	0	0	0	0
BB_p	NA	NA	NA	NA	NA	NA	NA
BB_c	NA	NA	NA	NA	NA	NA	NA
EB	0	0	0	0	0	0	0
DH	196	201	258	209	207	192	207
S	72	69	72	63	72	72	72
Energy production [MWh/y]:							
PV	0	473	415	471	543	476	543
ST	0	0	0	0	0	0	0
HP_water-water	150	221	0	208	208	235	208
HP_air-water	80	0	0	0	0	0	0
BB_pellets	0	0	0	0	0	0	0
BB_chips	0	0	0	0	0	0	0
EB	0	0	0	0	0	0	0
DH	68	76	297	89	89	62	89
Losses in Storage	2	1	1	1	1	1	1
Sum heat produced -losses	296	296	296	296	296	296	296
Grid							
Max el import [kWh/h]	182	176	158	174	174	179	174
Max el export [kWh/h]	0	406	355	404	469	409	469
GM-factor	0	2,31	2,24	2,32	2,70	2,29	2,70
Optimizing							
Gap (%):	0,75	0,22	0,22	0,22	0,20	0,22	0,20
Optimizing time (sec)	89	40	60	33	28	51	28

Comment: 1 % losses in storage. ST is a binary decision. Min production Bio boiler: 50kW. No storage restrictions. MIP gap cut-off = 1,5 %

TABLE A.4: Result table, All zero cases, no DH

Zero-constraint:	**noZero**	**zeroCO2**		**zeroPE**		**zeroPE**	
PE-factor:	*PE tot sym*	*PE tot sym*	*PE tot sym*	*PE n-r sym*	*PE n-r asym*	*PE tot sym*	*PE tot asym*
CO2-factor:	*CO2-NOR*	*CO2-NOR*	*CO2-EUR*	*CO2-NOR*	*CO2-NOR*	*CO2-NOR*	*CO2-NOR*
Objective:				*minCost*			
Cost:							
Total cost [1000 EUR]	684	2 114	2 096	2 074	2 271	2 293	2 543
Investment cost [1000 EUR]	125	1 553	1 527	1 503	1 710	1 837	2 086
Tot. Disc. Op.costs [1000 EUR]	559	561	569	570	561	456	457
Crediting:							
Emissions [kg CO2-eq/yr]	67 445	0	0	1 452	-6 042	0	-10 369
Primary Energy [MWhPE/yr]	1 038	295	319	0	0	0	0
Electricity exported [MWh/yr]	0	244	241	235	286	303	367
Installed capacity [kW]							
PV	0	483	476	468	538	573	661
ST (1/0)	0	0	0	0	0	0	0
HP_ww	36	0	0	0	0	108	93
HP_aw	36	7	2	2	8	18	10
BB_p	0	142	136	135	144	0	50
BB_c	NA	NA	NA	NA	NA	NA	NA
EB	183	27	36	38	23	92	66
DH	NA	NA	NA	NA	NA	NA	NA
S	82	569	569	569	569	252	248
Energy production [MWh/y]:							
PV	0	404	398	392	450	480	553
ST	0	0	0	0	0	0	0
HP_water-water	149	0	0	0	0	261	258
HP_air-water	96	19	5	3	18	29	22
BB_pellets	0	282	296	297	284	0	16
BB_chips	0	0	0	0	0	0	0
EB	52	1	3	3	1	9	4
DH	0	0	0	0	0	0	0
Losses in Storage	2	6	8	8	7	2	4
Sum heat produced -losses	296	296	296	296	296	296	296
Grid							
Max el import [kWh/h]	358	167	176	198	164	283	247
Max el export [kWh/h]	0	344	340	334	385	413	478
GM-factor	0	2,06	1,93	1,69	2,35	1,46	1,93
Optimizing							
Gap (%):	0	1,50	1,38	1,38	1,42	0,03	0,19
Optimizing time (sec)	139	98	124	137	140	48	317

Comment: 1 % losses in storage. ST is a binary decision. Min production Bio boiler: 50kW. No storage restrictions. MIP gap cut-off = 1,5 %

TABLE A.5: Result table, All zero cases, no DH no BB_p

Zero-constraint:	**noZero**	**zeroCO2**		**zeroPE**		**zeroPE**	
PE-factor:	*PE tot sym*	*PE tot sym*	*PE tot sym*	*PE n-r sym*	*PE n-r asym*	*PE tot sym*	*PE tot asym*
CO2-factor:	*CO2-NOR*	*CO2-NOR*	*CO2-EUR*	*CO2-NOR*	*CO2-NOR*	*CO2-NOR*	*CO2-NOR*
Objective:				*minCost*			
Cost:							
Total cost [1000 EUR]	684	2 293	2 293	2 293	2 542	2 293	2 542
Investment cost [1000 EUR]	125	1 837	1 837	1 837	2 088	1 837	2 088
Tot. Disc. Op.costs [1000 EUR]	559	456	456	456	453	456	453
Crediting:							
Emissions [kg CO2-eq/yr]	67 445	0	0	0	-9 514	0	-9 514
Primary Energy [MWhPE/yr]	1 038	0	0	0	0	0	0
Electricity exported [MWh/yr]	0	303	303	303	366	303	366
Installed capacity [kW]							
PV	0	573	573	573	660	573	660
ST (1/0)	0	0	0	0	0	0	0
HP_ww	36	108	108	108	113	108	113
HP_aw	36	18	18	18	17	18	17
BB_p	NA	NA	NA	NA	NA	NA	NA
BB_c	NA	NA	NA	NA	NA	NA	NA
EB	183	92	92	92	86	92	86
DH	NA	NA	NA	NA	NA	NA	NA
S	82	252	252	252	262	252	262
Energy production [MWh/y]:							
PV	0	480	480	480	553	480	553
ST	0	0	0	0	0	0	0
HP_water-water	149	261	261	261	265	261	265
HP_air-water	96	29	29	29	27	29	27
BB_pellets	0	0	0	0	0	0	0
BB_chips	0	0	0	0	0	0	0
EB	52	9	9	9	7	9	7
DH	0	0	0	0	0	0	0
Losses in Storage	2	2	2	2	4	2	4
Self consumption (of PV gen)	0	177	177	177	187	177	187
Sum heat produced -losses	296	296	296	296	296	296	296
Grid							
Max el import [kWh/h]	358	283	283	283	280	283	280
Max el export [kWh/h]	0	413	413	413	478	413	478
GM-factor	0	1,46	1,46	1,46	1,71	1,46	1,71
Optimizing							
Gap (%):	0	0	0	0	0	0	0
Optimizing time (sec)	24	232	215	215	221	47	222

Comment: 1 % losses in storage. ST is a binary decision. Min production Bio boiler: 50kW. No storage restrictions. MIP gap cut-off = 1,5 %

TABLE A.6: Result table, 2-periods, ZeroCO_2-NOR, allTech

Zero-constraint:	**1 period**	**2 periods-all tech**			**2 periods-no BBp**			**2 p.-no BBp noDH**		
Objective:	*minCost*					*minCost*				
Zero-constraint:	noZero					zeroCO2				
PE-factor:	*PE tot sym*					*PE tot sym*				
CO2-factor:	*CO2-NOR*					*CO2-NOR*				
CO2: electricty	*130*	*130*	*130*	*10*	*130*	*130*	*10*	*130*	*130*	*10*
Period:	*1(of 1)*	*1 (of 1)*	*1 (of 2)*	*2 (of 2)*	*1 (of 1)*	*1 (of 2)*	*2 (of 2)*	*1(of 1)*	*1 (of 2)*	*2 (of 2)*
Cost:										
Total cost [1000 EUR]	653	2 063	2 131	0	2 202	2 237	0	2 293	2 293	0
Investment cost [1000 EUR]	96	1 492	1 576	0	1 708	1 758	0	1 837	1 837	0
Tot. Disc. Op.costs [1000 EUR]	557	571	555	0	494	479	0	456	456	0
Annual op. costs [1000 EUR]	34	35	34	34	31	30	30	28	28	28
Crediting:										
Emissions [kg CO2-eq/yr]	62 306	0	0		0	0		0	0	
Primary Energy [MWhPE/yr]	1 193	294	234		6	14		0	0	
Electricity exported [MWh/yr]	0	247	261		298	303		303	302	
Installed capacity [kW]										
PV	0	483	509		565	572		573	573	
ST (1/0)	0	0	0		0	0		0	0	
HP_ww	36	0	3		58	74		108	108	
HP_aw	26	0	6		0	4		18	18	
BB_p	0	97	90		NA	NA		NA	NA	
BB_c	NA	NA	NA		NA	NA		NA	NA	
EB	0	0	8		0	48		92	92	
DH	196	110	94		201	147		NA	NA	
S	72	325	359		69	72		252	252	
Energy production [MWh/y]:										
PV	0	404	426	426	473	479	479	480	480	480
ST	0	0	0	0	0	0	0	0	0	0
HP_water-water	150	0	9	20	221	235	237	261	261	262
HP_air-water	80	0	17	45	0	14	15	29	29	29
BB_pellets	0	279	255	213	0	0	0	0	0	0
BB_chips	0	0	0	0	0	0	0	0	0	0
EB	0	0	0	9	0	0	31	9	9	9
DH	68	22	18	14	76	47	15	0	0	0
Losses in Storage	2	5	4	5	1	1	1	2	2	4
Sum heat produced -losses	296	296	296	296	296	296	296	296	296	296
Grid										
Max el import [kWh/h]	182	158	170		176	232		283	283	
Max el export [kWh/h]	0	345	365		406	411		413	413	
GM-factor	0,00	2,19	2,15		2,31	1,77		1,46	1,46	
Optimizing										
Gap (%):	0	0		0	0		0	0		0
Optimizing time (sec)	24	232		215	215		221	47		222

Comment: 1 % losses in storage. ST is a binary decision. Min production Bio boiler: 50kW. No storage restrictions. MIP gap cut-off = 1,5 %

TABLE A.7: Result table, alpha-grid-restriction, ZeroCO_2-NOR, allTech

alpha value:	**0,3**	**0,4**	**0,5**	**0,6**	**0,7**	**0,8**	**0,9**	**1,0**
Zero-constraint:				**zeroCO2**				
PE-factor:				PE tot sym				
CO2-factor:				CO2-NOR				
Objective:				minCost				
Cost:								
Total cost [1000 EUR]	0	2 671	2 316	2 130	2 050	2 039	2 039	2 039
Investment cost [1000 EUR]	0	2 097	1 748	1 563	1 478	1 466	1 466	1 466
Tot. Disc. Op.costs [1000 EUR]	0	574	568	567	571	574	574	574
Crediting:								
Emissions [kg CO2-eq/yr]	0	0	0	0	0	0	0	0
Primary Energy [MWhPE/yr]	0	287	298	300	290	285	285	285
Electricity exported [MWh/yr]	0	236	241	243	246	247	247	247
Installed capacity [kW]								
PV	0	535	498	484	483	483	483	483
ST (1/0)	0	0	0	0	0	0	0	0
HP_ww	0	0	0	0	0	0	0	0
HP_aw	0	0	0	0	0	0	0	0
BB_p	0	127	115	111	109	107	107	107
BB_c	NA	NA	NA	NA	NA	NA	NA	NA
EB	0	198	126	71	26	0	0	0
DH	0	24	39	56	115	173	173	173
S	0	3470	1725	684	106	21	21	21
Energy production [MWh/y]:								
PV	0	448	417	405	404	405	405	405
ST	0	0	0	0	0	0	0	0
HP_water-water	0	0	0	0	0	0	0	0
HP_air-water	0	0	0	0	0	0	0	0
BB_pellets	0	274	284	286	276	271	271	271
BB_chips	0	0	0	0	0	0	0	0
EB	0	50	18	5	1	0	0	0
DH	0	2	5	9	20	26	26	26
Losses in Storage	0	30	11	4	0	0	0	0
Sum heat produced -losses	0	296	296	296	296	296	296	296
Grid								
Max el import [kWh/h]	0	158	158	158	163	158	158	158
Max el export [kWh/h]	0	182	228	274	319	346	346	346
GM-factor	0,00	1,15	1,44	1,73	1,96	2,19	2,19	2,19
Optimizing								
Gap (%):	0,00	0,22	0,25	0,27	0,26	0,25	0,25	0,25
Optimizing time (sec)	10	359	61	51	54	257	91	69

Comment: 1 % losses in storage. ST is a binary decision. Min production Bio boiler: 0kW. MIP gap cut-off = 1,5 % No storage restrictions.

Table A.8: Result table, beta-CO2-relaxation, ZeroCO_2-NOR, allTech

beta value:	**1**	**0,9**	**0,8**	**0,7**	**0,6**	**0,5**	**0,4**	**0,3**	**0,2**	**0,1**	**0**
Zero-constraint:						**zeroCO2**					
PE-factor:						PE tot sym					
CO2-factor:						CO2 - NOR					
Objective:						minCost					
Cost:											
Total cost [1000 EUR]	653	681	783	931	1 084	1 239	1 397	1 556	1 717	1 878	2 039
Investment cost [1000 EUR]	96	82	164	327	489	652	815	978	1 140	1 303	1 466
Tot. Disc. Op.costs [1000 EUR]	557	599	619	605	594	587	582	579	576	575	574
Crediting:											
Emissions [kg CO2-eq/yr]	62	56	50	44	37	31	25	19	12	6	0
Primary Energy [MWhPE/yr]	964	1 040	1 051	956	860	764	669	573	477	381	285
Electricity exported [MWh/yr]	0	0	0	82	266	540	871	1 239	1 634	2 047	2 473
Installed capacity [kW]											
PV	0	0	26	83	140	197	255	312	369	426	483
ST (1/0)	0	0	0	0	0	0	0	0	0	0	0
HP_ww	36	14	0	0	0	0	0	0	0	0	0
HP_aw	26	0	0	0	0	0	0	0	0	0	0
BB_p	0	66	105	105	106	106	106	106	107	107	107
BB_c	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
EB	0	0	0	0	0	0	0	0	0	0	0
DH	196	204	175	174	173	173	173	172	172	173	173
S	72	12	20	21	22	22	22	22	21	21	21
Energy production [MWh/y]:											
PV	0	0	22	70	117	165	213	261	309	357	405
ST	0	0	0	0	0	0	0	0	0	0	0
HP_water-water	150	83	0	0	0	0	0	0	0	0	0
HP_air-water	80	0	0	0	0	0	0	0	0	0	0
BB_pellets	0	165	269	270	270	270	270	270	271	271	271
BB_chips	0	0	0	0	0	0	0	0	0	0	0
EB	0	0	0	0	0	0	0	0	0	0	0
DH	68	48	27	27	26	26	26	26	26	26	26
Losses in Storage	2	0	0	0	0	0	0	0	0	0	0
Sum heat produced -losses	296	296	296	296	296	296	296	296	296	296	296
Grid											
Max el import [kWh/h]	182	165	158	158	158	158	158	158	158	158	158
Max el export [kWh/h]	0	0	2	45	88	131	174	217	260	303	346
GM-factor	0	0	0,02	0,29	0,56	0,83	1,10	1,37	1,64	1,92	2,19
Optimizing											
Gap (%):	0,75	0,71	0,64	0,54	0,46	0,40	0,36	0,32	0,29	0,27	0,25
Optimizing time (sec)	48	60	50	53	50	51	76	40	42	73	41

Comment: 1 % losses in storage. ST is a binary decision. Min production Bio boiler: 0kW. No storage restrictions. MIP gap cut-off = 1,5 %

Appendix B

Discounted Cost

B.1 Operational Cost of Discounted Inv. cost

In the model the annual operation and maintenance (OM) cost are calculated annually, and discounted to year zero. The OM costs are given as an annual percentage value of the total investment cost. Since the input investment costs to the model are the discounted cost of all investments and reinvestments done throughout the lifetime of the building, do the OM percentage value need to be altered for giving the same annual OM cost as for the investment cost before the discounting. This is done in table B.1.

TABLE B.1: Operational cost altered for discounted investment cost.

	For normal lifetime			**For 60 years discounted lifetime**			
Technology	OM-cost	Inv. Cost	Annual OM cost	OM-cost	Inv. Cost	Annual OM cost	Differernce annual costs
	% of Inv.Cost	EUR/kW	EUR/kW	% of Inv.Cost	EUR/kW	EUR/kW	EUR/kW
PV-panels	0,02	2170	43	0,008	2843	22	-22
Solar thermal collector	0,01	275	3	0,007	387	3	0
Heat pump (water-water)	0,03	350	11	0,008	1297	10	0
Heat pump (air-water)	0,03	325	10	0,018	852	15	6
Bio boiler (pellets)	0,03	482	14	0,015	679	10	-5
Bio boiler (chips)	0,055	542	30	0,022	764	17	-13
District heating	0	-	0	0	-	0	-
Electric boiler	0,02	145	3	0,014	204	3	0
Heat storage (accumulator tank)		90	0		127	0	0

(1): The initial operational costs were assumed to be slightly high for some technologies, such as PV and BB chips. Thus, the dicounted operational costs were altered to get reduced variations in operational costs. (2): Operation and maintaince cost of distric heating is included in annual fixed charge to the

B.2 Discounted Specific Investment Cost

TABLE B.2: Discounted Specific Investment Cost

Investement technologies:	**Investment cost:**		**Life-time [y]**	**P.V. Investment cost cost at y = 0 (sum 60y)**	**P.V. Inv.cost at y = 0 Inv.cost at y = n**	**n (year) from y = 0**												**Salvage rest life time: [y]**
						0	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	
PV-panels	18,000 NOK/kW	**2170** Euro/kWp	25	**2843** Euro/kWp	PV, y = 0:	2170					506					118		
					y = n:	*2170*					*2170*					*2170*		*15*
Solar thermal collector	2,280 NOK/m2	**275** Euro/m2	20	**387** Euro/m2	PV, y = 0:	275				86				27				
					y = n:	*275*				*275*				*275*				
Heat pump (water-water)				**1297** Euro/kW	PV, y = 0:	1000			136			57		66	24			
(heat pump unit)	2,700 NOK/kW	**325** Euro/kW	15		*y = n:*	*325*			*325*			*325*			*325*			
(energy well)	5,600 NOK/kW	**675** Euro/kW	40		*y = n:*	*675*								*676*				*20*
Heat pump (air-water)	4,250 NOK/kW	**512** Euro/kW	15	**852** Euro/kW	PV, y = 0:	512			214			89			37			
					y = n:	*512*			*512*			*512*			*512*			
Bio boiler (pellets)	4,000 NOK/kW	**482** Euro/kW	20	**679** Euro/kW	PV, y = 0:	482				150				47				
					y = n:	*482*				*482*				*482*				
Bio boiler (chips)	4,500 NOK/kW	**542** Euro/kW	20	**764** Euro/kW	PV, y = 0:	542				169				53				
					y = n:	*542*				*542*				*542*				
EB - Electric boiler	1,200 NOK/kW	**145** Euro/kW	20	**204** Euro/m3	PV, y = 0:	145				45				14				
					y = n:	*145*				*145*				*145*				
District Heating					PV, y = 0:	6084												
(connection cost - fixed)	50,000 NOK	**6024,1** Euro/kW	60	**6024** Euro/kW	*y = n:*	*6024*												
(connection cost - spesific)	500 NOK/kW	**60** Euro/kW	60	**60** Euro/kW	*y = n:*	*60*												
Hot water storage	750 NOK/kWh	**90** Euro/kWh	20	**127** Euro/kWh	PV, y = 0:	90				28				9				
					y = n:	*90*				*90,36*				*90,36*				
				Discount factor: P(A/P,r,n)		1	0,75	0,56	0,42	0,31	0,23	0,17	0,13	0,10	0,07	0,05	0,04	

Appendix C

Details of Energy Cost

C.1 PV Specific Power Output Calculations

The total power output form the PV panels are provided on an hourly resolution.

In order to find the optimal size of the PV, the amount of electricity output from the PV-panels per installed kWp, needs to be estimated. The specific power output per kWp installed is found by dividing the total power output by the total nominal capacity installed, as seen in equation (C.1).

$$Spesific\ P_{output\ to\ grid}\ \frac{[kW]}{[kWp_{installed}]} = \frac{Total\ P_{output\ to\ grid}\ [W]}{Total\ installed\ capacity\ [kWp] \cdot 1000} \tag{C.1}$$

C.2 Heat Storage Investment Cost Calculations

To find optimal size of the heat storage tank, specific investment cost in Euro/kWh is needed. The storing capacity of a heat storage is dependent on the volume of the tank, as well at the temperature differential from maximum to minimum temperature during operation. For calculating the specific cost of heat storage, an accumulator tank with the properties presented in table C.1 is assumed.

The energy content of heat stored in a volume with a temperature differential of ΔT is generally expressed as in equation (C.2) [32].

$$[h]\dot{Q}\left[kWh\right] = \Delta T\left[K\right] \cdot Cp\left[\frac{kJ}{kg \cdot K}\right] \cdot \rho\left[\frac{kg}{L}\right] \cdot V\left[L\right]\left[\frac{kW}{kJ \cdot s}\right] \cdot \frac{1}{3600}\left[\frac{h}{s}\right] \tag{C.2}$$

Table C.1: Heat Storage Input Data

Temperature differential ($T_{max} - T_{min}$):	Δ T = 45°K	
Heat capacity water at 45°C:	C_p = 4.18 kJ/kg K	[32]
Density water at 45°C:	ρ = 0.990 kg/L	
Ratio kilo watt per kilo joule:	1 kW = 1 kJ/s	[32]
Seconds per hour:	1 h = 3600 s	

Applying equation (C.2) to the input data in table C.1, gives the specific costs of 90 Euro/kWh as summarized in table C.2, and presented in table 4.2. Additionally the volume per energy ratio of 19.3 L/kWh is emphasized.

Table C.2: Heat Storage Calculations

Volume	1000	L
Price (NOK)	38.750	NOK
Price (Euro)	4.670	Euro
Available energy (Δ T)	51.73	kWh
Liter per kWh ratio	19.3	L/kWh
Spesific cost (NOK)	750	NOK/kWh
Spesific cost (Euro)	90	Euro/kWh

Properties of model Oslo Maxi Turbo [51], Exchange rate: 8.3 (20/06/14).

C.3 Overview Electricity and District Heating Costs

TABLE C.3: Summary Grid Charges

Grid company:	Hafslund Nett [53]	EB Nett [73]	Agder Energi (AE) Nett [74]		Hafslund Nett	EB Nett	Agder Energi (AE) Nett	
Grid charge, buy								
Fixed charge	4960	5000	7500	NOK/year	598	602	904	Euro/year
Power charge								
Peak, winter$^{(1)}$	74	72	200	NOK/kW$_{pk,m}$	8.92	8.67	24	Euro/kW$_{pk,m}$
Peak, summer$^{(2)}$	25	72	600	NOK/kW$_{pk,m}$	3.01	8.67	72	Euro/kW$_{pk,m}$
Energy charge								
winter day$^{(3)}$	6.40	5.20	6.40	øre/kWh	0.77	0.63	0.77	¢/kWh
winter night	6.40	4.60	6.40	øre/kWh	0.77	0.55	0.77	¢/kWh
summer	4.25	3.60	6.40	øre/kWh	0.51	0.43	0.77	¢/kWh
Public charges								
El comsumption tax [45]	12.39	12.39	12.39	øre/kWh	1.49	1.49	1.49	¢/kWh
Energy fund (Enova) [75]	800	800	800	NOK	96	96	96	Euro
Grid charge, sell$^{(4)}$								
Feed-in charge		1.20	-4.00	øre/kWh		0.14	-0.48	¢/kWh
Energy charge								
winter day		-1.60		øre/kWh		-0.19		¢/kWh
winter night		-1.50		øre/kWh		-0.18		¢/kWh
summer		-1.50		øre/kWh		-0.18		¢/kWh

Exchange rate: 8.3 (20/06/14). All prices for 2014. (1) winter = October-March, (2) summer = April - September, (3) day = Monday - Friday 07:00 - 20:00, (4) negative charge: customer gets paid from grid company

TABLE C.4: Summary Electricity Charges

Electricity company: **Electricity charge**	Hafslund Strøm [54]	EB Strøm [76]		Hafslund Strøm	EB Strøm	
Charges energy company						
Fixed charge	0	250	NOK/year	0	30	Euro/year
Energy charge (typical)	1.2	$1.4^{(1)}$	øre/kWh	0.15	0.17	¢/kWh
Electricity cost	spot price	spot price	øre/kWh	spot price	spot price	¢/kWh
El certificate charge [42]	1.65	1.65	øre/kWh	0.20	0.20	¢/kWh

(1) Including electricity disclosure. Exchange rate: 8.3 (20/06/14). All prices for 2014

TABLE C.5: Summary District Heating Cost

District heating company: **Heat cost**	Hafslund Varme [55]	Drammen FV [77]	AE Varme [61, 78]		Hafslund Varme	Drammen FV	AE Varme	
Fixed charge	3000		800	NOK/year	362		96	Euro/year
Power charge								
Peak, winter$^{(2)}$	74	72	540	NOK/kW$_{pk,m}$	8.92	8.67	65	Euro/kW$_{pk,m}$
Peak, summer$^{(3)}$	25	72	180	NOK/kW$_{pk,m}$	3.01	8.67	22	Euro/kW$_{pk,m}$
Energy charge								
winter day$^{(4)}$	(1)	20.24	6.40	øre/kWh		2.44	0.77	¢/kWh
winter night		19.64	6.40	øre/kWh		2.37	0.77	¢/kWh
summer		18.64	6.40	øre/kWh		2.24	0.77	¢/kWh
Heat cost		spot price	spot price	øre/kWh		spot price	spot price	¢/kWh
(Cover el. con. tax)			12.39	øre/kWh			1.49	¢/kWh

Exchange rate: 8.3 (20/06/14). All prices for 2014. (1) Equals 2% reduction of grid charges of Hafslund Nett: 98% (el consumption tax + grid charge + sport price)
(2) winter = October - March, (3) summer = April - September, (4) day = Monday - Friday 07:00 - 20:00.

Appendix D

Model Files

D.1 Model Control Parameter File

"Model-control"

Value is read to mosel, and can be changed (Value is not equal 'defalt' setting)
Value is read to mosel, and can be changed (Value is active / not-zero)
Value is read to mosel, and can be changed (Value is a constant or 0)
Value is used in excel only

Optimizing options:

Run objective function:	on/off: (1/0)	Default
Objective function: Minimize Total Cost	1	1

Zero-constraints:		Value (for relaxation)		on/off: (1/0)		
Zero CO2 / Emission (netto annualy)	Beta (relax CO2-restriction)	0	(beta)	0	0	0
Zero Primary Energy (netto annualy)	Gamma (relax CO2-restriction)	0	(gamma)	0	0	0

Grid burden:			on/off: (1/0)		
Limit both import and export	0	(alpha_tot)	0	0	0
Limit export	0	(alpha_exp)	0	0	0

Primary Energy Factros:	on/off: (1/0)	
PE total asym	0	0
PE total sym	1	1
PE non-renewable asym	0	0
PE non-renewable sym	0	0

CO2 Factros:	on/off: (1/0)	
CO2 - a (No) - Norwegian	1	1
CO2 - b (EN) - European Norm	0	0
CO2 -3 (Houly emission factors)	0	0

Investement technologies, I:	on/off: (1/0)	
1: PV - PV solar panels	1	1
9 : ST - Solar thermal collector	1	1
2: HP_ww - Heat pump (water-water)	1	1
3: HP_aw - Heat pump (air-water)	1	1
4: BB_p - Bio boiler (pellets)	1	1
5: BB_f - Bio boiler (chips)	0	0
6: EB - Electric boiler	1	1
7: DH - District Heating	1	1
8: S - Hot water storage	1	1

Min production bio boiler (% of installed capacity):	Value (kW)	on/off: (1/0)	
Max innstalled capacity heat storage	15000	1	1
Max charge rate of heat storage of total heat storage, per hour (0.0 -1.0)	0,5	0	0
Min production Bio boiler (pellet)	50	1	1
Min production Bio boiler (chips)	50	1	1

Optimizing time parameters:	Value:	
LIFE: Lifetime of building:	60	60
YRN: Number of years in each periode, [years/periode]	60	
PN: Number of periodes in the lifetime of the technologies, [-]	1	1

	Value:	
r: Discount rate (0.0-1.0)	0,06	0

Exchange rate:

Exchange rate NOK/EUR	June 2014	8,3	8

FIGURE D.1: Model Control Parameter File

D.2 Model Input Parameter File

Input data, constants:

adjusted as spesified in the "Control Parameter File"

Energy carrier, E:	
1: El_import	EL_imp
2: El_export	EL_exp
3: Bio_pellets	BIO_p
4: Bio_chips	BIO_c
5: Heat_dh	HEAT_dh

Investement technologies, I:	
1: PV - PV solar panels	PV
2 : ST - Solar thermal collector	ST
3: HP_ww - Heat pump (water-water)	HP_ww
4: HP_aw - Heat pump (air-water)	HP_aw
5: BB_p - Bio boiler (pellets)	BB_p
6: BB_f - Bio boiler (chips)	BB_c
7: EB - Electric boiler	EB
8: DH - District Heating	DH
9: S - Hot water storage	S

Intallation cost, spesific	Intallation cost, fixed without VAT		Intallation cost, spesific without VAT	
1: PV - PV solar panels	0	EUR	2843	EUR/kW
2 : ST - Solar thermal collector	29061	EUR	0	EUR/kW
3: HP_ww - Heat pump (water-water)	0	EUR	1297	EUR/kW
4: HP_aw - Heat pump (air-water)	0	EUR	852	EUR/kW
5: BB_p - Bio boiler (pellets)	0	EUR	679	EUR/kW
6: BB_f - Bio boiler (chips)	0	EUR	764	EUR/kW
7: EB - Electric boiler	0	EUR	204	EUR/kW
8: DH - District Heating	6024	EUR	60	EUR/kW
9: S - Hot water storage	0	EUR	127	EUR/kW

Running/Operational costs (exl power cost):		
1: PV - PV solar panels	0,0076	decimal
2 : ST - Solar thermal collector	0,0070	decimal
3: HP_ww - Heat pump (water-water)	0,008	decimal
4: HP_aw - Heat pump (air-water)	0,018	decimal
5: BB_p - Bio boiler (pellets)	0,014	decimal
6: BB_f - Bio boiler (chips)	0,022	decimal
7: EB - Electric boiler	0,014	decimal
8: DH - District Heating	0	decimal
9: S - Hot water storage	0	decimal

Efficiencys technologies		
1: PV - PV solar panels		
2 : ST - Solar thermal collector		
3: HP_ww - Heat pump (water-water)	3,2	decimal
4: HP_aw - Heat pump (air-water)		
5: BB_p - Bio boiler (pellets)	0,9	decimal
6: BB_f - Bio boiler (chips)	0,85	decimal
7: EB - Electric boiler	0,98	decimal
8: DH - District Heating	1	decimal
9: S - Hot water storage	0,99	decimal

Primary energy factors	PE tot asym	PE tot sym	PE non-ren asym	PE non-ren sym	
Power grid, import (HydroPower)				0,5	kWh_p/kWh_s
Power grid, import	2,5	2,0	2,5	2,5	kWh_p/kWh_s
Power grid, export	2,0	2,0	2,0	2,5	kWh_p/kWh_s
Wood, pellets	1,05	1,05	0,05	0,05	kWh_p/kWh_s
Wood, chips	1,05	1,05	0,05	0,05	kWh_p/kWh_s
Heat, district heatning	0,70	0,70	0,70	0,70	kWh_p/kWh_s

CO2 factors	CO2 a (No)	CO2 b (EN)	
Power grid, import	130	350	CO2-eq, g/kWh_s
Power grid, export	130	350	CO2-eq, g/kWh_s
Wood, pellets	7	14	CO2-eq, g/kWh_s
Wood, chips	4	14	CO2-eq, g/kWh_s
Heat, district heatning	40	40	CO2-eq, g/kWh_s

FIGURE D.2: Model Input Parameter File (part 1)

Fixed energy costs:		
Grid: Fixed monthly max load charge summer, GRPPCH_s	3,01	EUR/kWmax, mon
Grid: Fixed monthly max load charge winter, GRPPCH_w	8,90	EUR/kWmax, mon
Grid: Yearly fixed charge grid and energy, GRFYCH	0	EUR/year
Bio: Fuel pellets	0,040	EUR/kWh
Bio: Fuel chips	0,030	EUR/kWh
DH: Yearly fixed charge , DHYFCH	362	EUR/year
DH: Fixed monthly max load charge summer, DHPPCH_s	3,01	EUR/kWmax, mon
DH: Fixed monthly max load charge winter, DHPPCH_w	8,90	EUR/kWmax, mon
For relaxation of restrictionnnns/limit grid export		
M_grid_connection: Maximum electricity import(export) to (from) building	456	kW
G_REF_tot: Total reference emissions	1038429	CO2-eq, g / yr
PE_REF_tot: Total reference primary energy	19891	kWh_pyr
Building		
INV: Investment cost of building	0	EUR
G_embodied: CO2-emissions embodied in the building	0	CO2-eq, g
PE_embodied: Primry ennergy embodied in the building	0	kWh_p
Other:		
Exchange rate NOK/EUR June 2014	8,3	
Optimizing max value on x_variables (optimizing_dummy)	1000	kW
Time parameters:		
TN: Number of timesteps during one year, [hours/year]	8760	
MN: Number of months in each periode, [months/year]	12	

Figure A.2: Model Input Parameter File (part 2)

Appendix E

Result Multiple Goal Function

Table E.1: Result table, multiple goal functions. The results are based on preliminary input data. Due to the need of severe tuning of weighting factors for the multiple goal function, this method is not followed further.

Objective:	**min Cost**	**min Cost**	**min Cost**	**min Export**	**min Export**	**min Grid**	**min Grid**
Zero-constraint:	*none*	*zero PE*	*zero CO2*	*zero PE*	*zero CO2*	*zero PE*	*zero CO2*
60y:							
Total cost [EUR]:	693 327	2 424 491	2 194 004	7,58E+09	5,75E+09	6,89E+09	7,63E+09
Annualy:							
OM cost [EUR/yr]	34 462	39 296	39 086	8,51E+07	6,17E+07	7,40E+07	8,29E+07
Emissions [CO2-eq/yr]	5 281 815	-645 591	0	-410 455	0	-410 455	0
PE [kWh_P/yr]	21 401	0	2 150	0	1 330	0	3 077
Installed capacity [kW]							
PV	0	542	468	431 137	386 773	464 392	493 395
$HP_{water\text{-}water}$	68	0	0	1,04E+06	9,29E+05	1,12E+06	1,19E+06
$HP_{air\text{-}water}$	0	0	0	1,83E+06	1,22E+06	1,47E+06	1,67E+06
$BB_{pellets}$	0	150	145	279	279	279	279
BB_{chips}	0	0	0	0	0	0	0
EB	163	52	63	288 745	255 222	267 907	362 907
Storage	190	360	324	15 000	15 000	15 000	15 000
ST (0/1)**	0	0	0	0	0	0	0
Energy prod. [kWh/y]:							
PV	0	454 359	392 567	3,61E+08	3,24E+08	3,89E+08	4,14E+08
$HP_{water\text{-}water}$	247 382	0	0	1,14E+09	1,02E+09	1,23E+09	1,30E+09
$HP_{air\text{-}water}$	0	0	0	1,43E+07	8,19E+06	1,12E+07	1,62E+07
$BB_{pellets}$	0	295 617	294 642	21 510	21 510	21 510	21 510
BB_{chips}	0	0	0	0	0	0	0
EB	53 864	2 711	3 704	1,83E+06	1,29E+06	1,12E+06	1,92E+06
Losses in Storage*	3 956	1 039	1 057	1,15E+09	1,03E+09	1,24E+09	1,32E+09
Grid							
Max el import [kWh/h]	330	212	221	158	158	158	200
Max el export [kWh/h]	0	390	335	73 502	45 408	52	42
GM-factor	0,00	1,84	1,51	465,08	287,32	0,33	0,21

* 1 % losses in storage. ** ST is a binary decision

Appendix F

Code

F.1 Mosel code: Model formulation

```
Main_Mosel.mos

!==============================================================
!         Optimization of investments in ZEB-buildings
!              Created 02/07/2014 by Astrid Anestad
!==============================================================

model Project_AA
options explterm
options noimplicit
uses "mmxprs","mmodbc","mmive","mmsystem";
!Enable time-parameters
setparam('xprs_verbose',true);
!Enable message printing by the Optimizer
setparam('xprs_miplog',-20);
!Global print control
setparam('xprs_miprelstop', 0.015);
!Stop MIP if the gap between MIP object value and best bound object
   value < 0,1% 0.001

setparam("timefmt", "%0H:%0M:%0S");
setparam("datefmt", "%y-%0m-%0d");
setparam("datetimefmt", "%y-%0m-%0dT%0H:%0M:%0S,%s");

writeln("Start running model");

declarations
```

```
ControlFile
= "mmodbc.excel:noindex;ControlParameterFile.xlsx";

InputDataFile
= "mmodbc.excel:grow;noindex;InputDataFile.xlsx";
ResultFile: string;

end-declarations

forward procedure
initialize_General_Parameters_from_InputFile

forward procedure
initialize_Control_Parameters_from_ControlFile

forward procedure
defineResultFile

forward procedure
write_Results_to_Excel_File


! __ DECLARATION AND INITALIZATION ______________________________

! -- Defining sets: --------------------------------------------

declarations

I :  set of string;
! Investment tech: PV,ST,HP_ww,HP_aw,BB_p,BB_c,EB,DH,S
I_heat : set of string;
! Subset of I: Heat producing: tech,HP_ww,HP_aw,BB_p,BB_c,EB,DH
E :  set of string;
! Energy carrieres: EL_imp,EL_exp,BIO_p,BIO_c,HEAT_dh
TN : integer;
! Total number of hours within a year, yr.
YRN  : integer;
! Total number of years within each period, p.
PN : integer;
! Total number of periodes, PN = (LIFE/YR).
MN : integer;
! number of months per year [day]

T : set of integer;
! Sets of time steps during one year, staring at 1, t
TT : set of integer;
! Sets of time steps during one year, starting at 0, t
```

```
YR : set of integer;
! Set of year within each period, yr
MM : set of integer;
! Set of months within each period, m
Mw : set of integer;
! Subset of MM: winter months, m
Ms : set of integer;
! Subset of MM: summer months, m
P : set of integer;
! Set of periods, lifetime building, p

end-declarations

initializations from InputDataFile

I as "set_invest_tech";
I_heat as "set_invest_tech_heat";
E as "set_energy_carriers";
TN as "t_TN";
MN as "t_MN";
Ms as "t_Ms";
Mw as "t_Mw";

end-initializations

initializations from ControlFile

YRN as "t_YRN";
PN as "t_PN";

end-initializations

T:= 1 .. TN; finalize(T);
TT:= 0 .. TN; finalize(TT);
MM:= 1 .. MN; finalize(MM);
YR:= 1 .. YRN; finalize(YR);
P:= 1 .. PN; finalize(P);

! -- Defining parameters: --------------------------------------

declarations

D_el: array(P,T) of real;
! Electricity demand building [kWh/h]
D_heat: array(P,T) of real;
! Heat demand building [kWh/h]
```

```
C_inv_spesific_i: array(I) of real;
! Investment cost of technology, year zero, spesific, adjusted for
    life time [EUR/kW_installed]
C_inv_fixed_i: array(I) of real;
! Investment cost of technology, year zero, fixed initial investment
    time [EUR]
C_run_i: array(I) of real;
! Running cost of technology, percent of installation cost, annual [
    decimal]
INV_cost_building: real;
! Investement cost of the building

Y_PV: array(P,T) of real;
! El delivered from PV-panels [kWh/h/kW installed]
Q_ST: array(P,T) of real;
! Heat delivered from ST [kWh/h].

Eff_COP_ww: real; ! Coefficient of performance, heat pump (water-
    water) [decimal]
Eff_COP_aw: array(P,T)   of   real;
! Coefficient of performance, heat pump (air-water) [decimal]
Eff_BB_p: real;
! Efficiency of bio boiler pellets [decimal]
Eff_BB_c: real;
! Efficiency of bio boiler chips [decimal]
Eff_EB: real;
! Efficiency of electric boiler [decimal]
Eff_DH: real;
! Efficiency of districh heating distribution [decimal]
Eff_S: real;
! Efficiency of the accumulator tank [decimal]

P_el_buy: array(P,T) of real;
! Price, Electricity: Price of el bought from the grid (incl tax) [
    EUR/kWh]
P_el_sell: array(P,T) of real;
! Price, Electricity: Price of el bought from the grid (excl tax) [
    EUR/kWh]
GRPPCH_s: real;
! Charge, Electricity: Cost of max power per month grid cost [EUR/kWh
    /h_max_month]
GRPPCH_w: real;
! Charge, Electricity: Cost of max power per month grid cost [EUR/kWh
    /h_max_month]
GRYFCH: real;
! Charge, Electricity: Fixed yearly charge for energy and grid [EUR/
    year]
```

```

P_bio_p: real;
! Price, Bio: Price of bio fuel, pellets  [EUR/kWh]
P_bio_c: real;
! Price, Bio: Price of bio fuel, chips  [EUR/kWh]

P_heat_dh: array(P,T) of real;
! Price, Distric heating: Price of heat bought from the DH grid (incl
    tax) [EUR/kWh]
DHYFCH: real;
! Charge, Distric heating: Fixed yearly charge [EUR/year]
DHPPCH_s: real;
! Charge, Distric heating: Cost of max power per month grid cost [EUR
   /kWh/h_max_month]
DHPPCH_w: real;
! Charge, Distric heating: Cost of max power per month grid cost [EUR
   /kWh/h_max_month]

G_grid_t: array(P,T) of real;
! CO2-emission factors active, grid, array of (t) [CO2-eq, g/kWh_s]
G_CO2a_No: array(E) of real;
! CO2-emission factors, Norwegian, constant [CO2-eq, g/kWh_s]
G_CO2b_EN: array(E) of real;
! CO2-emission factors, European, constant [CO2-eq, g/kWh_s]

PE_tot_asym: array(E) of real;
! Primary energy factor total asymmetrical, constant [kWh_p/kWh_s]
PE_tot_sym: array(E) of real;
! Primary energy factor total symmetrical, constant [kWh_p/kWh_s]
PE_non_ren_asym: array(E) of real;
! Primary energy factor asymmetrical, constant [kWh_p/kWh_s]
PE_non_ren_sym: array(E) of real;
! Primary energy factor symmetrical , constant [kWh_p/kWh_s]

M_grid_connection: real;
! Max electricity import (export) to (from) the building.
M_primary_energy: real;
! Max primary energy.
Min_prod_BB_p: real;
! Min production (cut-off) of bio boiler_pellet [kW]
Min_prod_BB_c: real;
! Min production (cut-off) of bio boiler_chips [kW]
Max_storage: real;
! Max heat storage size at deltaT = 45 C [kWh]
Max_charge_rate: real;
! Max charge rate of heat storage (0.0-1.0 of total installed
   capacity kW) [-]
```

```
M_inv_capacity: real;
! Dummy: Limits the feasable region to reduce optimizing time [kW],
   all x < max_x_dummy

PE_tot_REF: real;
! For restriction relaxation: total reference PE kWh_p/yr
G_tot_REF: real;
! For restriction relaxation: total reference Emissions CO2-eq,/yr
G_embodied: real;
! CO2-emisisons embodied in the building [CO2-eq, g]
PE_embodied: real;
! Primary Energy embodied in the building [CO2-eq, g]

alpha_tot: real;
! Grid burden restriction: import and export
alpha_exp: real;
! Grid burden restriction: export only
beta: real;
! Relaxation of CO2-restriction
gamma: real;
! Relaxation of PE-restriction

r: real;
! Discount rate [decimal]
Days_acc: array(MM) of real;
! Accumulated days per month, used for peak load cost  [days]

end-declarations

! -- Defining constriants: -------------------------------------

declarations

!Zero-constraints

Zero_Emissions: linctr;
Zero_Primary_energy: linctr;
Zero_El_net_grid: linctr;

Limit_import_and_export: dynamic array(P,T) of linctr;
Limit_export: dynamic array(P,T) of linctr;
Limit_import: dynamic array(P,T) of linctr;

!General:

Total_Cost: linctr;
Investment_Cost: linctr;
```

```
Operational_Cost: dynamic array(P) of linctr;
Emissions_Total: linctr;
Primary_Energy_Total: linctr;

El_balance: dynamic array(P,T) of linctr;
El_exported: linctr;
Grid_pk_imp_month: dynamic array(P,MM) of linctr;
Max_el_import: dynamic array(P,T) of linctr;
Max_el_export: dynamic array(P,T) of linctr;
If_importing: dynamic array(P,T) of linctr;
If_exporting: dynamic array(P,T) of linctr;
Grid_logic_constraint: dynamic array(P,T) of linctr;

Heat_balance: dynamic array(P,T) of linctr;
DH_pk_month: dynamic array(P,MM) of linctr;
Energy_balance_heat_storage: dynamic array(P,T) of linctr;
Heat_storage_initial_conditions: dynamic array(P) of linctr;
Capacity_heat_tech: dynamic array(I_heat,P,T) of linctr;
Capacity_storage: dynamic array(P,TT) of linctr;
Inv_logic_max_constraint: dynamic array(I) of linctr;
Max_capacity_S: linctr;
Max_charging_S: dynamic array(P,T) of linctr;
Max_decharging_S: dynamic array(P,T) of linctr;

Energy_balance_PV: dynamic array(P,T) of linctr;
Energy_balance_ST: dynamic array(P,T) of linctr;
Energy_balance_HP_ww: dynamic array(P,T) of linctr;
Energy_balance_HP_aw: dynamic array(P,T) of linctr;
Energy_balance_BB_p: dynamic array(P,T) of linctr;
Energy_balance_BB_c: dynamic array(P,T) of linctr;
Energy_balance_DH: dynamic array(P,T) of linctr;
Energy_balance_EB: dynamic array(P,T) of linctr;

end-declarations


! -- Defining control parameters: ------------------------------

declarations

!sens_an_a_grid_load_is_active:    integer;
! If = 1 run sensitivity analysis
Is_active_obj_min_cost: integer;
! If = 1 run min(TotalCost)

Is_active_obj_min_PE: integer;
! If = 1 run min(PrimaryEnergy)
```

```
Is_active_zero_primary_energy: integer;
! If = 1 set Total Net Annual Primary Energy Use = 0
Is_active_zero_emissions: integer;
! If = 1 set Total Net Annual Emissions = 0
Is_active_limit_imp_and_exp: integer;
! If = 1 limit import and export
Is_active_limit_exp: integer;
! If = 1 limit export

Is_active_PE_tot_asym: integer;
! If = 1 use Primary Energy factors PE_tot_asym (total)
Is_active_PE_tot_sym: integer;
! If = 1 use Primary Energy factors PE_tot_sym (total)
Is_active_PE_non_ren_asym: integer;
! If = 1 use Primary Energy factors PE_non_ren_asym (asymmetrical)
Is_active_PE_non_ren_sym: integer;
! If = 1 use Primary Energy factors PE_non_ren_sym (symmetrical)

Is_active_CO2a_No: integer;
! If = 1 use CO2-factors CO2a Norwegian
Is_active_CO2b_EN: integer;
! If = 1 use CO2-factors CO2b European standard
Is_active_G_el_t: integer;
! If = 1 uses hoully CO2 factors for electricity

Is_active_tech: array(I) of integer;
! If = 1 possible to invest in technology i.
Is_active_ST: integer;
! If = 1 possible to invest in ST
Is_active_min_bio_prod_p: integer;
! If = 1 limiting bio production, pellets to be 0 or above min_prod_BB_p
Is_active_min_bio_prod_c: integer;
! If = 1 limiting bio production, chips to be 0 or above min_prod_BB_c
Is_active_charging_constraint: integer;
! If = 1 limiting charging/decharging of heat storage, to max_charge_rate

runTime1: real;
runTime2: real;

end-declarations


! -- Initialize parameters: -----------------------------------
```

```

include "Mosel_read_from_excel.mos"
initialize_General_Parameters_from_InputFile;
initialize_Control_Parameters_from_ControlFile;


! -- Defining variables: ---------------------------------------

declarations

x: dynamic array(I) of mpvar;
! Installed capacity of technology i [kW]
x_if_inv: dynamic array(I) of mpvar;
! If technology i is installed =1 , if not installed =0,
x_grid_max_exp: mpvar;
! Max y_exp, export of electricity [kWh/h]
x_grid_max_imp: mpvar;
! Max y_imp, import of electricity [kWh/h]

y_imp: dynamic array(P,T) of mpvar;
! El bougth from grid at time t [kWh/h]
y_exp: dynamic array(P,T) of mpvar;
! Electricity exported  to the grid)at time t  [kWh/h]
y_PV: dynamic array(P,T) of mpvar;
! El produced by PV at time t [kWh/h] (y_PV(p,t) = x("PV")*Y_PV(t),
   where Y_PV(t) is a series of set power output(kWh/h) per
   kWp_installed.)
q: dynamic array(I_heat,P,T) of mpvar;
! Heat provided from technology i at time t [kWh/h]
q_ST: dynamic array(P,T) of mpvar;
! Heat provided form ST at time = Q_ST(t) if installed, where Q_ST(t)
    is a series of absolute heat output of a given solar thermal
   collector
u : dynamic array(P,T) of mpvar;
! Heat taken out/stored to the accumulator tank  [kWh/h]
s: dynamic array(P,TT) of mpvar;
! Heat storage in accumulator tank at end of hour [kWh/h]

d_hp_ww: dynamic array(P,T) of mpvar;
! El consumed by water-water heat pump at time t [kWh/h]
d_hp_aw: dynamic array(P,T) of mpvar;
! El consumed by air-water heat pump at time t [kWh/h]
d_eb: dynamic array(P,T) of mpvar;
! El consumed by electric boiler at time t [kWh/h]
b_p: dynamic array(P,T) of mpvar;
! Bio fuel (pellets) consumed by bio boiler_p at time t [kWh/h]
b_c: dynamic array(P,T)  of mpvar;
```

```
! Bio fuel (chips) consumed by bio boiler_c at time t [kWh/h]
h_dh: dynamic array(P,T) of mpvar;
! Heat (district heatning) bought from district heating grid at time
   t [kWh/h]
grid_PPM_imp: dynamic array(P,MM) of mpvar;
! Peak power from El-grid per month [kWh/h]
dh_PPM: dynamic array(P,MM) of mpvar;
! Peak power from DH-grid per month [kWh/h]
delta_imp: array(P,T) of mpvar;
! Variables for indicator constraints: either export or import at
   every t
delta_exp: array(P,T) of mpvar;
! Variables for indicator constraints: either export or import at
   every t

totCost: mpvar;
! Total costs
invCost: mpvar;
! Total investment cost, sum all technologies [EUR]
omCost: dynamic array(P) of mpvar;
! Summarized operational and maintenance cost  all technologies per
   yr [EUR]
emissions_total: mpvar;
! Summarized emissions from  all technologies per t [g CO2-eq]
primary_energy_total: mpvar;
! Summarized primary energy use from  all i,[kWh]
el_exported_total: mpvar;
! Summarized electricity exported [kWh]

end-declarations

! Create variables

forall (p in P,t in T)
do
create(y_PV(p,t));
create(q_ST(p,t));
create(y_imp(p,t));
create(y_exp(p,t));
create(u(p,t));
create(d_hp_ww(p,t));
create(d_hp_aw(p,t));
create(d_eb(p,t));
create(b_p(p,t));
create(b_c(p,t));
create(h_dh(p,t));
forall (ih in I_heat)
```

```
do
create(q(ih,p,t));
end-do
end-do

forall (i in I)
do
create(x(i));
create(x_if_inv(i));
end-do

forall (p in P)
do
create(omCost(p));
end-do

forall (p in P, tt in TT)
do create(s(p,tt));
end-do

forall (p in P, m in MM)
do
create(grid_PPM_imp(p,m));
create(dh_PPM(p,m));
end-do

! Define variables to be free, binary or semicontinious

emissions_total is_free;
primary_energy_total is_free;
x("ST") is_binary;

forall (i in I)
do
x_if_inv(i) is_binary;
end-do

forall (p in P, t in T)
do

omCost(p) is_free;
u(p,t) is_free;

delta_imp(p,t) is_binary;
delta_exp(p,t) is_binary;

if (Is_active_min_bio_prod_p =1)
```

```
then
q("BB_p",p,t) is_semcont Min_prod_BB_p;
end-if

if (Is_active_min_bio_prod_c =1)
then
q("BB_c",p,t) is_semcont Min_prod_BB_c;
end-if

end-do


! __ CONSTRAINTS (CONTROL CONSTRAINTS) __________________________

! -- Cost: -----------------------------------------------------

!#EQ 1 : Total Cost, discounted to t=0

Total_Cost :=
( invCost
+ sum(p in P)(1/((1+r)^(YRN*(p-1)))
*omCost(p)*sum(yr in YR)((1/((1+r)^(yr)))))
= totCost);

!#EQ 2 : Investment Costs, at t=0

Investment_Cost:=
( INV_cost_building
+ sum(i in I)(C_inv_spesific_i(i)*x(i)
+ C_inv_fixed_i(i)*x_if_inv(i))
= invCost); !

!#EQ 3 : Annual running/operational and maintenance Costs

forall (p in P)
do
Operational_Cost(p):=
( um(i in I|i<>"ST")(
C_run_i(i)*C_inv_spesific_i(i)*x(i))
! Sum running costs per year
+ (C_run_i("ST")*C_inv_fixed_i("ST")*x("ST"))
! Operational cost of solar thermal collectors
+ GRYFCH
! Yearly fixed charge, grid
+ DHYFCH
! Yearly fixed charge, DH
+ sum(t in T)
```

```
 (y_imp(p,t)*P_el_buy(p,t)
 ! Cost el bought from grid
- y_exp(p,t)*P_el_sell(p,t)
! Gain el sold to grid
+ b_p(p,t)  *P_bio_p
! Cost bio fuel_pellets bought
+ b_c(p,t)  *P_bio_c
! Cost bio fuel_chips bought
+ h_dh(p,t) *P_heat_dh(p,t))
+ sum(m in Ms)(
grid_PPM_imp(p,m)*GRPPCH_s
+ dh_PPM(p,m)*DHPPCH_s )
! Cost peak power charge (extra charge for the hour with highest load
    per month)
+ sum(m in Mw)(
grid_PPM_imp(p,m)*GRPPCH_w
+ dh_PPM(p,m)*DHPPCH_w )
! Cost peak power charge (extra charge for the hour with highest load
    per month)
= omCost(p)
! = Total annual running/operation&maintainance cost
);
end-do


! -- Emissions: ----------------------------------------------

Zero_Emissions:=
(emissions_total+G_embodied)*Is_active_zero_emissions
<= G_tot_REF*YRN*PN*beta;

!#EQ 5 : Total Emissions

Emissions_Total:=
sum(p in P, t in T)((
y_imp(p,t)*(((
  G_CO2a_No("EL_imp") *Is_active_CO2a_No
+ G_CO2b_EN("EL_imp") *Is_active_CO2b_EN ) * (1-Is_active_G_el_t) )
+(G_grid_t(p,t)*Is_active_G_el_t ) )
- y_exp(p,t)*(((
  G_CO2a_No("EL_exp") *Is_active_CO2a_No
+ G_CO2b_EN("EL_exp") *Is_active_CO2b_EN ) * (1-Is_active_G_el_t) )
+(G_grid_t(p,t)*Is_active_G_el_t ) )
+ b_p(p,t)     *  (
  G_CO2a_No("BIO_p")  *Is_active_CO2a_No
+ G_CO2b_EN("BIO_p")  *Is_active_CO2b_EN )
+ b_c(p,t)  *  ( G_CO2a_No("BIO_c")  *Is_active_CO2a_No
```

```
+ G_CO2b_EN("BIO_c")  *Is_active_CO2b_EN )
+ h_dh(p,t) *  ( G_CO2a_No("HEAT_dh")*Is_active_CO2a_No
+ G_CO2b_EN("HEAT_dh")*Is_active_CO2b_EN ) )*YRN)
= emissions_total;


! -- Primary Energy: -------------------------------------------

!#EQ 6 : Zero Primary Energy

Zero_Primary_energy:= (
primary_energy_total+PE_embodied)*Is_active_zero_primary_energy
<= PE_tot_REF*YRN*PN*gamma;

!EQ 7 : Total Primary Energy

Primary_Energy_Total :=
sum(p in P,t in T)((
 y_imp(p,t) *(
   PE_tot_asym("EL_imp") *Is_active_PE_tot_asym
+  PE_tot_sym("EL_imp") *Is_active_PE_tot_sym
+  PE_non_ren_asym("EL_imp") *Is_active_PE_non_ren_asym
+  PE_non_ren_sym("EL_imp") *Is_active_PE_non_ren_sym )
- y_exp(p,t) *(
PE_tot_asym("EL_exp") *Is_active_PE_tot_asym
+  PE_tot_sym("EL_exp") *Is_active_PE_tot_sym
+  PE_non_ren_asym("EL_exp") *Is_active_PE_non_ren_asym
+  PE_non_ren_sym("EL_exp") *Is_active_PE_non_ren_sym )
+ b_p(p,t)   *(
PE_tot_asym("BIO_p")  *Is_active_PE_tot_asym
+  PE_tot_sym("BIO_p")  *Is_active_PE_tot_sym
+  PE_non_ren_asym("BIO_p")  *Is_active_PE_non_ren_asym
+  PE_non_ren_sym("BIO_p")  *Is_active_PE_non_ren_sym )
+ b_c(p,t)   *(
PE_tot_asym("BIO_c")  *Is_active_PE_tot_asym
+  PE_tot_sym("BIO_c")  *Is_active_PE_tot_sym
+  PE_non_ren_asym("BIO_c")  *Is_active_PE_non_ren_asym
+  PE_non_ren_sym("BIO_c")  *Is_active_PE_non_ren_sym )
+ h_dh(p,t)  *(
PE_tot_asym("HEAT_dh")*Is_active_PE_tot_asym
+  PE_tot_sym("HEAT_dh")*Is_active_PE_tot_sym
+  PE_non_ren_asym("HEAT_dh")*Is_active_PE_non_ren_asym
+  PE_non_ren_sym("HEAT_dh")*Is_active_PE_non_ren_sym ))*YRN)
= primary_energy_total;


! -- Grid/Electricity: ----------------------------------------
```

```
!EQ 8/9 : Limit import and export

forall (p in P, t in T)
do

Limit_import_and_export(p,t):=
(y_imp(p,t) + y_exp(p,t)) * Is_active_limit_imp_and_exp
<= alpha_tot * M_grid_connection ;

Limit_export(p,t):=
y_exp(p,t) * Is_active_limit_exp
<= alpha_exp * M_grid_connection ;

end-do


!# 10 : Total Electricity Exported

El_exported:=
sum(p in P, t in T)(y_exp(p,t)*YRN)
= el_exported_total;


!___ CONSTRAINTS (GENERAL SYSTEM BALANCES) _____________________

! -- Electricity constraints: ---------------------------------
!# 11 : General Electricity Balance

forall (p in P,t in T)
do
El_balance(p,t):=
y_imp(p,t)
+ y_PV(p,t)
- d_hp_ww(p,t)
- d_hp_aw(p,t)
- d_eb(p,t)
- y_exp(p,t)
= D_el(p,t);
end-do

!# 12 : Max Electricity Load per Month

forall (p in P, m in MM, t in T)
do

if (t <= Days_acc(m))
```

```
then
Grid_pk_imp_month(p,m):=
(y_imp(p,t)
<= grid_PPM_imp(p,m));
end-if

if (t <= Days_acc(m))
then
DH_pk_month(p,m):= (q("DH",p,t)
<= dh_PPM(p,m));
end-if

end-do


! -- Heat constraints: -----------------------------------------

!# 13 : General Heat Balance

forall (p in P,t in T)
do
Heat_balance(p,t):=
sum(ih in I_heat)(q(ih,p,t))
+ q_ST(p,t)
!Heat from ST
+ s(p,(t-1))*Eff_S
!Heat in storage at time 't-1'*Efficicency of heat storage (heat
   losses)
- s(p,t)
!Heat in storage at time 't'
= D_heat(p,t);
end-do

!# 14 : Heat Storage Balance

!Balance to keep track of the heat taken out of the storage/delivered
    to the storage for every t.
forall (p in P,t in T)
do
Energy_balance_heat_storage(p,t):=
s(p,t)- s(p,(t-1)) = u(p,t);
end-do

!# 15 : Heat Storage, Boundary Conditions

! Level of heat in the storage at t= 0 is equal to the level in t= nT
! Storage time 1 = storage time TT
```

```
forall (p in P)
do
Heat_storage_initial_conditions(p):=
s(p,TN) = s(p,0);
end-do

! -- Installed capacity: --------------------------------------

!# 16 : Grid Load, (max Export / max Import)

forall(p in P,t in T)
do
Max_el_import(p,t):=
y_imp(p,t)
<= x_grid_max_imp;

Max_el_export(p,t):=
y_exp(p,t)
<= x_grid_max_exp;
end-do

!# 17 : Grid, (prevent export and import at same t)

forall(p in P,t in T)
do

If_importing(p,t):=
y_imp(p,t)
<= delta_imp(p,t)*M_inv_capacity;

If_exporting(p,t):=
y_exp(p,t)
<= delta_exp(p,t)*M_inv_capacity;
Grid_logic_constraint(p,t):=
delta_imp(p,t) + delta_exp(p,t)
<= 1;

end-do

!# 18 : Capacity of Technologies

forall(p in P,t in T, ih in I_heat)
do
Capacity_heat_tech(ih,p,t):=
q(ih,p,t)
<= x(ih)*Is_active_tech(ih);
end-do
```

```
! # 18 : Optimizing dummy constraint (to limit feasible region)
!Max value of x, to limit the feasible region to ease the
    optimization-process. 'Max_x_dummy' is set to be much larger than
    a possible solution for x(i).

forall (i in I| i<>"S")
do
Inv_logic_max_constraint(i):=
x(i)
<= x_if_inv(i)*M_inv_capacity;
end-do

!# 19 : Capacity heat storage

forall(p in P,tt in TT)
do
Capacity_storage(p,tt):=
s(p,tt)
<= x("S");
end-do

!# 20 : Max Capacity of Storage

Max_capacity_S:=
x("S")
<= Max_storage*Is_active_tech("S");

!# 21 : Max charging/discharging of Heat Storage

forall (p in P,t in T)
do

Max_charging_S(p,t):=
u(p,t)*Is_active_charging_constraint
<= (Max_charge_rate*x("S"));

Max_decharging_S(p,t):=
-u(p,t)*Is_active_charging_constraint
<= (Max_charge_rate*x("S"));

end-do

! -- Energy balances: -----------------------------------------

!# 22 : Energy Balances

```

```
forall (p in P,t in T)
do

Energy_balance_PV(p,t):=
y_PV(p,t)
= x("PV")*Y_PV(p,t)*Is_active_tech("PV");

Energy_balance_ST(p,t):=
q_ST(p,t)
= x("ST")*Q_ST(p,t)*Is_active_tech("ST");

Energy_balance_HP_ww(p,t):=
q("HP_ww",p,t)
= d_hp_ww(p,t)*Eff_COP_ww ;

Energy_balance_HP_aw(p,t):=
q("HP_aw",p,t)
= d_hp_aw(p,t)*Eff_COP_aw(p,t);

Energy_balance_BB_p(p,t):=
q("BB_p",p,t)
= b_p(p,t)*Eff_BB_p;

Energy_balance_BB_c(p,t):=
q("BB_c",p,t)
= b_c(p,t)*Eff_BB_c;

Energy_balance_DH(p,t):=
q("DH",p,t)
= h_dh(p,t)*Eff_DH;

Energy_balance_EB(p,t):=
q("EB",p,t)
= d_eb(p,t)*Eff_EB;

end-do


!---------------------------------------------------------------

! Declare results

declarations

New_ResultFile: string;

Run_Date_excel: date;
```

```
Run_Time_excel: time;
Run_Best_Bound_excel: real;
Run_runtime_excel: real;
Optimizing_data_Min_excel: string;
Optimizing_data_Zero_excel: string;
Optimizing_data_PE_excel: string;
Optimizing_data_CO2_excel: string;

Objective_value_excel: real;
TotalCost_excel: real;
ElExported_excel: real;
Investment_cost_excel: real;
Operational_cost_excel: array (P) of real;
Emissions_excel: real;
Primary_energy_excel: real;

x_excel: array (I) of real;
x_excel_output: array (I) of string;
x_grid_max_exp_excel: real;
x_grid_max_imp_excel: real;

y_imp_excel: array (P,T) of real;
y_exp_excel: array (P,T) of real;
y_PV_excel: array (P,T) of real;
q_ST_excel: array (P,T) of real;
q_HP_ww_excel: array (P,T) of real;
q_HP_aw_excel: array (P,T) of real;
q_BB_p_excel: array (P,T) of real;
q_BB_c_excel: array (P,T) of real;
q_EB_excel: array (P,T) of real;
q_DH_excel: array (P,T) of real;
u_excel: array (P,T) of real;
s_excel: array (P,T) of real;

d_HP_ww_excel: array (P,T) of real;
d_HP_aw_excel: array (P,T) of real;
d_EB_excel: array (P,T) of real;
b_p_excel: array (P,T) of real;
b_c_excel: array (P,T) of real;
h_DH_excel: array (P,T) of real;
grid_PPM_imp_excel: array (P,MM)of real;
dh_PPM_excel: array (P,MM)of real;

alpha_tot_excel: real;
alpha_exp_excel: real;
beta_excel: real;
gamma_excel: real;
```

```
Max_charge_rate_excel: real;
Min_prod_BB_p_excel: real;
Min_prod_BB_c_excel: real;

end-declarations

!=================================================================

! __ OBJECTIVE FUNCTION:________________________________________


!# 19 Objective Function

include "Mosel_write_to_excel.mos"
defineResultFile;
ResultFile:= New_ResultFile;
runTime1:=     gettime;

minimize (totCost);

runTime2:=     gettime;
writeln("Start output to file");
write_Results_to_Excel_File;
writeln("End running model");

end-model
```

F.2 Mosel code: Reading procedures

```
Mosel_read_from_excel.m


!! PROCEDURE: Read from Input File
!!===============================================================

procedure initialize_General_Parameters_from_InputFile

initializations from InputDataFile

!Data Series
```

```

D_heat as "demand_heat";
D_el as "demand_el";

Y_PV as "Y_PV";
Q_ST as "Q_ST";

P_el_buy as "P_el_cost_buy";
P_el_sell as "P_el_cost_sell";
P_heat_dh as "P_heat_dh_cost";

G_grid_t as "G_grid_t";
Eff_COP_aw as "eff_COP_aw";

!Constants

C_inv_spesific_i as "c_inv_spesific_i";
C_inv_fixed_i as "c_inv_fixed_i";
C_run_i as "c_run_i";

Eff_COP_ww as "eff_COP_ww";
Eff_BB_p as "eff_BB_p";
Eff_BB_c as "eff_BB_c";
Eff_EB as "eff_EB";
Eff_DH as "eff_DH";
Eff_S as "eff_S";

GRPPCH_s as "p_GRPPCH_s";
!Grid Peak Power Charge Summer
GRPPCH_w as "p_GRPPCH_w";
!Grid Peak Power Charge Winter
GRYFCH as "p_GRYFCH";
!Grid Annual Fee
P_bio_p as "P_bio_p_cost";
P_bio_c as "P_bio_c_cost";
DHYFCH as "p_DHYFCH";
!DH Annual Fee
DHPPCH_s as "p_DHPPCH_s";
!DH Peak Power Charge Summer
DHPPCH_w as "p_DHPPCH_w";
!DH Peak Power Charge Winter

PE_tot_asym as "PE_tot_asym";
PE_tot_sym as "PE_tot_sym";
PE_non_ren_asym as "PE_non_ren_asym";
PE_non_ren_sym as "PE_non_ren_sym";
```

```
G_CO2a_No as "G_CO2a_No";
G_CO2b_EN as "G_CO2b_EN";

G_tot_REF as "G_REF_tot";
PE_tot_REF as "PE_REF_tot";
G_embodied as "G_embodied";
PE_embodied as "PE_embodied";

M_grid_connection as "Max_grid_cap";
M_inv_capacity as "Max_inv_cap";

Days_acc as "t_days_per_month_accumulated";

end-initializations

writeln("End input from InputDataFile");

end-procedure



!! PROCEDURE: Read from Control File
!!=================================================================

procedure initialize_Control_Parameters_from_ControlFile

initializations from ControlFile

r as "ec_rate_discount";

alpha_tot as "alpha_tot";
alpha_exp as "alpha_exp";
beta as "beta";
gamma as "gamma";

Min_prod_BB_p as "min_prod_BB_p";
Min_prod_BB_c as "min_prod_BB_c";
Max_charge_rate as "max_charge_rate";
Max_storage as "max_inv_S";

Is_active_obj_min_cost as "is_active_obj_min_cost";
Is_active_limit_imp_and_exp as "is_active_limit_imp_and_exp";
Is_active_limit_exp as "is_active_limit_exp";

Is_active_zero_primary_energy as "is_active_zero_primary_energy";
Is_active_zero_emissions as "is_active_zero_emissions";
```

```
Is_active_tech as "is_active_tech";
Is_active_min_bio_prod_p as "is_active_min_bio_prod_p";
Is_active_min_bio_prod_c as "is_active_min_bio_prod_c";
Is_active_charging_constraint as "is_active_charging_constraint";

Is_active_PE_tot_asym as "is_active_PE_tot_asym";
Is_active_PE_tot_sym as "is_active_PE_tot_sym";
Is_active_PE_non_ren_asym as "is_active_PE_non_ren_asym";
Is_active_PE_non_ren_sym as "is_active_PE_non_ren_sym";

Is_active_CO2a_No as "is_active_CO2a_No";
Is_active_CO2b_EN as "is_active_CO2b_EN";
Is_active_G_el_t as "is_active_houly_CO2_el_factors";

end-initializations

writeln("End input from ControlFile");

end-procedure
```

F.3 Mosel code: Writing procedures

```
Mosel_write_to_excel.m



!! PROCEDURE: Create/Define Result File
!!============================================================

procedure defineResultFile
if(PN = 1) then
fcopy("reslt_template_1period.xlsx", "RESULTS_1p_.xlsx");
New_ResultFile:= "mmodbc.excel:grow;RESULTS_1p_.xlsx";
else
fcopy("reslt_template_2period.xlsx", "RESULTS_2p_.xlsx");
New_ResultFile:= "mmodbc.excel:grow;RESULTS_2p_.xlsx";
end-if
end-procedure
```

```
!! PROCEDURE: Write results to excel
!!================================================================

procedure write_Results_to_Excel_File
Run_Date_excel:= date(SYS_NOW); ! Returns date-stamp of optimizing
Run_Time_excel:= time(SYS_NOW); ! Returns time-stamp of optimizing
Run_Best_Bound_excel:= getparam("XPRS_LPOBJVAL");
Run_runtime_excel:= runTime2-runTime1;

if    (Is_active_obj_min_cost = 1)then Optimizing_data_Min_excel:= "minCost";
elif (Is_active_obj_min_PE = 1)then Optimizing_data_Min_excel:= "minPE";
elif (Is_active_obj_min_export = 1)then Optimizing_data_Min_excel:= "minExport";
elif (Is_active_obj_min_grid_burden = 1)then Optimizing_data_Min_excel:= "minGridBurden";
else writeln("error: option min, in Model Options");
end-if

if    (Is_active_zero_primary_energy = 1)then Optimizing_data_Zero_excel:= "zeroPE";
elif (Is_active_zero_emissions = 1)then Optimizing_data_Zero_excel:= "zeroCO2";
else Optimizing_data_Zero_excel:= "noZero";
end-if

if    (Is_active_PE_tot_asym = 1)then Optimizing_data_PE_excel:= "PE tot asym";
elif (Is_active_PE_tot_sym = 1)then Optimizing_data_PE_excel:= "PE tot sym";
elif (Is_active_PE_non_ren_asym = 1)then Optimizing_data_PE_excel:= "PE n-r asym";
elif (Is_active_PE_non_ren_sym = 1)then Optimizing_data_PE_excel:= "PE n-r sym";
else writeln("error: option PE, in Model Options");
end-if

if    (Is_active_CO2a_No = 1)then Optimizing_data_CO2_excel:= "CO2a No";
elif (Is_active_CO2b_EN = 1)then Optimizing_data_CO2_excel:= "CO2b EN";
elif (Is_active_G_el_t = 1)then Optimizing_data_CO2_excel:= "CO2 t_el";
else writeln("error: option CO2, in Model Options");
end-if
```

```
Objective_value_excel:= getobjval;
TotalCost_excel:= getsol(totCost);
Primary_energy_excel:= getsol(primary_energy_total)/YRN;
ElExported_excel:= getsol(el_exported_total)/YRN;
Investment_cost_excel:= getsol(invCost);
Emissions_excel:= getsol(emissions_total)/YRN;
x_grid_max_imp_excel:= getsol(x_grid_max_imp);
x_grid_max_exp_excel:= getsol(x_grid_max_exp);

forall(p in P,m in MM, t in T)do
Operational_cost_excel(p):= getsol(omCost(p));
y_imp_excel(p,t):= getsol(y_imp(p,t));
y_exp_excel(p,t):= getsol(-y_exp(p,t));
y_PV_excel(p,t):= getsol(y_PV(p,t));

q_HP_ww_excel(p,t):= getsol(q("HP_ww",p,t));
q_HP_aw_excel(p,t):= getsol(q("HP_aw",p,t));
q_BB_p_excel(p,t):= getsol(q("BB_p",p,t));
q_BB_c_excel(p,t):= getsol(q("BB_c",p,t));
q_EB_excel(p,t):= getsol(q("EB",p,t));
q_DH_excel(p,t):= getsol(q("DH",p,t));
s_excel(p,t):= getsol(s(p,t));
u_excel(p,t):= getsol(-u(p,t));

d_HP_ww_excel(p,t):= getsol(d_hp_ww(p,t));
d_HP_aw_excel(p,t):= getsol(d_hp_aw(p,t));
d_EB_excel(p,t):= getsol(d_eb(p,t));
b_p_excel(p,t):= getsol(b_p(p,t));
b_c_excel(p,t):= getsol(b_c(p,t));
h_DH_excel(p,t):= getsol(b_c(p,t));
grid_PPM_imp_excel(p,m):= getsol(grid_PPM_imp(p,m));
dh_PPM_excel(p,m):= getsol(dh_PPM(p,m));
end-do

forall (i in I)do
x_excel(i):= getsol(x(i));
if (Is_active_tech(i)=0)then
x_excel_output(i):= "NA";
else
x_excel_output(i):= strfmt(x_excel(i),0,0);
end-if
x_red_cost_excel(i):= getrcost(x(i));
end-do

declarations
Sheet: string;
end-declarations
```

```
forall(pp in P)do
Sheet:= "[Results_p"+pp;

initializations to ResultFile
Run_Date_excel as Sheet+"$E6]";
Run_Time_excel as Sheet+"$E7]";
Run_Best_Bound_excel as Sheet+"$E47]";
Run_runtime_excel as Sheet+"$E49]";

Optimizing_data_Min_excel as Sheet+"$E9]";
Optimizing_data_Zero_excel as Sheet+"$E10]";
Optimizing_data_PE_excel as Sheet+"$E11]";
Optimizing_data_CO2_excel as Sheet+"$E12]";

TotalCost_excel as Sheet+"$E14]"; ! Total Cost
Investment_cost_excel as Sheet+"$E15]";
Operational_cost_excel as Sheet+"$D17:E17]";
Emissions_excel as Sheet+"$E18]";
Primary_energy_excel as Sheet+"$E19]"; ! Total Primary Energy Use
ElExported_excel as Sheet+"$E20]"; ! Total Electricity Exported

x_grid_max_imp_excel as Sheet+"$E43]";
x_grid_max_exp_excel as Sheet+"$E44]"; ! Grid burden

x_excel_output as Sheet+"$D22:E30]";

y_exp_excel as Sheet+"$V5:X5]";
y_imp_excel as Sheet+"$Y5:AA5]";
y_PV_excel as Sheet+"$AB5:AD5]";
q_HP_ww_excel as Sheet+"$AF5:AH5]";
q_HP_aw_excel as Sheet+"$AI5:AK5]";
q_BB_p_excel as Sheet+"$AL5:AN5]";
q_BB_c_excel as Sheet+"$AO5:AQ5]";
q_EB_excel as Sheet+"$AR5:AT5]";
q_DH_excel as Sheet+"$AU5:AW5]";
q_ST_excel as Sheet+"$AX5:AZ5]";
u_excel as Sheet+"$BA5:BC5]";
s_excel as Sheet+"$BD5:BF5]";

d_HP_ww_excel as Sheet+"$BH5:BJ5]";
d_HP_aw_excel as Sheet+"$BK5:BM5]";
d_EB_excel as Sheet+"$BN5:BP5]";
b_p_excel as Sheet+"$BR5:BT5]";
b_c_excel as Sheet+"$BU5:BW5]";
h_DH_excel as Sheet+"$BX5:BZ5]";
grid_PPM_imp_excel as Sheet+"$CB5:CD5]";
dh_PPM_excel as Sheet+"$CF5:CH5]";
```

```
x_red_cost_excel as Sheet+"$D61:E69]";
!Is_active_min_bio_prod_p as Sheet+"$E58]";
!Min_prod_BB_p as Sheet+"$E59]";
!I!s_active_min_bio_prod_c as Sheet+"$E60]";
!Min_prod_BB_c as Sheet+"$E61]";
!I!s_active_charging_constraint as Sheet+"$E62]";
!Max_charge_rate as Sheet+"$E63]";
end-initializations
end-do

end-procedure



!! PROCEDURE: Create/Define Result File
!!==============================================================

procedure defineResultFile
if(PN = 1)
then
fcopy("reslt_template_1period.xlsx", "RESULTS_1p_.xlsx");
New_ResultFile:= "mmodbc.excel:grow;RESULTS_1p_.xlsx";
else
fcopy("reslt_template_2period.xlsx", "RESULTS_2p_.xlsx");
New_ResultFile:= "mmodbc.excel:grow;RESULTS_2p_.xlsx";
end-if
end-procedure



!! PROCEDURE: Write results to excel
!!==============================================================

procedure write_Results_to_Excel_File

Run_Date_excel:=
date(SYS_NOW);
! Returns date-stamp of optimizing

Run_Time_excel:=
time(SYS_NOW);
! Returns time-stamp of optimizing

Run_Best_Bound_excel:=
getparam("XPRS_LPOBJVAL");
```

```
Run_runtime_excel:=
runTime2-runTime1;

if (Is_active_obj_min_cost = 1)
then
Optimizing_data_Min_excel:=
"minCost";
else
writeln("error: option min, in Model Options");
end-if

if(Is_active_zero_primary_energy = 1)
then
Optimizing_data_Zero_excel:=
"zeroPE";
elif (Is_active_zero_emissions = 1)
then
Optimizing_data_Zero_excel:=
"zeroCO2";
else
Optimizing_data_Zero_excel:=
"noZero";
end-if

if (Is_active_PE_tot_asym = 1)
then
Optimizing_data_PE_excel:=
"PE tot asym";
elif (Is_active_PE_tot_sym = 1)
then
Optimizing_data_PE_excel:=
"PE tot sym";
elif (Is_active_PE_non_ren_asym = 1)
then
Optimizing_data_PE_excel:=
"PE n-r asym";
elif (Is_active_PE_non_ren_sym = 1)
then
Optimizing_data_PE_excel:=
"PE n-r sym";
else
writeln("error: option PE, in Model Options");
end-if

if (Is_active_CO2a_No = 1)
then
Optimizing_data_CO2_excel:=
```

```
"CO2a No";
elif (Is_active_CO2b_EN = 1)
then
Optimizing_data_CO2_excel:=
"CO2b EN";
elif (Is_active_G_el_t = 1)
then
Optimizing_data_CO2_excel:=
"CO2 t_el";
else
writeln("error: option CO2, in Model Options");
end-if

Objective_value_excel:= getobjval;
TotalCost_excel:= getsol(totCost);
Primary_energy_excel:= getsol(primary_energy_total)/(YRN*PN);
ElExported_excel:= getsol(el_exported_total)/(YRN*PN);
Investment_cost_excel:= getsol(invCost);
Emissions_excel:= getsol(emissions_total)/(YRN*PN);
x_grid_max_imp_excel:= getsol(x_grid_max_imp);
x_grid_max_exp_excel:= getsol(x_grid_max_exp);

forall(p in P,m in MM, t in T)
do
Operational_cost_excel(p):= getsol(omCost(p));
y_imp_excel(p,t):= getsol(y_imp(p,t));
y_exp_excel(p,t):= getsol(-y_exp(p,t));
y_PV_excel(p,t):= getsol(y_PV(p,t));
q_HP_ww_excel(p,t):= getsol(q("HP_ww",p,t));
q_HP_aw_excel(p,t):= getsol(q("HP_aw",p,t));
q_BB_p_excel(p,t):= getsol(q("BB_p",p,t));
q_BB_c_excel(p,t):= getsol(q("BB_c",p,t));
q_EB_excel(p,t):= getsol(q("EB",p,t));
q_DH_excel(p,t):= getsol(q("DH",p,t));
s_excel(p,t):= getsol(s(p,t));
u_excel(p,t):= getsol(-u(p,t));
d_HP_ww_excel(p,t):= getsol(d_hp_ww(p,t));
d_HP_aw_excel(p,t):= getsol(d_hp_aw(p,t));
d_EB_excel(p,t):= getsol(d_eb(p,t));

b_p_excel(p,t):= getsol(b_p(p,t));
b_c_excel(p,t):= getsol(b_c(p,t));
h_DH_excel(p,t):= getsol(b_c(p,t));
grid_PPM_imp_excel(p,m):= getsol(grid_PPM_imp(p,m));
dh_PPM_excel(p,m):= getsol(dh_PPM(p,m));
end-do
```

```
forall (i in I)
do
x_excel(i):= getsol(x(i));
if (Is_active_tech(i)=0)
then
x_excel_output(i):= "NA";
else
x_excel_output(i):= strfmt(x_excel(i),0,0);
end-if
end-do

if (Is_active_limit_imp_and_exp = 1)
then
alpha_tot_excel:= alpha_tot;
else
alpha_tot_excel:= 0;
end-if

if (Is_active_limit_exp = 1)
then
alpha_exp_excel:= alpha_exp;
else
alpha_exp_excel:= 0;
end-if

if (beta > 0)
then
beta_excel:= beta;
else
beta_excel:= 0;
end-if

if (gamma > 0)
then
gamma_excel:= gamma;
else
gamma_excel:= 0;
end-if

if (Is_active_min_bio_prod_p = 1)
then
Min_prod_BB_p_excel := Min_prod_BB_p;
else
Min_prod_BB_p_excel := 0;
end-if

if (Is_active_min_bio_prod_c = 1)
```

```
then
Min_prod_BB_c_excel := Min_prod_BB_c;
else
Min_prod_BB_c_excel := 0;
end-if

if (Is_active_charging_constraint= 1)
then
Max_charge_rate_excel:=  Max_charge_rate;
else
Max_charge_rate_excel := 0;
end-if

declarations Sheet: string;
end-declarations Sheet:= "[Results";

initializations to ResultFile
Run_Date_excel as Sheet+"$E6]";
Run_Time_excel as Sheet+"$E7]";
Run_Best_Bound_excel as Sheet+"$E47]";
Run_runtime_excel as Sheet+"$E49]";

Optimizing_data_Min_excel as Sheet+"$E9]";
Optimizing_data_Zero_excel as Sheet+"$E10]";
Optimizing_data_PE_excel as Sheet+"$E11]";
Optimizing_data_CO2_excel as Sheet+"$E12]";

TotalCost_excel as Sheet+"$E14]";
! Total Cost
Investment_cost_excel as Sheet+"$E15]";
Operational_cost_excel as Sheet+"$D16:E17]";
Emissions_excel as Sheet+"$E18]";
Primary_energy_excel as Sheet+"$E19]";
! Total Primary Energy Use
ElExported_excel as Sheet+"$E20]";
! Total Electricity Exported

x_grid_max_imp_excel as Sheet+"$E43]";
x_grid_max_exp_excel as Sheet+"$E44]";
! Grid burden

x_excel_output as Sheet+"$D22:E30]";

y_exp_excel as Sheet+"$V5:X5]";
y_imp_excel as Sheet+"$Y5:AA5]";
y_PV_excel as Sheet+"$AB5:AD5]";
q_HP_ww_excel as Sheet+"$AF5:AH5]";
```

```
q_HP_aw_excel as Sheet+"$AI5:AK5]";
q_BB_p_excel as Sheet+"$AL5:AN5]";
q_BB_c_excel as Sheet+"$AO5:AQ5]";
q_EB_excel as Sheet+"$AR5:AT5]";
q_DH_excel as Sheet+"$AU5:AW5]";
q_ST_excel as Sheet+"$AX5:AZ5]";
u_excel as Sheet+"$BA5:BC5]";
s_excel as Sheet+"$BD5:BF5]";

d_HP_ww_excel as Sheet+"$BH5:BJ5]";
d_HP_aw_excel as Sheet+"$BK5:BM5]";
d_EB_excel as Sheet+"$BN5:BP5]";
b_p_excel as Sheet+"$BR5:BT5]";
b_c_excel as Sheet+"$BU5:BW5]";
h_DH_excel as Sheet+"$BX5:BZ5]";
grid_PPM_imp_excel as Sheet+"$CB5:CD5]";
dh_PPM_excel as Sheet+"$CF5:CH5]";

beta_excel as Sheet+"$E51]";
gamma_excel as Sheet+"$E52]";
alpha_tot_excel as Sheet+"$E53]";
alpha_exp_excel as Sheet+"$E54]";

Min_prod_BB_p_excel as Sheet+"$E56]";
Min_prod_BB_c_excel as Sheet+"$E57]";
Max_charge_rate_excel as Sheet+"$E58]";
end-initializations

end-procedure
```