Cost-optimal energy system design in Zero Energy Buildings with resulting grid impact: A case study of a German multi-family house

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Highlights

- We investigate the optimal energy system design and optimal operation of ZEBs
- Hourly net electricity load characteristics are provided for all ZEB cases analysed
- The most important factors that influence the ZEB's grid impact are identified
- A ZEB heated by natural gas has 45 % higher peak export compared to a ZEB with bio
- Heat pumps are not cost-optimal in ZEBs with the current energy market situation

Abstract

Zero Energy Buildings (ZEBs) are considered as one of the key elements to meet the Energy Strategy of the European Union. This paper investigates cost-optimal solutions for the energy system design in a ZEB and the subsequent grid impact. We use a Mixed Integer Linear (MILP) optimisation model that simultaneously optimises the building's energy system design and the hourly operation. As a ZEB have onsite energy generation to compensate for the energy consumption, it is both importing and exporting electricity. The hourly time resolution identifies the factors that influence this import/export situation, also known as the building's grid impact. An extensive case study of a multi-family house in Germany is performed. The findings show that the energy system design and the grid impact greatly depend on the ZEB definition, the existing policy instruments and on the current energy market conditions. The results indicate that due to the feed-in-tariff for PV, the cost-optimal energy design is fossil fuelled CHP combined with a large PV capacity, which causes large grid impacts. Further, we find that heat pumps are not a cost-optimal choice, even with lower electricity prices or with increased renewables in the electric power system.

Keywords: cost-optimality, mixed-integer linear programming (MILP), zero energy building (ZEB), load profiles, grid impact, self-consumption, policy implications, primary energy factor (PE), CO_2 factor, feed-in tariff (FiT), energy system design

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1 Introduction

In the European Union, buildings are responsible for nearly 40 % of final energy consumption and 36 % of the greenhouse gas emissions [1]. The emissions reflect both *direct emissions,* from the use of gas or oil for heating purposes, and *indirect emissions* through the use of electricity and district heat. The concept of zero energy buildings (ZEB) was introduced in the recast of the Energy Performance of Building's Directive (EPBD) in 2010, to make the buildings a part of the solution to combat GHG emissions and increase security of supply, by incentivising local energy production as well as energy efficiency.

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 [1]. 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. This paper, aims to identify which factors that determines the grid impact of ZEB buildings, i.e. how they interact with the electricity grid.

1.1.1 Definition of ZEB buildings

According to the EPBD each member state must develop a definition of the 'nearly zero energy building', including a ZEB methodology, and how 'near' zero the ZEB target should be. Even though the definition can be set individually, the framework of how to calculate the energy balance is given by the EPBD [2] as follows (see Eq.(1)): the weighted annual energy imports to the building, subtracted the annual weighted energy exports from the building, summed over all energy carriers, *i*. The weighting is done by use of weighting factors *f*, which are unique for each energy carrier. Using primary energy factors, lead to a Zero *Energy* Building (ZEB), whereas using CO_2 factors lead to a Zero *Emission* Building or Zero *Carbon* Building (ZCB). However, in the following, whenever using ZEB, it embraces both ZEB and ZCB.

$$\sum_i f_i \cdot \text{imported}_i - \sum_i f_i \cdot \text{exported}_i = G \tag{1}$$

When the balance is strictly zero ($G = 0$), the building is a 'strictly' ZEB. To fulfil the target of a strictly ZEB can be challenging as the weighted on-site energy generation must equalize the weighted energy consumption of the building[1]. The target is fulfilled by reducing the consumption through energy efficiency measures, and/or applying on-site electricity generation [3]. However, it is also possible to relax the strictly zero target by letting $G > 0$, heading for a 'nearly' ZEB. Thus, maybe the most important element of the ZEB definition is determining the level of ZEB.

Another element of the ZEB definition is what energy consumption to include in the energy balance. For example, some claim that energy used for elevators or equipment, such as computers or IT-servers, are dependent on the user and should not be a part of the energy balance of the building [4]. While others claim that not only all the energy consumed by the building, but also embodied energy of the materials and construction of the building should be included [5].

Summed up, the definition of ZEB that each member state is free to decide, has the following elements:

1) the *metric* of the weighting factor (primary energy or CO_2)
2) the *value* of the weighting factors (see examples in Table 4)
3) the *level* of ZEB ('strictly' or 'nearly' ZEB)
4) what *energy consumption* is included (partly operational, all operational, or all operational & embodied)

Previous work in Lindberg et al. [6] show that when applying the ZEB target on a Norwegian building it mainly affects the energy imports for heat because the electric specific demand of the building (i.e. electric equipment and lighting), cannot be replaced by other energy carriers than electricity. This is confirmed in Noris et al. [7] which shows that the weighting factors influence the preferred heat technology choice. In many European countries, bio energy has the lowest weighting factor because of its renewable status, thus making a bio boiler the preferred heat technology choice [7]. As an example, when using the European primary energy factors [2], the weighted energy imports for heating is reduced by a ratio[2] of 13 if using a bio boiler rather than a heat pump.

1.1.2 ZEB's grid impact

The on-site energy generation in ZEBs often tend to be large PV installations, which is confirmed by several case studies in e.g. [7]–[12], even though the technology choices may also comprise solar thermal (ST) modules, micro-wind turbines or micro-CHPs. However, building integrated micro wind turbines have challenges with noise and vibrations [13], and a ZEB with CHP still needs to compensate for the gas

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[1] It can be shown that calculating the balance by weighted energy consumed and generated rather than weighted imported and exported from the building, gives the same answer for the energy balance, *G*.

[2] With values from Table 2 and Table 4: (heat from HP) / (heat from BB) = $(PE_{electricity} / COP_{HP}) / (PE_{bio} / \eta_{BB})$ =12,6.

imports. Solar thermal can provide heat in summer time, but cannot contribute to the energy exports from the building unless it is attached to a district heating grid.

One of the challenges of ZEBs in northern European countries is that heat demand occurs in winter when PV generation is low, thereby making the building importing energy in winter both for heat and electricity demand. To fulfil the zero energy balance of the ZEB building, the electric power system must serve as a seasonal storage that is 'charged' in summer and 'depleted' in winter. This is also known as the seasonal 'mismatch' problem [14]. As electricity needs to be consumed the instance it is produced, there has to be enough electricity demand in the rest of the power system, which can utilize the exported electricity from ZEBs in summer. Likewise, the power system must be able to provide the ZEB buildings with electricity in winter.

Hourly or instantaneous 'mismatch' is another challenge of the ZEBs. Due to the often large PV installations of ZEB buildings, grid challenges, such as over-voltages, may occur in summer when many ZEBs are located within a geographically small area [15]. To ease the mismatch problems of the individual ZEB buildings, research on local energy systems for small areas are emerging (see e.g. [16]–[18]). The idea is to exploit the characteristics of different energy sources and technologies, e.g. PVs, micro-CHPs and micro-wind, with the different energy demand profiles, e.g. service buildings and residential buildings, and additionally applying smart control on top of it all. Having a local energy system perspective rather than a building perspective [17], showed that the seasonal mismatch problems of the local area can be reduced, even though the mismatch problems of the buildings are unchanged.

As the focus in this paper is on a building level, the identified grid challenges of ZEBs are attached to both the seasonal and hourly mismatch problems. It is of vital importance to communicate where policy makers can contribute to ease the grid challenges, but still being able to fulfil the ZEB target given by the EPBD. This paper identifies how the definition of ZEBs and the current energy market conditions and taxes impact the grid challenges of ZEBs. In the literature, the grid challenges are analysed by using several grid indicators (see Salom et al. [8] for a thorough explanation). In this paper, we focus on the graphical presentation of the *net electricity load profiles*, as they show the building's maximum import and export values and annual electricity exports in an informative way. The self-consumption rate and additional grid connection capacity (GM values) are also presented.

1.1.3 The aim of this study

The aim of this study is to identify the most important factors that affect the ZEB's grid impact. A case study of a German multi-family house (MFH) is performed, where several input parameters are varied, regarding both energy market conditions and the definition of ZEB. We use a mixed-integer optimisation model, which is introduced and described in Lindberg et al. [6], hence only a brief introduction of the model concept is given in this paper. To the authors' knowledge, only Milan et al. [9] presents a similar model on a building scale. The model introduced in Lindberg et al. improves Milan's model in two ways; 1) by applying binary variables on the investment decision and hourly heat generation, making it a mixed-integer linear optimization problem (MILP), and 2) expanding the implemented number of energy technologies, including the sizing of the heat storage. Ten different energy technologies are implemented, and the model finds the optimal mix and size that minimises total discounted costs over the lifetime of the building. Through the model's hourly time-resolution, the cost-optimal hourly operation is also undertaken, enabling investigation of the hourly electricity import and export from the building.

Based on the case study, we show that the most important factors that influence the building's net electric load profile are: 1) how 'near' zero the ZEB target is, and 2) the choice of heat technology, which is influenced by the value of the weighting factors, technology costs, energy prices, and policy instruments (investment support schemes, feed-in-tariffs, taxes).

1.1.4 Paper structure

Section 2 introduces the case study and presents the cost-optimisation model and input parameters. Section 3 shows the results of the German MFH while applying a 'nearly' ZEB target, a 'strictly' ZEB target, and for comparison, a case without any ZEB target. In Section 4, sensitivity analysis are performed, investigating how future market conditions may influence the energy system design and the grid impact. Section 5 provides general discussion of selected results, before making final conclusions in Section 6.

2 Case study: Multi-family house

A case study of a simulated multi-family-house (MFH) located within the area of Berlin in Germany is performed. The building is a representative new MFH according to German statistics and is assumed to have 10 apartments and a total heated area of 1000 m^2. The architectural design and building physics are treated as given, and fulfils the passive standard. The energy technologies implemented in the model are chosen according to the available energy carriers in the region. The total system scheme, including the implemented energy technologies, is shown in Figure 1.

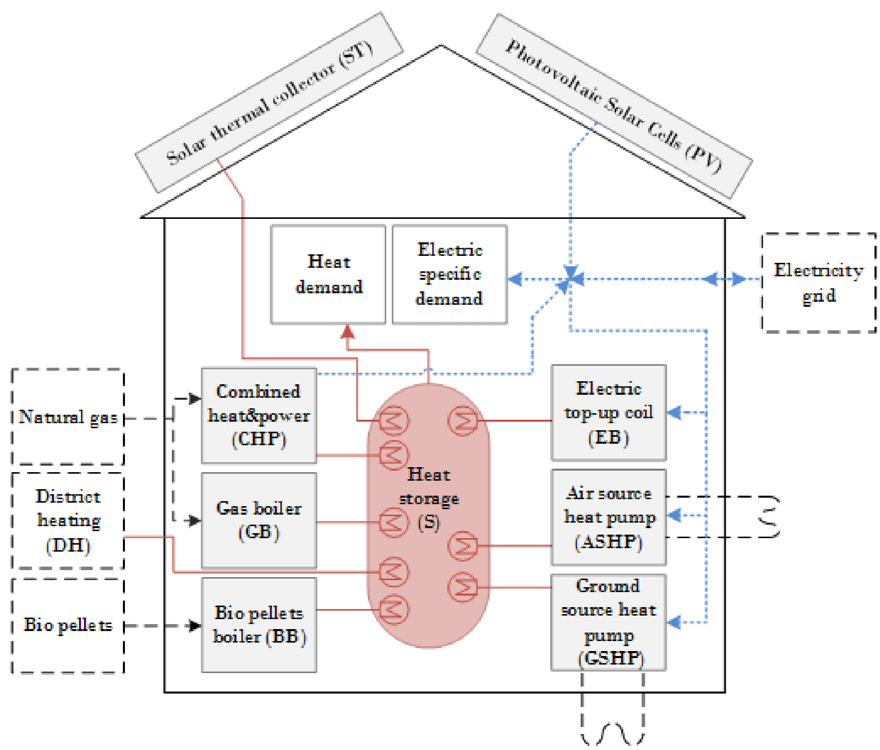


Figure 1 System scheme and energy flows of the building.

The ZEB target is in this case study defined to include operational energy consumption, i.e. embodied energy is not taken into account. Even though the target is set on an annual basis, the energy consumed and generated are calculated each hour, making the building importing electricity in some hours, and exporting electricity in other hours.

The inputs to the model described in Section 2.2 are fitted to the climatic conditions and energy market conditions for the region of Berlin. This especially affects the heat demand of the building, the hourly COP of the heat pumps, the energy generation from ST and PV panels, and the feed-in-tariffs of electricity from PV and CHP. The lifetime of the building is set to 40 years, and the calculations are done with a discount rate of 4 %.

2.1 Cost optimisation model - in brief

This section briefly describes the cost optimisation model which is implemented in MOSEL Xpress [19]. For an in-depth description, see Lindberg et al. [6].

Figure 2 illustrates the basic idea of the model, where total costs are minimised, based on inputs of technology costs, prices and the building's energy demand. Hence, the optimal investments and operation of the building are decided simultaneously. The main outputs are capacity sizes of the chosen energy technologies, together with their hourly fuel consumption. Accordingly, the building's hourly net electric load profile is found, which forms the basis for analysing the grid impact.

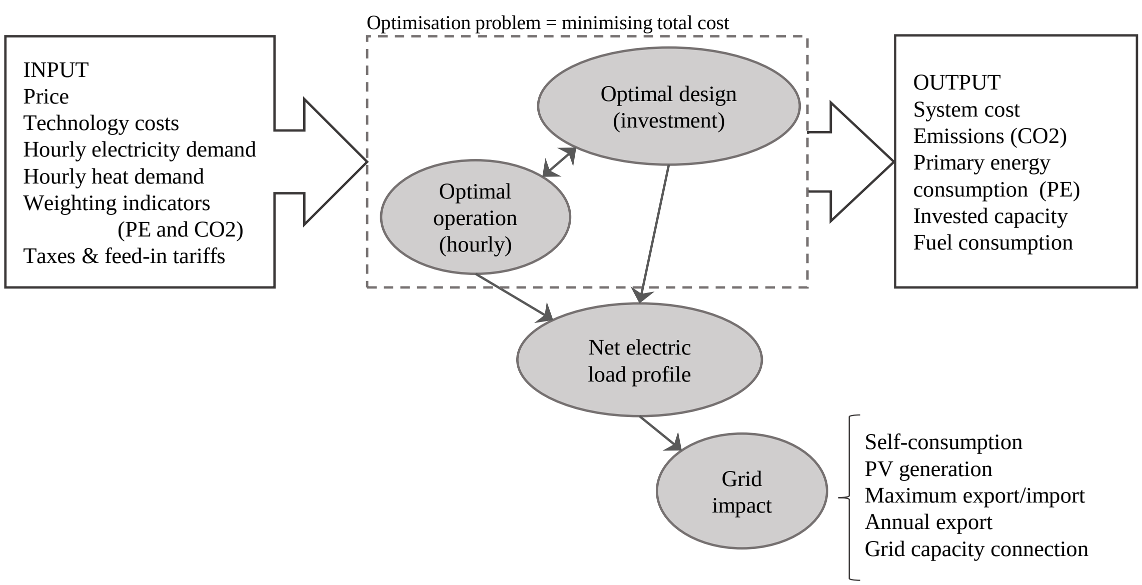


Figure 2 Model description with main inputs and outputs. Grid impacts are consequences of the optimal design and operation.

The objective function π represents the net present value of the total costs of the energy system within the building, which depends on the installed capacity, x, of each energy technology i. The discounted investment costs, C^{inv}, consist of reinvestments throughout the entire lifetime of the building, N, minus its salvage value at the end of the lifetime. C^{run} is the sum of fixed maintenance costs and variable fuel costs. The discounted net present value of the total operational costs equals the annual operational costs multiplied by the net present factor, ρ. The annual fuel costs are calculated each hour throughout one representative year within each period. The building's energy system must fulfil equality $\mathbf{h}(\mathbf{x})$, and inequality $\mathbf{g}(\mathbf{x})$, constraints dependent on the installed capacity for all the energy technologies, forming the vector $\mathbf{x}$.

$$\begin{aligned} &\min\ \pi = \sum_{i \in I} C_i^{\mathrm{inv}}(x_i) + \rho \cdot C_i^{\mathrm{run}}(x_i) \qquad , \quad \text{where} \ \ \rho = \sum_{\tau=1}^{N} \frac{1}{(1+r)^{\tau-1}} \\ &\text{s.t.} \ \ \mathbf{h}(\mathbf{x}) = 0 \\ &\qquad \mathbf{g}(\mathbf{x}) \le 0 \end{aligned} \tag{2}$$

The electricity balances of the building, given in Eq.(3)-(6), are influenced by the special electricity tariffs in Germany (see Section 2.3.2). As described graphically in Figure 3, the tariff structure makes it necessary to keep the flows of self-consumed electricity $\left(y_{i,t}^{\mathrm{selfcD}}, y_{i,t}^{\mathrm{selfcHP}}\right)$, exported electricity $\left(y_{i,t}^{\mathrm{exp}}\right)$ and imported electricity $\left(y_{i,t}^{\mathrm{impD}}, y_{i,t}^{\mathrm{impHP}}\right)$ separate. Notice that the building's electricity consumption includes both the electric specific demand of the building, D_t^{el}, and the electricity consumed by the electric boiler, $d_{\mathrm{EB},t}$, and the heat pumps, $d_{\mathrm{ASHP},t}, d_{\mathrm{GSHP},t}$.

Building: $$D_t^{\mathrm{el}} + d_{\mathrm{EB},t} = y_{\mathrm{PV},t}^{\mathrm{selfcD}} + y_{\mathrm{CHP},t}^{\mathrm{selfcD}} + y_t^{\mathrm{impD}} \qquad \forall\, t \tag{3}$$

Heat pump: $$d_{\mathrm{ASHP},t} + d_{\mathrm{GSHP},t} = y_{\mathrm{PV},t}^{\mathrm{selfcHP}} + y_t^{\mathrm{impHP}} \qquad \forall\, t \tag{4}$$

PV: $$y_{\mathrm{PV},t} = y_{\mathrm{PV},t}^{\mathrm{exp}} + \left(y_{\mathrm{PV},t}^{\mathrm{selfcD}} + y_{\mathrm{PV},t}^{\mathrm{selfcHP}}\right) \qquad \forall\, t \tag{5}$$

CHP: $$y_{\mathrm{CHP},t} = y_{\mathrm{CHP},t}^{\mathrm{exp}} + y_{\mathrm{CHP},t}^{\mathrm{selfcD}} \qquad \forall\, t \tag{6}$$

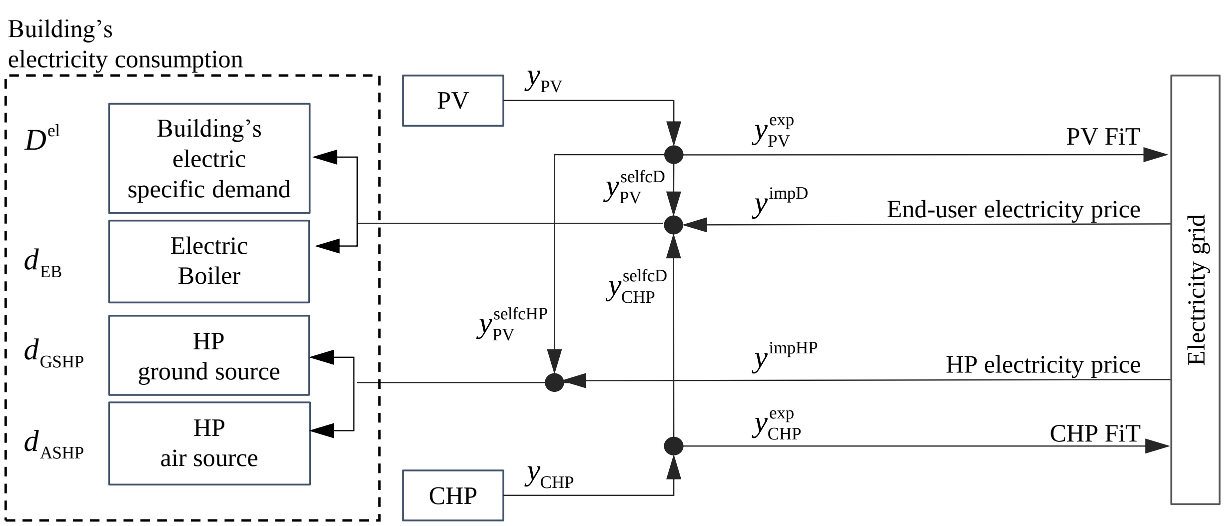


Figure 3 Detailed graphical explanation of the electricity flows in Figure 1, together with their electricity price or export value.

The net electric load profile of the building, ne_t , is equal to the electricity imported subtracted the electricity exported from the building to the grid, as presented in Eq. (7), and illustrated in Figure 3.

$$\begin{aligned} \mathrm{ne}_t &= \text{electricity import } (t) - \text{electricity export } (t) \\ &= \left(y_t^{\mathrm{impD}} + y_t^{\mathrm{impHP}} \right) - \left(y_t^{\mathrm{PVexp}} + y_t^{\mathrm{CHPexp}} \right) \end{aligned} \quad (7)$$

2.2 Input parameters of the energy technology models

This section presents the input parameters of the energy technologies, and for determining the load profiles of heat and electricity demand.

2.2.1 Building's energy demand

Hourly energy loads are constructed using SynPro, a bottom-up model where stochastic behaviour of the occupants is linked to the stock of electric appliances [20]. First the electricity load and domestic hot water load (DHW) is determined based on stochastic behaviour of the residents sampled from the German time-of-use-survey [21], and secondly, the electricity load is set as internal gains when determining the space heat demand calculated for climatic conditions of Potsdam for 2012 [22]. The U-values of the building envelope are set according to the German passive building standard. The resulting annual heat demand (sum of space heating and DHW) and electric specific demand are respectively 28 MWh/yr and 33 MWh/yr. The maximum hourly peak demand is 23 kW and 13 kW, for heat and electricity respectively.

2.2.2 Hourly COP for air source and ground source heat pumps

The heat pump models for air source heat pump (ASHP) and ground source heat pump (GSHP) take the supply temperature into account. The heating curve used to determine the supply temperature for space heating is shown in Figure 4, and the average supply temperature of the DHW is assumed to be 55°C. Together with the COP models presented in [6], and the heat demand determined in Section 2.2.1, the hourly COPs for 2012 for Potsdam are found (see Figure 5).

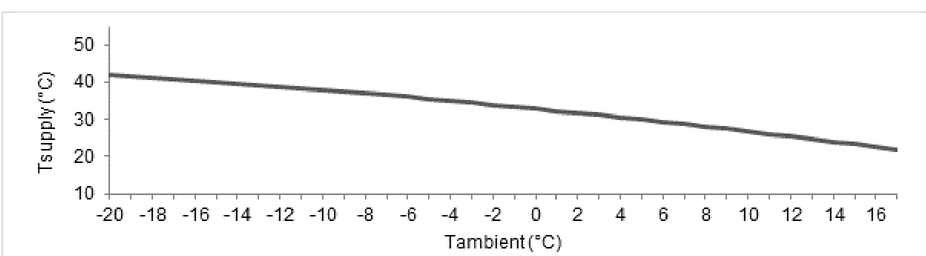


Figure 4 Heating curve. Supply temperature for space heating vs. outdoor temperature.

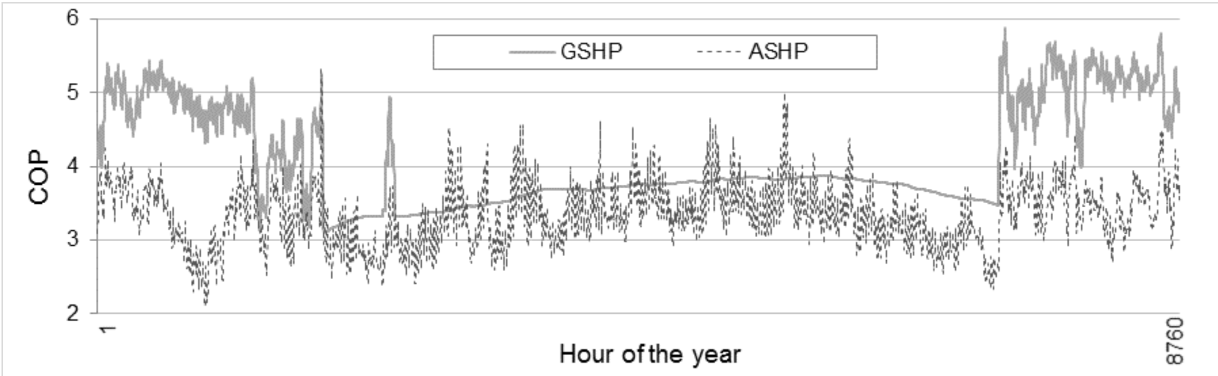


Figure 5 Hourly COP of ground source heat pump (GSHP) and air source heat pump (ASHP) with climatic data for Berlin, Germany in 2012.

2.2.3 Investment cost of heat storage in energy terms

The heat storage is formulated as a single node, serving both DHW and SH demand. As the cost of the accumulator tank is determined by the volume, given in EUR/liter, the temperatures in the storage is needed to obtain the cost per heat capacity in EUR/kWh. The conversion factor ε is found by multiplying the ΔT of the storage tank by the specific volume, ν, density ρ_{water}, and heat capacity Cp, of water as shown in Eq. (8).

$$\varepsilon = \nu \cdot \rho_{\text{water}} \cdot \text{Cp} \cdot \Delta T \qquad [\text{kWh/ltr}] \tag{8}$$

Hedegaard and Balyk [23], uses a ΔT of 15°C, and argues that this does not reflect the real ΔT of the storage, but rather how much energy that is available for being utilised by the model. In this case study, we assume the ΔT to be 30°C, reflecting an average maximum temperature of 60°C, and an average minimum temperature of 30°C.

2.2.4 Solar thermal efficiency

The model of the solar thermal collector (ST) presented in [6], takes the temperature of the water from the collector, $T^{\text{collector}}$, into account. The ST heat is often supplied to the bottom of the storage tank, and thus the collector temperature is assumed equal to the lower temperature of the storage, 30°C. In real life, dependent on the control of the system, the temperature from the ST will vary every hour and might reach up to 90°C in summer. However, a higher value of $T^{\text{collector}}$ decreases module efficiency, and the assumption of 30°C gives an optimistic value for the efficiency of the ST collector. When investigating the results in Section 3, ST is not found as an economic optimal technology choice, even with the higher efficiency, indicating that the 30°C collector temperature is not a limiting factor of the model.

2.2.5 Available roof and façade area

The findings of the case studies in Noris et.al. [7] show that the available façade and roof area for installation of ST or PV might be a limiting factor in order to reach the ZEB balance. However, as the main intention of this paper is to analyse the ZEBs if everything is possible, it is decided to let the available façade and roof area be without limitations.

2.3 Technology costs and energy prices

This section presents the costs and efficiencies of the energy technologies implemented. The energy market conditions for Germany is presented through fuel prices, and special electricity tariffs.

2.3.1 Technology costs and efficiencies

A newly built house needs to install energy technologies at the time of construction which fits to its demand. As the specific technology costs (EUR/kW) are assumed constant, they must be collected for the appropriate size of the building in question [6]. In this paper, investment costs are collected for heat technology sizes of 5-10 kW to fit the heat demand found in Section 2.2.1. The minimum capacity of the boilers, if invested, is set to 5 kW_{th}, which equals 3,2 kW_{el} for the CHP.

Table 1 Specific investment costs (EUR/kW), and annual operation and maintenance cost (%) and fixed investment costs (EUR) for technology sizes of 5-10 kW.

	Specific investment cost		**Fixed annual O&M costs**	**Fixed investment cost**		**Refe-rence**
	EUR/kW_{th}	Description	(% of inv.costs)	EUR	Description	
PV	1 800	Module cost (per kWp)	1,0 %	1 000	Mounting and installation	[24]
ST – Solar thermal collector	570	Module cost (per m^2)	1,0 %	4 000	Mounting and installation	[25]
GSHP – Heat pump (liq-water)	770	Unit cost	2,0 %	17 000	Drilling of well, installation and engineering costs	[25]
ASHP – Heat pump (air-water)	1 150	Unit cost	2,0 %	3 000	Mounting and installation	[25], [26]
BB – Bio pellets boiler	610	Unit cost	3,0 %	4 000	Storage/Silo with automatic feeder	[25]
EB – Electric top-up coil	60	Unit cost	2,0 %			[25]
DH – District heating	80	Grid connection	0 %	4 000	Connection to district heating grid	[25], [26]
GB – Gas boiler	600	Unit cost	1,5 %	1 600	Connection to gas grid	[26]
CHP – Combined Heat & Power	3 400	Unit cost (per kW_{el})	3,0 %	1 600	Connection to gas grid (not active if GB already invested)	[25], [26]
AT – Hot water storage	90	Unit cost (EUR/kWh)	0 %			[25]

The efficiencies of the energy technologies are given in Table 2, where the calculated seasonal average COP is based on the hourly COP in Figure 5. The CHP has a constant relationship between the electricity and heat efficiency, so if 1 kWh heat is needed, the unit simultaneously generates 0,63 kWh electricity. The last row of the table shows the hour-by-hour dispersion factor of the heat storage which is not the same as the seasonal average efficiency of the storage.

Table 2 Technology efficiencies.

	Efficiency [-]	**Comment**	**Reference**
ASHP – Heat pump (air-water)	3,28	Simulated SCOP	
GSHP – Heat pump (liq-water)	4,45	Simulated SCOP	
BB – Bio pellets boiler	0,90		[27]
EB – Electric top-up	0,98		[28]
DH – District heating	0,98		
GB – Gas boiler	0,96		[29]
CHP – Electric Efficiency	0,33		[29] [30]
CHP – Heat Efficiency	0,52		[29]
AT – Hot water storage	0,99		

2.3.2 Electricity tariffs

In Germany, the feed-in tariff (FiT) for roof mounted PV up to 500 kW is about 11 ct/kWh [31], and the FiT for highly energy efficient CHPs, regardless of fuel, is 5,4 ct/kWh [32]. Currently, the FiT for PV is being replaced by a market premium model, depending on the actual price of electricity in the EEX-market each hour instead of a fixed feed-in. Even though the income varies from hour to hour, the overall income for the building owner should be more or less unchanged [33]. Therefore, for simplicity reasons, the selling price of PV electricity, is set equal to the FiTPV which is constant for all hours. Due to the current resistance to the EEG-tax in Germany, on-site electricity generation directly self-consumed by the building must pay 30 % of the EEG-tax, which equals 1,85 ct/kWh [33].

2.3.3 Fuel prices

Representative fuel prices are based on current offered contracts in Germany. The contracts for fuels attached to a distribution grid have a fixed annual charge and a specific energy charge, as shown in Table 3. Notice that the price for electricity used for heat pumps is 5 ct/kWh lower compared to the general electricity price [34].

Table 3 Fuel prices for end-users. Energy prices [EURcent/kWh] and fixed annual grid charges [EUR/yr]

Energy carrier	Category	**Energy price** cent/kWh	**Fixed annual charge** EUR/yr	**Reference**
Bio pellets		6,0		[35]
GAS	Gas distribution grid	5,5	170	[36]
DH	District heating grid	7,2	327	[37]
EL	Import price from electricity grid	24,1	140	[38] [34]
EL	Import price HP electricity	19,0		[34]
EL	Export price PV electr (FiTPV)	10,8		[31] [34]
EL	Export price CHP electr (PiTCHP)	5,4		[32] [34]
EL	Self-consumption (30 % of EEG-tax)	1,9		[33]

2.4 Weighting factors – PE and CO_2

Table 4 shows weighting factors used for calculating the ZEB balance. The CO_2 factors are according to IEA [39], and primary energy factors are according to the EPBD. The *non-renewable* primary energy factors (PEnr) reflect the amount of non-renewable energy required to attain 1 kWh of the respective energy carrier, whereas the *total* primary energy factors (PEtot) reflect the total use of energy, both renewable, fossil and nuclear, per kWh. Comparing PEnr and PEtot, the major difference occur for bioenergy which increases by 1. Another alternative of the PE factor is to apply asymmetric factors to electricity, which value exported electricity less than imported electricity, in order to increase the incentive for self-consuming on-site generated electricity.

Table 4 Weighting factors (Primary Energy [2] , and CO_2 [39]).

	CO_2	**Primary Energy (PE)**			
		Non-renewable PE		**Total PE**	
	CO_2	**PEnr-sym**	***PEnr-asym***	**PEtot-sym**	***PEtot-asym***
Metric (unit of measure)	$g_{CO2\text{-}eq.}$/kWh	$kWh_{PEn.r.}$/kWh	*$kWh_{PEn.r.}$/kWh*	kWh_{PEtot}/kWh	*kWh_{PEtot}/kWh*
Power grid, import	350	2,3	*2,3*	2,5	*2,5*
Power grid, export	350	2,3	*2,0*	2,5	*2,0*

Wood, pellets	14	0,05	*0,05*	1,05	*1,05*
District heat	270[3]	1,3	*1,3*	1,3	*1,3*
Natural gas	210	1,05	*1,05*	1,05	*1,05*

3 Results

In the Introduction, four elements of the ZEB definition was identified. As it is already defined that all consumed energy is included in the ZEB balance, the first three of these four elements are investigated in the following; i.e. 1) the metric of the weighting factors, 2) the value of the weighting factors, and 3) the level of ZEB. The first sub-section investigates the impact on the energy system design of the building, and the second sub-section analyses the corresponding grid impact.

3.1 Energy system design

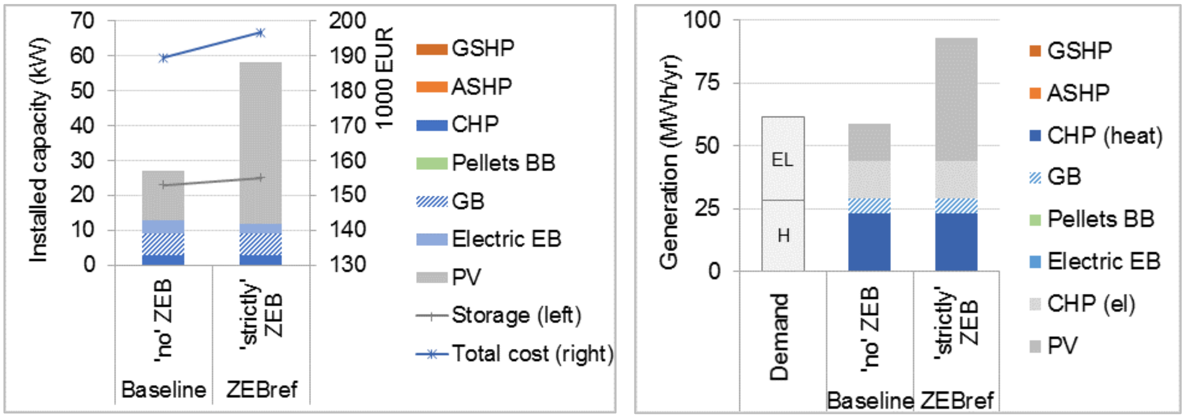
3.1.1 Baseline - no ZEB target

For comparison, we first investigate which solution people would choose if only minimising costs without posing the ZEB restriction. Figure 6 shows that the most economic way to serve the passive building with energy, is to install a micro CHP unit of 3,5 kW_{el} which provides both heat and electricity. To cover peak heat demand, a gas boiler, an electric top-up coil and a heat storage are installed. In addition, it is profitable to invest in 14 kWp of PV, both because of the FiTPV of 11 ct/kWh, and the saved costs of imported electricity due to self-consumed PV. Since the roof area of the building is not restricted, this is an inner optimum. Even without the FiTPV, it is profitable to invest in 7 kWp PV. This supports the claim that PVs have reached grid-parity in Germany.

3.1.2 'Strictly' ZEB

When the building is to be strictly ZEB, all energy consumed by the building has to be compensated by on-site energy generation. Figure 6 shows the investment decision when using the CO_2 factors given in Table 4. CHP is still the most economic way of serving the building with heat and electricity, despite its high investment cost. There are two reasons for this. First, the alternative cost of electricity for the building owner at 24 ct/kWh, is far above the gas price at 5,5 ct/kWh. As the CHP unit generates both 0,55 units of heat and 0,33 units of electricity from the same gas unit, the self-generated electricity from the CHP is highly valued. Secondly, the feed-in tariff for PV compensates for much of the investment cost of the PV, and thus, reaching the annual net zero balance is met by adding more PV as it constitutes little additional cost for the building owner. This is confirmed in Figure 6a where the total cost of the 'strictly' ZEB only increases by 2-4 % compared to *Baseline*. This means that it is profitable to invest in more PV (46 kWp) to compensate for the weighted energy imports from using natural gas, rather than reducing the weighted imports to the heat generation itself.

[3] Based on a conversion factor of 200 g_{CO2} / kWh_{PE} for district heating obtained from [46].



a) b)

Figure 6 Installed capacity (kW) (a) and annual energy generation (MWh/yr) (b) of a 'strictly' ZEB compared to a Baseline case without any ZEB target.

The annual energy generated from each of the technologies is shown in Figure 6b, where the CHP unit provides 79 % of the heat demand and the gas boiler 20 %. The electric top-up coil only contributes with 1 % to cover peak heat demand and is hardly visible in the graph. The installed capacity of the PV is 46 kWp for *'strictly'ZEB* case which equals an area of approximately 250 m^2 if using a conversion factor of 5,3 m^2/kWp[4]. Compared to the size of the multi-family house of 1000 m^2, this could be physically possible with an adapted architectural design.

If using the primary energy factors given in Table 4, instead of the CO_2 weighting factors, the energy system design remains the same. The only difference when changing the weighting factors is the PV size, which is determined by the relationship between the weighting factor of electricity export and natural gas import, given in Table 8. Readers who are interested in the details of these findings, please see Appendix. Hence, we can conclude that whether the ZEB is a Zero Emission or a Zero Energy Building does not impact the heat technology choice.

When the FiTPV is applied together with the ZEB target, it makes the fossil based heat technology choice remain unchanged. Due to the FiTPV the ZEB target is met by adding more PV to the building, rather than reducing the weighted energy imports for heating purposes, by switching to renewable heating, and this is done without increasing the cost for the building owner significantly.

3.1.3 'Nearly' ZEB

The ambition level of the ZEB reflects how 'near' to zero the ZEB target is set. Figure 7 shows the investment results of a 50 % nearly ZEB target when using CO_2 factors. Compared to *Baseline*, the only difference is found in the size of the PV which is doubled from 14 to 30 kWp. Notice also that the self-consumption starts at 80 % in *Baseline* and decreases towards 40 % in the *'strictly'ZEB* case. This logically reflects that the more PV that is installed, the smaller amount of the generated PV electricity the building is able to consume itself.

[4] This reflects a relatively high module capacity of 300 Wp, which normally has an area of 1,6 m^2.

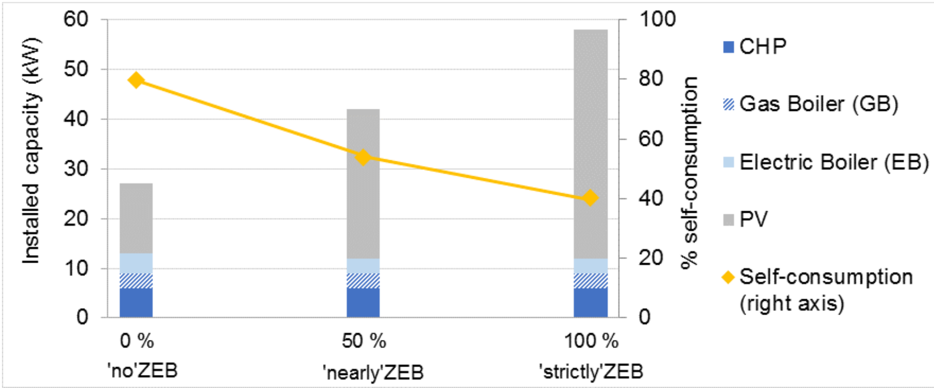


Figure 7 Installed capacity (kW) of a ‘nearly’ ZEB case. Relaxing the ZEB constraint.

As a conclusion, when relaxing the ZEB target aiming at a ‘nearly’ ZEB, the size of the weighted energy imports remains unchanged, meaning that the building is still very energy efficient. However, a ‘nearly’ ZEB will claim a smaller amount of weighted energy exports, leading to a smaller PV size, which is important for the grid impact (see Section 4.2).

3.2 Grid impact

The hourly operation of the building is necessary for understanding its net electric load profile. This section first investigates the hourly optimal operation of the energy system of the *‘strictly’ZEB*, which lies the basis for understanding the net electric load characteristics of the building.

3.2.1 Hourly load characteristics of the ‘strictly’ ZEB

The hourly operation of the building is best seen by investigating the heat and electricity balances in parallel. In the following, three consecutive days in summer are analysed. Figure 8 and Figure 9 show the hourly operation of the building of heat and electricity balances respectively. The black solid lines indicate the hourly heat or electricity demand of the building, which are inputs to the model.

The heat generation in Figure 8 shows that during daytime, the CHP is only run if the heat storage is empty, and never such that CHP electricity is exported to the grid. This is because the marginal cost of operating the CHP and the heat storage is higher than the income of selling CHP electricity for export. When the sun sets and the PV no longer generates electricity (see Figure 9), the CHP unit is run such that it covers the heat demand and fills up the heat storage, provided that its electricity generation does not exceed the electricity consumption of the building.

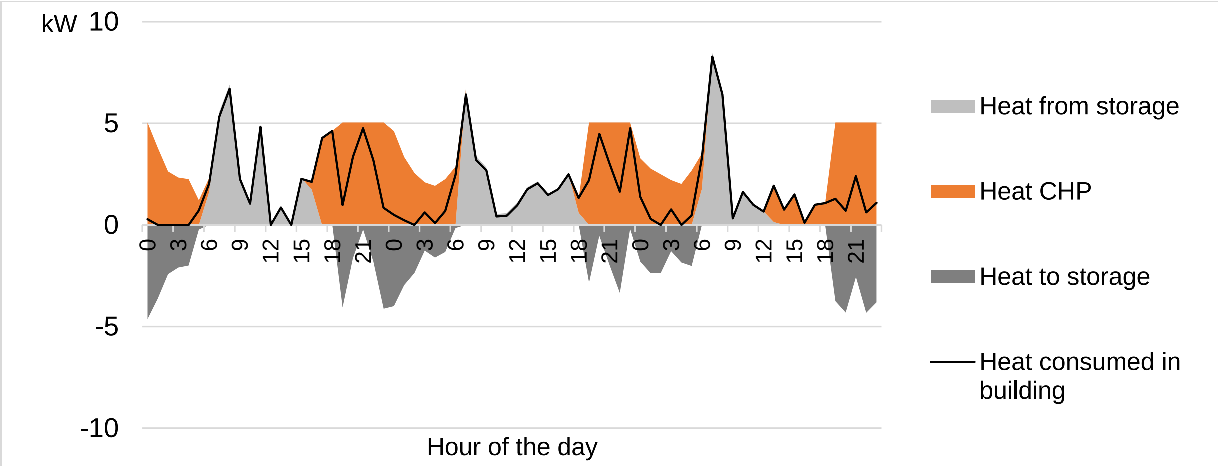


Figure 8 Hourly heat generation (kWh/hr) for the *'strictly'ZEB* with CHP, for three days in August (Tuesday – Thursday).

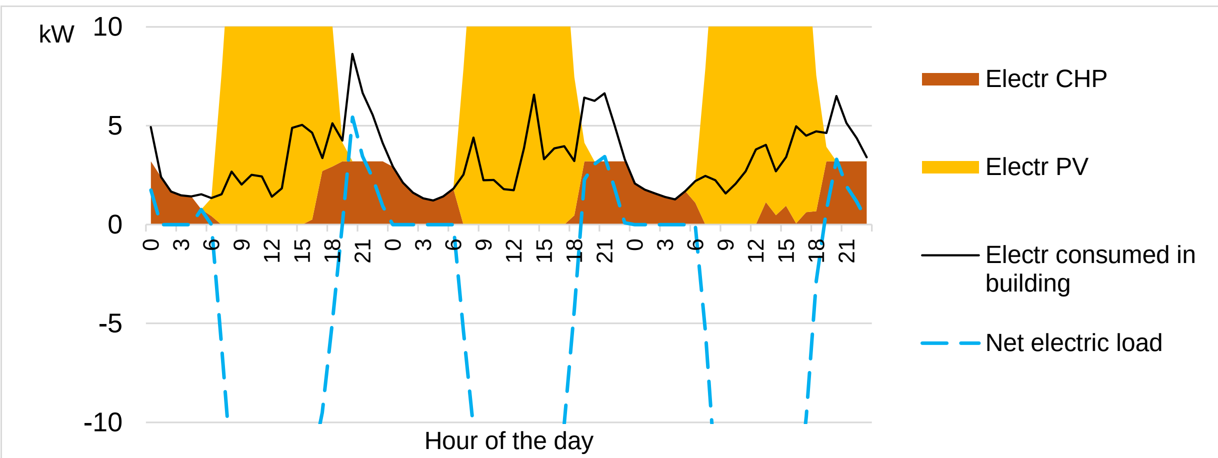


Figure 9 Hourly electricity generation (kWh/hr) for the *'strictly'ZEB* with CHP, for three days in August (Tuesday – Thursday). (Notice that the peak values of PV electricity generation and net electric load exceed the borders of the graph).

The net electric load of the building is the blue dashed line in Figure 9, which shows that electricity is exported during daytime, reaching maximum values of up to 31,3 kW. In the evening, even though the CHP is run at its maximum, it is not able to cover the evening peak electricity demands, and thus the building imports electricity in the late hours from 19hr – 24hr.

On the coldest winter day, when heat demand is high, the CHP is operated at maximum load all 24 hours. The gas boiler (GB) is also run throughout the day, while the electric top-up coil and heat storage is contributing at peak heat hours. As the CHP unit also runs during daytime, its electricity generation is added to the PV generation. On a sunny day in February, this may result in export values up to 30,7 kW because of the relatively low electricity demand of the household during daytime. Consequently, the maximum electricity export from the building in winter is not very different from the one in summer (see also Figure 10).

3.2.2 Comparing grid impact of 'no', 'nearly' and 'strictly' ZEB

When plotted for a whole year, the hourly net electric load profiles for *'strictly'ZEB* (equal to the blue dashed line in Figure 9) becomes like shown in Figure 10. For comparison, the *Baseline* with *'no'ZEB* is also plotted. The positive values indicate electricity imports to the building, and negative values export.

When sorting the hourly net electric load, we obtain load duration curves as shown in Figure 11. In *'no'ZEB*, the installed PV size is 14 kWp, which is doubled to 30 kWp in *'nearly'ZEB*, and more than tripled to 46 kWp in *'strictly'ZEB*. Thus, the largest difference in their net electric load duration curves occurs in the peak export hours, from 9 kW, to 20 kW and 31 kW. The import values, however, are unchanged as the operation of the CHP is not altered. As seen in Table 6, the annual export of electricity is five times higher for the 'strictly' ZEB reference case compared to the Baseline case. Notice that in both cases, the peak export values are lower than the installed PV capacity due to some self-consumption, and to the fact that the PV generation seldom reaches its installed capacity due to inverter efficiency and clouds.

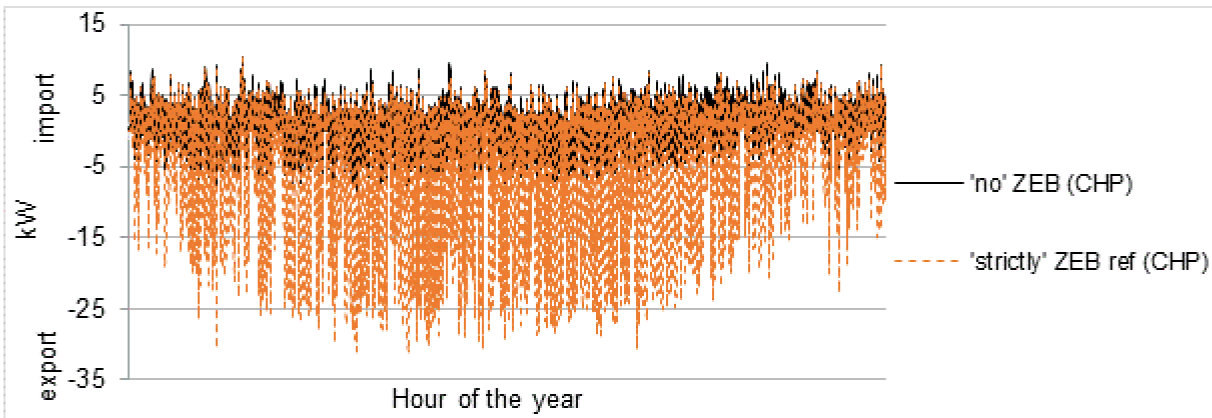


Figure 10 Net electric load profile for baseline ('no' ZEB) and 'strictly' ZEB case, both with CHP serving the base heat load (kWh/hr).

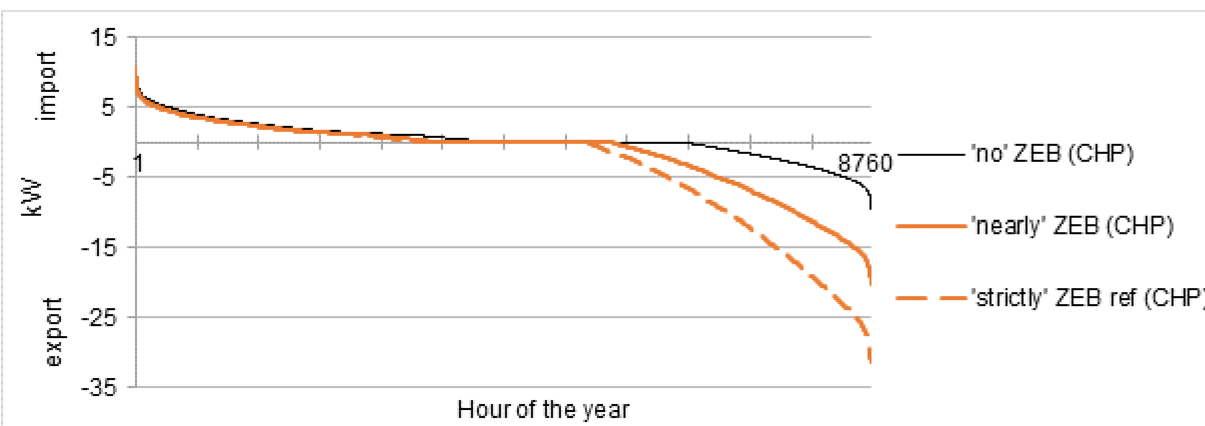


Figure 11 Impact of 'nearly' ZEB on the load duration curves. Comparing Baseline ('no' ZEB) to, 50 % ZEB and 'strictly' ZEB, all with CHP serving the base heat load (kWh/hr).

4 Sensitivity analysis

The first findings show that the optimal technology choice is fossil based, regardless of whether the ZEB target is Zero Emission or Zero Energy, and whether the ZEB level is 'nearly' or 'strictly'. Section 4.1 investigates how changes of future energy market parameters might alter the optimal energy system design towards renewable heating choices of a 'strictly' ZEB. Whereas Section 4.2 analyses how the energy system design affects the building's grid impact. The *'strictly'ZEB* case from Section 3 is in the following denoted as *ZEBref*.

4.1 How robust is the choice of CHP?

When looking into the future, several parameters may change from today's conditions. According to EU's energy and climate policy, EU shall have 80 % renewable energy in their electricity production mix within 2050, which will lower the weighting factor for electricity. Further, the electricity price in the power market is also expected to decrease as the marginal cost of renewable electricity production is close to zero. Further, the political landscape in Europe could change, and if gas imports are restricted, and/or gas demand increases, the gas price might increase. The investigated sensitivities are shown in Table 5.

Table 5 Investigated future gas price, electricity price and electricity weighting factor.

End-user gas price		**End-user electricity price**		**Feed-in-tariff for PV**		**Electricity weighting factor**	
ct/ kWh	comment	ct/ kWh	comment	ct/ kWh	comment	gCO2/ kWh	comment
6,6	+20%	19,0	-21% Equal to HP tariff	11	Today's FiT for PV	210	Equal to natural gas
8,25	+50%	12,0	-50% Halving the price	5,4	Equal to FiT for CHP electricity	170	Halving today's factor.
						130	Average carbon factor of European electricity for the next 60 years, if the target of 90 % reduction within 2050 is reached [4].
		9,6	-60% Similar to end-user prices in Scandinavia.	3,5	No FiT for PV. Export price equal to average EEX power price (2013-2015).	70	80 % reduction of today's factor.

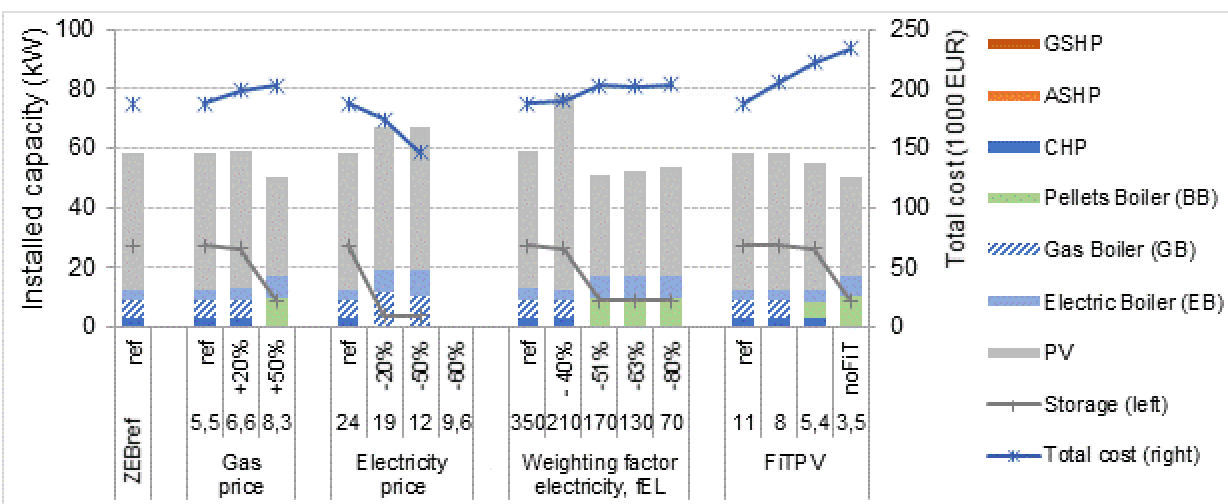


Figure 12 Results of the sensitivity analysis. Influence of higher gas price (ct/kWh), lower electricity price (ct/kWh), reduced weighting factors for electricity (gCO2/kWh) and lower FiT for PV (ct/kWh), on installed capacity (kW) and total discounted cost (1000 EUR).

4.1.1 Higher natural gas price

Figure 12 shows that when the gas price increases by 20 %, the CHP is still a cost optimal choice. Increasing the gas price further, the gas boiler is replaced by a bio pellets boiler. Notice that the PV size is reduced by 31 % because bio energy has a lower weighting factor compared to natural gas, leading to smaller amount of required weighted energy export.

4.1.2 Lower electricity price, P_{EL}

Today's electricity price on the EEX[5] electricity market is about 3-4 ct/kWh, so the main part of the end-user price of 24 ct/kWh consists of taxes. Even though the market price of electricity might decrease, it is still unclear how the end-user price will evolve because it is mainly influenced by policy makers – it might stay constant, or it could decrease towards levels as in Norway and Sweden. Regardless of the actual development, it is of interest to see how the energy system design would be affected by a lower electricity price.

Figure 12 shows that reducing the electricity price from 24 to 19 ct, the electricity generated from the CHP becomes less valuable as the alternative price for electricity from the grid decreases, and thus, the gas boiler is chosen instead of the CHP. Reducing the electricity price further to 12 ct/kWh (also for the HPs), a gas boiler is still the preferred option, but the electric boiler for peak load increases slightly. Reducing the electricity price below the FiTPV to 9,6 cent/kWh, the building gets more paid for PV electricity sold to the grid than what it buys, which is not a realistic option.

The electricity price thus only affects the cost-competitiveness of the CHP. Higher electricity price, the more cost-optimal is the CHP. Lower electricity price leads to the next best heat technology choice, which is GB. Notice that the heat pump is still not a viable option due to its relatively high investment costs, even though the fuel costs are low.

4.1.3 Lower electricity weighting factor, f_{EL}

Reduced CO_2 factor for electricity would intuitively lead to less need of installed on-site energy generation (PVs) as the imported electricity is "greener". However, as the findings in Figure 12 show, the opposite effect occurs. The reason lies in the strictly zero restriction, because not only is the imported electricity less polluted, but the exported electricity also displaces less pollution in the grid. In order to compensate for the unchanged amount of imported natural gas, the amount of exported PV electricity increases as the weighting factor for electricity decreases. Because of the FiTPV, the increased PV size influences total cost little, and the preferred heat technology remains unchanged. However at 130 g/kWh$_{el}$, it is necessary to change towards more renewable heat generation, but the heat pump is still not chosen due to its higher investment and fuel costs compared to the bio boiler.

4.1.4 Reduced FiTPV

If the FiT for PV is reduced, Figure 12 shows that the CHP is still the favoured heat technology however, the peak heat load is covered by a BB instead of a GB. Also notice that the total cost has increased as expected, because of the lower income from the exported PV. When removing the FiT for PV, the building owners may sell their PV electricity in the electricity market, which was about 3-4 ct/kWh in 2012-2015 [40]. Without the FiTPV, the PV installation becomes more expensive and it is necessary to

[5] EEX – European Energy Exchange AG www.eex.com/en/

reduce the emissions from the heat generation, and a BB is chosen for both peak and base load heat demand.

The FiT is introduced to give incentives for the end-user to invest in local energy generation. However, when applied together with the ZEB requirement that demands PV in the first place, the FiTPV leads to lowering the total cost for the building owner. This makes it profitable to use fossil fuels for covering heat demand, at the cost of higher installed PV and consequently higher electricity exports from the building. When reducing or removing the FiTPV, the building’s possibility of reaching the zero balance becomes more expensive, and the fossil fuelled heat generation is replaced by a greener alternative, the bio pellets boiler.

4.1.5 Increased RES in the grid - Combining lower f_{EL} and FiTPV

When more renewable energy sources (RES) are introduced in the electric power system, most likely the FiTPV will decrease along with the weighting factor for electricity (f_{EL}). Hence, three model cases *30%RES*, *50%RES* and *80%RES* are developed by combining the two. Figure 14 shows the results.

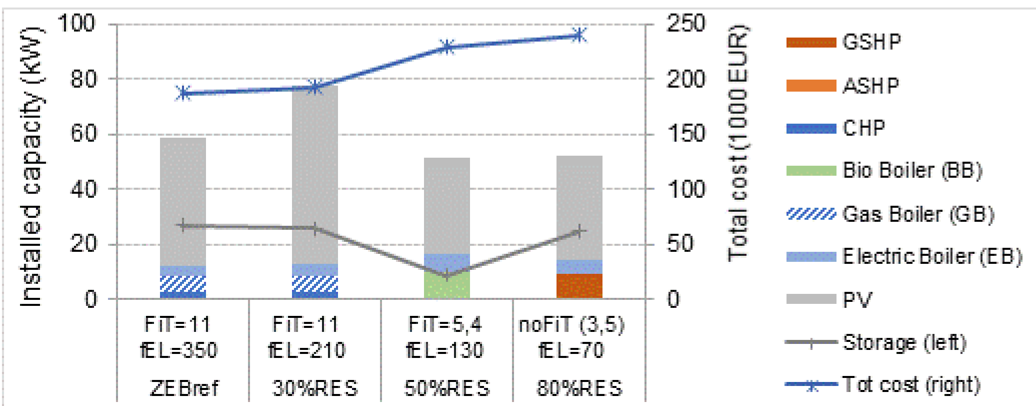


Figure 13 Results of greener electricity production mix. Influence of reduced weighting factors for electricity (gCO2/kWh), combined with lower FiT for PV (ct/kWh), on installed capacity (kW) and total discounted cost (1000 EUR).

As found in Section 4.1.3, when the weighting factor, f_{EL}, is reduced (from *ZEBref* to *30%RES*) while everything else stays constant, this leads to increased PV area, but the heat technology unaffected. As the FiTPV is unchanged at 11 ct/kWh, the total cost increases with only 3 % even though the PV size is 30 % larger. In *50%RES*, the f_{EL} is reduced further, which contribute to larger PV size and higher costs if not changing the heat technology. Hence, the heat technology is changed to a BB, and even though the PV size is reduced, the halved FiTPV and the more expensive BB makes the total cost increase with 22 %, when compared to *ZEBref*.

When the FiT is removed in *80%RES*, together with further decreased weighting factor for electricity, a HP is installed. Even though the electricity price is unchanged and the technology costs are unchanged, lowering the weighting factor for electricity to 70 g/kWh and removing the FiTPV makes the heat pump a cost-optimal choice. The reason is as follows. When the electricity weighting factor is decreased, a ZEB with BB will need to increase its amount of PV exports. When reducing the FiTPV, the increased PV size will become more expensive. Reducing one at a time, Figure 12 showed that BB was chosen in both cases. However, when reducing both the FiTPV and the electricity weighting factor simultaneously, the choice finally becomes HP. Another option is to increase the weighting factor for bio energy, however this is not investigated in the current work.

4.1.6 Concluding comment on Investment Decision

Because the price of electricity is high compared to the other energy carriers (see Table 3), the benefit of generating your own electricity makes CHP the favoured heat technology choice.

The choice of CHP seems to be very robust when changing each input parameter separately. A lower electricity price was the only thing that could make the CHP less profitable, as the cost of the electricity generated from the CHP becomes higher than the price of electricity from the grid.

When reducing the FiT and the weighting factor for electricity simultaneously have a larger effect than lowering the electricity price alone. The sensitivity analysis also shows that the opportunity window for HP is narrow (see more in Section 5.3).

Comparing the technology choices in Figure 12 shows that whenever BB, or CHP, is chosen as main heat technology, the composition of the other heat technologies in the ZEB building is the same. That is, in the cases that lead to investment in BB (e.g. higher gas price or lower electricity price), the composition of installed capacity of the BB, electric boiler, and storage are identical, regardless on what grounds the choice was made. When the installed capacity is the same, the annual energy consumption is the same, and the optimal hourly operation is also identical.

The findings in Section 3, together with the sensitivity analysis in this section, show two main trends that are important for the grid impact. 1) once the main heating technology is determined, the hourly heat operation is identical; and 2) the ZEB level only affects the PV size, which is critical for the grid impact.

4.2 How does the energy system design affect the ZEB's grid impact?

Another finding of the sensitivity analysis in Section 4.1 is that the PV area changes with the choice of heat technology. From Section 3.2, we know that the PV size is decisive for the grid impact of the ZEB. Thus, it is interesting to see how the grid impact is affected by the main heat technology choice, while keeping all other input variables unchanged. Thus, this section analyses the grid impact of a 'strictly' ZEB with four different main heating technologies; BB, HP, GB and CHP. Their grid impact is further compared to the grid impact of *'no'ZEB* and *'nearly'ZEB* from Section 3.1. Table 6 summarises the findings elaborated on in the following.

Table 6 Key performance indicators and grid indicators of investigated ZEB cases.

ZEB level		**'no' ZEB**	**'nearly' ZEB**	**'strictly' ZEB**			
(explanation of case)		*Baseline*	*50% ZEB*	*ZEBref*			
Main heating technology		CHP	CHP	CHP	Gas boiler (GB)	Bio boiler (BB)	Heat pump (GSHP)
Electricity imported (MWh/yr)		8	8	8	20	21	25
Electricity exported (MWh/yr)	PV	6	22	38	37	22	25
	CHP	0	0	0	-	-	-
Electricity generated (MWh/yr)	PV	15	32	49	51	35	41
	CHP	15	15	15	-	-	-
PV installed (kWp)		14	30	46	48	33	38
Self-consumption (MWh/yr)		24	25	26	14	13	16
Self-consumption, total (%)		80 %	54 %	40 %	27 %	37 %	40 %

Self-consumption, PV (%)	*60 %*	*31 %*	*22 %*	*27 %*	*37 %*	*40 %*
Max export value (kWh/hr)	9	20	31	33	22	25
Max import value (kWh/hr)	11	11	11	13	13	18
GM	0,8	1,8	3,0	2,6	1,6	1,4
GMref (ref = 12,6 kW)	0,7	1,6	2,5	2,6	1,7	2,0

4.2.1 Net electric load duration curve

Figure 14 shows how the net electric load duration curve is influenced by the main heat technology choice, i.e. GSHP, BB, GB and CHP, for a 'strictly' ZEB. The positive part of the load duration curve, i.e. the electricity import, is identical for ZEBs with BB or GB as the operation of the boiler do not influence the electricity imports. A ZEB with CHP has the lowest duration curve for electricity imports. As found in Section 3.2.1, this is because all electricity generated from the CHP is self-consumed, and hence, the net electric import curve is shifted downwards 2-3 kWh/hr compared to a ZEB with a boiler (GB or BB). When using a heat pump, the electricity imports increase, as electricity is also used for heating purposes. However, the net imports of the ZEB with HP in Figure 14 is only 0,5-1 kW higher compared to the boilers. There are two reasons for this; 1) the low heat demand of the building, and 2) the high seasonal COP at 4,5. The largest difference occurs in the peak import value of 18 kW for the HP, which is caused by the electric top-up coil in peak heat hours. As shown in Table 6, the peak import value with HP is about 40 % and 70 % higher when compared to a ZEB with a boiler or CHP, respectively.

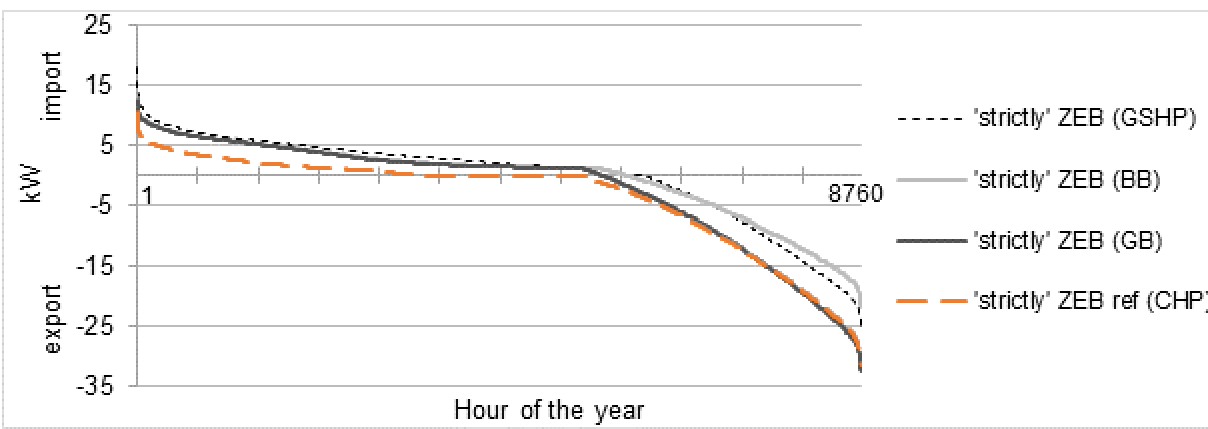


Figure 14 Duration curves of the net electric load for 'strictly' ZEBs (kWh/hr). Comparing cases with HP, BB, GB or CHP serving the base heat load, respectively.

The load duration curve for electricity export is heavily influenced by the size of the PV. Table 6 shows that the fossil fuelled heat technologies require the largest PV size, which is reflected in the peak export values reaching 31 and 33 kW for CHP and GB, respectively. The shape of the duration curve of electricity export is also very similar for these two. The BB has a similar shape, though the export values are smaller. The shape of the HP electricity export differs from all the other heat technologies as it has the least amount of hours with export, but as soon as it starts exporting, the curve becomes steeper, and finally reaching a maximum export value of 25 kW.

Lastly, we observe for ZEB with HP, that import values between 50-100 % of the peak import only occurs in 3 % of the hours. This is due to the price structure of electricity in this case study, which do not have a component for maximum load from the grid. This may cause problems for electricity grids with transmission capacity limitations, or for electric power systems with capacity limitations for flexible generation, which hence must provide capacity payment in so-called capacity markets.

4.2.2 Self-consumption

For a ZEB with either GB or BB, the boilers are operated to cover heat demand only, and consequently do not influence the way the building is utilising the electricity grid. Therefore, the self-consumption is only related to how much of the PV that can be utilised for the building's electric specific demand (i.e. appliances, lighting, fans&pumps). Because of the larger PV size of the GB compared to the BB, the self-consumption rate is 27 % with GB and 37 % with BB, even though the amount of self-consumed PV is the same, at 13-14 MWh/yr.

A HP on the other hand, can shift its operation to consume PV generated electricity by utilising the heat storage. However, the self-consumption only increases by 3 MWh/yr compared to the BB because the heat demand is low when the sun shines. Even though the amount of self-consumed electricity is higher for the HP case, the share is only 3 %-points higher compared to the BB due to the larger PV generation (41 vs. 36 MWh/yr).

The highest amount of self-consumed on-site electricity generation, and thus the lowest amount of annual electricity imports of 8 MWh/yr, is found when CHP is the main heating technology. In Section 3.2.1, the CHP was found to be operated such that all the on-site CHP generated electricity is self-consumed. This is confirmed in Table 6 where no CHP electricity is exported to the grid, and the self-consumption at 26 MWh/yr is twice as high compared to the ZEB with a boiler.

4.2.3 Additional grid connection capacity

The GM-ref is the relation between the peak export and a reference peak import value, and reflects the need for additional grid connection capacity for the building compared to a reference building without on-site electricity generation. Table 6 shows that the GB and the CHP in theory demands 2,5 higher grid connection capacity, whereas the BB demands 70 % more.

4.2.4 Concluding comment on Grid Impact

From the findings above, we may conclude that the CHP and GB have the highest peak export value, the HP somewhat lower, and the BB the lowest export value. It is surprising that even though the CHP has the highest self-consumption, the peak export value is still one of the highest. The reason lies in the use of natural gas which demands a large PV area. The maximum export value occurs in summer when heat demand is low, and therefore, is determined by the PV size alone. If bio gas had been used in the CHP, the PV size would have been smaller, and thus, the CHP case would have had the lowest export value and the highest self-consumption rate, i.e. the lowest grid-impact.

5 Discussions

The results of this study are dependent on the assumptions made, especially regarding the level of ZEB, the value of the weighting factors, fuel prices and cost of the available technologies. However, there are some general characteristics of ZEBs that become evident from the investigated cases in this paper.

5.1 PV size

The findings in this paper reveals three elements of the PV size in ZEB buildings: 1) A minimum PV size is determined by the electricity specific demand, regardless of the electricity weighting factor, and 2) The total PV size is determined by a) the ZEB-level and b) the weighting factor of the electricity grid.

Electric specific demand of the building is present 24 hrs a day, also when the sun is not shining, and thus a minimum amount of imported electricity to the building is always required. This means that the building needs to export at least the equal amount of electricity, regardless of the weighting factor, as long as it is > 0. Therefore, a ZEB needs a minimum PV size, only determined by the electric specific demand, regardless of PV cost nor the weighting factor of electricity. In this case study, this minimum PV size is about 30 kWp. When compared to the four 'strictly' ZEB cases in Table 6, the additional heat determined PV size ranges from 3-18 kWp, dependent on fuel. Thus, it is evident that the electric specific demand dominates the determination of the PV size.

Whether the building is a 'nearly' or 'strictly' ZEB, is directly reflected in the PV size. Here, the *'nearly'ZEB* has 35 % smaller PV size compared to the *'strictly'ZEB* (see Figure 6 and Table 6).

The sensitivity analysis of the weighting factor of electricity revealed another aspect of the PV size. If the heat technology is a CHP, a greener electricity grid (i.e. lower factor of electricity) claims a larger PV size. As the exported PV must compensate for the amount of weighted gas imports (which is unchanged), a lower weighting factor of electricity reduces the value of the weighted exported electricity. Hence, the amount of electricity export has to increase in order to reach the zero target. The same applies for ZEBs with other heating technologies. The exemption is HPs, where the weighting factor does not influence the PV size at all as it is an all-electric building.

5.2 Storage size dependent on heat technology

Investigations of the hourly operation reveals that the storage size of the boilers (GB and BB), depends on the peak heat load in winter, and the cost of the base load technology. The gas boiler has a relatively low investment cost, thus the size of the GB is high, whereas the storage size is small. The bio boiler have higher investment cost, leading to larger peak load unit and larger storage size. However, when heat pumps or CHP is chosen, the storage size is larger as the storage is sized for summer conditions. In the case of CHP the storage is sized to store heat generated at night time, to cover the morning peak heat demand. The heat pump on the other hand operates during daytime when PV electricity is available, and the storage is dimensioned to cover the heat demand at night. As discussed in Section 2.2.3, the size of the heat storage should be used with care, as they rely on an assumption of $\Delta T = 30°C$.

Table 7 Storage size of strictly ZEBs by main heating technology.

ZEB level	**'strictly' ZEB**			
Main heating technology	CHP	Gas boiler (GB)	Bio boiler (BB)	Heat pump (GSHP)
Storage size (kWh)	25	4	9	14

It can also be mentioned that a seasonal heat storage was never an economically beneficial decision, regardless of storage efficiency. A seasonal storage would enable PV electricity being stored as heat in summer and used for heat demand in winter. However, as the building must export electricity to reach its annual zero requirement, there is no benefit of storing heat seasonally.

5.3 Heat pump opportunity in ZEBs

When the electricity grid becomes greener in near future, many studies expect that heat pumps will replace fossil fuelled heating [23], [41]–[44]. A lower electricity weighting factor should intuitively lead to HP investments. However, because the investment cost and operational cost of the HP is more expensive than the BB, the sensitivity analysis shows that both the FiTPV and the weighting factor for electricity must be reduced substantially to make the HP a cost-optimal choice over a BB.

When moving from fossil fuelled to renewable heat for the ZEB building, the BB is a more cost-efficient choice compared to the HP. Even reducing the electricity price did not affect this solution. The reason lies in the weighting factor of bio energy which demands a smaller PV size compared to the HP. The choice of whether to install HP or BB is thus influenced by 1) the investment and fuel cost of the heat technologies on the one hand, and 2) on the FiTPV and PV installation cost on the other hand, which determines the cost of compensating the weighted energy imports to the building.

5.4 Solar thermal never chosen

For none of the cases investigated, solar thermal (ST) was profitable. In general, using solar thermal (ST) collectors reduces the need for alternative heat generation, which subsequently reduces the weighted energy imports and therefore lowers the required PV investment to balance them off. Thus, the choice of investing in ST is determined by the trade-off of saved fuel costs for alternative heat generation, together with lower investment costs of PV panels, versus the investment costs of ST. As the heating technologies are dimensioned to cover the peak heat load in winter, they are very well capable of also covering the heat demand in summer. Hence, installing ST does not reduce the installed capacity of the heating technologies, but only saves the fuel costs. In order for the ST to be chosen, the specific cost had to be reduced by 75 % to 200 EUR/m^2, with a size of 14 m^2. When studying the hourly operation, it is seen that this size fits well with the domestic hot water demand in summer. This confirms the findings in [45] which investigated ways of finding the optimal size of a ST system, and found that cost minimization would lead to no investments in ST at all, and consequently developed an alternative algorithm for sizing of the system. Further, our findings are also in line with [7] which concluded that if available roof area is limited, then it is more beneficial to use it for PV panels compared to ST collectors, despite the higher efficiency of the ST.

5.5 Aspects not considered

The analysis is performed on a single building containing 10 apartments, thus the possible benefits of utilising different energy sources in a local energy system for several buildings is not a part of the present work. Sensitivity analysis of future development of the technology costs is not performed in this paper, even though the modelling framework allows for this. Bio gas is not included in the analysis. If this had been done, dependent on price, the optimal technology might be CHP fuelled by bio gas rather than natural gas. The weighting factor of district heating is quite high for the present European conditions as it is linked to the thermal power plants. As for the weighting factor of electricity, this may change in future. Electric storage can be a viable option with the present support system of batteries in Germany, which will be implemented in future work.

6 Conclusion

This paper identifies the most important factors that influence the grid impact of a ZEB situated in Germany. The analyses are performed using a MILP model which finds the cost-optimal energy system design within the ZEB.

We find that whether the building is a 'nearly' or 'strictly' ZEB building impacts the import/export situation of the building, but it does not affect the choice of energy technologies. The cost-optimal technology mix is thus the same, however the PV size increases by 53 % when going from 'nearly' to 'strictly' ZEB. This directly affects the grid impact, and the peak export value is increased by 55 % from 20 to 31 kW.

Whether the ZEB balance is calculated using CO_2 factors (Zero Emission Building) or primary energy factors (Zero Energy Building), the choice and size of energy technologies are not altered. In this case study, a CHP combined with a GB, EB and PV is the cost-optimal technology choice independently of whether the building is a Zero Emission or a Zero Energy Building. The only exemption is the size of the PV, which is determined by the relation between the weighting factor of electricity export and the factor of the other energy carriers. The closer the weighting factor of electricity is to the weighting factor of the other energy carriers, the larger PV size is required to reach the ZEB balance.

The choice of whether to use a CHP, GB, BB or HP to cover the base load of the heat demand, is a trade-off between the investment & fuel cost, and the cost of the PV which generates the weighted energy exports. On the one hand, CHP or GB has the lowest costs, but also the highest weighted energy imports, which requires the largest PV size. On the other hand, BB or HP has higher costs, but lower weighted energy imports, leading to smaller PV size (see Table 6). The present FiT of PV in Germany, makes the additional cost of a larger PV size negligible compared to the saved fuel and investment costs by using natural gas for heating. In other words, the choice of heat technologies of a ZEB is dependent on the trade-off between higher costs for renewable heat generation vs. saved costs of smaller required PV size.

For ZEBs with HPs or BBs, it is the electric specific demand that dominates the required amount of energy generation, i.e. the PV size. First, because of the relatively low heat demand, and secondly, because the weighting factor of biomass is low and the efficiency of HP is high. In this case study, the PV size determined by the electric specific demand is 30 kW. In the case of the BB or HP, this corresponds to 91 and 70 % of the total required PV capacity, respectively.

Solar thermal (ST) is not a cost-optimal choice in any of the investigated cases. ST competes with the fuel cost of alternative heating technologies and not with the PV. The only benefits for the ST are the saved fuel costs for heating and the lower PV investment costs, which are not enough to make it economically attractive.

Onsite PV installation leads to challenges for the grid in peak hours when the generation exceeds the electricity consumption within the building, creating large export values. A ZEB with fossil fuelled heating technologies requires the largest PV installation, and has consequently higher grid impact. When compared to a ZEB which uses bio fuel, the annual export of electricity to the grid is 73 % higher, the maximum export value is 41% higher, and the self-consumed PV is reduced to about 25 %.

In future, the FiT of PV is most likely to be reduced or even removed. When removing the FiTPV, the findings from the sensitivity analysis show that BB is the preferred heat technology. A HP is not a cost-optimal choice until the weighting factor of electricity is reduced by 80 % (equal to 70 g/kWh). Thus, using bio energy for heating purposes seems like a robust technology choice for ZEBs in the future. However, is there enough resources available to cover this demand if all Germany is to be heated by bio energy? Thus, for future policy development, it might be an option to assess a direct investment subsidy, not only for CHPs, but also for heat pumps.

One of the main takeaways from this paper is that applying both the ZEB target and the FiTPV lead to fossil fuelled based heating technologies with a large PV area. This contradiction should be addressed when the political definition of ZEB buildings is determined. A mayor concern is also the design of the ZEB definition. There are certain reasons for wanting specific heating technology choices in some countries, and the value of the weighting factors can affect this decision.

Acknowledgements

This work has been supported by the Research Council of Norway and several partners through the Research Centre on Zero Emission Buildings (ZEB) and the Research Centre for Sustainable Energy Studies (CenSES). The authors acknowledge the support from the Norwegian Water Resources and Energy Directorate (NVE) in Oslo, Norway, and Fraunhofer Institute for Solar Energy System (ISE) in Freiburg, Germany. The first and second authors would like to thank Viessmann for providing technology cost data for current market conditions in Germany. The first author would also like to thank Dr. Thomas Erge with the Fraunhofer ISE for valuable input on the current energy market conditions in Germany, and Dr. Torgeir Ericson with the NVE for constructive comments on the structure of the paper.

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Appendix

When applying non-renewable primary energy factors (PEnr-sym), Figure 15 shows that the installed capacity of the CHP, GB, EB and heat storage is the same as when using CO_2 factors. The only difference is seen in the PV size which is 7 kWp lower. When using the total primary energy factors (PEtot-sym), where the factor for bio energy is increased from 0,05 to 1,05, there is still no change, as bioenergy is not a part of the ZEB solution, only that the PV size is 9 kWp smaller.

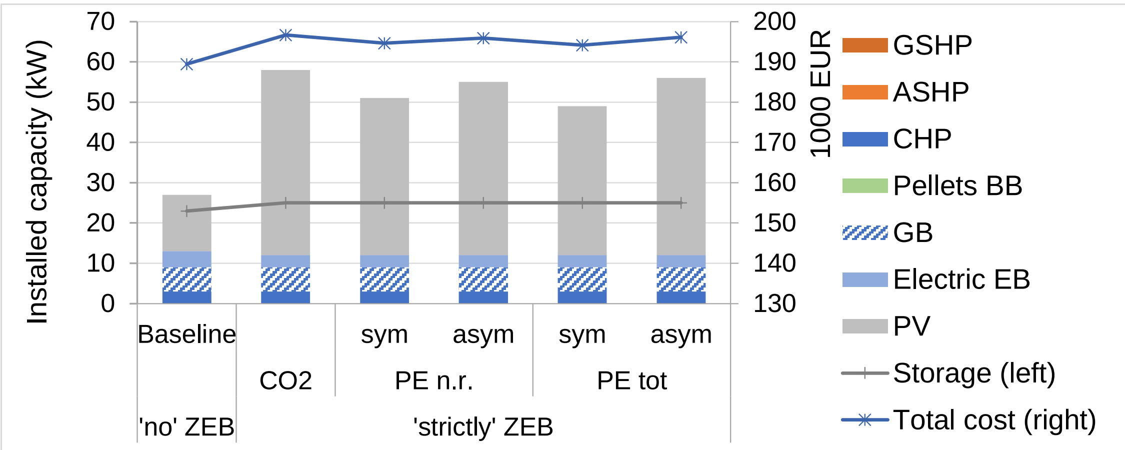

Figure 15 Installed capacity (kW) of ZEBs using different weighting factors; Baseline ('no' ZEB) is compared to a zero emission, zero non-renewable primary energy (symmetric and asymmetric), and zero total primary energy (symmetric and asymmetric) building.

When applying asymmetric factors for electricity, where export (2,0) is valued less than import (2,3 or 2,5), the incentive for self-consuming on-site PV generation increases. The findings from Figure 6 shows that the only change from symmetric to asymmetric factors is increased PV area. Due to the optimal operation strategy of the model, the self-consumption is already maximised, and the imported electricity is already minimised. By applying the asymmetric factors for electricity, the exported generation is less valued when calculating the balance, and thus the building needs to export more kWh's in order to reach the zero balance.

Summed up, the only difference when using either CO_2 or primary energy factors, is the size of the PV system. The PV size is determined by the relationship between the factors of electricity exports and natural gas imports, given in Table 8. The lower weighting factor of the electricity export is, compared to the weighting factor of the gas import, the larger amount of annual electricity export is required to compensate for the energy imports. In Table 8, the CO_2 factors have the smallest difference between the weighting factor for electricity export and gas import and requires thus the largest PV size, which is confirmed by the findings in Figure 15.

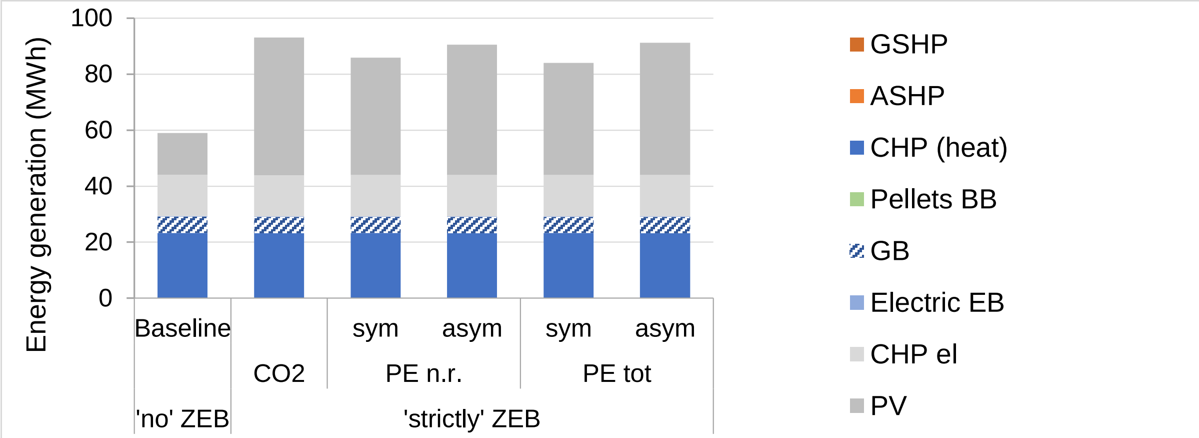

Figure 16 Annual energy generation (MWh/yr) in the baseline case (noZero), compared to when applying five different ZEB targets: zero emission, zero non-renewable primary energy (symmetric and asymmetric), and zero total primary energy (symmetric and asymmetric).

The annual energy generated from each of the technologies is shown in Figure 16, where the CHP unit provides 79 % of the heat demand and the gas boiler 20 % regardless of weighting factor. The electric top-up coil only contributes with 1 % to cover peak heat demand and is hardly visible in the graph.

Table 8 Relationship between weighting factors for electricity and natural gas, and between electricity and bio pellets.

Weighting factor	**Description**	**Natural gas vs. Electricity**	**Bio pellets vs. Electricity**
CO2	Zero Emission (using CO_2 factors)	(210 : 350) Relation 1 : 1,7	(14 : 350) Relation 1 : 25
PEnr-sym	Zero Primary Energy (using symmetric non-renewable PE factors)	(1,05 : 2,3) Relation 1 : 2,2	(0,05 : 2,3) Relation 1 : 46
PEtot-sym	Zero Primary Energy (using symmetric total PE factors).	(1,05 : 2,5) Relation 1 : 2,4	(1,05 : 2,5) Relation 1 : 2,4