Methodology for optimal energy system design of Zero Energy Buildings using mixed-integer linear programming

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Highlights

- The cost-optimal choice of energy technologies in a ZEB is determined
- Simultaneous optimisation of investments and hourly operation is performed
- How policies influence the energy technology choice, can be investigated
- By dividing the lifetime into periods, future changes are taken into account
- The ZEB's grid interaction is analysed through the hourly net electric load profile

Abstract

According to EU's Energy Performance of Buildings Directive (EPBD), all new buildings shall be nearly Zero Energy Buildings (ZEB) from 2018/2020. How the ZEB requirement is defined have large implications for the choice of energy technology when considering both cost and environmental issues. This paper presents a methodology for determining ZEB buildings' cost optimal energy system design seen from the building owner's perspective. The added value of this work is the inclusion of peak load tariffs and feed-in-tariffs, the facilitation of load shifting by use of a thermal storage, along with the integrated optimisation of the investment and operation of the energy technologies. The model allows for detailed understanding of the hourly operation of the building, and how the ZEB interacts with the electricity grid through the characteristics of its net electric load profile. The modelling framework can be adapted to fit individual countries' ZEB definitions. The findings are important for policy makers as they identify how subsidies and EPBD's regulations influence the preferred energy technology choice, which subsequently determines its grid interaction. A case study of a Norwegian school building shows that the heat technology is altered from HP to bio boiler when the ZEB requirement is applied.

Keywords: mixed-integer linear optimisation (MILP), cost-optimality, zero energy building (ZEB), load profiles, weighting factors, grid interaction, self-consumption, demand side management (DSM), storage, feed-in-tariffs (FiT), PV, solar thermal

1 Introduction

The recast of the EU Directive on Energy Performance of Buildings (EPBD) states that all new buildings are to be nearly Zero Energy Buildings[1] (ZEB) from 2018/2020 [1]. The definition of nearly ZEBs in the EPBD states that "*a nearly zero-energy building means a building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby"* [2]. Generally speaking a nearly ZEB is an energy efficient building with low energy demand that to a high extent is covered by on-site generated renewable energy [3]–[5]. Because ZEBs need on-site energy generation in order to compensate for their energy use, they will inevitably become an active and integrated part of the energy system.

Even though the EPBD sets a definition framework, each of the EU member states shall define their own boundary conditions, weighting factors and ambition level when calculating the zero energy balance, due to differences in climate, culture & building tradition, policy and legal frameworks. As of April 2015, about half of the member states of the EU have accomplished this, and about 5 of the 28 states have chosen to use carbon emissions as weighting factors, thus aiming at Zero *Emission* Buildings[2], rather than Zero *Energy* Buildings [6]. Accordingly, a Zero Emission Building is essentially the same as a Zero Energy Building, the only difference is that the balance is calculated by using carbon emissions instead of energy units (see more in Section 1.1). Whenever using ZEB in the following it embraces both Zero Energy and Zero Emission Buildings.

The balance of a ZEB is calculated as energy consumed minus energy generated over a year or over the total lifetime of the building. However, the building still exchanges electricity with the grid on an hourly or minute basis, as the instantaneous on-site generation may not always correspond with the load. As electric energy must be consumed the instant it is produced, on-site electricity generation from photo voltaic (PV) solar cells, lead to situations where the building is exporting electricity to the grid. Such electric energy generating buildings are also denoted as prosumers, which imports electricity in some hours and exports electricity in other hours.

1.1 Definition of ZEB

A significant effort was made from 2008-2013 to define what ZEBs are, especially through the IEA Solar Heating and Cooling Programme Task 40 "Net Zero Energy Solar Buildings" (IEA SHC Task 40) [7]. One of the issues addressed was whether export of electricity should equalise import of natural gas or bio energy, when calculating the zero energy balance. Or should they be weighted according to their energy quality? Today, all member states use weighting factors, either primary energy factors (PE), in kWh_{PE} / kWh_f, or carbon factors, in $g_{CO2\text{-}eq}$ / kWh_f, which differs for each energy carrier, f, when calculating the ZEB balance. PE also have different versions; non-renewable PE and total PE, and additionally symmetric and asymmetric PE factors for electricity. As each member state is free to decide these factors, they differ slightly from country to country, however indicative values of non-renewable PE and total PE factors for European conditions are published in the EPBD [1].

[1] The notation net ZEB, or nZEB, is also commonly used in order to highlight that the balance is calculated on an hourly or monthly level, because the ZEB target is on an annual or lifetime level. In the following of this paper, whenever using ZEB this means net ZEB.

[2] Zero Emission Buildings are also denoted as Zero Carbon Buildings.

Within the work of IEA SHC Task 40, several case studies of both simulated and monitored ZEBs were performed. Noris et al. [8] analyse six ZEB buildings in four European countries, investigating the possibility of reaching the ZEB target by varying the weighting factor for calculating the ZEB balance. The findings show that regardless of using carbon or PE factors, bio energy is the preferred heat technology, as it has the lowest weighting factor in almost all European countries. The only exemption is the Danish PE factors, which favours heat pumps and district heating over bio energy. The paper concludes, without considering costs, that the chosen weighting factors have a large impact on the preferred heat technology within the building, which again influences the demanded PV area and the building's interaction with the electricity grid.

1.2 Grid indicators

The initial experience from the first ZEB pilot projects showed that reaching the zero balance is possible, and in almost all cases on-site PV generation is an inevitable part of the solution [8]–[11]. With PV as the main way of reaching the ZEB target, the building exports electricity to the grid in summer, and imports electricity in winter. This may lead to challenges for the grid depending on the capacity and conditions of the feeders and the transformers in the local distribution grid [12]. In order to evaluate the effect of the import/export situation on the grid, various grid indicators have been proposed and investigated [10]-[11], [13]. Salom et al. [10] conclude that a representation of net exported electricity in load duration curves is useful for showing maximum import and export values together with the amount of annual exported and imported electricity, especially when comparing different ZEBs. Further, it is stated that hourly time resolution is sufficient to capture the correlation between on-site demand and supply of energy.

1.3 Optimisation of ZEBs

When designing a ZEB, several aspects need to be taken into account, e.g. building physics, technical systems and their costs on the one hand, and the operation of the building, including energy prices and grid tariffs on the other. The complexity of this task has led to the development of several optimisation models which have;

1. Different *objectives*, such as maximising thermal comfort, or minimising costs or emissions. Mostly, multi-objective optimisation models have been developed.
2. Different *constraints*, such as emissions or thermal comfort
3. Different *modelling approaches*, such as simulating several different alternatives and weighting the energy performance, thermal performance and/or cost performance of the different cases in order to select the "best" cases occurring along a pareto front line, or using optimisation modelling, like LP or MILP, with one objective.
4. Different *time resolution*. The level of detail varies from minute to hourly simulations.
5. The *scope* of investigation is often either focused on optimal building design, or optimal operation.

The initial experience with ZEB pilot projects and case studies identified a trade-off between reducing energy demand vs. generation of on-site energy, when cost is considered [14]. As a consequence, different methodologies and tools for optimisation of building design occurred. Huws et al. [15] and Hamdy et al. [16] use multi-objective optimisation by stepwise varying different design parameters. Huws finds the optimal design by comparing emission vs. cost, cost vs. discomfort, and discomfort vs. emissions, and determines the heat and renewable energy (RES) technologies within the building after the building design is concluded. Hamdy also separates the optimisation into different stages, where the first stage minimises heat demand and life cycle costs (LCC) of the building envelope. This leads to selected cases that lie on the pareto front for thermal demand vs. costs. In the second step, operation costs are calculated for each of the cases from step 1 when simulating four different heating and cooling systems. In the third and last step, ways of improving the costs and the energy consumption in step 2 are investigated by adding on-site renewable energy generation (solar thermal collectors and/or PV). In both Huws and Hamdy, the outcome depends on the weighting factors between their objectives; emissions, costs, discomfort and heat demand, and thus it may be difficult to draw clear conclusions. Lu [17] also optimises the energy system by a multi-objective function by minimising costs, emissions and grid interaction, but again the outcome depends on the weighting factors between the three. The operation of the building is simulated in both Hamdy, Huws and Lu while varying different design parameters, which might not reflect the cost-optimal operation of the building.

The optimal operation of buildings for a given design have been investigated in various studies (see e.g. [12], [18]–[22]). Especially with the introduction of on-site energy generation different control algorithms are developed, however in these studies, the energy technologies (choice and size) and the design of the building are treated as given, which means that the system may be over or under dimensioned according to what is economically profitable.

This paper aims at finding the optimal investment decision of the energy technologies when taking into account an optimal hourly operation of the energy system. Investment decisions for buildings can entail many details and contradictory objective functions [23]. Models that both optimise investment decisions and operation, are mostly found in energy system modelling tools such as TIMES [24], Balmorel [25] and ReMod [26], which optimise the whole energy system from a macroeconomic perspective. Similar modelling approaches are also found in Korpås et al. [27] and Slungård et al. [28]. Korpås study an integrated wind-hydrogen power system with co-optimisation of investments and operation using deterministic LP, and Slungård developed a deterministic dynamic programming tool to determine the optimal choice and size of heat technologies in a district heating grid.

On a building level, to our knowledge, only Milan et al. [29] have developed a similar LP optimisation tool for a ZEB building, with hourly time resolution and which take the building energy loads as input. However, the number of technologies implemented is limited, and the size of the heat storage tank is predefined to fit the standard size of a Danish single-family home, and is not a freedom of choice. Hence, larger buildings, such as multi-family houses (MFH) or non-residential buildings, are not addressed.

1.4 The aim of this study

The focus of this work is to develop a mixed-integer linear modelling (MILP) framework to identify the cost-optimal choice and dimensioning of energy technologies for ZEBs, while simultaneously optimising the operation of the building. The framework is designed to investigate how the solution is influenced by the weighting factors (both choice and value of the factors), as well as the ZEB level and economic parameters. Moreover, it is possible to evaluate the effect of policy incentives, such as feed-in-tariffs and investment subsidies, on the building owner's choice of energy technologies for ZEB buildings. Naturally, the various energy technologies interacts with the power system in different ways, and the model facilitates the evaluation of this interaction for the optimal solution. This is done through selected grid indicators proposed in Section 3, e.g. load duration curves of the hourly net electricity load, and self-consumption of on-site electricity generation (see also Section 1.2).

Previous experience showed that when using a multi-objective approach by minimising both emissions and costs, the outcome is dependent on the weighting between them. Giving higher value to minimisation of emissions lead to unreasonable large capacity investments, because cost is of less importance, in order to avoid emissions in a few hours [30]. In the current work, it is therefore decided to use a single objective function, minimising the total discounted costs while posing restrictions on the weighted energy consumed by the building. This approach leads to a clear outcome of the results and is consistent with the optimal operation of the building with the given energy prices. The design of the building is predetermined, and thereby treating the energy loads as input. In contrast to already existing literature, the model developed also determines the optimal sizing of the heat storage tank and contains mixed-integer variables.

This paper gives a thorough description of the developed mixed-integer linear deterministic optimisation model, while leaving in-depth case studies for coming papers. The model structure captures the whole lifetime of the building, and incorporates effect of parameters[3] that might change in future by dividing the lifetime into periods. The integrated optimisation of the investment and operation strongly connects the investment decision with the operational outcome as well as the influence of support schemes, which can be included in the model. Thus, it is possible to analyse how different assumptions on e.g. various subsidies, feed-in tariffs, market prices, energy indicators and ZEB ambition level (nearly or strictly ZEB?) change the optimal energy solutions of the building.

The hourly time resolution of the operation of the building's energy system ensures an optimal utilisation of the heat storage and the on-site renewable energy generation. Optimal utilisation of the heat storage indirectly facilitates demand side management (DSM) as it enables the optimal way to shift the heat loads according to market conditions. The hourly time resolution also enables investigation of the building's grid interaction in detail for the different cases.

This paper is structured as follows. In Section 2, the methodology of the model is presented. The sub-models of the energy technologies are presented in Section 2.2, and the objective function is described in Section 2.3. Section 2.4 explains the main restrictions, including the hourly heat and electricity balances, and the lifetime ZEB balance. Section 3 presents the criteria selected for assessing the ZEB building's interaction with the power grid. Examples of model results are given in Section 4 based on a case study of a Norwegian school building. The most important assumptions of the model framework are discussed in Section 5, before making concluding remarks in Section 6.

Nomenclature

Sets

I^{heat}	Heat technologies, subset of I, $I^{\text{heat}} = \{\text{ST, ASHP, GSHP, EB, BB, DH, GB, CHP}\}$
I^{el}	Power technologies, subset of I, $I^{\text{el}} = \{\text{PV, CHP}\}$
I	All energy technologies, $I = I^{\text{el}} \cup I^{\text{heat}}$

[3] As the lifetime of a building can be up to 60 years, it is possible to divide the lifetime into three periods, each containing 20 years. Thus, e.g. the weighting factor for electricity can be set lower with more renewable electricity, and the FiTPV can be reduced or even removed in the second and third period.

F	Energy carriers, $F = \{\text{el import, el export, bio pellets, natural gas, district heat}\}$

Indexes

p	period
τ	year within period, $\tau = 1,\dots,N$
t	time step within year, $t = 1,\dots,T$
i	energy technology
f	energy carrier
m	month within year, $m = 1,\dots,12$
k	reinvestment number

Parameters

C_i^{totspec}	Discounted specific investment costs, including reinvestments, for technology i [EUR/kW]
C_i^{totfixed}	Discounted fixed investment costs, including reinvestments, for technology i [EUR]
C_i^{am}	Annual maintenance costs for energy technology i [EUR/kW per year],
Φ_i	Expected lifetime of energy technology i [years]
$D_{t,p}^{\text{el}}$	Electricity demand of building, at hour t within an average year in period p [kWh/hr]
$D_{t,p}^{\text{heat}}$	Heat demand of building, at hour t, in period p [kWh/hr]
$P_{t,p}^{\text{buy,D}}$	Price of electricity bought from the grid at hour t, in period p [EUR/kWh]
$P_{t,p}^{\text{buy,HP}}$	Price of electricity bought from the grid at hour t, in period p [EUR/kWh]
$P_{t,p}^{\text{sell,PV}}$	Feed-in-tariff of PV electricity exported to the grid at hour t, in period p [EUR/kWh];
$P_{t,p}^{\text{sell,CHP}}$	Feed-in-tariff of CHP electricity exported to the grid at hour t, in period p [EUR/kWh];
P_p^{bio}	Price of bio pellets in period p [EUR/kWh];
P_p^{gas}	Price of natural gas in in period p [EUR/kWh];
r	Discount rate [-]
η_i	Efficiency of technology i [-]
$\eta_{i,t,p}$	Efficiency of technology i, at hour t, in period p [-]
$\text{COP}_{i,t,p}$	Coefficient of performance of technology i, at hour t, in period p [-]
$Y_{\text{PV},t,p}$	Specific PV electricity generation, at hour t, in period p [kW/kWp]
$Q_{\text{ST},t,p}$	Specific solar heat generation, at hour t, in period p [kW/m^2]
$G_{f,p}$	Carbon emissions for energy carrier *f*, in period p [$g_{CO2\text{-}eq}$/kWh]
$\text{PE}_{f,p}$	Primary Energy Factor for energy carrier *f*, in period p [kWh_{PE}/kWh]
$\text{PE}^{\text{embodied}}, \text{G}^{\text{embodied}}$	Weighted embodied energy (PE or carbon) [kWh_{PE} or $g_{CO2\text{-}eq}$]

$\mathrm{PE}^{\mathrm{ref}}, \mathrm{G}^{\mathrm{ref}}$	Weighted energy imports (PE or carbon) without ZEB restriction [$\mathrm{kWh_{PE}}$ or $\mathrm{g_{CO2\text{-}eq}}$]
GRCH	Annual grid charge [EUR]
PPCH_m	Peak power charge, for each month m [EUR/kW]
H_m^{acc}	Hour number of the last hour, for each month m [-]
$T_{t,p}^{\mathrm{SH}}$	Temperature of water for space heating demand, at hour t, in period p [°C]
$T_{t,p}^{\mathrm{DHW}}$	Temperature required for DHW, at hour t, in period p [°C]
$T_{t,p}^{\mathrm{source}}$	Temperature of the heat source for HPs (ambient air temperature for ASHP, and ground temperature for GSHP) [°C]
$T_{t,p}^{\mathrm{collector}}$	Temperature within the ST collector (assumed equal to storage temperature) [°C]
$T_{t,p}^{\mathrm{amb}}$	Ambient air temperature [°C]
$\mathrm{IRR}_{t,p}^{\mathrm{tilt}}$	Global irradiation on a tilted plane at hour t, in period p [W/m^2]
γ	Factor for ZEB level [-]

Variables

x_i	Installed capacity of technology i [kW]
c_p^{run}	Annual operational cost, for a typical year in period p [EUR/yr]
$q_{i,t,p}$	Heat generated by technology i, at hour t, for a typical year in period p [kWh/hr]
$d_{i,t,p}$	Electricity consumed by technology i, at hour t, for a typical year in period p [kWh/hr]
$b_{t,p}$	Bio pellets consumed in BB at hour t, for a typical year in period p [kWh/hr]
$g_{t,p}^{\mathrm{CHP}}$	Natural gas consumed in CHP at hour t, for a typical year in period p [kWh/hr]
$g_{t,p}^{\mathrm{GB}}$	Natural gas consumed in GB at hour t, for a typical year in period p [kWh/hr]
$s_{t,p}$	Heat stored in accumulator tank (S) at end of hour t, in period p [kWh/hr]
$y_{i,t,p}$	Electricity generated by technology i, at hour t, for a typical year in period p [kWh/hr]
$y_{i,t,p}^{\mathrm{exp}}$	Electricity exported to the grid, from technology i, at hour t, in period p [kWh/hr]
$y_{i,t,p}^{\mathrm{selfcD}}$	Electricity consumed in the building, from technology i, at hour t, in period p [kWh/hr]
$y_{i,t,p}^{\mathrm{selfcHP}}$	Electricity consumed in HPs, from technology i, at hour t, in period p [kWh/hr]
$y_{t,p}^{\mathrm{impD}}$	Electricity imported from the grid, at hour t, for a typical year in period p [kWh/hr]
$y_{t,p}^{\mathrm{impHP}}$	Electricity imported from the grid to HP, at hour t, for a typical year in period p [kWh/hr]
$\delta_{t,p}^{\mathrm{exp}}$	Binary variable, 1 if electricity is exported from the building, 0 if import

$\delta_{t,p}^{\text{imp}}$	Binary variable, 0 if electricity is exported from the building, 1 if import
$y_{m,p}^{\text{maximp}}$	Monthly maximum electricity import value, for each month m, in period p [kWh/hr]

FiT	Feed-in tariff
Electric specific demand	Demand of electricity services (lighting, fans&pumps, appliances, etc.)
Heat demand	Demand of heat services (space heating and domestic hot water demand)
Electricity consumption	Consumption of electricity, including electricity for heating purposes (if any)

2 Optimisation model

This paper investigates cost-optimal solutions for ZEBs for different energy indicators with a financial perspective. For this purpose, a dynamic deterministic mixed-integer linear optimisation model (MILP) is developed which optimises both the investments (technology choice and size), and the operation of the energy technologies simultaneously. This model is presented in the following.

2.1 System Description

Figure 1 illustrates the energy technologies and energy flows that are implemented in the model, where solid and minor dashed arrows indicate the hourly flows of respectively electricity and heat within the building. The ZEB balance is achieved on the life cycle as embodied energy is included (see Section 2.4.4).

The energy technologies available are a micro combined heat and power unit (CHP), gas boiler (GB), district heat exchanger (DH), bio pellets boiler (BB), air source heat pump (ASHP), ground source heat pump (GSHP), electric top-up coil (EB), solar thermal collectors (ST), photovoltaic modules (PV) and a heat storage (S). The availability of a heat storage makes the system capable of shifting the heat generation to when it is economically profitable, while still being able to cover the heat demand at a later or earlier stage.

The selection of energy technologies to be implemented in the model is made on grounds of common available energy sources and energy technologies in European countries, and is inspired by the first experiences from the ZEB pilot projects in the IEA SHC Task 40 [7], [8], [10]. It is assumed that the building is attached to the electricity grid, and depending on the geographical situation, a natural gas grid and district heating grid may also be present. Even though natural gas is a fossil energy carrier, CHP and gas boilers was installed in some of the ZEB pilot projects [8], and it is of interest to study the effect of using natural gas on the ZEB balance of the building. Bio energy and heat pumps are seen as key technologies to lower Europe's climate emissions, especially as the electricity grid is expected to become greener in future [31], [32]. In general, energy systems require a technology for providing base load capacity and peak load capacity. Both the electric top-up coil and the gas boiler may serve as peak load technologies. For the building to become a ZEB, it needs onsite renewable energy generation. ST collectors and PV panels are the two technologies that may provide the building with this.

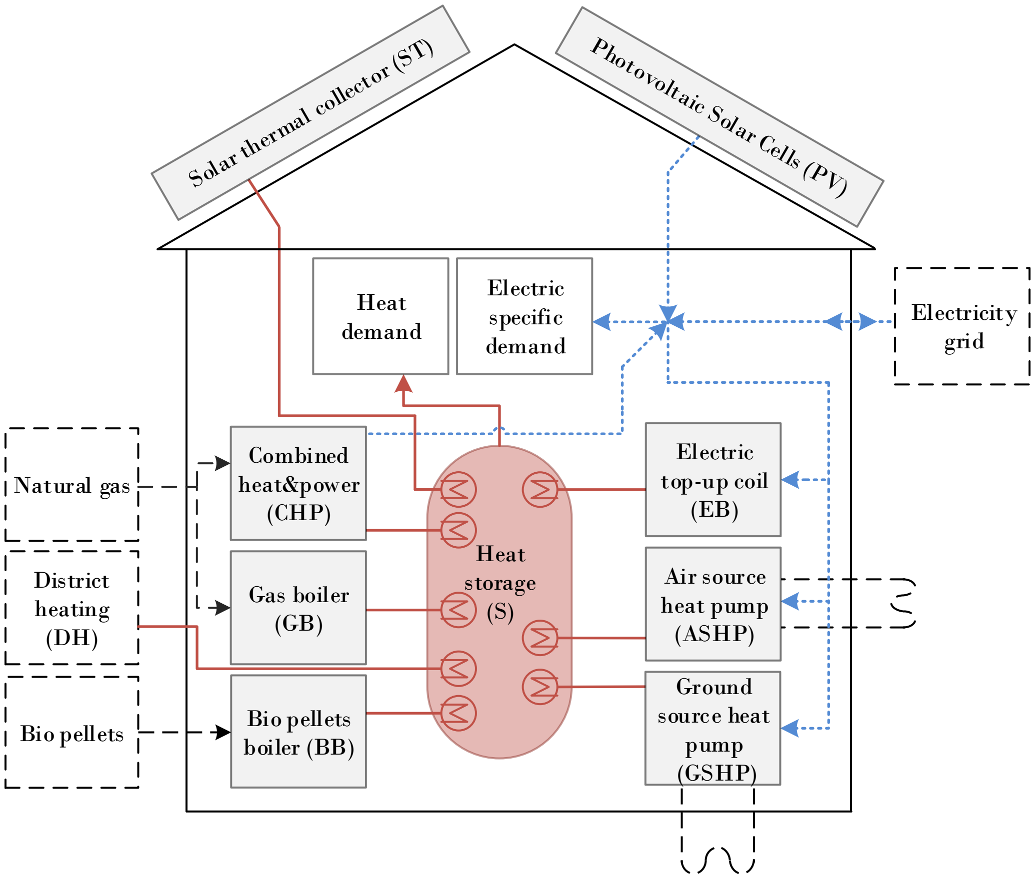

Figure 1 System scheme and energy flows of the building; heat flows (red solid lines) and electricity flows (dotted blue lines).

2.2 Modelling of energy technologies

The installed capacity of the heat pumps (HP), pellets boiler, gas boiler and the micro CHP unit are semi-continuous variables. Hence, the technology is either invested, or not, and if invested, a minimum required capacity has to be installed. In real life, technology costs are dependent on size, as larger units often have lower specific costs (EUR/kW) than smaller units. The integer formulation of minimum installed capacity is important when specific technology costs are assumed constant (EUR/kW). Without it, the model would choose to install in several different technologies, some with a very small capacity. As end-users tend to invest in one base load technology and one peak load, and not a variety of technologies, we are able to correct for this. The operation of the heat technologies, is also semi-continuous, this explains it can either be shut down, and if operating they must generate heat above a minimum capacity level (approximately 30 % of minimum installed capacity). The only exception is the solar thermal system, which naturally operates whenever the sun shines. The model is implemented in the optimisation modelling tool MOSEL Xpress provided by FICO systems [33].

2.2.1 Building's Energy Loads

Hourly heat and electricity demand of the building are given as input to the model as time series of heat, $D_{t,p}^{heat}$, and electricity, $D_{t,p}^{el}$, varying by hour, t, and period, p. The heat demand is the sum of domestic hot water demand (DHW) and space heating demand (SH), whereas electric specific demand includes electricity for electric appliances, lighting, fans & pumps and for cooling machines. The energy loads can be provided from either building simulation models, or from statistical models based on energy measurements of buildings (see e.g. [34], [35], [36]).

2.2.2 Constant efficiency for boilers and CHP

The CHP, and the gas, electric and bio boilers are modelled with a constant efficiency. Because the efficiency varies with the load, this is a simplification to keep the model linear. In order to compensate for this, the minimum operating capacity is set to 30 % of the installed capacity. This means, that the heat generated from the heat technologies, $q_{i,t,p}$, is modelled as a semi-continuous variable being either 0 or going from 30 % of the installed capacity, x_i. The exemption is the electric boiler, which mostly have the same efficiency regardless of part load, and is thus assumed to have a continuous heat generation variable, $q_{\mathrm{EB},t,p}$.

Equation (1) reflects the energy balances for each of the boilers: gas boiler, bio boiler and electric boiler.

$$q_{\mathrm{GB},t,p} = g_{t,p}^{\mathrm{GB}} \cdot \eta_{\mathrm{GB}} \quad , \quad q_{\mathrm{BB},t,p} = b_{t,p} \cdot \eta_{\mathrm{BB}} \quad , \quad q_{\mathrm{EB},t,p} = d_{\mathrm{EB},t,p} \cdot \eta_{\mathrm{EB}} \qquad \forall\ t,p \qquad [kWh] \tag{1}$$

The CHP is modelled with two efficiencies, one for heat generation and one for electricity generation, similar to the approach in [26] and [37]. This means that when the model decides to generate one unit of electricity from the CHP, $\eta_{\mathrm{CHPheat}} / \eta_{\mathrm{CHPel}}$ units of heat are simultaneously generated. Similarly, if the model decides to generate one unit of heat, $\eta_{\mathrm{CHPel}} / \eta_{\mathrm{CHPheat}}$ units of electricity are generated.

$$q_{\mathrm{CHP},t,p} = g_{t,p}^{\mathrm{CHP}} \cdot \eta_{\mathrm{CHPheat}} \quad , \quad y_{\mathrm{CHP},t,p} = g_{t,p}^{\mathrm{CHP}} \cdot \eta_{\mathrm{CHPel}} \qquad \forall\ t,p \qquad [kWh] \tag{2}$$

2.2.3 Variable efficiency for air source and ground source heat pumps

The conversion efficiency of electricity into heat (COP) of a heat pump is dependent on the heat source temperature, in this case air or ground temperature, and the supply temperature, which is the temperature of the accumulator tank. The latter is approximated by weighing the required energy demand with its set-point temperature. In the model, the heat demand of the building is treated as the sum of the domestic hot water demand (DHW) and the space heating demand (SH), on the assumption that they are supplied by a stratified storage tank. The supply temperature for the domestic hot water is assumed constant throughout the year. The supply temperature of the space heating, however, is dependent on the outdoor temperature and determined according to a heating curve, which is dependent on the heat distribution technology used (see examples in Figure 2).

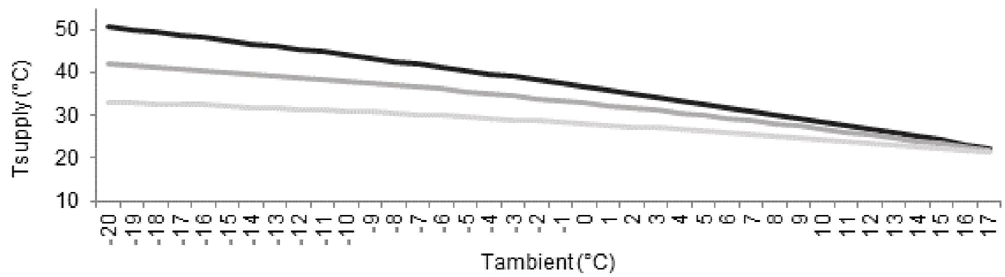

Figure 2 Heating curve. (supply temperature for space heating vs. outdoor temperature).

The COP of the heat pump is represented by a polynomial based on a fit of manufacturer's data presented in [38]. The coefficients k_0 to k_3 are dependent on the technology used, and thereby respecting the characteristics of either the ground source heat pump (GSHP), where $T_{t,p}^{\text{source}}$ is the ground temperature, or the air source heat pump (ASHP), where $T_{t,p}^{\text{source}}$ is the same outdoor temperature used for creating the building's heat demand, $D_{t,p}^{\text{heat}}$ (see Section 2.2.1).

$$\begin{aligned} &\text{COP}_{t,p} = k_0 - k_1\left(T_{t,p}^{\text{supply}} - T_{t,p}^{\text{source}}\right) + k_2\left(T_{t,p}^{\text{supply}} - T_{t,p}^{\text{source}}\right)^2 \quad \forall\ t, p \quad [-] \\ &\text{where} \quad T_{t,p}^{\text{supply}} = T^{\text{DHW}} \quad \text{for} \quad \text{DHW} \\ &\qquad\quad\ T_{t,p}^{\text{supply}} = T_{t,p}^{\text{SH}} \quad \text{for} \quad \text{SH} \end{aligned} \tag{3}$$

The heat storage is modelled as a single node, serving both DHW and SH demand. Thus, the average COP of the heat pump when delivering to the whole tank is assumed to be a weighted average of the COP for DHW and for SH as described in Eq.(4), where $D_{t,p}^{\text{DHW}}$ is the demand of hot water, and $D_{t,p}^{\text{SH}}$ the demand for space heating.

$$\text{COP}_{t,p} = \frac{D_{t,p}^{\text{DHW}}\text{COP}_{t,p}^{\text{DHW}} + D_{t,p}^{\text{SH}}\text{COP}_{t,p}^{\text{SH}}}{D_{t,p}^{\text{heat}}} \quad \forall\ t, p \quad [-] \tag{4}$$

Equation (5) reflects that the heat generated from the ASHP, $q_{\text{ASHP},t,p}$, equals the electricity consumed, $d_{\text{ASHP},t,p}$, multiplied by the COP. Similarly, the energy balance for the GSHP is given in Eq.(5). Notice that the COP changes by hour as the supply temperature and temperature of the source also varies by hour.

$$q_{\text{ASHP},t,p} = d_{\text{ASHP},t,p} \cdot \text{COP}_{t,p}^{\text{ASHP}} \quad , \quad q_{\text{GSHP},t,p} = d_{\text{GSHP},t,p} \cdot \text{COP}_{t,p}^{\text{GSHP}} \qquad \forall\ t, p \quad [kWh] \tag{5}$$

2.2.4 District heating

District heating is modelled with a constant efficiency, reflected in Eq. (6).

$$q_{\mathrm{DH},t,p} = \mathrm{DH}_{t,p} \cdot \eta_{\mathrm{DH}} \qquad \forall\ t,p \quad [kWh] \tag{6}$$

2.2.5 Storage

The energy balance of the storage is equal to the heat balance of the total heat system of the building shown in Eq. (17), which incorporates the heat losses of the storage.

In order to make the optimal solution independent of the final storage content, the storage is required to contain the same amount of heat at the start ($t = 0$) and at the end ($t = T$) of the year. See Eq. (7).

$$s_{0,p} = s_{T,p} \qquad \forall\ p \quad [\mathrm{kWh/hr}] \tag{7}$$

2.2.6 Solar energy – PV and solar thermal collectors

The efficiency of the flat plate solar thermal collector (ST) is represented by a polynomial (see eq. (8)) where the constants are determined by laboratory experiments in [39]. The total irradiation on the tilted plane, $\mathrm{IRR}^{\mathrm{tilt}}$, varies hourly and is calculated according to Quaschning [40] with the same climatic conditions as when calculating the building's energy loads in Section 2.2.1. The temperature within the solar thermal collector, $T_{t,p}^{\mathrm{collector}}$, must be determined exogenously. As Eq. (8) shows, a higher value of the temperature from the collector decreases the module efficiency. Thus, an assumption of e.g. 30°C of the collector temperature will give an optimistic value for the efficiency of the ST.

$$\eta_{\mathrm{ST},t,p} = c_0 - c_1 \frac{T_{t,p}^{\mathrm{collector}} - T_{t,p}^{\mathrm{amb}}}{\mathrm{IRR}_{t,p}^{\mathrm{tilt}}} - c_2 \frac{\left(T_{t,p}^{\mathrm{collector}} - T_{t,p}^{\mathrm{amb}}\right)^2}{\mathrm{IRR}_{t,p}^{\mathrm{tilt}}} \qquad \forall\ t,p \quad [-] \tag{8}$$

The input time series of ST heat generation, $Q_{\mathrm{ST},t,p}$, in Eq. (9) is equal to the total irradiation on the tilted plane, $\mathrm{IRR}_{t,p}^{\mathrm{tilt}}$, multiplied with the collector efficiency, $\eta_{\mathrm{ST},t,p}$. The utilised ST heat, $q_{\mathrm{ST},t,p}$, within the building can be either equal to or lower than the actual ST heat generation, which is necessary if heat demand is low and the storage tank is full at the time of ST heat generation.

$$Q_{\mathrm{ST},t,p} = \mathrm{IRR}_{t,p}^{\mathrm{tilt}} \cdot \eta_{\mathrm{ST},t,p} \qquad \forall\ t,p \quad \left[kWh/m_{\mathrm{collector}}^2\right] \tag{9}$$

$$q_{\mathrm{ST},t,p} \leq Q_{\mathrm{ST},t,p} \cdot x_{\mathrm{ST}} \qquad \forall\ t,p \quad [kWh] \tag{10}$$

The PV electricity generation, $Y_{\mathrm{PV},t,p}$, in Eq.(11), is found by using the same irradiation on the tilted surface as described above for ST. The efficiency of the PV module and the inverter is calculated based on a methodology proposed by Huld et al. [41] which takes cell temperature and module type into account, in addition to solar irradiation and outdoor temperature.

$$Y_{\mathrm{PV},t,p} = \mathrm{IRR}_{t,p}^{\mathrm{tilt}} \cdot \eta(\mathrm{IRR}_{t,p}^{\mathrm{tilt}}, T_{t,p}^{\mathrm{amb}})_{\mathrm{PV},t,p} \qquad \forall\ t,p \quad [kWh/kWp] \tag{11}$$

$$y_{\mathrm{PV},t,p} = Y_{\mathrm{PV},t,p} \cdot x_{\mathrm{PV}} \qquad \forall\ t,p \quad [kWh] \tag{12}$$

2.3 Objective function

This section presents the objective function which minimises total costs, while posing restrictions on the emissions or primary energy consumed.

A single objective function is used, which minimises discounted investment and operational costs over the total lifetime of the building. The lifetime of the building may be divided into periods, p , where the model is run for a representative year within each period. Hence, the total lifetime of the building equals the total number of periods, P , multiplied by the number of years within each period, N .

Equation (13) shows the objective function which sums the discounted investment costs (fixed [EUR] and specific [EUR/kW]), for each technology, i , and the total discounted annual operational costs. Starting from the right in Eq. (13), the annual operational costs, c_p^{totrun} , for a representative year in a period, p , are discounted and summed for all years, τ , within the period. Next, the operational costs for each period are discounted for all periods.

$$\min\ \pi = \sum_{i \in I} \left(C_i^{\text{totspec}} x_i + C_i^{\text{totfixed}} \right) + \sum_{p=1}^{P} \frac{1}{(1+r)^{(p-1)\cdot N(p)}} \cdot \sum_{\tau=1}^{N} \frac{c_p^{\text{totrun}}}{(1+r)^{\tau}} \qquad [EUR] \tag{13}$$

The lifetime adjusted specific investment costs, C_i^{totspec}, are found for each technology, i , on the basis of its expected lifetime, Φ_i , as shown in Eq.(14), where C_i^{spec} is the investment cost [EUR/kW], and $\left(\frac{P\cdot N(p)}{\Phi_i} - 1\right)$ is the number of reinvestments, k, needed throughout the lifetime of the building. As an example, if the total lifetime of the building is 40, the number of reinvestments of an ASHP with an expected lifetime of 20 years equals $\frac{40}{20} - 1 = 1$, and the salvage value is zero.

$$C_i^{\text{totspec}} = \sum_{k=0}^{\left(\frac{P\cdot N(p)}{\Phi_i} - 1\right)} \frac{C_i^{\text{spec}}}{(1+r)^{k\cdot \Phi_i}} - Z^{\text{salvage}} \qquad [EUR/kW] \tag{14}$$

$$C_i^{\text{totfixed}} = \sum_{k=0}^{\left(\frac{P\cdot N(p)}{\Phi_i} - 1\right)} \frac{C_i^{\text{fixed}}}{(1+r)^{k\cdot \Phi_i}} - Z^{\text{salvage}} \qquad [EUR] \tag{15}$$

Equation (16) reflects that the annual operational costs for a representative year within each period, c_p^{totrun}, equals the cost of energy imports in all hours, t , which is the price for each energy carrier, $P_{t,p}^{f}$, multiplied by the amount of electricity, $y_{t,p}^{\text{imp}}$, bio pellets, $b_{t,p}$, or natural gas, $g_{t,p}$, consumed. Notice that in some countries, electricity used for heat pumps, $y_{t,p}^{\text{impHP}}$, has a lower tariff than normal electricity consumption, and is thus specified separately. In the second line, the cost of self-consumption of on-site electricity generation $\left(P_{t,p}^{\text{selfc}} \cdot y_{t,p}^{\text{selfc}}\right)$ is added, and in the third line, the income of electricity sold to the grid is subtracted $\left(P_{t,p}^{\text{sell}} \cdot y_{t,p}^{\text{exp}}\right)$. The last line presents the fixed annual maintenance cost for each technology, $C_i^{\text{am}} \cdot x_i$, and two special taxes of the electricity grid, where PPCH_m reflects the monthly peak power charge (see more in Section 2.4.3) and GRT the annual grid charge.

$$c_p^{\text{totrun}} = \sum_{t \in T} \begin{pmatrix} P_{t,p}^{\text{buy,D}} y_{t,p}^{\text{impD}} + P_{t,p}^{\text{buy,HP}} y_{t,p}^{\text{impHP}} + P_p^{\text{bio}} b_{t,p} + P_p^{\text{gas}} \left(g_{t,p}^{\text{GB}} + g_{t,p}^{\text{CHP}} \right) \\ + P_{t,p}^{\text{selfc}} \left(\left(y_{t,p}^{\text{PVselfc\_D}} + y_{t,p}^{\text{PVselfc\_HP}} \right) + y_{t,p}^{\text{CHPselfc}} \right) \\ - \left(P_{t,p}^{\text{sell,PV}} y_{t,p}^{\text{PVexp}} + P_{t,p}^{\text{sell,CHP}} y_{t,p}^{\text{CHPexp}} \right) \end{pmatrix} + \sum_{i \in I} C_i^{\text{am}} x_i + \sum_{m \in M} \text{PPCH}_m \, y_{m,p}^{\text{maximp}} + \text{GRCH} \qquad \forall\, p \qquad \left[EUR / year \right] \tag{16}$$

The model can easily be adapted to investigate conditions in countries where there is no peak power charge, or fee for self-consumption by letting them be zero. Further, if no feed-in-tariffs are present, the $P_{t,p}^{\text{sell,PV}}$ and $P_{t,p}^{\text{sell,CHP}}$ are replaced with the spot price in the electricity market.

This means that both the investment problem and the operation problem are solved at the same time. In other words, the least cost solution for the operation of the building with the optimal technologies and their sizing is found.

2.4 Restrictions

The optimal solution is found according to a set of constraints that cannot be violated. The technology restrictions were elaborated on in Section 2.2. This section presents the constraints reflecting the hourly heat and electricity balance and the lifetime ZEB balance of the building. Additional restrictions, such as grid tariffs and maximum available façade area, are also explained.

2.4.1 Heat balance

For each hour, the heat demand of the building has to be met. Equation (17) reflects the heat balance where the sum of heat generated from all heat technologies, $q_{i,t,p}$, added the content of the storage at the beginning of hour t, must equal the heat demand of the building, $D_{t,p}^{\text{heat}}$, plus the energy content of the storage at the end of hour t, $s_{t,p}$. Notice that the content of the storage at the beginning of the hour equals the content of the storage at the end of the previous hour, $s_{t-1,p}$, multiplied with an efficiency factor, η_S.

$$\sum_{i \in I^{\text{heat}}} q_{i,t,p} + \eta_S \cdot s_{t-1,p} = D_{t,p}^{\text{heat}} + s_{t,p} \qquad \forall\; t, p \tag{17}$$

2.4.2 Electricity balance

Similar as for heat, the electricity demand of the building, $D^{\text{el}}_{t,p}$, must be met every hour. Figure 3 illustrates the four electricity balance equations, where Node I reflects that the electricity demand of the building, $D^{\text{el}}_{t,p}$, and the electric top-up coil $d_{EB,t,p}$, must be met by electricity bought from the grid, $y^{\text{impD}}_{t,p}$, and/or on-site generated electricity from PV, $y^{\text{selfcD}}_{PV,t,p}$, and/or CHP, $y^{\text{selfcD}}_{CHP,t,p}$ (see Eq. (18)). As explained in Section 2.3, electricity used for heat pumps may have a separate tariff, and is thus treated separately as seen in Node II in Figure 3. Equation (19) reflects the electricity balance of the heat pumps, where the electricity demanded by the heat pumps, $d_{ASHP,t,p} + d_{GSHP,t,p}$, is covered by import from the grid, $y^{\text{impHP}}_{t,p}$, and/or on-site generated electricity from PV, $y^{\text{selfcHP}}_{PV,t,p}$. It is assumed that if a CHP is installed, a HP will not be installed additionally, and accordingly, the option of CHP providing electricity to the HP is left out. Node III and IV, reflects the electricity balances for the PV and the CHP (given in Eq. (20) and (21)) respectively, where generated electricity, $y_{i,t,p}$, can be exported to the grid, $y^{\text{exp}}_{i,t,p}$, and/or self-consumed within the building.

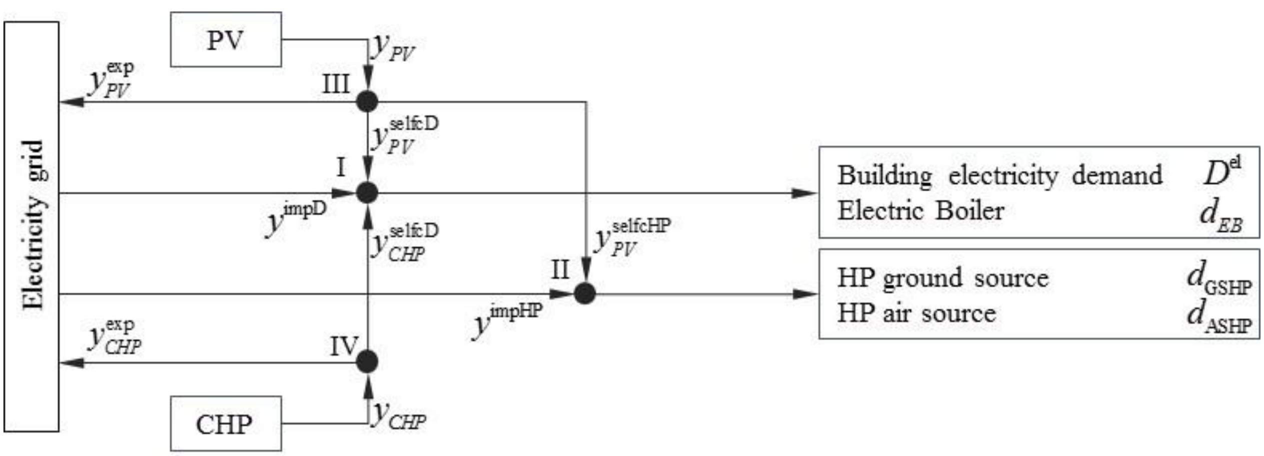

Figure 3 Graphical description of the hourly electricity balance.

I $$D^{\text{el}}_{t,p} + d_{EB,t,p} = y^{\text{selfcD}}_{PV,t,p} + y^{\text{selfcD}}_{CHP,t,p} + y^{\text{impD}}_{t,p} \qquad \forall\ t,p \qquad (18)$$

II $$d_{ASHP,t,p} + d_{GSHP,t,p} = y^{\text{selfcHP}}_{PV,t,p} + y^{\text{impHP}}_{t,p} \qquad \forall\ t,p \qquad (19)$$

III $$y_{PV,t,p} = y^{\text{exp}}_{PV,t,p} + \left(y^{\text{selfcD}}_{PV,t,p} + y^{\text{selfcHP}}_{PV,t,p} \right) \qquad \forall\ t,p \qquad (20)$$

IV $$y_{CHP,t,p} = y^{\text{exp}}_{CHP,t,p} + y^{\text{selfcD}}_{CHP,t,p} \qquad \forall\ t,p \qquad (21)$$

Equations (18)–(21) must be separate, if not, the export from the CHP will “turn to” PV export because the payment is often higher for PV export. Further, because the feed-in tariff (FiT) for CHP export is lower than the FiT for PV export, the model will always choose to export electricity from PV in favour of CHP, and thus, there is no need for additional restrictions for the import-export situation.

2.4.3 Grid constraints

To avoid import and export of electricity within the same hour, the following three constraints are applied in order to force the model to either import or export. This is done by use of binary variables (0 or 1), $\delta_{t,p}^{\text{exp}}$ and $\delta_{t,p}^{\text{imp}}$, that get the value one if respectively export or import is positive. M^{grid} is an exogenously determined parameter that has to be large enough for the equations to hold.

If import: $$\left(y_{t,p}^{\text{impD}} + y_{t,p}^{\text{impHP}}\right) \leq \delta_{t,p}^{\text{imp}} \cdot M^{\text{grid}} \qquad \forall\ t,p \qquad (22)$$

If export: $$\left(y_{t,p}^{\text{PVexp}} + y_{t,p}^{\text{CHPexp}}\right) \leq \delta_{t,p}^{\text{exp}} \cdot M^{\text{grid}} \qquad \forall\ t,p \qquad (23)$$

Either import or export: $$\delta_{t,p}^{\text{exp}} + \delta_{t,p}^{\text{imp}} \leq 1 \qquad \forall\ t,p \qquad (24)$$

Grid companies may operate with a monthly peak power charge. To include this, the monthly peak power needs to be found. Equation (25) determines the highest monthly peak value of electricity import, where H_m is a vector containing the time step number of the last hour of the last day in the month, $\theta(m)$, for every month throughout the year.

$$if \quad t \leq H_m = H_{m-1} + 24 \cdot \theta(m) \quad \rightarrow \quad y_{m,p}^{\text{maximp}} \geq (y_{t,p}^{\text{impD}} + y_{t,p}^{\text{impHP}}) \qquad \forall\ t,m,p \qquad (25)$$

The value of the first month (January) is $H_1 = 744$, while the last month (December), is $H_{12} = 8760$. For every month, the peak electricity import value will be stored in the variable $y_{m,p}^{\text{maximp}}$. The monthly peak power charge thus equals $\left(\text{PPCH}_m \cdot y_{m,p}^{\text{maximp}}\ \forall m,p\right)$, as seen in Eq.(16).

2.4.4 ZEB constraints

The modelling framework developed allows for modification of boundary conditions, weighting factors and ZEB ambition level in order to fit individual countries’ ZEB definitions. Here, the boundary condition is set at the building’s physical walls, and the ZEB ambition level includes energy used for constructing the building (embodied energy) and all energy consumed within the building. In line with the EPBD [1] the balance of the ZEB building is calculated as weighted energy imported minus weighted energy exported over the total lifetime of the building.

Equation (26) and (27) reflect the zero primary energy and zero emission constraint, respectively. In Eq. (26) the total primary energy imports over the entire lifetime of the building equals the sum of operational and embodied energy, G^{embodied}. The operational energy import is found by multiplying the import of each energy carrier, f, with its primary energy factor, $\text{PE}_{f,p}$, for each time step, t, summed over a representative year within each period, p, multiplied by the number of years within each period, N, and lastly summed over all periods, P. Notice that the balance only includes energy carriers either exported from or imported to the building. As an example, solar thermal generation is not explicitly accounted for, however its heat indirectly contributes to reduced energy imports for heat generation.

In order to investigate a relaxation of the ZEB constraints, γ is introduced which can take the values {0, ... , 1}. PE^{ref} represents the building's primary energy consumption when only minimising costs without enabling the ZEB constraint, and is afterwards set as an exogenous parameter when activating the ZEB constraint. Imposing $\gamma = 1$ means that the building is a strictly ZEB, and the restriction in Eq. (26) equals zero. When $\gamma = 0$, there is no ZEB requirement, and the cost-optimal solution without considering primary energy consumption is found. Imposing $\gamma = 0,6$ means that the primary energy consumption, $\text{PE}^{\text{totref}}$, must be reduced by 60 %, reflecting a 60 % nearly ZEB. As the environmental impact for the energy carriers might change in the future, especially for electricity, the primary energy factors, $\text{PE}_{f,p}$ [kWh $_{\text{PE}}$ / kWh $_f$], can be changed according to the period.

$$\sum_{p\in P}\left(N(p)\sum_{t\in T}\sum_{f\in F}\left(\left(y_{t,p}^{\text{impD}}+y_{t,p}^{\text{impHP}}\right)_f-\left(y_{t,p}^{\text{PVexp}}+y_{t,p}^{\text{CHPexp}}\right)_f+\left(b_{t,p}\right)_f+\left(g_{t,p}^{\text{GB}}+g_{t,p}^{\text{CHP}}\right)_f\right)\cdot \text{PE}_{f,p}\right) + \text{PE}^{\text{embodied}} = (1-\gamma)\cdot \text{PE}^{\text{ref}} \quad [\text{kWh}_{\text{PE}}] \tag{26}$$

The zero emission constraint in Eq. (27) has a similar layout as the zero primary energy constraint, where the primary energy factors, $\text{PE}_{f,p}$, are replaced with carbon factors, $G_{f,p}$ [g $_{\text{CO2-eq}}$ / kWh $_f$].

$$\sum_{p\in P}\left(N(p)\sum_{t\in T}\sum_{f\in F}\left(\left(y_{t,p}^{\text{impD}}+y_{t,p}^{\text{impHP}}\right)_f-\left(y_{t,p}^{\text{PVexp}}+y_{t,p}^{\text{CHPexp}}\right)_f+\left(b_{t,p}\right)_f+\left(g_{t,p}^{\text{GB}}+g_{t,p}^{\text{CHP}}\right)_f\right)\cdot G_{f,p}\right) + G^{\text{embodied}} = (1-\gamma)\cdot G^{\text{ref}} \quad [\text{g}_{\text{CO2-eq}}] \tag{27}$$

2.4.5 Technology capacity constraints

For each technology, i, capacity constraints and energy balances are applied, which states that the heat, Eq. (28), or electricity, Eq. (29), generated cannot surpass the installed capacity, x_i, of each technology. Constraints for ST and PV are given in Eq. (10) and Eq. (12), respectively.

$$x_i \geq q_{i,t,p} \qquad \forall \;\; i\in I^{\text{heat}}\setminus \text{ST},\; t,\; p \qquad [\text{kW}] \tag{28}$$

$$x_i \geq y_{i,t,p} \qquad \forall \;\; i\in I^{\text{el}}\setminus \text{PV},\; t,\; p \qquad [\text{kW}] \tag{29}$$

Maximum available façade and roof area for mounting PVs and ST modules is shown in Eq. (30). Notice that the installed ST is given in m^2, and the installed PV in kWp. Thus a factor of Ω m^2/kWp is multiplied to the latter. With a relatively high module performance of e.g. 300 W, a factor of 5,3 m^2/kW may be reasonable.

$$x_{ST} + \Omega \cdot x_{PV} \leq A^{max} \qquad [m^2] \qquad (30)$$

3 Assessment criteria: Grid Interaction indicators

A thorough presentation of assessment criteria for ZEBs is given in the report of Salom et al [13], and further elaborated on in [10]. In this work, five grid interaction indicators are chosen for assessing the building's interaction with the power grid (see Table 1).

The self-consumption evaluates the share of on-site electricity generation that is consumed within the building. A graphic illustration of the hourly net electricity load is useful for showing maximum import and export values together with the annual exported and imported amount of electricity. The generation multiple (GM) relates the maximum export value to the maximum import value, and gives an indicative value on how much stronger the grid connection capacity needs to be if the maximum export value exceeds the maximum import value. As the choice of energy technology impacts the net electricity load profile, the reference generation multiple ($\mathrm{GM}_{\mathrm{ref}}$) can be used to compare the different cases on the same grounds, i.e. in relation to a reference peak import value.

Table 1 Indicators chosen to evaluate the building's grid interaction.

Grid Indicator	Description	Formula
Self-consumption	Share of on-site electricity generation used by the building. First introduced by [12]. (Also called "supply cover factor")	$\gamma_S = \frac{\sum_{t\in T}\left(y_t^{\text{PVselfc}} + y_t^{\text{CHPselfc}}\right)}{\sum_{t\in T}\left(y_t^{\text{PVexp}} + y_t^{\text{CHPexp}}\right)}$ (31)
Annual Export	Yearly electricity exported.	$\text{EX} = \sum_{t\in T}\left(y_t^{\text{PVexp}} + y_t^{\text{CHPexp}}\right)$ (32)
Net electricity load	Annual duration curves of hourly net electricity import (+ import, - export). (This is the opposite of the definition in [11] which defines duration curves for net electricity export (- import, + export), however as buildings normally pose a load on the grid, import is given a positive sign.)	$ne_t = \left(y_{t,p}^{\text{impD}} + y_{t,p}^{\text{impHP}}\right) - \left(y_t^{\text{PVexp}} + y_t^{\text{CHPexp}}\right)$ (33)
GM factor	Generation Multiple relates the maximum export value to the maximum import value of electricity.	$\text{GM} = \frac{\max_{t\in T, p\in P}\left\{y_{t,p}^{\text{PVexp}} + y_{t,p}^{\text{CHPexp}}\right\}}{\max_{t\in T, p\in P}\left\{y_{t,p}^{\text{impD}} + y_{t,p}^{\text{impHP}}\right\}}$ (34)

GM_{ref} factor	GM_{ref} relates the maximum export value to the maximum import value of electricity in a reference case.	$$GM_{ref} = \frac{\max\limits_{t\in T,p\in P}\left\{y_{t,p}^{PVexp}+y_{t,p}^{CHPexp}\right\}}{\left(\max\limits_{t\in T,p\in P}\left\{y_{t,p}^{impD}+y_{t,p}^{impHP}\right\}\right)_{ref}} \quad (35)$$

4 Results

This section presents selected results in order to illustrate how the modelling framework can be used as a tool to optimize the energy system of ZEBs. The modeling framework can also be used to study the impact of different incentives and governmental support schemes for energy efficiency and local energy generation, which will be presented in papers to come.

The techno-economic optimization model described in this paper requires an extensive amount of input data. In order to avoid a detailed description of the input parameters, they are taken from a case study conducted on a simplified version of the model in [42]. The case study is a relatively large school building of 10 000 m^2 with an assumed lifetime of 60 years, situated in Norway. The technology costs and efficiency data, the energy market conditions and climatic conditions are adapted to the country specific conditions.

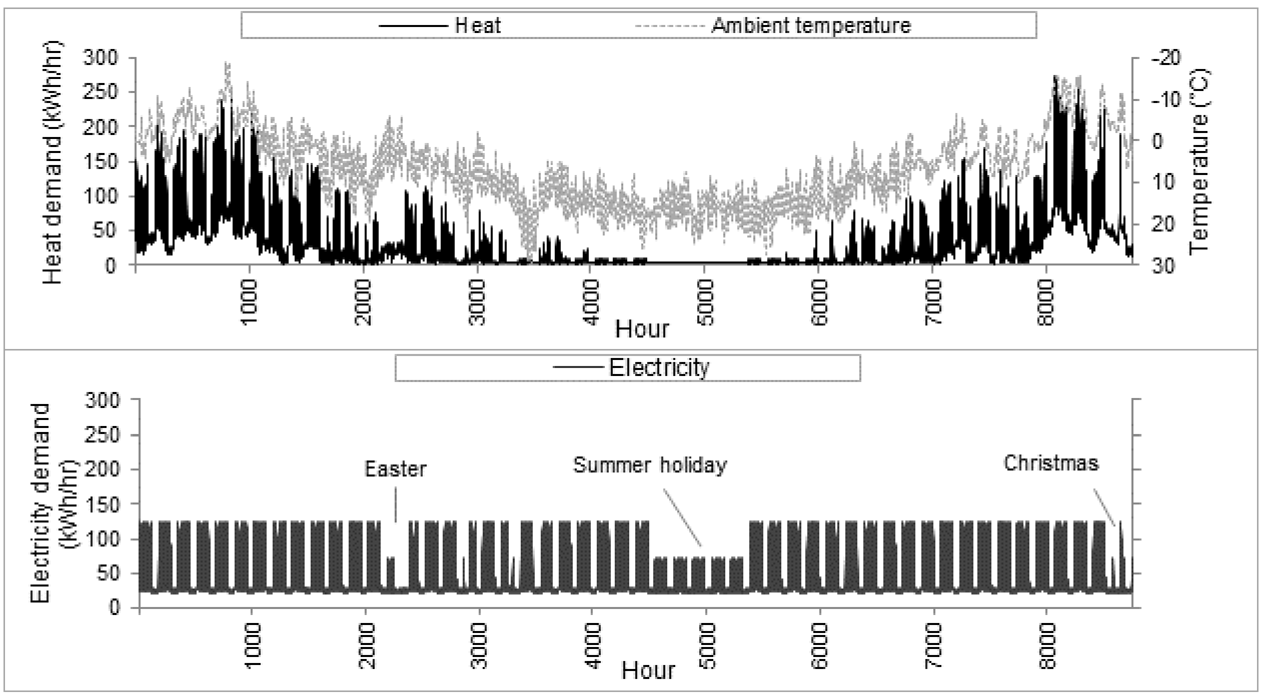

Figure 4 Hourly heat (upper) and electricity (lower) demand for a passive school building situated in southern Norway.

It is assumed that a ZEB is a building with passive energy standard, but with on-site energy generation. The load inputs are given by regression models based on hourly measurements of electricity and district heat consumption of a passive school building in Norway [35],[36]. Figure 4 shows that the building's heat demand is correlated with the ambient temperature. When the temperature hits -15˚C, the hourly heat demand is between 270-290 kWh, however at temperatures above 10-15˚C the heat demand reflects only the hot tap water demand. The number of months with a heating strategy for the school building is thus about 7 months. The electricity demand on the other hand, is related to the school holidays when lights are switched off and the operation of the ventilation system is reduced. Further, there is no cooling demand in summer as the school is closed.

As mentioned in the introduction, every EU member state is obliged to define its own ZEB definition and ambition level. The ambition level reflects how "nearly" ZEB, or how close to zero the ZEB target, is set to be. With the additional features of the γ presented in Section 2.4.4, the relaxation of the ZEB constraint can be investigated. The following thus investigates the relaxation of the ZEB constraint when using carbon factors.

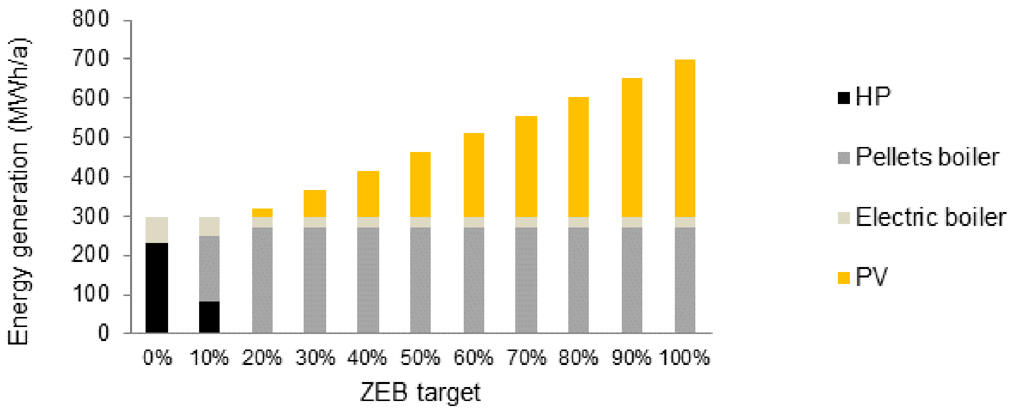

Figure 5 Relaxation of the zero emission constraint. Impact on annual heat and electricity generation (MWh/yr) within the building, by technology.

Figure 5 shows how the technology choice is influenced by the ZEB ambition level; here varying from no-ZEB (0 %-ZEB) to strictly ZEB (100 %-ZEB). The energy technology choice shifts from heat pump (HP) to bio pellets boiler and PV when strengthening the ZEB target from 0 % to 100 %. The most cost efficient way to reduce the carbon emissions is first to reduce the operational emissions. In this case, electricity used for heat pumps is replaced by bio pellets used in a bio boiler, which emits less carbon per heat unit. When the heat pump is fully replaced by the bio pellets boiler, the next option is to compensate the emissions by onsite renewable energy generation, where the installed PV capacity starts at 26 kWp for 20 %-ZEB, and reaches 483 kWp for 100 %-ZEB.

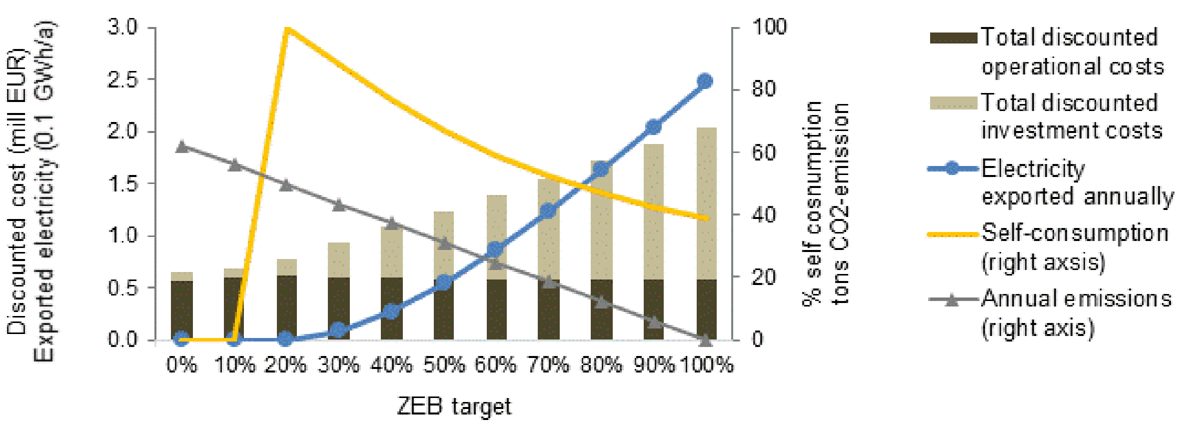

Figure 6 Relaxation of the zero emission constraint. Impact on total discounted investment and operational costs (1000 EUR), annual electricity exported (100 kWh/yr) and self-consumption rate (%).

Figure 6 shows the impact on the energy system costs, the annual electricity export and the self-consumption rate. The total discounted investment cost increases from 0,65 mill EUR (no-ZEB) to 2,04 mill EUR (100 %-ZEB), which is mainly caused by the increased PV investments. The total discounted operational costs increases by 11 % at 20 %-ZEB, due to the more expensive operation & fuel cost of the bio boiler compared to the heat pump. From 30 %-ZEB and onwards, the operational costs declines due to the increased income from sold electricity to the grid. Because Norway do not have a feed-in tariff for PV, the income of the exported PV electricity is limited, and the total discounted operational cost reaches 0,57 mill EUR at 100 %-ZEB, which is only 3 % lower compared to the 0 %-ZEB case.

The self-consumption rate is the amount of on-site PV generation that is consumed within the building calculated on an hourly level (see definition in Eq. (31)). When there is no PV present, the self-consumption is not defined and is seen as 0 % in the graph. As the PV is introduced at 20 %-ZEB, the amount of PV is so small that almost all the generation is consumed within the building and the self-consumption is 100 %. As the ZEB target becomes more ambitious, the PV installation increases, and the generation thus becomes larger than the building's electricity consumption in the hours when there is sunshine. Consequently, the self-consumption decreases to 40 % in the 100 %-ZEB case.

Figure 6 underlines the challenges of ZEBs because as the stronger the target is, the more PV needs to be installed, but the less of the actual on-site generated electricity can be self-consumed. Consequently, the building imports electricity in winter, and exports electricity in summer, using the electricity grid as a virtual seasonal storage. This is emphasized in Figure 7 which shows that the 100%-ZEB building is exporting electricity in 26 % of the hours, and the peak export value at 345 kW is higher than the peak import value at 229 kW, leading to a GM-value of 1,5.

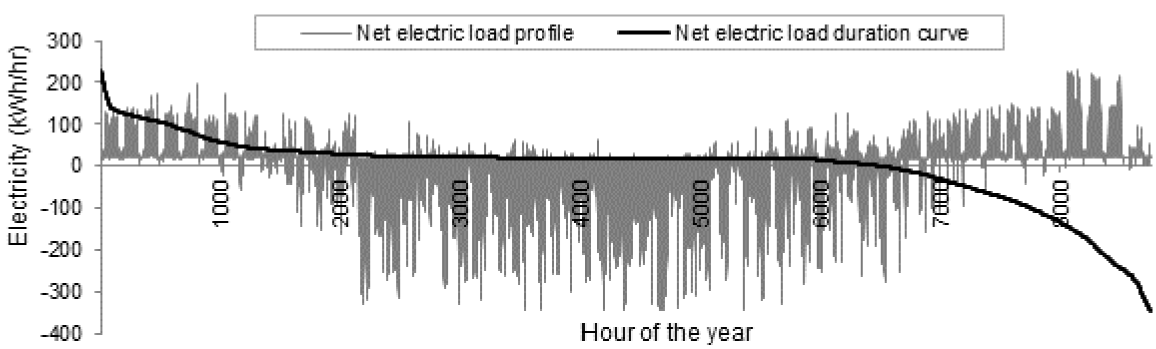

Figure 7 Hourly net electricity load profile and the sorted load duration curve for the strictly ZEB (100%).

Summed up, the modelling framework can be used for evaluating at which level it is reasonable to set the ZEB-target. Should it be at 20 %, when self-consumption is at its highest, or at 50 % when both emissions and electricity exports are within reasonable values, or will the grid handle everything and the cost of PVs drop further so that the 100 % target will be applicable?

5 Discussion of the modelling framework

The time resolution of the presented work is on hourly level. To capture all variations of load and generation, especially from PV, the time resolution would benefit from being closer to 15 or even 1 minute. This can be seen in for example de Baetens et al. [12] who use a 1-minute time resolution to investigate the impact on grid-feeder level of the operation of a ZEB, but where investment decisions are taken as input. Salom et al. [11] investigate measurements of three ZEBs, showing that using sub-hourly data is preferred to hourly data when evaluating grid impact of a household, as the stochasticity of the load leads to high fluctuation for the imported electricity values which is not captured in the hourly data. However, on a building or cluster level, hourly values are adequate to make reliable conclusions on the correlation between import and export of electricity [10]. This assumption is also confirmed by [43] where a smoothening effect on the short-term variability of PV power output was identified at an aggregated level.

In the present work, when investigating investment decisions in ZEBs, a more detailed time resolution of 15 min would increase the number of binary variables from 8760 to 35 040 multiplied by the number of available technologies within the model. Thus, it seems adequate to make the investment decision based on an hourly time resolution, however when investigating the real operation of one single building, sub-hourly values would be preferred.

As temperatures of the heat distribution within the building is not considered in the modelling framework, the feedback of the ST and heat pumps on the heat storage are not considered explicitly. In previous studies of energy investment analysis, the energy storage is often also treated as a single node, see e.g. [25], [44] or [45] . This formulation may however lead to too efficient components in some hours, thus slightly too optimistic, or small, sizes of the considered technologies. A dynamic simulation of operation of a building would definitely need temperatures, but again, as the focus of this work is on the investment decision, it is considered adequate to treat the heat as energy flows and the heat storage tank as a single node.

6 Summary and conclusions

The introduction of the concept nearly ZEB buildings has changed the view on buildings from being passive receivers of power, i.e. consumers, towards becoming active players in the electricity system by both consuming and producing electricity, i.e. prosumers. This development has opened new perceptions on building's energy systems e.g. for combining heat and electricity systems such as PV coupled with heat pumps in a thermal-electric system. When the operation of such buildings is evaluated, the investment decision considering dimensioning and choice of energy technologies should be optimised accordingly. This part has received little attention over the past years.

This paper presents a modelling framework for assessing the cost optimal dimensioning of the energy technology system for a zero energy, or zero emission, building (ZEB) from the building owner's perspective. The framework builds on the definition in the EPBD, and can study any country's specific ZEB definition by adapting e.g. the weighting factors, the ZEB level, and/or the energy market conditions such as feed-in tariffs, investment subsidies, peak load tariffs or other grid tariffs.

The model structure captures the whole lifetime of the building, and is able to take into account altered conditions in future by dividing the lifetime into periods. This is important especially for the weighting factor for electricity (with more renewable energy in the electricity production mix), and for future energy market conditions (such as feed-in-tariffs for PV electricity). The interaction between the different components of the building is optimised each hour throughout a representative year within each period, and the primary energy consumption and carbon emissions throughout the lifetime of the building is calculated.

With semi-continuous variables on investment decisions and hourly operation of the heat technologies, the linear optimisation formulation is able to reflect the dynamics of the building's energy system in a sufficient way. The heat storage is modelled as a single node, thus treated as an energy bucket where heat may be stored or taken out. The hourly loads of heat and electricity are treated as given input. Heat demand includes demand for space heating (both radiators or floor heating system and ventilation heat) and hot tap water, including distribution losses. Electricity demand includes electricity for covering e.g. lighting and electric appliances. This means that the building design, including U-values and dimensioning of ventilation ducts, are treated as given.

The strength of this model is the combined optimisation of investments and operation costs, together with a high level of detail for the component models compared to general energy system models like TIMES, MARKAL and Balmorel. Because of the hourly time resolution, results of electricity import and export from the building are given as hourly time series, which enables investigation of the buildings grid impact. Hourly optimal operation of both heat and electricity system within the building, and the resulting net electricity load profile, will be analysed in detail in coming papers.

The influence of altered weighting factors (carbon emissions, and primary energy indicators), and policy incentives will be investigated in coming papers. For example, how the combination of a ZEB target and a feed-in tariff for PV electricity may lead to unintended outcomes. Thus, the modelling framework facilitates a holistic approach, which enables us to analyse how policies, technology data, ZEB targets and weighting factors affect the energy system design within ZEBs, and consequently their impact on the electricity grid.

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