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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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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.

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. 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,

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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.

$$\sum_i f_i \times \text{imported}_i - \sum_i f_i \times \text{exported}_i = G \quad (1)$$

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:

- the *metric* of the weighting factor (primary energy or CO_2)
- the *value* of the weighting factors (see examples in Table 4)
- the *level* of ZEB ('strictly' or 'nearly' ZEB)
- 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.

1.2. 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 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.

1.3. 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 multifamily 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.

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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) = $(PE_{electricity}/COP_{HP})/(PE_{bio}/\eta_{BB}) = 12{,}6$.