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On-site or off-site renewable energy supply options? Life cycle cost analysis of a Net Zero Energy Building in Denmark

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ABSTRACT

The concept of a Net Zero Energy Building (Net ZEB) encompasses two options of supplying renewable energy, which can offset energy use of a building, in particular *on-site* or *off-site renewable energy supply*. Currently, the on-site options are much more popular than the off-site; however, taking into consideration the limited area of roof and/or façade, primarily in the dense city areas, the Danish weather conditions, the growing interest and number of wind turbine co-ops, the off-site renewable energy supply options could become a meaningful solution for reaching 'zero' energy goal in the Danish context. Therefore, this paper deploys the life cycle cost analysis and takes the private economy perspective to investigate the life cycle cost of different renewable energy supply options, and to identify the cost-optimal combination between energy efficiency and renewable energy generation. The analysis includes five technologies, i.e., two on-site options: (1) photovoltaic, (2) micro combined heat and power, and three off-site options: (1) off-site windmill, (2) share of a windmill farm and (3) purchase of green energy from the 100% renewable utility grid. The results indicate that in case of the on-site renewable supply options, the energy efficiency should be the first priority in order to design a cost-optimal Net ZEB. However, the results are opposite for the off-site renewable supply options, and thus it is more cost-effective to invest in renewable energy technologies than in energy efficiency.

1. Introduction

The concept of a Net Zero Energy Building (Net ZEB) implies that on an annual basis the primary energy use of a building is offset by the energy generated from conversion of renewable sources. The technologies, which convert renewable sources, are generally divided into two groups. The first group encompasses the systems installed either on/in the building or on the ground directly attached to the building. The second group includes the systems placed outside the boundaries of the building site, which either are the property of the building owner or the building owner just purchases the generated energy in order to reach the 'zero' energy goal. The first group is often labelled as '*on-site renewable energy supply (on-site RES)*', and the latter as '*off-site renewable energy supply (off-site RES)*'.

The above described division is done with focus on the actual location of the renewable technology. Torcellini et al. [1] adopt the same terminology, 'on-site' and 'off-site'; however, they group the systems not according to the location of production but to the origin of used renewable energy source. Generally, the two approaches are very similar. The major difference concerns the biomass/biofuel micro Combined Heat and Power (micro CHP). By adopting the first approach, this technology is an on-site renewable supply option. However, according to Torcellini's system, the CHP is an off-site supply option because the biomass/biofuel, before being converted to useful form of energy, i.e., electricity or heat, has to be transported from outside the boundaries of the building site. In this paper, the renewable technologies are labelled according to the location of the conversion, e.g., inside the boundaries of the building site – on-site, and outside the boundaries – off-site.

According to Marszal et al. [2] and Voss & Musall [3], the most commonly used on-site renewable technologies, primarily generating energy and thus meeting the 'zero' energy goal, are photovoltaic (PV) and solar thermal panels. Similar to the international trends, the Net ZEBs in Denmark exploit solely on-site systems [4–7]. Also, the Net ZEB definition proposed by the Danish Strategic Research Centre on Zero Energy Buildings includes only on-site and building connected renewable energy technologies [8]. Keeping this approach, Marszal and Heiselberg [9] deployed a life cycle cost analysis to investigate the cost-optimal relation between energy efficiency improvement and on-site renewable energy supply for a multi-storey Net ZEB. The authors concluded that from a private economy perspective, the cost optimized Net ZEB is a building with

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Nomenclature

E	energy use [kWh/per year]
ρ	density of water [kg/m^3] – (1000 kg/m^3)
c_p	specific heat capacity of water [J/kg K] – (4200 J/kg K)
V	water demand [m^3/per year]
T_u	temperature of cold water [°C] – (12 °C)
T_i	temperature of warm water [°C] – (55 °C)
PV	present-value of the payment [€]
PA	annually recurring cost [€/year]
PF	future cash amount occurring at the end of the year t [€]
n	study period of the analysis/lifetime of the building [years]
t	year when the PF occurs
d	real interest rate [%]
mb	marginal benefit [€/kWh]

greatly reduced energy use (around 20 kWh/m^2 per year of primary energy, corresponding to the minimum level of energy performance requirements for residences in 2020 in Denmark) and a small on-site renewable energy system. The cost-optimal on-site renewable system is a PV installation in combination with a ground source heat pump. However, taking into consideration the limited area of roof and/or façade, primarily in the dense city areas, the Danish weather conditions, the growing interest and number of wind turbine co-ops [10], the off-site renewable energy supply options could become a meaningful solution for reaching 'zero' energy goal in the Danish context.

Therefore, by acknowledging that the user/building owner perspective and economy [11,12] are crucial factors for a successful adaption of environmental- and climate-friendly technologies, this paper deploys the life cycle cost analysis to investigates the cost-optimal path towards 'zero' energy goal in case of off-site RES. The study includes three levels of energy performance requirements, i.e., level 0, level 1 and level 2, with level 0 being the most demanding one. The off-site renewable energy supply options included in the analysis are: (1) private windmill, (2) shares in a windmill farm or (3) purchase of energy from 100% renewable utility grid. By combining the results of this analysis with the results of [9], and additionally by adding the less popular in Denmark micro CHP as on-site RES to the investigations, there are all together 10 different renewable energy supply systems. Thus, this paper provides a comprehensive overview of life cycle cost of different RES from a private economy perspective.

Moreover, as the energy use of the Net ZEB is modelled by using a mean monthly-based steady-state calculation tool (Be10) [13] and an hourly-based dynamic simulation tool (BSim) [14], the paper verifies the influence of the resolution of simulations on the energy performance and the life cycle cost of a newly constructed Net ZEB.

2. Methodology

The first step of this analysis was to calculate the energy use of the reference Net ZEB. In order to conduct this investigation, two models were made, i.e., a simplified mean monthly-based model in Be10 software tool and a detailed hourly-based model in BSim, which includes additional input data about user profiles. The second step focused on sizing the renewable energy system components that will generate enough renewable energy to offset consumption and thus to meet the zero energy goal on the annual basis, e.g., the area of PV, the capacity of CHP or windmill. This was done for both Be10 and BSim models. The last step was to calculate the life cycle cost of all solutions based on both - simplified and detailed buildings' performance models, respectively.

This chapter is divided into the following parts. Firstly, it shortly sketches the reference Net ZEB and outlines the background information on the cases development. Secondly, it describes the deployed LCC method and points out the most important data used in the calculation.

2.1. Minimum energy performance requirements

The three energy performance levels included in the LCC analysis are defined to follow the Danish building regulations BR10 [15]. Level 2 corresponds to the currently in force minimum energy performance requirements, level 1 and level 0 reflect the low-energy class 2015 and class 2020, respectively. Table 1 provides an overview of the particular energy requirements of the three levels for the reference Net ZEB and corresponding U-values of the envelope construction.

According to BR10 [15], the primary energy consumption for new residential buildings must include energy for heating, cooling, domestic hot water, ventilation, and auxiliary energy. This requirement is followed in the analysis when defining the level of energy performance of the building. However, for the further analysis and for the dimensioning of the energy supply systems, the total primary energy use of the building is taken into consideration, including energy use for appliances and lighting. The energy embodied in the building construction and the energy used during the construction, maintenance and demolition phase of the building is beyond the scope of this paper. In the primary energy use calculations, the electricity use is multiplied by a factor of 2.5, heat from district heating by a factor 0.8 and renewable energy sources, i.e., biomass, biogas and hydrogen by factor 0. The multiplication factors represent the Danish primary energy factors used in the calculation of energy performance of a building. The primary energy factors of heat from district heating and electricity differ between energy frames. However, it was decided to use the same multiplication factors for all energy frames. The low-energy class 2015 factors were chosen because when the LCC calculations were conducted the factors for class 2020 were yet undefined.

2.2. Reference Net ZEB

The reference Net ZEB is a multi-storey residential building located in Denmark. The model of the building is based on the design of the winning project of BOLIG+ competition [16]. The building is north–south orientated and consists of two parts: one 6-storey high and second 10-storey high, see Fig. 1. The building footprint and total area is 824 m^2 and 7000 m^2, respectively. The glazing area is 1607 m^2, which corresponds to 23% of the total heated area. The Net ZEB is designed for 180 occupants (60 apartments). Table 2 presents design parameters of the building.

It should be noted that the construction concept applied in the reference Net ZEB is also adopted from the winning BOLIG+ project.

Table 1
Energy performance requirements and U-values.

	Unit	Level 2	Level 1	Level 0
Energy frame	kWh/m^2 per year	52.7	30.1	20
External wall U-values	W/m^{2}K	0.29	0.2	0.1
Floor U-values	W/m^{2}K	0.19	0.13	0.08
Roof U-values	W/m^{2}K	0.19	0.13	0.07
Window U-values	W/m^{2}K	1.78	1.4	1.0