Renewable Energy 44 (2012) 154–165

Contents lists available at SciVerse ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

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

Anna Joanna Marszal*, Per Heiselberg, Rasmus Lund Jensen, Jesper Nørgaard

Department of Civil Engineering, Aalborg University, Sohngaardsholmsvej 57, 9000 Aalborg, Denmark

ARTICLE INFO

Article history:
Received 8 November 2011
Accepted 10 January 2012
Available online 9 February 2012

Keywords:
Net Zero Energy Building (Net ZEB)
Renewable energy supply option
Life cycle cost (LCC)
PV
Micro combined heat and power (micro CHP)

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

* Corresponding author. Tel.: +45 9940 8587; fax: +45 9940 8552.
E-mail address: ajm@civil.aau.dk (A.J. Marszal).

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doi:10.1016/j.renene.2012.01.079

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

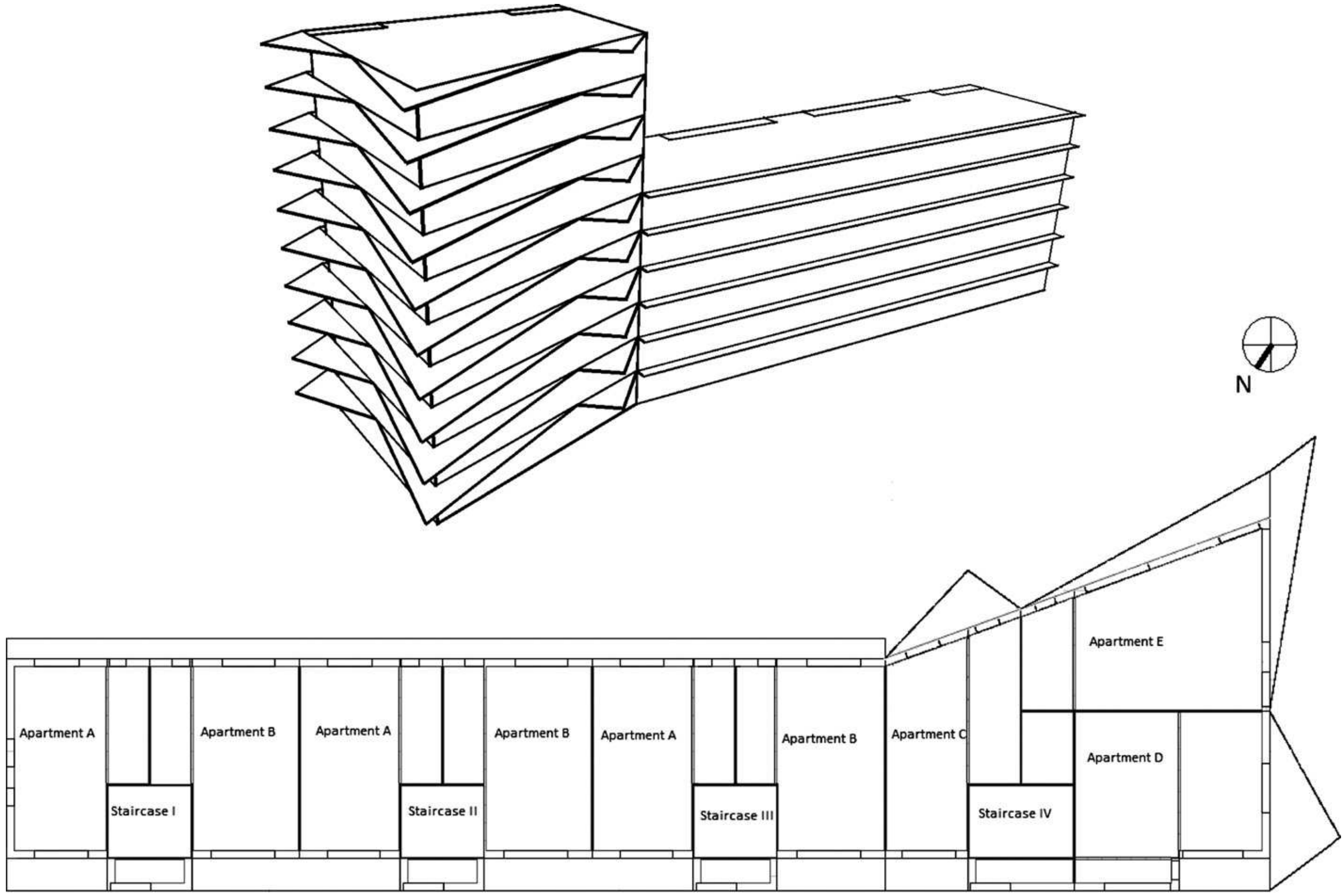

Fig. 1. Sketch and floor plan of the reference Net ZEB.

It represents a relatively new approach towards more prefabricated and industrialized building processes. The building is assembled from 114 modules with an average area of 61.4 m^2. The modular building system allows optimization of the insulation thickness, minimization of the cold bridges and improvement of the acoustics of the building.

The energy use of the building is calculated by the software program Be10 and simulated in dynamic simulation tool BSim. Be10 is a Danish energy rating software program which applies a simplified method for calculation of energy use based on mean monthly average values for climate data, heat losses, heat gains and occupants schedule. BSim is an hourly-based dynamic simulation tool for calculating and analysing indoor climate conditions, power demand and energy consumption in buildings. As being a transient model, the Net ZEB hourly profiles of occupancy and household electricity use (including appliances and lighting) are implemented in the BSim model of the Net ZEB. The domestic hot water (DHW) usage is not integrated into BSim; therefore, the DHW profiles and corresponding heat demand are computed separately, and later added to simulation results. All profiles are defined based on the profiles developed using measured data at Aalborg University [17]. The household electricity use profiles were developed based on both the measurements of low-energy buildings done within different projects [18–20] and the data available from Energinet.dk publications on electricity use in different parts of Denmark [21]. The heat used for preheating the water is calculated based on Eq. (1). The factor 1.33 includes the installation heat losses. The profiles of DHW use are developed based on [18,19,22]. It should be noted that the DHW profiles have been verified with the European Standards.

Table 2
Features of the reference Net ZEB.

Design parameter	Description
Design indoor temperature	22 °C
Air flow rate	0.3 l/s per m^2 (mechanical ventilation in winter period) 1.2 l/s per m^2 (natural ventilation in summer period)
Heat recovery	85%
Air tightness n_{50}	0.6 1/h (which corresponds to average infiltration of 0.1 1/h)
Loads	
People load	1.72 W/m^2 (an average value for the whole building)
Domestic hot water	26.8 l/person per day
Appliances + lighting	1.71 W/m^2 (1725 kWh/apartment per year)

$$E = \rho \cdot c_p \cdot V \cdot (T_i - T_u) \cdot 1.33 \qquad (1)$$

Fig. 2 presents the household electricity use profiles, which differ for weekdays and weekends and also between seasons. The DHW profiles are different only for weekdays and weekends, see Fig. 3. The occupancy profile are built based on three main assumptions (1) in Denmark on average the house-occupancy is 16.3 h/per person per day, (2) the house is empty for 5.4 h/per day and (3) weekdays' profile is different from weekends' profile, see Fig. 4.

2.3. Options of renewable energy supply systems

The analysis encompasses two on-site renewable supply options: (1) photovoltaic and (2) micro CHP unit and three off-site

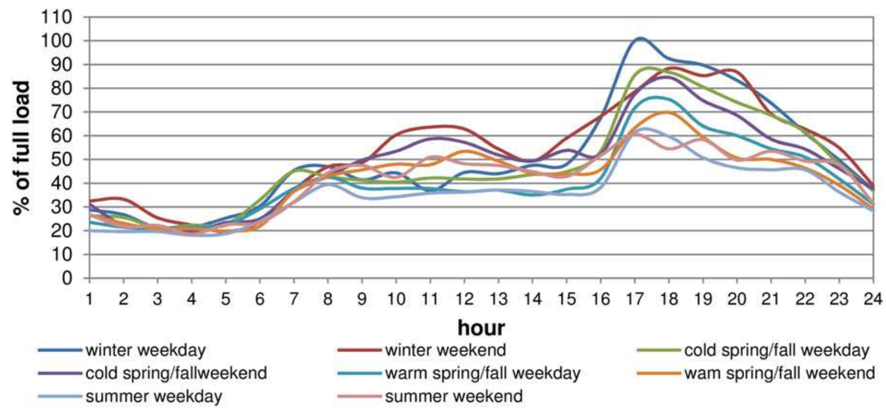

Fig. 2. Household electricity profiles (plug loads and lighting) [17].

renewable supply options: (1) private windmill, (2) shares in a windmill farm and (3) purchase of green energy from a 100% renewable utility grid. There are three types of micro CHP: (1) micro fuel cell CHP fuelled with biogas, (2) micro fuel cell CHP fuelled with hydrogen and micro Stirling biomass CHP. The micro CHPs run with heat demand as priority; therefore, if electricity demand exceeds electricity production from micro CHP, a PV installation is added to meet the demand. The micro CHP is sized to cover 60% of the peak heat demand; therefore, when not produced by the micro CHP, heat is delivered to the building by a boiler, which uses the same fuel as applied micro CHP unit.

Moreover, the analysis includes two additional options, except the micro CHP, to supply heat to the building: (1) a ground source heat pump (HP), which supplies 100% of the peak heat demand or (2) the district heating grid (DH).

The goal of this analysis is not to optimize the position of PV panels. Therefore, the PV panels have a fixed south orientation and a slope of 40° within this analysis. This is the most efficient PV position in Denmark [23] and thus the needed PV area is the smallest.

In the RES configurations, where the Net ZEB is connected both to the electricity and the district heating grid, the building can offset the heat consumption by feeding more electricity to the utility grid. In order to estimate how many kWh of electricity have to be produced additionally, the factor of 3.125 is introduced ($1\ kWh_{el} = 3.125\ kWh_{heat}$). It is calculated as the fraction of primary energy factors for electricity and heat (2.5/0.8). Table 3 summarizes the efficiencies of particular technologies. There are all together 10 renewable energy systems in the analysis that can be applied in Net ZEB:

PV-HP: Building with on-site photovoltaic installations and a ground source heat pump. PV is sized to meet corresponding electricity demand.

PV-MiCHP(biogas): Building with on-site photovoltaic installations and a micro fuel cell biogas CHP. Biogas is supplied via a gas pipeline system.

PV-MiCHP(biomass): Building with on-site photovoltaic installations and a micro Stirling biomass CHP. Biomass is transported to the building site.

PV-MiCHP(H_2): Building with on-site photovoltaic installations and a micro fuel cell CHP fuelled with hydrogen. Hydrogen is transported to the building site.

PV-DH: Building with on-site photovoltaic installations and connection to the district heating grid. The PV installation is sized to offset heat consumption from district heating.

WM-HP: Building with off-site windmill and a ground source heat pump.

SofW-HP: Building owning share of a windmill farm and a ground source heat pump.

$El_{100\%}$-HP: Building connected to power grid, which in 100% is supplied with renewable energy sources and a ground source heat pump.

W-DH: Building with off-site windmill and connection to the district heating grid. The windmill is sized to offset heat consumption from district heating.

SofW-DH: Building owning share of a windmill farm and with connection to the district heating grid. The share of windmill farm offsets also heat consumption from district heating.

2.4. Life cycle cost analysis

The life cycle cost analysis deployed in this paper is built upon the LCC approach developed by Fuller and Petersen [28], where the LCC is defined as an economic method that adopts a structured

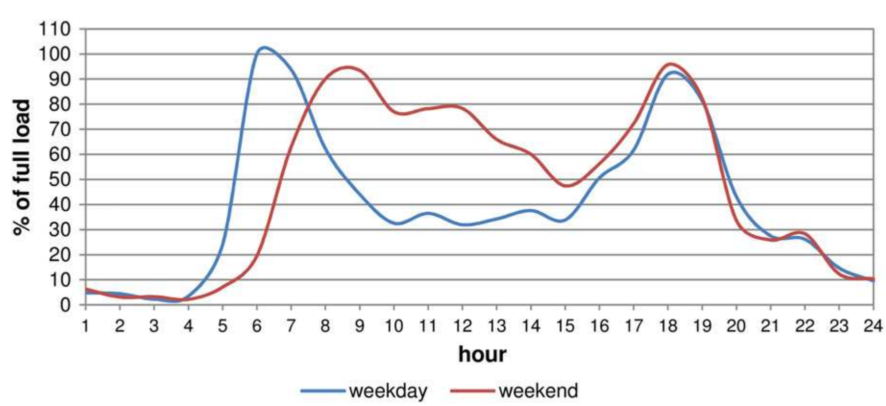

Fig. 3. Domestic hot water profiles [17].

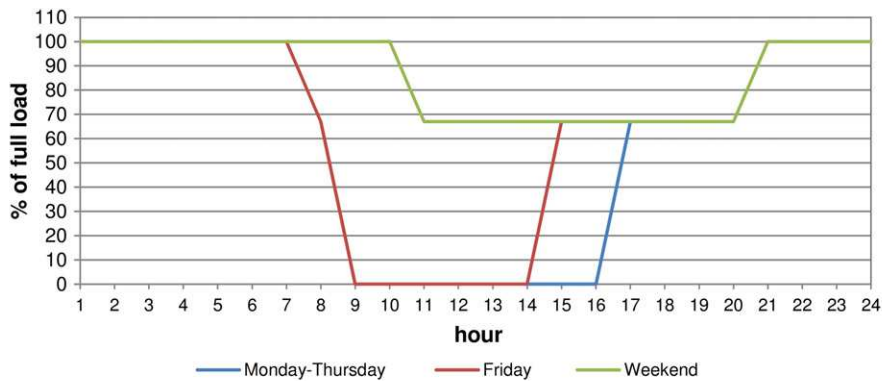

Fig. 4. Occupancy profiles for a 3 persons' apartment [17].

approach to address all the different costs of the 'project' over the given study period with all the potential cost adjusted to reflect the time-value of money. This method complies with the one described in ISO 15686-5 [29] and with the cost-optimal method recently defined by the EU [30], which is based on EN 15459 [31]. However, it should be noted that the cost categorisation system defined in EN 15459 differs slightly from the usually system of life cycle cost analysis applied by Fuller and Petersen and in ISO 15686-5.

The main goal of the LCC is to determine the cost-optimal solution out of different alternatives, and the alternatives are comparable only with the same economic assumptions, the same study period and service date. According to Fuller and Petersen [28], the LCC can be estimated in present-value terms and annual-value terms. The first calculation method requires that all future costs are discounted to their present-value equivalent. As in the second method, all projects costs are evenly amortised over the study period, taking into account the time-value of money. Fuller and Petersen name 3 three additional measures of economic performance that are consistent with the LCC method, such as, Net Savings (NS), Savings-to-Investment Ratio (SIR) and Adjusted Internal Rate of Return (AIRR). The SIR and AIRR measures are useful mainly for ranking independent projects, e.g., new windows in building A and new HVAC system in building B, and they should not be used to identify the cost-effective alternative. The NS measure can be applied for determining the cost-optimal alternative among two or more mutually exclusive alternatives, but there is always a need for the base line case. However, this LCC does not focus on presenting the cost difference between various study cases and a reference case, it deploys the annual-value method to (1) determine the cost-optimal balance between energy savings and renewable energy production, and (2) to define the cost-effective renewable energy supply options for a new multi-storey Net ZEB.

In this paper, the LCC analysis of a building encompasses four types of cost, i.e., investment, operation and maintenance (O&M), replacement and demolition. Table 4 presents particular components included in specific cost types, and Table 5 summarizes the LCC data used in this paper. The costs of renewable technologies are assumed to remain constant throughout the analysis period. Although, in the cost-optimal methodology developed by the European Commission [30] recommended lifetime of a newly constructed building is 30 years, in this LCC analysis based on literature review presented by Sartori and Hestnes [32], the lifetime of a building is 50 years. The real interest rate $d = 3\%$ [33]. Hence the annuity factor equals 0.039. The investment, replacement and demolition cost are annualized using Eq. (2) and Eq. (3), respectively. The O&M cost are calculated annually.

$$\mathrm{PA} = \mathrm{PV}\cdot d/\left[1-(1+d)^{-n}\right] \tag{2}$$

$$\mathrm{PA} = \mathrm{PF}/(1+d)^{t}\cdot d/\left[1-(1+d)^{-n}\right] \tag{3}$$

2.5. Energy cost

The Net ZEB exchanges energy with the utility grid and on the annual basis the amount of energy imported from the grid equals the amount of energy exported to the grid. In theory, the Net ZEB can interact with the power grid and the district heating grid [2]; however, presently in majority of cases only the electricity is fed back to the grid [3]. This approach is also adopted in this paper. Looking at the building-grid integration from the economy perspective, there are two possible scenarios, i.e., (1) net-metering agreement, which means that electric meters run backwards when building feeds excess electricity to the power grid, and thus the purchase and feed-in tariffs are equal; (2) tariffs agreement, which means that there are different tariffs for imported and exported electricity. It is most often decided on the national level which policy is chosen. As this Net ZEB is located in Denmark, the Danish building-grid regulations are followed. This means that for the on-site renewable supply technologies, i.e., PV and Micro CHP, the net-metering agreement is adopted, and for the off-site renewable

Table 3
Efficiencies of technologies applied in the analysis.

Technologies	Heat	Electricity	COP	Ref.
Photovoltaic	–	0.075[a]	–	[24]
Ground source HP	–	–	3.1[b]	[25]
$MiCHP_{BM}$	0.71	0.18	–	[26]
$MiCHP_{BioG}$	0.6	0.3	–	[27]
$MiCHP_{H2}$	0.45	0.45	–	[27]
Boiler (biogas, H_2)	1	–	–	[27]
Boiler (biomass)	0.85	–	–	[27]

[a] 0.1 efficiency of PV panels and 0.75 efficiency of the building integrated PV (BIPV) system.
[b] In the BSim models COP changes depending on the season, and varies between 3 and 4.

Table 4
Disposition of components included in particular cost type.

	Investment	Operation & maintenance	Replacement	Demolition
Construction	x	x	x	x
Installations	x	x	x	
Utilities	x	x		
Renewable energy systems	x	x	x	
Energy cost		x		

Table 5
Cost date used in the analysis (incl. VAT).

	Unit	Lifetime	Inv. €/unit	Variable annual O&M €	Fixed annual O&M €	Ref. lifetime	Ref. cost
Technologies							
Photovoltaic	m^2	25	598.5	1% of inv.	–	[34]	[16]
Windmill	kW	20	4250	1% of inv.	–	[35]	[35]
Share of windmill	kWh-e	25	0.838	–	–	[36]	[36]
Micro CHP (biomass)	kW-e	15	7250	37.5/kW-e	0.0375/kWh-e	[26]	[26]
Micro CHP (biogas)	kW-e	10	12,500	100/kW-e	–	[37]	[26]
Micro CHP (H_2)	kW-e	10	12,500	100/kW-e	–	[37]	[26]
Ground source heat pump	kW	15/40[a]	1049	0.6% of inv.	137.5	[37]	[37,38]
Boiler (biomass)	kW-th	15	839.2	2.8% of inv.	475	[37]	[37,39]
Boiler (biogas, H_2)	kW-th	15	839.2	2.1% of inv.	250	[37]	[37,39]
DHW tank	m^3	40	1856	–	–	[25]	[25]
Building envelope							
Windows							
0.9 W/m^2K	m^2	30	346	–		[34]	[16]
1.4 W/m^2K	m^2	30	273	–		[34]	[40][b]
1.8 W/m^2K	m^2	30	145	–		[34]	[40][b]
Insulation							
Level 0	Building	–	141,875	–			[41]
Level 1	Building	–	99,313	–			[41]
Level 2	Building	–	56,750	–			[41]
Installations							
Water	m^2	–	20	–			[34]
Sewage	m^2	–	10	–			[34]
Electricity	m^2	–	60	–			[34]
Floor heating with DH	Building	40	59	0.5% of inv.		[34]	[34]
Floor heating with HP/CHP	Building	40	70	0.5% of inv.		[34]	[34]
Decentralized ventilation	Apartment	15	8392	1% of inv.		[34]	[42]
Utilities							
Water	Building	–	1208	890			[43,45]
Sewage	Apartment	–	7637	92			[43]
Electricity	Apartment	–	1485	122			[43]
Biogas	Building	–	–	193			[43][c]
District heating	m^2	–	3	4.9			[44]
	Stick		1192				[43]
	m		168				[43]

[a] 60% of investment for 15 years lifetime and 40% of investment for 40 years lifetime.
[b] The cost difference of windows with various U-values is used from Velfac, and not the actual cost.
[c] annual consumption over 200 m^3.

supply technologies, such as, windmill, share of a windmill farm applies the tariffs agreement. However, when in case of on-site RES the annual electricity export is larger than the annual electricity import, a situation of plus energy building, the excess feed-in electricity is priced with different tariff. It should be noted that the feed-in tariffs decrease over time and therefore, an average value for a 50 years lifetime of a building was calculated. Table 6 shows the prices of electricity, district heating and fuel and Table 7 presents the feed-in tariffs for on-site and off-site RES.

3. Results

A newly constructed Net ZEB equipped with ten different renewable energy systems, representing both on-site and off-site renewable energy supply options, is evaluated over 50 years lifetime for three levels of energy performance requirements (later in the paper also called energy frames). For each energy frame, energy use of a building is computed using both the calculation tool Be10 and the simulation tool BSim. The resulting energy use and life cycle cost are discussed below.

3.1. Hourly simulations versus monthly calculations

As is expected, the dynamic simulations results in lower electricity and space heating demand than the steady-state calculations, see Table 8. The exception of DHW demand is a consequence of higher heat losses of DHW installation included in profiles developed at Aalborg University. And the discrepancy of electricity demand is due to (1) different assumptions behind mean monthly calculations of electricity use and appliances profiles developed at Aalborg University and (2) slightly higher electricity used for fans in Be10 model.

The focus of this article is the cost-optimum analysis and not the evaluation of energy calculation/simulation tools; therefore, detailed study of differences in energy demands is not included in this paper.

Table 6
Energy cost.

	Unit	€/unit	Ref.
Electricity	kWh	0.238	[43]
Green electricity	kWh	0.239	[43]
District heating	kWh	0.082	[44]
Biogas	m^3	0.639	[43]
Biomass	GJ	15.751	[46][a]
Hydrogen	m^3	1.172	[47][a]

[a] Including transport to the user.

Table 7
The overview of the feed-in tariffs.

	Unit	€/unit	Ref.
PV, micro CHPs	kWh	0.238/0.0567[a]	[43,48]
Windmill	kWh	0.0546	[48]
Share of windmill farm	kWh	0.0445[b]	[36]

[a] 0.238 tariff according to net-metering agreement, 0.0567 tariff applied after for the excess exported electricity.
[b] Tariff is reduced by O&M cost of the windmill farm.

Table 8
Energy demands.

Energy demands	Unit		Be10	BSim
Electricity	kWh/m^{2}per year	Level 2	17.2	16.3
(household electricity		Level 1	17.1	16.3
use, fans pumps etc)		Level 0	17.0	16.2
Space heating	kWh/m^{2}per year	Level 2	32.6	27.4
		Level 1	20.6	17.0
		Level 0	11.2	9.7
DHW	kWh/m^{2}per year	–	14.4	16.5
Peak heat demand	kW	Level 2	172.8	197.7
		Level 1	139.2	159.2
		Level 0	103.4	119.4

The variations of the energy demands cannot always be noticed in the results of the annual cost. Figs. 5 and 6 show that the total annual cost and the trends of particular RES are the same for both software tolls. The difference is in the size and thus the cost of particular technologies. Due to higher peak heat demand in BSim models of Net ZEB, see Table 8, the capacities of heating units and corresponding costs are on average 15% higher than in the Be10 results. However, due to slightly lower electricity demand, higher electricity generation from CHPs, and lower electricity use of heat pumps, in BSim models, the sizes of solely electricity generating technologies are smaller, e.g., in PV-HP system PV installation is on average 4% smaller.

As the overall picture of the annual cost is similar for both energy simulations resolutions, further investigations described in this paper are only based on the BSim models of Net ZEB and corresponding life cycle cost calculations.

3.1.1. Total annual cost

In general, Fig. 5 indicates that the cost difference between the three energy frames is not very significant, with one exception of the MiCHP(H_2) system. This result is a consequence of prefabricated modular building construction type, where around 90% of construction cost is the same for all three energy frames, and the cost difference is only due to cost of materials, in particular various insolation thickness and windows types. Moreover, the subscription fees and installations cost are constant for all study cases.

Nevertheless, Fig. 5 shows that the on-site and the off-site renewable energy supply options have opposite trends, namely for the first group of supply options, the total annual cost decreases with significant energy use reduction and for the latter group, the results are reverse. It can be explained by looking at the marginal cost of energy efficiency and the marginal benefits due to smaller renewable energy systems. The marginal benefit is calculated taking into consideration the cost of technologies and fuel. The electricity cost is taken into account only for the GR-HP system, as the green electricity is seen as renewable energy supply option. The improvement of space heating demand by 10.4 kWh/m^2 per year is achieved with marginal cost of 0.18 €/kWh and further reduction by 7.3 kWh/m^2 requires additional cost of 0.16 €/kWh. For all on-site renewable energy systems, expect PV-MiCHP(biomass) which is described later in the paragraph, the corresponding marginal benefit (mb) is higher than the marginal cost, for example, PV-HP system $mb_{1-2} = 0.19$ €/kWh and $mb_{0-1} = 0.22$ €/kWh and MiCHP(H_2) system $mb_{1-2} = 1.24$ €/kWh and $mb_{0-1} = 1.48$ €/kWh. The marginal benefit in case of off-site RES is lower than the marginal cost, e.g., and SofW-HP system $mb_{1-2} = 0.06$ €/kWh and $mb_{0-1} = 0.08$ €/kWh and W-DH $mb_{1-2} = 0.13$ €/kWh and $mb_{0-1} = 0.08$ €/kWh.

The cost-optimal system within the on-site supply options is the PV-MiCHP(biomass) system, and within the off-site group two systems have almost the same and lowest cost, namely the SofW-HP and the GR-HP. These two systems are also the most cost-effective systems among all ten renewable energy supply options. When looking only on the electricity generating technologies, namely on PV, off-site windmill and a share of windmill farm, for Danish conditions the PV proves to be still the most expensive technology. The life cycle cost of PV generated electricity is 0.473 €/kWh, as for the windmill and share of the windmill farm it is 0.160 €/kWh and 0.048 €/kWh, respectively. When comparing with the 2010 electricity prices, the PV electricity is higher by a factor 2. The difference in windmill and share of windmill electricity price is a consequence of longer lifetime of large-scale windmills and the fact that the O&M of share of windmill farm are accounted in reduced feed-in electricity tariff. However, the cost difference between small-scale and large-scale technologies, see Table 9, clearly indicates that in the Danish context, the windmills should only be implemented in the large-scale, while the photovoltaic could be implemented in both scales, since the price of large-scale PV installations is not significantly lower than for small-scale systems.

Fig. 5 also indicates that the total annual cost of the alternatives, where heat is supplied to the building by district heating grid, is higher than the corresponding cases but equipped with ground source heat pump. This is due to the annual cost of district heating, in particular current accounting method used by supplying companies, which except the tariff for actual heat consumption has a second tariff that depends on the building size and is the same for buildings of the same size but very different heat demands. This issue and a proposal of alternative accounting method is further

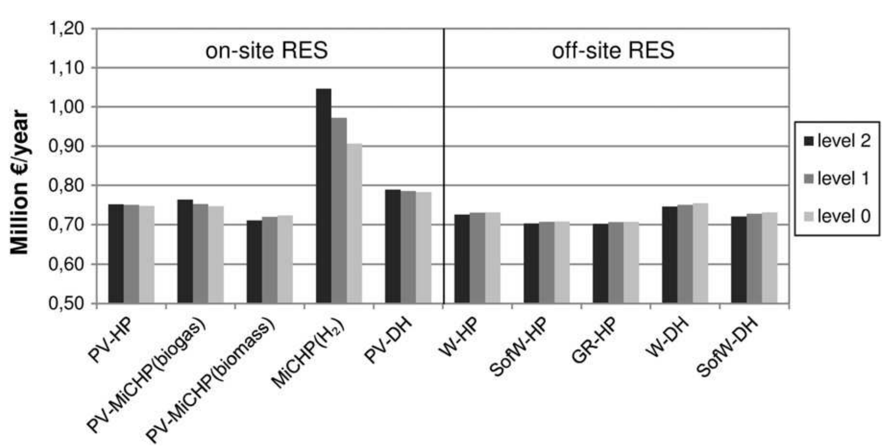

Fig. 5. Total annual cost of BSim simulation of Net ZEB for three levels of energy performance requirements and the renewable energy supply systems.

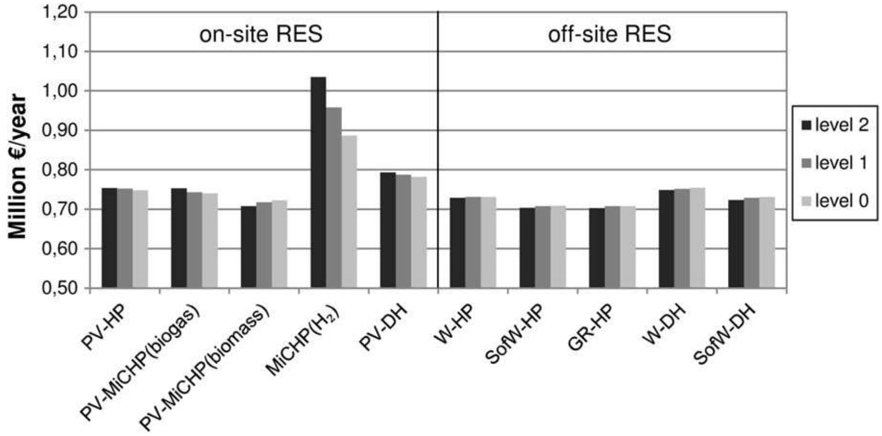

Fig. 6. Total annual cost of Be10 calculation Net ZEB for three levels of energy performance requirements and the renewable energy supply systems.

elaborated in [9]. The O&M cost for the alternatives with DH are on average higher than the HP alternatives by the factor 3.4 – PV; 7.5 – windmill; 31.2 share of a windmill farm. The differences increase with lower energy use of building.

The total annual cost of Net ZEB heated by biogas or biomass micro CHP indicates that these technologies have potential and could compete with PV and windmills. The micro CHP on hydrogen is much more expensive than the two other micro CHPs. It is due to still very expensive hydrogen price of 1.172 €/m^3. However, it should be noted that the micro CHPs on biogas and hydrogen have a major disadvantage of high excess electricity production, which is 60% - level 0, 104% - level 1 and 166% - level 2 of the corresponding electricity demand. This electricity is feed-in to the power grid; however, the feed-in tariff is only 0.0567 €/kWh due to the rules that all on-site generated electricity that is above the on-site electricity consumption is not included in the net-metering agreement. In consequence of electricity overproduction, in case of MiCHP(H_2), the PV installation is never needed. The situation is the same for level 1 and level 2 of MiCHP(biogas).

The PV-MiCHP(biomass) is a somewhat special case, because here energy efficiency is not a cost-effective path towards Net ZEB, and the total annual cost grows with more demanding energy frame. It is a consequence of higher share of CHP-electricity in overall renewable electricity generation for the Net ZEB with high energy use, and hence smaller PV area, which results in decreasing cost of renewable energy supplying systems.

3.2. Life cycle cost versus upfront investment

Although buildings are durable and building decisions have long-term consequences [51], often, building owners or investors focus only on the investment cost when they make decisions about, e.g., building design, equipment, energy systems, and they fully neglect future operation or replacement costs [33]. Unfortunately, this can lead to less cost-optimal building design when seeing this in a long-term perspective. Figs. 5 and 7 confirm this hypothesis. Not only is energy efficiency not cost-effective path towards cost-optimal Net ZEB in nine out of ten systems if cost benefits, such like, lower fuel cost or lower replacement cost are fully neglected. But also the district heating is a cheaper solution for heating the Net ZEB than a ground source heat pump.

Table 9
PV and windmill price overview.

	Unit	Small-scale		Large-scale	Ref
Photovoltaic	€/W	>10 kW	2.7–5.4	3.2–3.7	[26,49]
		<10 kW	2.7–6.7		
Windmill	€/W	2.7–8.0		~1.5	[50]

3.3. Annual cost of renewable energy supply systems and energy

For this analysis only the cost of level 0 energy frame are presented, as overall picture for level 1 and level 2 are similar as for level 0.

By excluding constant cost, namely the cost of construction, installations, subscription fees of electricity, water and sewage utilities, we can evaluate the life cycle cost of particular renewable energy supply systems and associated energy cost (including the cost/benefit of building-grid electricity exchange). Fig. 8 shows that only the PV-HP alterative has no energy cost, and its cost depends only on the technology prices. The reason for this is the net-metering agreement for exporting and importing electricity. The remaining four on-site supply options also exchange electricity applying the net-metering rule; however, they have additional fuel cost - MiCHPs and district heating cost - PV-DH, and small income due to excess on-site electricity generation. In case of MiCHP(H_2), the fuel cost is actually higher than the technology cost 53–45%, respectively. The off-site supply options have larger part of the annual cost used for energy cost, and thus the total annual costs are more sensitive for the energy prices fluctuations than the on-site supply options.

4. Sensitivity analysis

The robustness of the LCC analysis is verified by a sensitivity analysis of 3 parameters, in particular energy cost, real interest rate and PV price.

4.1. Energy cost

Table 10 presents three energy price scenarios included in the sensitivity analysis. This is based on the assumption that the prices of fuel and electricity will follow the change in oil prices [30]. The medium level represents the base line scenario corresponding to the 2010 price level. The high price level is based on *Current Policies* scenario included in the World Energy Outlook 2010 [52]. The low price scenario is calculated by subtracting the difference between the higher and the current fuel price level in the base line. The district heating cost scenarios are based on the 2010 heat prices in Denmark. The low price level represents the lowest 10% of prices and high price level corresponds to highest 10% of prices. It should be noted that the feed-in tariffs are constant, because it is not expected that they will follow the changes of energy prices.

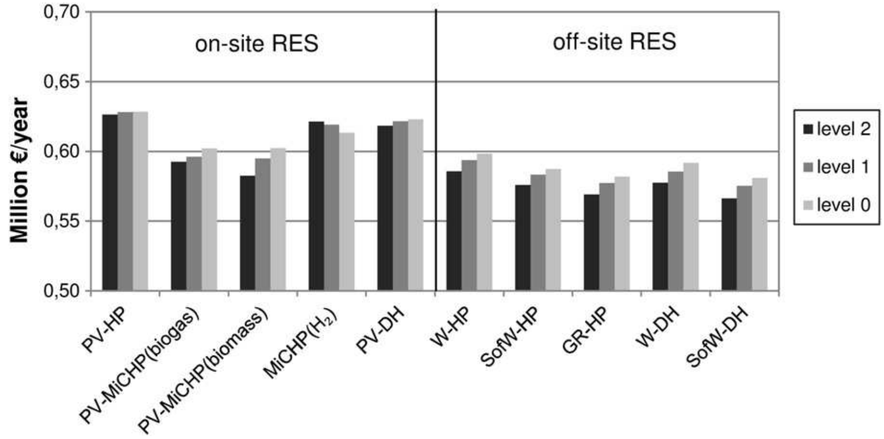

Fig. 7. Annual cost of the upfront investment of three levels of energy performance requirements and ten renewable energy supply systems.

The trend of total annual cost decreasing with more demanding energy frame for on-site renewable energy supply systems and the reverse trend for off-site systems is unchanged for low-energy price scenario. The cost-effective on-site RES is PV-MiCHP(biomass) and for the off-site RES it is SofW-HP and GR-HP having almost the same total annual cost. The decrease of total annual cost is most significant for the systems with high fuel consumption, e.g., MiCHP(H_2) system on average 13% reduction, and less significant for other systems, e.g., WM-HP, SofW-HP and GR-HP on average 4% reduction. The total annual cost of PV-HP system is unchanged.

For the scenario of high energy price, the total annual costs of the on-site RES have the same overall picture; however, the picture of total annual cost of the off-site systems changes. The total annual cost of WM-HP, SofW-HP and GR-HP systems have the lowest cost for level 0 energy frame. As for cost-effective system, the PV-MiCHP(biomass) system results to be the cost-effective option among ten RES options. Moreover, the total annual cost of level 0 energy frame for the on-site and off-site systems are more even, see Fig. 9.

4.2. PV price

Based on the current technology development and growing interest in photovoltaic panels [53], it is expected that price of 1 m^2 of PV panels decreases with time. Therefore, the sensitivity analysis is performed for two price scenarios, i.e., reduction by 50% and by 75% of the base line PV cost, which is 2992 €/m^2 and 1496 €/m^2, respectively. Moreover, only the systems including PV are analysed in this chapter, namely PV-HP, PV-MiCHP(biogas), PV-MiCHP(biomass) and PV-DH.

Fig. 10 shows that for both PV-HP and PV-DH, the trend for lower total annual cost with more demanding energy frame is reversed already for 50% price reduction. However, due to high constant cost, i.e., construction, installation, utilise subscriptions, the different is not so significant. As expected, the slope of trend line is for 75% reduction higher than for 50%. For the PV-MiCHP(biogas) and the PV-MiCHP(biomass) the total annual cost are lower for decreasing PV price; however, the overall trends of the total annual cost do not change.

For 50% PV price reduction, the total annual cost of PV-HP and PV-MiCHP(biomass) for all three energy frames are on the same level as the cost of SofW-HP and GR-HP. However, the distribution of the life cycle cost is different, as indicated in chapter 3.4. Further reduction of the PV price by 25% results in the PH-HP being the cost-effective RES system, and the PV-DH has lower total annual cost than two other DH alternatives, see Fig. 11.

4.3. Real interest rate

As advised by [30], the sensitivity analysis is computed by applying lower (1%) or higher (6%) real interest rate, compared to

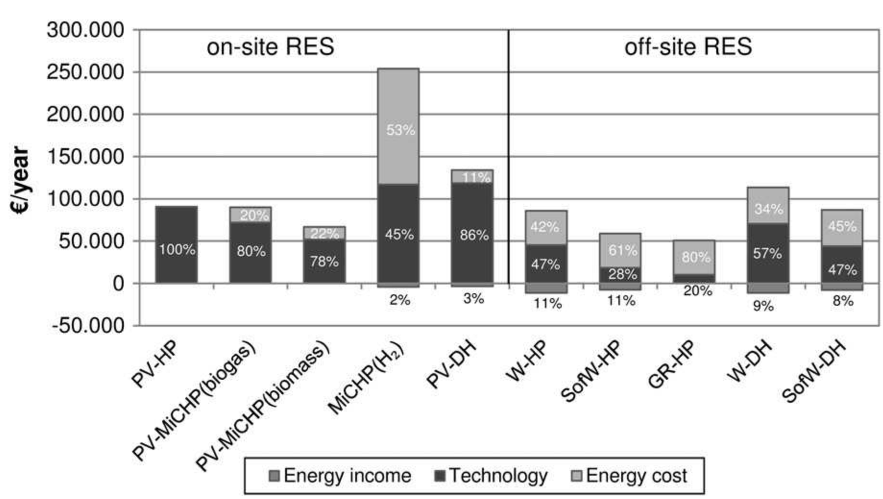

Fig. 8. Annual cost of renewable energy systems (technology), fuel, district heating and electricity (energy cost) and annual income from feeding electricity back to grid (energy income) of level 0 and ten alternatives of the renewable energy supply options.

Table 10
Energy price scenarios.

€/unit	Electricity	Green electricity	Biogas	Biomass	Hydrogen	District heating	
	kWh	kWh	m^3	GJ	m^3	kWh	m^2
Low	0.071	0.072	0.192	4.721	0.352	0.051	3.05
Medium	**0.238**	**0.239**	**0.639**	**15.751**	**1.175**	**0.082**	**4.90**
High	0.405	0.406	1.086	26.781	1.998	0.112	7.43

Bolded text represents the base line energy price scenario.

a base case of a 3% real interest rate. The overall picture of the results is not changed, but the cost difference between different renewable energy supply systems is smaller. However, by changing the real interest rate, the cost distribution is changed. By decreasing the real interest rate, decreases also the share of investment cost in the total annual cost. This comes from the effect that the future costs are discounted with lower rate, leading to higher annual-value. The results are opposite when increasing the real interest rate, see Table 11. The difference between the three energy frames is insignificant, around 1%; therefore Table 11 presents the average values. Moreover, Table 11 indicates that the cost distribution varies between different RES systems. For buildings connected to district heating or equipped with MiCHP(H_2) bigger part of the cost is allocated in O&M cost due to high district heating fees and expensive hydrogen, respectively. Net ZEBs with ground source heat pumps have similar cost distribution as buildings with MiCHP on biogas or biomass.

5. Discussion

This paper has deployed a life cycle cost analysis to define the cost-optimal combination between energy efficiency and renewable energy production for a multi-storey residential Net ZEB from private economy perspective. Both on-site and off-site renewable supply options were taken into consideration.

The analysis has shown that the life cycle cost of on-site and off-site RES options have reverse trends. As the total annual costs of the on-site supply options decrease with higher application of energy efficiency, the total annual costs of the off-site supply options increase. Moreover, generally from the private economic perspective, the off-site RES options have lower life cycle cost than the on-site RES options. Although, the off-site RES options have a cost advantage over the on-site RES, there are still a few issues of the off-site options that should be discussed.

Firstly, the off-site renewable energy supply options, e.g., share of a windmill farm or a windmill outside of the building site, require a power grid to transfer the generated energy to the building site. A growing number of the off-site supply options results in higher share of green energy in the overall energy infrastructure and thus lower primary factors of the grid. Therefore, this arises an issue of how the renewable energy should be accounted for to avoid double counting, once in the primary energy factors of the grid and then in the energy balance of a building? Moreover, in consequence of the need for energy transfer through power grid, the off-site energy supply options are more sensitive than on-site RES for fluctuations of energy prices, see Fig. 9. This can be seen as the strong advantage of the on-site RES, because although the total annual cost of, for example PV-HP is higher than W-HP, it is known and fixed for the whole building lifetime.

Furthermore, as indicated in Table 9, windmills are the technology, which is much more cost beneficial when installed in large-scale. As in case of photovoltaic, the cost difference between small- and large-scale installations is not so significant. In addition, the energy use of the building sector is mostly consumed during the daytime, which very well matches the profiles of PV electricity generation. Moreover, looking for the perspective of sustainable development, installing PV on buildings' roofs and facades saves ground for other purposes, e.g. crops growing, forests.

Finally, the on-site energy generating systems are clearly an integrated part of the building design that can contribute to the building's prestige and value, and sometimes can be even seen as an architectural quality. The off-site energy supply systems are more assigned to the particular building owner rather than to the building itself, which means that with change of the building occupants also building status of Net ZEB can be change. However, from architects' perspective, this feature is a very valuable advantage of the off-site RES.

For the current time being, the micro fuel cells CHPs are a rather costly technology, and have a relatively short lifetime of 10 years when comparing to other technologies, e.g., PV with lifetime of 25 years. However, it should be noted that fuel cells is still a developing technology, and it is anticipated a significant price reduction due to commercialization of the production process [26]. Also from the socioeconomic perspective of the Danish energy infrastructure, MiCHPs result to be an expensive solution to heat the buildings, which does not significantly contribute to fuel or CO_2 reductions [37]. As indicated in the results on annual basis the MiCHP(H_2) for all three energy frames and the MiCHP(biogas) for level 1 and level 2 energy frame have high excess electricity production, which increase with higher heat demand of the

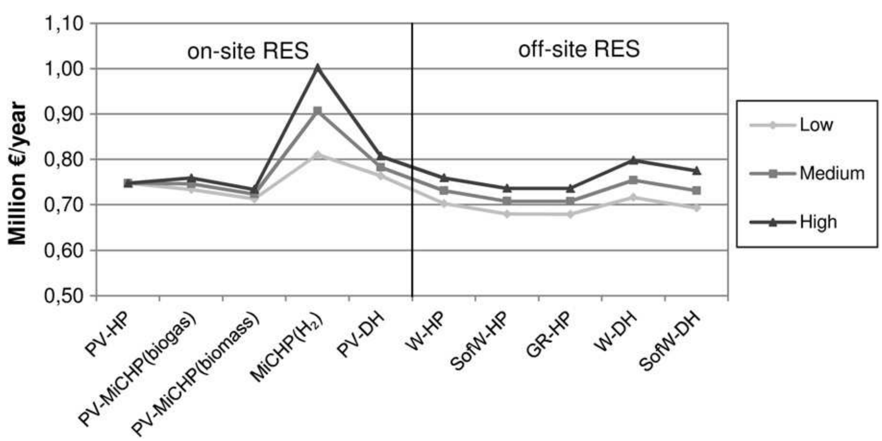

Fig. 9. Total annual cost of three energy cost scenarios for level 0 and ten renewable energy supply systems.

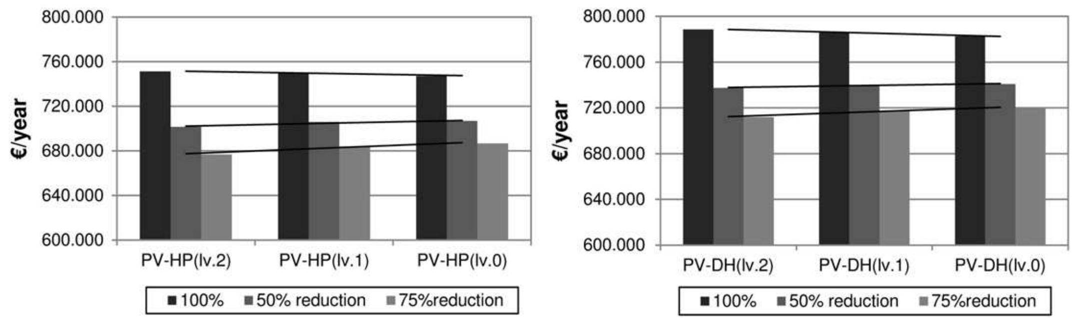

Fig. 10. Total annual cost of PV-HP (left) and PV-DH (right) for three energy frames and three PV price scenarios.

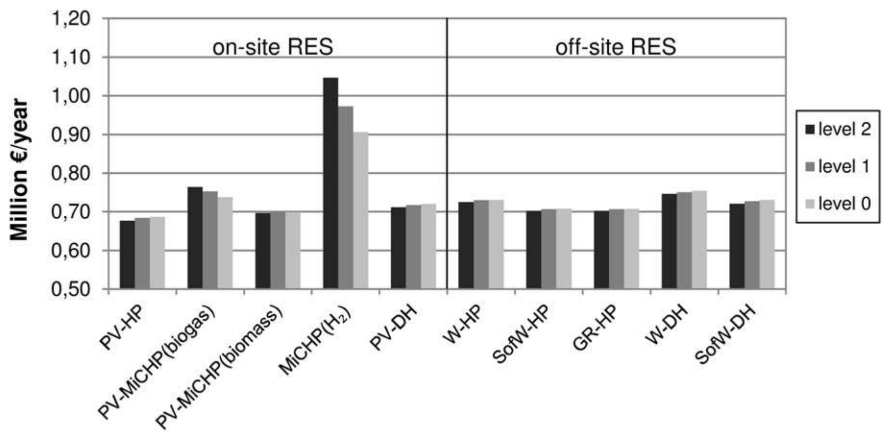

Fig. 11. Total annual cost of three levels of energy performance requirements and ten renewable energy supply systems for 75% reduction of PV price.

building. In this analysis, it was assumed that this electricity is directly exported to the utility grid, thus it produces an income. However, due to low feed-in tariff this income is relatively small comparing to fuel cost, for example, for MiCHP(biogas) level 2 energy frame income from excess electricity is only 7.2% of fuel cost. This issue could be solved by more detailed investigation of capacities of the CHP unit and the boiler.

The micro Stirling CHP on biomass results to be the most cost-effective on-site RES system, which can be a very attractive alternative for the situations in the dense city area, where the roof and/or façade areas are limited. However, similar as micro fuel cell CHPs, in small, building scale it is still a developing technology [54], which needs further investigations. Moreover, especially in dense city areas, there could be an issue of storage of biomass.

Table 11
Distribution of the total annual cost for interest rate of 1%, 3% and 6%.

	Real interest rate	Investment %	O&M %	Replacement %	Demolition %
X-HP	1%	73	12	12	3
	3%	**82**	**9**	**8**	**1**
	6%	90	6	4	0
X-DH	1%	69	18	10	3
	3%	**79**	**13**	**7**	**1**
	6%	87	9	4	0
MiCHP (biogas)	1%	72	11	15	3
MiCHP (biomass)	**3%**	**81**	**8**	**10**	**1**
	6%	89	6	5	0
MiCHP(H_2)	1%	52	27	18	3
	3%	**64**	**22**	**14**	**1**
	6%	75	16	9	0

X stands for photovoltaic, windmill or share of a windmill farm.
Bolded represents the base line real interest rate.

6. Conclusions

The main goal of this paper was to determine the life cycle cost of the on-site and off-site renewable energy supply systems, and to define the cost-optimal relation between energy efficiency and renewable energy generation of these systems for a newly constructed multi-storey residential Net ZEB. The findings of these studies contributes to the on-going discussion of cost-optimal level of energy efficiency for the Net ZEBs, and which renewable supply options should be included in the Net ZEB definition.

The analysis has shown that from the private economy perspective and with the current technologies' cost and energy price, in 4 out of 5 on-site RES options investment in energy efficiency is more cost-effective decision than investment in renewable energy technologies. However, decrease in PV price by 50% changes the life cycle cost trends for the PV-HP and PV-DH alternatives. The off-site RES options have a reverse life cycle cost trend, and for all systems the combination of less demining energy frame and high renewable energy generation is the most cost-optimal path towards Net ZEB. Hence, the off-site renewable energy supply options are not in-line with the Danish initiatives of further decrease of minimum energy performance requirements beyond 2010 regulations.

For the on-site and off-site RES options, the cost-effective system is PV-MiCHP(biomass) and SofW-HP or GR-HP, respectively. Moreover, the SofW-HP and GR-HP systems are also the cost-effective systems among all ten renewable energy supply options. However, as presented in Fig. 11, with the PV price reduction by 75%, the PV-HP results to be the cost-effective system.

Although, the on-site RES systems have slightly higher life cycle cost than the off-site RES systems, they have a smaller part of the life cycle cost allocated in the energy cost. Therefore, from the private economy perspective, these renewable energy supply options could be seen as more save investment, as it is more robust for the fluctuations of the energy prices.

This analysis did not take into consideration such a factor as convenience of various renewable energy supply options. However, it is clear that some options could be seen as more convenient than the others. For example, the off-site RES neither influence the design of a building nor occupy space inside or outside a building. However, having an off-site windmill requires that the building owner has also a peace of ground in a location with good wind conditions. In the case of the on-site RES, the PV panels could be seen as more convenient than the micro fuel cells CHP units. Firstly, they could be easily integrated into the building design, and secondly they do not require any technical room to be place in or storage for fuel, e.g. wood pallets.

The results also indicated that, not taking into consideration the future cost, i.e., the cost of replacement, operation and maintenance during the building design process, thus a lack of life cycle cost perspective in the decision making process, leads to a non-cost-optimal building design.

Finally, it can be concluded that the increase of resolution from monthly to hourly does not have a significant influence of the life cycle cost results. Therefore, the mean monthly-based steady-state calculation tool Be10 can be used as software for the calculations of energy demands of the building.

It should be emphasized, that the authors acknowledge that the modular type of the building construction and analysis of only one Net ZEB topology could be seen as the limitation of this life cycle cost analysis.

Acknowledgements

The authors would like to acknowledge the Aalborg Forsyningsvirksomhederne, Energinet.dk, H2 Logic, BAU-HOW, Danfoss, Velfac for support in data collecting. The financial support from Energiteknologisk Udviklings- og Demonstrationsprogram (EUDP) is gratefully acknowledged.

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