Cost Optimization of a Zero-Emission Office Building

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Abstract: The cost-effectiveness of energy efficiency measures meant to achieve a zero-emission office building is investigated and compared to business as usual energy efficiency measures. The laboratory for zero emission buildings, the ZEB Lab, located in Trondheim, Norway, is an office building designed and built to compensate its lifecycle emissions with the use of a large array of building-integrated photovoltaic panels, pursuing a zero-emissions ambition level. Three design alternatives are investigated by downgrading the building insulation level to the values recommended by the currently enforced Norwegian building code, the byggteknisk forskrift TEK17. A sensitivity analysis of the variation of the installed area of the photovoltaic panels is performed to evaluate if smaller areas give better cost performances. Net present values are calculated by using three scenarios of future increase of electricity price for a time horizon of 20 years. Results show that business as usual solutions give higher net present values. Optimized areas of the photovoltaic panels further increase the net present values of the business as usual solutions in the highest electricity price scenario. The zero-emission ambition level shows a higher net present value than that of the business as usual solutions for a time horizon of at least 36 years.

1. Introduction

Both the building industry and the building stock are energy-intensive sectors and cause significant greenhouse gas (GHG) emissions. Production, installation, transportation and disposal of building materials, and energy use are the main forces driving the current energy consumption rate. The building sector in the European Union (EU) accounted for 42% of total primary energy use in 2017 [1]. To pursue the planned reduction of GHG emissions in the EU industrial sectors [2], the European Commission set an ambitious energy performance for new buildings in the Energy Performance of Buildings Directive [3] and the 2016 Commission Recommendation [4] by defining nearly Zero Energy Buildings (nZEBs) and promoting their implementation in new buildings construction and renovation activities. nZEBs are defined as very energy efficient buildings whose low energy demand is to be covered by renewables. The quantification of the buildings' energy demand is left to each Member State (MS) to decide according to climatic conditions and national methods for the energy calculations. This led to a variety of nZEB definitions across the MSs in terms of building categories, boundaries for calculating the energy inflows/outflows, and national input data used in the energy calculation [5]. The European Commission highlighted that the national definitions of the nZEB are to implement levels of energy efficiency which should not be below the cost-optimal level of minimum requirements [4]. The cost–optimal level is defined as "the energy performance level which leads to the lowest cost during the estimated economic lifecycle" [3] from a financial perspective (lowest cost by considering the operational energy cost, the energy-related investment cost, and maintenance costs) and a macro-economic perspective (lowest

costs and highest benefits for society as a whole). Cost-optimality of nZEB designs and solutions has been widely discussed in literature. An overview of publications on this topic is presented by Ferrara et al. [6]. In this review, a cost-optimal primary energy performance of multi-family buildings is found between 120 kWh/m² years and 140 kWh/m² year for a global cost ranging from 250 EUR/m² and 400 EUR/m², for the regions in Europe with a humid continental climate according to the Köppen–Geiger climate classification. For such buildings, the U-value of external walls and roof vary between 0.12 W/m² K and 0.4 W/m² K, and between 0.09 W/m² K and 0.13 W/m² K, respectively. Most employed energy systems in residential (single-family and multi-family) and non-residential buildings falling in this climatic region rely on photovoltaic systems coupled with ground-source heat pumps. Kurnitski et al. [7] determined the cost-optimality of a reference nZEB office in Estonia and found that the cost-optimal design was achieved by district heating and yielded 140 kWh/m²·y of annual primary energy use and negative Net Present Value (NPV) in comparison to the business-as-usual (BAU) scenario. This was achieved by reducing the building's specific heat loss coefficient from 0.55 W/K·m² to 0.25 W/K·m² for the BAU and nZEB scenario, respectively. Hamdy et al. [8] developed an optimization method for finding cost-optimal solutions of nZEBs. They applied their method of analysis to a single-family house in Finland and found that higher energy-price-increase scenarios make investments in renewables more favorable than increasing insulation towards passive-house solutions. However, on-site renewables come with the drawback of a high investment cost and thus small photovoltaic (PV) systems can compete with other energy saving strategies for reaching cost-optimality. Arumägi and Kalamees [9] calculated the cost-optimality of a wooden nZEB kindergarten in Estonia. They showed that the most cost-effective solution for improving the insulation level of the building envelope is given by installing more energy-efficient windows first (max investment of EUR 13 per kWh/m²·y), and then by increasing the insulation thickness in the rest of the envelope (max investment EUR 80 per kWh/m²·y). Installation of PV panels gives the lowest investment per kWh of annual primary energy use. Niemelä et al. [10] investigated the cost optimality of different renovation measures applied to a building in Lappeenranta University of Technology to reach the national nZEB requirements. They calculated the cost optimality by varying the power output of a Ground Source Heat Pump (GSHP), the area of an on-site PV system, the thickness of insulation of the building envelope, and the insulation value of the windows. They found that a cost-optimal solution is given for a primary energy use of 95 kWh/m² year. By reducing the building's target of primary energy use below 65 kWh/m², the increase in NPV is higher than the improvement of the building's energy performance. They found that increasing the thermal insulation of the building envelope alone is not a cost-effective measure, whereas the largest improvement of the building's energy performance is shown to be given by the on-site PV system.

A Zero Emission Building (ZEB) is defined as a building that "produces at least as much emissions-free renewable energy as it uses from emissions-producing energy sources" [11]. This allows for defining different ZEB concepts based on which stages of the building's lifecycle are considered. From the definition of the building's lifecycle stages given in the EN 15978:2011, the Norwegian Research Centre on Zero Emission Buildings [12] provided different definitions of zero-emission buildings based on various ambition levels. The proposed ZEB definitions and corresponding ambition levels [13] are the followings:

- ZEB-O-EQ (zero GHG emission balance of operational energy use excluding energy use for appliances and equipment)
- ZEB-O (as above plus energy use for appliances and equipment)
- ZEB-OM (as above plus the embodied emissions of materials and their replacement)
- ZEB-COM (as above plus the emissions from the construction activities)
- ZEB-COME (as above plus emissions from building decommissioning and waste processing)

To achieve the highest ZEB ambition levels (ZEB-COM and ZEB-COME), the GHG emissions-credit generated from the on-site renewables have to counterbalance the embodied emissions from materials

production and their replacement. Therefore, moving from a nZEB to a ZEB requires an increased effort on energy saving measures and technologies and a holistic approach to reduce the building's embodied GHG emissions. Moreover, given the GHG emission balance is based on the energy-to-emission conversion factor, high ZEB ambition levels (ZEB-COM and ZEB-COME) would be difficult to reach with a low-carbon-intensity electricity grid [14,15]. Therefore, the large use of wood-based materials in substitution of concrete and other emission-intensive materials [16] helps reducing the impact of one building's embodied emissions to reach more easily such ZEB ambition levels. As occurred in many European countries [17], the Norwegian building regulation (TEK) became more stringent in relation to buildings' energy use and requirements for insulation values [18]. As an example, the TEK 1997 defined an insulation values of 1.6 W/m^2 K for windows of rooms at temperature higher than 20 °C, and in its revision of 2007, a limit of 165 kWh/m^2 year of net energy need was defined for office buildings. The currently enforced TEK17 [19] defines a maximum net energy need of 115 kWh/m^2 year and an insulation value of 1.2 W/m^2 K for windows in any room. However, as described in Sartori et al. [20], the path towards ZEBs requires both better than BAU energy efficiency measures and the installation of on-site renewables. Environmental impact analyses of buildings are typically performed on a time-horizon of 50–60 years, which considers the average service life of buildings and of most of their components [21]. Moreover, the impact of GHGs on the radiative forcing in the Earth atmosphere is typically calculated for a 100-year time-horizon [22]. In such a perspective, buildings designed to target zero GHG emissions during their service lives sport solutions that are optimized for long-lasting environmental effects. On the other hand, most of non-residential buildings' cost optimization analyses are performed with a time-horizon of 20 years [6], which is in line with the recommendation of the Delegated Regulation (EU) No 244/2012 of the European Commission [23]. This may lead to cost-optimized results that do not reflect the environmental benefits for which these buildings were designed.

This paper presents the results of a cost analysis of one of the demonstration buildings investigated in NERO. NERO is a Horizon 2020 Coordination and Support Action [24] which aims at demonstrating technical solutions for the cost reduction in wooden nZEBs, compared to BAU practices. The Norwegian demonstration building investigated in NERO is a ZEB office building recently completed in Trondheim, the ZEB Lab [25]. The ZEB Lab was designed to be a zero-emission building, and specifically a ZEB-COM office. For this reason, additional measures of thermal insulation and a large array of PV panels were implemented in the building to reach an energy performance lower than the requirements of the currently enforced Norwegian building code, the TEK17. The scope of this paper is to investigate if the energy efficiency measures used in the ZEB-COM design are profitable in relation to the minimum requirements of TEK17 standard, by extending the time-horizon beyond the recommended 20 years.

This paper is structured as such:

- First, description of the demonstration building and method used in the cost analysis;
- Second, the results are presented and divided in those pertaining the simulated energy performance of the building, those pertaining the cost and profitability of the ZEB level solution compared to the building code requirements, and those pertaining to the optimal PV area in relation to minimal investment cost;
- Third, the consequences of the findings of this paper and the limitations of the analysis method are discussed;
- Fourth and last, conclusions from this work are drawn.

2. Materials and Methods

2.1. Building Description

The ZEB Lab is the newly built office and educational building for SINTEF (Trondheim, Norway) and NTNU (Trondheim, Norway) employees. Its completion and opening are expected in October 2020. The building, located in Trondheim, Norway, consists of four floors with a Heated Floor Area

(HFA) of 1742 m^2 and a Gross Total Area (GTA) of 2001 m^2. The ZEB Lab is designed according to the ZEB-COM definition. The electricity-to-GHG-emissions conversion factor is calculated according to the future EU energy imports–exports scenario that optimizes the use of renewable sources to achieve a carbon-neutral electricity grid by 2054 [14,26]. The zero balance of the GHG–emissions over the building's lifetime is achieved by feeding the electricity grid with a yearly surplus of renewable energy provided by the building integrated photovoltaic panels (BIPVs). The ZEB Lab, therefore, displays an area of 1170 m^2 of BIPVs on the roof, the south, east, and west facades. Details of installed area and characteristics of the BIPVs are in Table 1.

Table 1. Main characteristics of the building integrated photovoltaic panel (BIPV) installed on the zero-emission building (ZEB) Lab.

PV Location	Module Efficiency (%)	Area (m^2)	kWp	Azimuth (°)	Altitude (°)	Energy Production (kWh/Year)	Energy Production (kWh/m^2·Year)	PV Module Type
Roof	21.5 [1]	524	112	0	30	108,669	207	Mono-SI
Shelter area-1	16.1 [1]	152	24	0	40	23,312	153	Multi-SI
Shelter area-2	16.1 [1]	14	2	0	40	2147	153	Multi-SI
South façade-1	21.5 [1]	117	24	0	90	20,736	177	Mono-SI
South façade-2	16.1 [1]	13	2	0	90	1800	138	Multi-SI
East façade	16.1 [1]	175	28	−90	90	16,217	93	Multi-SI
West facade	16.1 [1]	175	28	66	90	19,056	109	Multi-SI
Total	-	**1170**	**220**			**191,937** [2]	**164**	-

[1] A yearly degradation rate of 0.28% is applied to the module efficiency. The efficiency loss is retrieved from the technical sheet of the PV module. [2] An overall efficiency loss of 15% is applied to the BIPV system. The resulting total energy production is 163,146 kWh/year equal to 139 kWh/m^2·year.

The building ventilation is supplied via a hybrid ventilation system with a heat recovery of 80%. The specific fans' power (SFP) is reduced from 1 kW/m^3/s during the occupied time to 0.5 kW/m^3/s during the unoccupied time. The design SFP-values are considered ambitious compared to conventional buildings and are possible due to a displacement ventilation system and by using the stairwells for extracting air. This solution is found in similar high-energy-efficient buildings in Norway, such as in the Powerhouse Kjørbo and Powerhouse Brattørkaia [27]. The heating system consists of a ground source heat pump (Q = 25 kW) which covers space heating, air heating, and domestic hot water.

To minimize the embodied GHG emissions of the building materials, wood products are largely used in the building. The building's structural system consists of an external frame of glulam trusses and internal CLT elements (vertical partitions, stairwells, elevator shaft, and floors). The façades are built on a timber frame anchored to the above-mentioned glulam frame. Concrete is used in the building's foundation and ground floor.

2.2. Parameters of the Energy Calculations

The currently enforced building code in Norway is the TEK17 which requires new office buildings to have a yearly net energy need equal or lower than 115 kWh/m^2·year. In addition to the above, minimum requirements of the insulation values and air tightness of the building's envelope must also be fulfilled, and these are described in Table 2.

Table 2. TEK17 energy efficiency requirements and ZEB Lab values.

Reference	Windows and Doors (W/m²·K)	Roof (W/m²·K)	External Walls (W/m²·K)	Floor (W/m²·K)	Infiltration Rate at 50 Pa (ACH) [1]
TEK17 minimum requirements	≤1.20	≤0.18	≤0.22	≤0.18	≤1.50
ZEB-COM	0.80	0.09	0.15	0.10	0.30

[1] ACH = air changes per hour.

To comply with the ZEB-COM definition, the building is highly insulated and airtight, by a larger extent that what is required by the TEK17, as the Table 2 shows.

To investigate the cost effectiveness of the ZEB Lab energy efficiency solution (ZEB-COM), the as-built design of ZEB Lab is compared to three different variants satisfying the above-mentioned requirements of TEK17. The ZEB-COM and three TEK17-variants are modelled and simulated in SIMIEN (v6.012) [28]. SIMIEN (ProgramByggerne AS, Skollenborg, Norway) is a commercial software largely used in Norway for buildings' energy assessment in compliance with the TEK code. SIMIEN allows for dynamic energy simulations based on a resistance-capacitance model of the building. Thus, differently from tools based on differential equations (such as Energyplus and IDA Indoor Climate and Energy IDA ICE), it relies on a simpler calculation method. Features of the software includes separation into thermal zones, but for this energy calculation only one zone was used, as the main focus was the heat loss from the building envelope. Climatic inputs, such as solar radiation, wind direction and velocity, air temperature, humidity and CO_2 level, and internal loads, such as lighting, technical equipment, water heating and people, are used to calculate the change in the condition of the building at 15-min intervals. The building body's heat storage and dissipation are taken into account. The simulation follows the model for dynamic simulation of energy needs described in NS 3031:2007. The standard assessment procedure, described in the NS 3031:2014, requires the building to be simulated with standard input data from the NS 3031:2014. This includes relatively high values of energy use for lighting and appliances compared to those used in the design of the ZEB Lab, as Table 3 shows.

Table 3. NS 3031 energy consumptions for building end-uses and ZEB Lab values.

Reference	Lighting (kWh/m²·Year)	Technical Equipment (kWh/m²·Year)	Domestic Hot Water (kWh/m²·Year)	Total (kWh/m²·Year)
NS 3031:2014	25.0	34.0	5.0	64.0
ZEB-COM	9.4	10.0	1.0	20.4

Moreover, the energy assessment procedure for the TEK17 requires simulations to be performed with Oslo-climate, even though the ZEB Lab is in Trondheim, thus resulting in a different yearly energy performance. The following climatic data are used in SIMIEN: external dry bulb air temperature, relative humidity, wind velocity and direction, direct and diffused solar radiation, sun azimuth and altitude.

Therefore, to include the TEK17 procedure in the energy calculations presented in this paper, a two-step analysis is performed. First, the yearly net energy need of the TEK17 variants and the ZEB-COM are simulated with the Oslo climate and by using the standard inputs of the energy end-uses described in the NS 3031:2014. Despite the climatic difference between Oslo and Trondheim, the Oslo climate is used in the first step to follow the energy performance assessment according to the NS 3031:2014. To make sure all the TEK17 variants comply with the required net energy need of 115 kWh/m²·year, variations of the infiltration rate and the insulation values of windows, doors, roof, facades, and ground floor are performed, as described in Table 4.

Table 4. Variation of the U-values of the building components from the ZEB-COM design values.

Variation of Minimum Requirements	Net Energy Need with Oslo Climate [kWh/m²·Year]
ZEB-COM	95.8
Windows, U-value 0.8 -> 1.2 W/m²·K	104.2
Doors, U-value 0.8 -> 1.2 W/m²·K	96.3
Roof, U-value 0.09 -> 0.18 W/m²·K	98.3
External walls, U-value 0.15 -> 0.22 W/m²·K	99.9
Ground floor, U-value 0.10 -> 0.18 W/m²·K	97.1
TEK17 all minimum requirements	125.9

Table 4 shows the results of the variation of the net energy need of the ZEB-COM design by using the TEK17 minimum requirement for each component of the building's envelope. Rows 2–6 of Table 4 show the variation of the net energy need given by changing the insulation value of one building component only. Row 7 shows the net energy need resulting by applying all the TEK17 minimum requirements (described in rows 2–6), which is higher than the TEK17 limit for net energy need.

The result of this analysis is thereafter used to define the three TEK17 variants, which consist of combinations of the above-mentioned insulation values (rows 2–6 in Table 4) made to fulfill the required yearly net energy need (115 kWh/m²·year). The resulting characteristics of the envelope of the ZEB-COM and the three TEK17 variants are therefore described in Table 5.

Table 5. Description of layers and U-value of the building components of the base case and variants.

Building Components	Properties	ZEB-COM	TEK17 v-1	TEK17 v-2	TEK17 v-3
External walls	Layers	Timber frame of solid wood w/mineral wool 223 mm, 73 mm lathing w/mineral wool	Timber frame of solid wood w/mineral wool 223 mm, 73 mm lathing w/mineral wool	Timber frame of solid wood w/mineral wool 150 mm, 50 mm lathing w/mineral wool	Timber frame of solid wood w/mineral wool 150 mm, 50 mm lathing w/mineral wool
	U-value (W/m²·K)	0.15	0.15	0.22	0.22
Roof	Layers	Rafter roof 48 × 400 mm I-studs, 200 + 200 mm mineral wool	Rafter roof 48 × 400 mm I-studs, 200 mm mineral wool	Rafter roof 48 × 400 mm I-studs, 200 + 200 mm mineral wool	Rafter roof 48 × 400 mm I-studs, 200 mm mineral wool
	U-value (W/m²·K)	0.09	0.18	0.09	0.18
Floor	Layers	Floor on foundation. Insulation 250 mm EPS 0.037 W/m·K	Floor on foundation. Insulation 250 mm EPS 0.037 W/m·K	Floor on foundation. Insulation 100 mm EPS 0.037 W/m·K	Floor on foundation. Insulation 250 mm EPS 0.037 W/m·K
	U-value (W/m²·K)	0.10	0.10	0.18	0.10
Windows and glazed doors	Layers	4 mm glass low-e + 16 mm argon + 4 mm glass + 16 mm argon + 4 mm glass low-e	4 mm glass + 16 mm argon + 4 mm glass low-e	4 mm glass low-e + 16 mm argon + 4 mm glass + 16 mm argon + 4 mm glass low-e	4 mm glass + 16 mm argon + 4 mm glass low-e
	U-value (W/m²·K)	0.80	1.20	0.80	1.20

Despite being the infiltration rate a known factor of buildings' energy losses, its variation is not considered in the second step of the energy simulations, and it is set to 0.3 air changes per hour (ACH) at 50 Pa for all the three variants and the ZEB-COM, which is the air infiltration rate designed for the ZEB lab. This is because the cost difference of implementing lower airtightness solutions in the building could not be quantified. However, preliminary energy simulations of the building with different infiltration rates showed that by increasing the infiltration rate from 0.3 ACH to 1.5 ACH (minimum requirements of TEK17), the yearly net energy need for heating and ventilation increases by 11 kWh/m²·year, equivalent to a 11.5% increase in net energy need. The difference between operational costs given by the variation of the building's airtightness is discussed in Section 4.

Second, the ZEB-COM and the three variants are simulated with the Trondheim climate and by using the internal energy loads designed for the ZEB-COM (shown in Table 3). The delivered energy

of the four designs is calculated by including the annual system efficiency (COP = 3) of the heat pump, and the cost analysis is then performed on this last set of simulations. The heat pump covers 100% of the heating load and 70% of the domestic hot water (DHW) demand, of which the remaining 30% is covered by direct electricity. The building is not designed to have a cooling system, except for only two identical rooms used for research purposes on the indoor environment, and for this reason energy for cooling is not calculated. The annual temperature efficiency of the heat recovery is set to 80% in the energy simulations of all the four designs. The yearly energy production of the BIPV system is calculated by using the Photovoltaic Geographical Information System (PVGIS) available at the EU Science Hub web page (www.ec.europa.eu/jrc/en/pvgis) and inputs given in Table 1.

2.3. Parameters of the Cost Analysis

2.3.1. Energy Price

Given the energy system of the building is entirely run by electricity, the variation of the future electricity price is expected to influence the global cost of the ZEB-COM and the variants by a large extent. The electricity price used in this calculation is the sum of the electricity fee, the grid rent, the electricity price, and the value added tax (VAT). The electricity fee (or consumption tax) is set by the Norwegian government and change slightly over time. The price of the grid rent is paid to the local grid company and it depends on the county where the building is located in. The grid rent price varies throughout the year and it is typically more expensive in winter than in summer due to higher peak demands. For non-residential buildings, such as the ZEB Lab, the grid rent price is set according to the highest average of hourly power consumption in peak months. As measurement data of the ZEB Lab power demand is not yet available, a flat historical price for a similar reference building (40 kW and 160,000 kWh/year) was used for the grid rent price, which is set to 0.028 EUR/kWh [29]. This is the 2019 average of the grid rent price in the Trøndelag county, where the ZEB Lab is located. The electricity price is fluctuating throughout the year and the price given in Table 6 is the historic average of the national electricity price for year 2019.

Table 6. Variation of the U-values of the building components from the ZEB-COM design values.

Electricity Cost Items	NOK/kWh	EUR/kWh [1]
Electricity fee [30]	0.16	0.015
Grid rent [29]	0.30	0.028
Electricity price [30]	0.45	0.042
Sum	0.91	0.085
VAT (25%)	0.23	0.021
Total	1.14	0.106

[1] NOK/EUR currency conversion set at 15.09.2020. 1 NOK = 0.094 EUR.

The above-mentioned prices are all given in NOK/kWh and converted to EUR/kWh by the NOK/EUR currency rate set at 15.09.2020. Since future energy prices depend on numerous factors, such as the renewable energy share in the EU, price of CO_2-quotas, political decisions, and so on, it was decided to perform a sensitivity analysis by simulating three scenarios of 2%, 4% and 6% electricity price increase per year.

2.3.2. Cost of Building Components

The cost of the building components designed according to either the TEK17 minimum requirements or the ZEB-COM design requirements are retrieved from the Norsk Prisbok [31] and shown in Table 7.

Table 7. Cost of the building components for the ZEB-COM and TEK17 variants.

| Building Component | | | ZEB-COM Design Requirements (Table 2) | | TEK17 Minimum Requirements (Table 2) | |
Name	Area (m²)	Service Life (Years)	Cost (EUR/m²)	Cost (EUR)	Cost (EUR/m²)	Cost (EUR)
External walls	1130	60	224	252,838	175	197,750
Roof	535	60	229	122,381	193	102,988
Ground floor	440	60	133	58,300	103	45,100
Windows fixed, wood	22	40	505	11,110	411	9048
Windows fixed, wood + alu.	207	60	590	122,130	528	109,193
Windows openable, wood	3	40	680	2040	596	1789
Windows openable, wood + alu.	197	60	721	142,086	644	126,819
Doors	4 pcs	60	1635 [1]	6540	1223 [1]	4890
BIPV system	1170	30	541	633,289	541	633,289

[1] Cost of doors is per piece.

The difference of cost of the building components (e.g., windows, roof, etc.) between the ZEB-COM design requirements and the TEK17 minimum requirements are due to their different insulation values, as described in Tables 2 and 5. There is no difference in the cost of the BIPV system, as this does not vary between the different designs.

The costs include the cost of materials, work hours, and subcontractors, and are to be considered for the whole building components, as described in Table 5, with default layers (laths, plaster, vapor barrier) needed for a full construction. The interior and exterior finishing layers are assumed identical in all the four designs. The costs calculation is performed for the building envelope only (the components that influence the building's energy performance) and therefore the cost of the internal structures is not considered. Four different types of windows are specified: fixed, openable, in wood, and wood with aluminum mantling. The ZEB Lab has both manual and motorized openable windows to enable the hybrid ventilation. Motorized windows are more expensive than manually openable windows, but because no cost information of motorized windows was available in the Norsk Prisbok, all windows are assumed to be manual.

The extra costs associated to increasing the airtightness of the building was not calculated because of little relevant literature. These costs are typically associated to the additional labor costs for craftsmen (carpenters, electricians, and so on), as well as air-tightening products, such as tape, sealing products for components (pipes, ducts, etc.) going through the membranes, fittings, and joint-sealing compounds. Proper planning in the early design phase, more documentation and tests are also needed and produce to additional costs.

2.4. Calculation of the Net Present Value

The Net Present Value (NPV) of the different design solutions is calculated according to Equation (1) by using the method described in the Delegated Regulation (EU) No 244/2012 of the European Commission [23]:

$$C_G(\tau) = C_I + \sum_j \left[\sum_{i=1}^{\tau} (C_{a,i}(j) \cdot R_d(i)) - V_{f,\tau}(j) \right] \tag{1}$$

where τ is the calculation period; $C_G(\tau)$ is the NPV, which calculates the total cost (referred to starting year τ_0) at the end of the calculation period; C_I is the initial investment costs for measure or set of measures j; $C_{a,i}(j)$ is the annual cost during year i for measure or set of measures j; $V_{f,\tau}(j)$ is the residual value of measure or set of measures j at the end of the calculation period (discounted to the starting year τ_0); $R_d(i)$ is the discount factor for year i based on the discount rate. The cost calculations are performed for a time horizon of 20 years (non-residential buildings), starting from year 2020 when the ZEB Lab is completed, and a discount rate of 4% is used. The annual cost of operational energy use $C_{a,i}(j)$ is calculated by multiplying the yearly electricity price by the delivered energy, which includes the energy system efficiency (COP = 3).

The building components have an economic residual value, $V_{f,\tau}(j)$ at year 20 of the calculation period, and this is included in the NPV calculation. It is assumed that the economic residual value

at the end of the component service life is zero. The residual value of each components is therefore calculated according to Equation (2):

$$V_{f,\tau}(j) = C_I(j)/[T(j) \cdot (T(j) - \tau)] \tag{2}$$

where $C_I(j)$ is the initial investment of measure or set of measures j; $T(j)$ is the service life of measure or set of measures j. The service life of the building components was retrieved from environmental product declarations (EPDs). According the EPDs of the windows manufacturer [32], their expected service life varies between 40 and 60 years, depending on the type of window. On the other hand, some studies suggest that windows service life varies between 30 and 50 years [33,34]. A worst-case scenario of 40 years was used for the service life of the windows. The residual value is discounted to the starting year. All the building components and the PV systems are assumed not to be replaced during the calculation period. The price per kWh of the surplus electricity sold to the grid is equivalent to that of the electricity purchased from the grid.

Since the ZEB Lab does not produce profits, the profitability of the base case and the TEK17 variants can be evaluated by assessing the savings from the lower investment against the additional costs for operational energy use. The profitability of the TEK17 variants is therefore given according to Equation (3):

$$P(\tau)_{v\text{-}i} = C_G(\tau)_{ZEB\text{-}COM} - C_G(\tau)_{v\text{-}i} \tag{3}$$

where $P(\tau)_{v\text{-}i}$ is the profitability of the TEK17 variant i for the calculation period τ; $C_G(\tau)_{ZEB\text{-}COM}$ and $C_G(\tau)_{v\text{-}i}$ are the NPVs of the ZEB-COM and TEK17 variant i for the calculation period τ, respectively. According to Equation (3), higher values correspond to higher profitability of the TEK17 variants.

2.5. Calculation of the Cost-Optimal BIPV Area

The area of installed BIPVs is designed to make the ZEB Lab achieve a yearly balance of zero emissions by compensating the emission of operational energy use, the embodied emission of materials and their replacement, and the emissions of construction activities. This means the BIPV system produces more electricity than what is used by the building. It is therefore worth finding the minimum BIPV area for which the sum of the annual costs $C_{a,i}$ is zero for the time horizon of the calculation period (20 years) and the different electricity price scenarios. This is found by performing a what-if analysis with the solver function integrated in Microsoft Excel. The objective of the solver function is set to find the operational and investment cost by varying the BIPV area, and given the following constraints: the variation of the BIPV area is between 0 m² and 1170 m², the total cash inflow/outflow (operational cost minus surplus electricity sold to the grid) for the calculation period is zero. The analysis is performed in two steps. First, the average electricity production per unit area of BIPV is assumed to be the same for all the optimized areas. This means that proportionally smaller areas of BIPV are present on each of the building envelope surfaces described in Table 1. Optimized areas are therefore found. Second, the yearly energy production is adjusted by maximizing the number of PV modules installed on the roof, where the average production is highest. New BIPV optimized areas are therefore calculated with the new area-weighted average electricity production.

3. Results

3.1. Energy Results

Figure 1 shows the net energy need and the delivered energy of the four designs simulated with the Trondheim climate.

Values are normalized to building's HFA. The yearly electricity production of the BIPV is given by the dashed line. The difference between the net energy need and the delivered energy is due to the efficiency of the heat pump (COP = 3), which covers the energy use for heating, ventilation, and DHW. Both the net energy need and delivered energy include the energy use for heating, ventilation, DHW,

lighting and appliances. When simulated with the Trondheim climate, the four designs use less energy than that of the same designs simulated with the Oslo climate. This is due to the lower average outdoor temperature in the heating season in Oslo than that in Trondheim, whose climate has 318 heating degree days less than the climate in Oslo. The ZEB-COM uses 38.4 kWh/m²·year, and the TEK17 variants 1, 2 and 3 use 43.0 kWh/m²·year, 40.6 kWh/m²·year, and 44.7 kWh/m²·year, respectively. The yearly electricity production from the BIPV system is 94.0 kWh/m²·year of HFA.
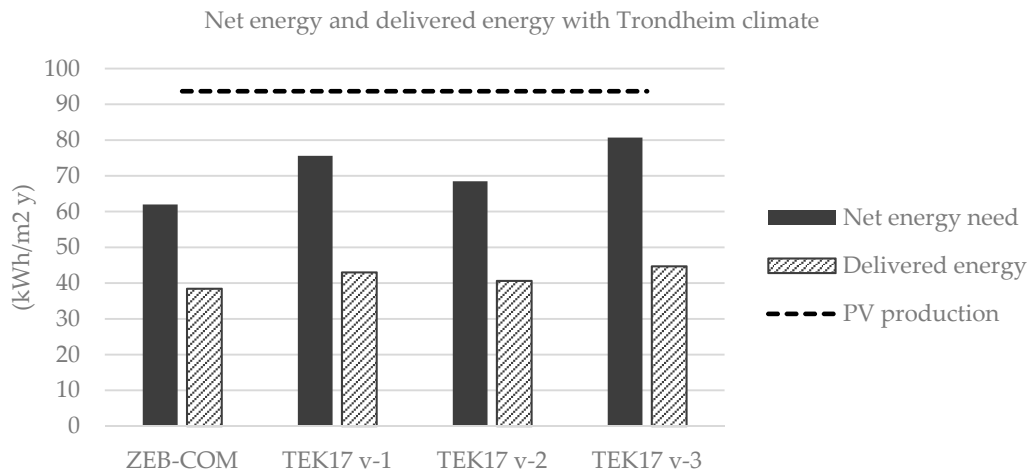
Figure 1. Net energy need and delivered energy of the four designs simulated with the Trondheim climate.

3.2. Cost Results

3.2.1. Total Costs of Designs

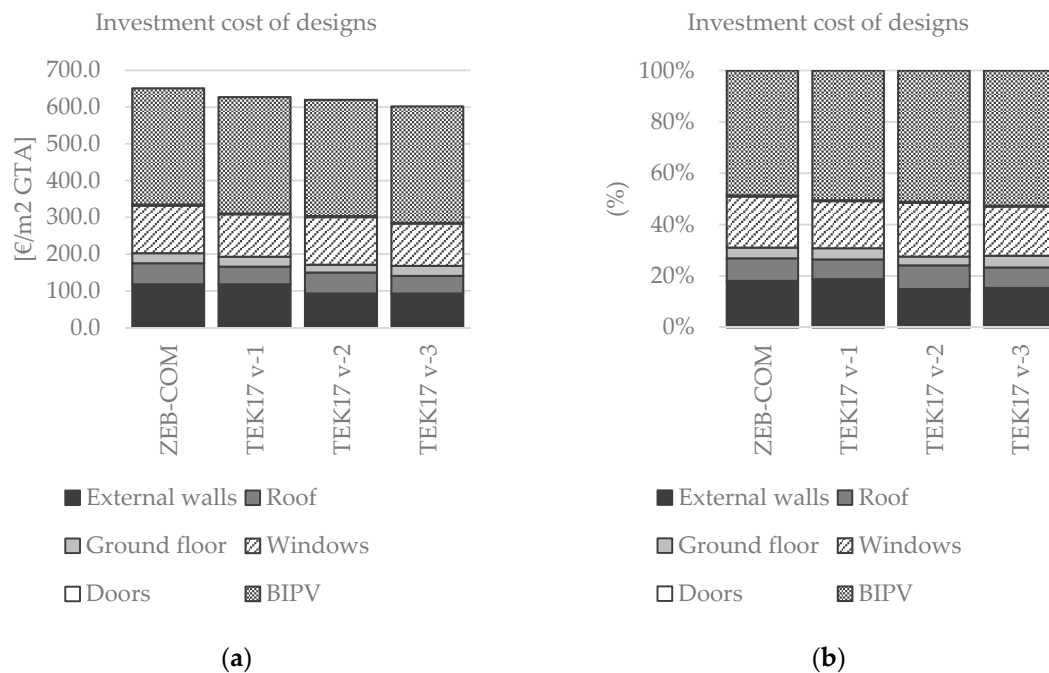Figure 2 shows the initial investment cost C_I of the ZEB-COM and the three TEK17 variants.

Figure 2. Initial investment costs of the four designs shown in euros (**a**) and as shares of the total (**b**).

The values are shown in EUR/m² GTA (Figure 2a) and as shares of the total (Figure 2b). The values include a VAT = 25%. The investment cost of the different solutions is 651.1EUR/m² for the ZEB-COM,

628.8 EUR/m² for the TEK17 variant 1, 619.8 EUR/m² for the TEK17 variant 2, and 601.6 EUR/m² for the TEK17 variant 3. The investment cost of the BIPV (316.5 EUR/m²) is the same for each of the design, and it represent between 49% and 53% of the total initial investment cost of the ZEB-COM and the TEK17 v-3, respectively. The difference of total costs between the ZEB-COM and the TEK v-3 is 49.5 EUR/m² (equal to 99,012 EUR), which corresponds to 15% of the initial investment of the building envelope of the ZEB-COM (excluding the BIPV system). The share of the investment cost of the windows is between 18% and 21% of the total investment of the TEK17 variant 1 and 3, respectively. This is because the windows area (428 m²) is large in comparison to the area of the external walls (1130 m² excluding the windows) and the average windows cost is 3 times the average cost of the external walls. The windows used in the ZEB-COM design cost 15% more than those complying with the minimum TEK17 requirements. The share of the investment cost of the external walls varies between 15% and 19% of the total investment of the TEK17 variant 3 and 1, respectively. The external walls used in the ZEB-COM costs 27% more than thosecomplying with the TEK17 minimum requirement. The ground floor solution used in the ZEB-COM has the highest additional cost in comparison to a TEK17-ground-floor solution, and it is 29% more expensive. Given the small floor area, the share of the ground floor cost is between 3% and 5%, depending on the design. The ZEB-COM roof cost 18% more than the TEK17-roof.

Figure 3 shows the initial investment cost C_I, the sum of the annual costs $C_{a,i}$ (cash inflow from the BIPV electricity sold to the grid minus cash outflow from the operational energy use) during the calculation period (τ = 20 years), the residual value $V_{f,\tau}$ discounted to the starting year, and the net present value (NPV) discounted to the starting year and calculated according to Equation (1).
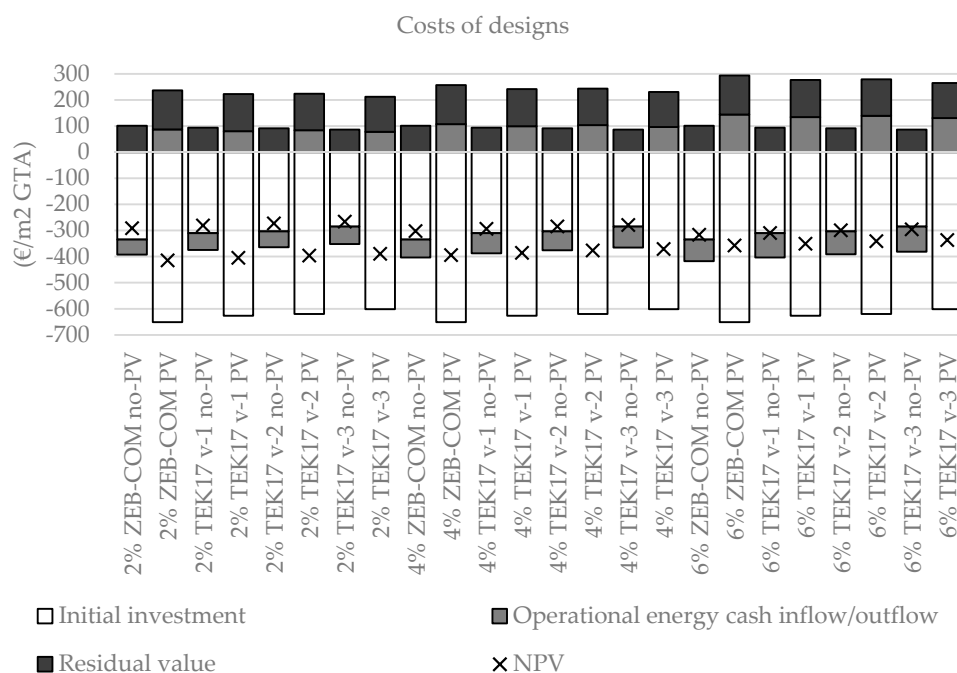

Figure 3. Initial investment costs, residual values, net present values, and sum of the annual costs of the four designs calculated with the 2%, 4%, and 6% electricity price increase scenario. All values are given for the solutions with and without the building integrated photovoltaic panel (BIPV) installed.

The sum of the annual costs is calculated for the three scenarios of electricity price increase, 2%, 4%, and 6%. The NPV is calculated for both the designs with and without the BIPV system to show its overall economic influence on the initial investment costs. Negative values represent costs (cash outflows) whereas positive values represent incomes (cash inflows). In such a perspective, higher NPVs (closer to 0) are preferable to lower NPVs. The residual values are positive because represent capital assets; the annualized costs of the solutions with the BIPV system (operational energy cash

inflow/outflow) are positive because the on-site electricity production is higher than the delivered energy, and thus represent cash inflows.

The result of the NPV calculation shows that all the TEK17 variants yields higher NPVs than that of the ZEB-COM, for any of the electricity price scenario. Moreover, for any of the design and electricity price scenario, the NPV of the solutions without the BIPV system is higher than that of the solutions with the BIPV system. This is because the initial investment of the BIPVs system is not paid back at the end of the calculation period, despite the substantial cash inflow given by the surplus electricity production and the higher residual value. The difference between the NPVs of any of the solution with and without the BIPV decreases at increasing electricity price. This is 123.4 EUR/m^2 for the 2% scenario, 92.0 EUR/m^2 for the 4% scenario, and 42.7 EUR/m^2 for the 6% scenario. The difference between the NPVs represents an additional economic loss that varies between 37% and 12% of the initial investment of the ZEB-COM solution without the BIPV (334.6 EUR/m^2), for the 2% and 6% scenario, respectively. Such a loss is higher for the TEK17 designs because their initial investment is lower than that of the ZEB-COM design. The difference between the operational energy cash inflows/outflows between ZEB-COM and the TEK17 variants describe the additional cost due to higher operational energy use of the TEK17 variants. These are highest for variant 3 and lowest for variant 1, and they increase at increasing electricity price. By looking at variant 3, the additional costs for energy use vary between 9.5 EUR/m^2 (2% scenario) and 13.7 EUR/m^2 (6% scenario), which is 28% of the additional investment needed for the ZEB-COM design. In the worst-case scenario (6% electricity price increase), the expected savings for operational energy use covers less than a third of the additional investment needed for the ZEB-COM. This explains the very small variation of the NPV across the different designs with or without the BIPV system and for the three electricity price scenarios. The main reasons of such a low return of investment are the high cost of materials and labor in Norway in comparison to electricity price, the very efficient energy system, and the very low infiltration rate. It is worth remembering that the sum of the annual cost is discounted to the starting year. In such a perspective, the future electricity price scenario is a critical factor for evaluating the profitability of each of the designs.

Since the surplus of energy production given by the BIPV system does not pay back its initial investment cost, for any of the designs and scenarios in the given calculation period, it is worth investigating if better NPVs can be found by extending the calculation period. Specifically, if the NPVs of the designs with the BIPV become higher than those of the designs without it. Figure 4 shows the variation of the NPVs calculated with 5-year-steps for the designs with the BIPV (continuous lines) and the designs without the BIPV (dashed lines), for the three electricity price increase scenarios.

The continuous lines with cross markers represent the difference between the above-mentioned lines for same designs and electricity price scenarios. The calculation period is extended to 30 years, time at which the BIPV system is expected to be entirely replaced, when its residual value equals zero. The calculation is not carried on beyond this time horizon, as a new investment of BIPV would be needed. Moreover, the cost of manufacturing PV modules has been historically decreasing and it is expected to continue as such. More efficient PV technologies at lower prices are likely to be market available in future years [35], and it is therefore difficult to predict what would be the expected energy production of the future installed system. Despite the calculation period being extended by additional 10 years, the NPVs of all the designs with the BIPV system remain still the lowest. The difference between the two lines (NPV of designs with BIPV minus NPV of designs without BIPV) is maximum at year 25 (EUR 268,582) beyond which starts decreasing.
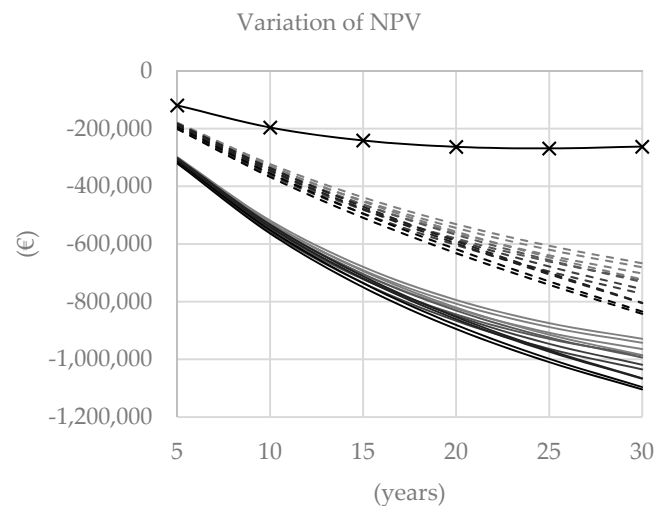
Figure 4. Interpolated and smoothed 5-year-step variation of Net Present Value in relation to different calculation periods for the four designs and the three electricity price increase scenarios. Continuous and dashed lines represent the designs with and without the BIPV, respectively. Continuous line with cross markers represents the difference given by the installation of the BIPV in any of the design.

3.2.2. Profitability of TEK17 Variants

Figure 5 shows the absolute difference between the NPV of the ZEB-COM and the NPV of the TEK17 variants, calculated according to Equation (3).
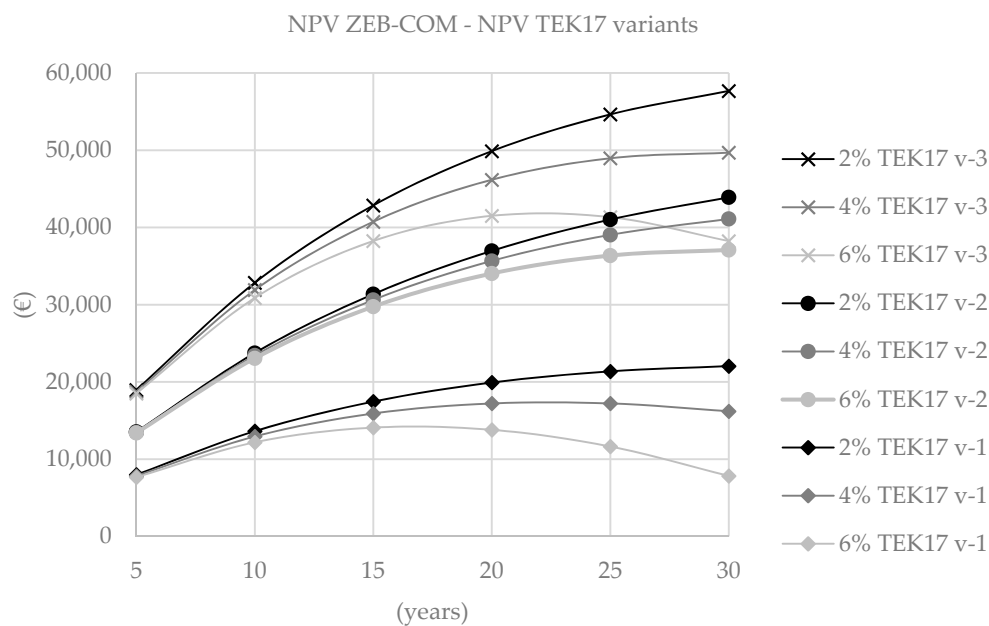

Figure 5. Interpolated and smoothed 5-year-step absolute difference between the NPV of the ZEB-COM and the NPV of the TEK17 variants.

The difference is calculated for designs with correspondingly same electricity price scenarios. Differences between the NPVs of the designs with the BIPV system yields same results, and therefore not shown in figure. It is worth remembering that the NPV is negative for all the designs, as shown in Figure 4. As shown in Figure 5, variant 3 gives the highest profitability in all the electricity price scenarios. Variant 1 gives the lowest profitability in all the electricity price scenarios. It is interesting to note that at increasing the calculation period, the maximum profitability value varies in relation to the electricity price scenario. Specifically, the highest annual electricity price increase makes the peak value

of profitability recede. As an example, the maximum profitability of variant 3 is at year 30 for the 4% scenario (EUR 49,691) and it is at year 22 for the 6% scenario (EUR 42,263). By assuming the calculation period is performed for a time horizon of 60 years, and by including the cost of replacements of the windows with a 40-year service life discounted at year 40 (equivalent to EUR 1680, as shown in the equations in Table 8 and described in Table 7), the polynomial regression equations in Table 8 can be used to estimate at which year the profitability of any given variant equals zero.

Table 8. Polynomial regression equations of the curves in Figure 5.

Variant	y	R^2	y = 0 [Years]
2% TEK17 v-3	$-53.8x^2 + 3403.4x + 3653.6 + 1680$	0.9991	64.8
4% TEK17 v-3	$-61.766x^2 + 3369.5x + 3827.7 + 1680$	0.9986	55.9
6% TEK17 v-3	$-76.789x^2 + 3449.2x + 3547 + 1680$	0.9978	46.3
2% TEK17 v-2	$-36.332x^2 + 2467.4x + 2363.5 + 1680$	0.9994	69.5
4% TEK17 v-2	$-39.123x^2 + 2455.5x + 2424.5 + 1680$	0.9992	64.3
6% TEK17 v-2	$-44.389x^2 + 2483.4x + 2326.1 + 1680$	0.9991	59.7
2% TEK17 v-1	$-24.5x^2 + 1406.2x + 1752 + 1680$	0.9985	59.7
4% TEK17 v-1	$-30.326x^2 + 1381.4x + 1879.4 + 1680$	0.9962	47.9
6% TEK17 v-1	$-41.314x^2 + 1439.7x + 1674$	0.9953	35.9

This tells the time horizon beyond which the ZEB-COM design is more profitable. As shown in Table 8, variant 1 gives the shortest time horizon for the 6% scenario (35.9 years) and does not include the additional investment of EUR 1680 for windows replacement. This is because the ZEB-COM design is more profitable than the TEK17 variant 1 in this scenario before reaching 40 years. The TEK17 variant 1 is followed by variant 3 for the 6% scenario (46.3 years), and variant 1 with the 4% scenario (47.9 years). All the other combinations of variants and electricity price scenarios become less profitable than the ZEB-COM for time horizons longer than 50 years. It is interesting to see in Figure 5 that the difference of profitability between variant 2 and 3 calculated at year 20 decreases considerably for longer time horizons. As shown in Table 8, in the same electricity price scenarios, variant 2 gives the longest time horizons at which the equations equal zero, and thus the highest profitability. This can be seen in Figure 5, by comparing the difference of NPVs given by the ZEB-COM and either variant 3 or variant 2 at year 30 for the 6% scenario. Therefore, the results show that the initial lower investment and higher annual energy cost of variant 3 do not pay beyond a 30-year time horizon, when the additional cost for operational energy is predominant. This is a critical aspect to be considered for evaluating the profitability of investments which are expected to have long-term environmental benefits.

3.2.3. Cost-Optimal BIPV Area

This part of the cost analysis of the ZEB Lab aims at showing what would be the NPV of the ZEB-COM and the variants by reducing the BIPV area. The cost-optimal BIPV area is here defined as that to ensure a zero sum of the annual costs $C_{a,i}$ for a 20-year time horizon. Specifically, the zero sum of the annual costs determines the four designs to be Zero Energy Buildings, as the price of purchasing electricity from the grid is equal to that of selling it to the grid. Due to the degradation rate of the PV module efficiency, the zero sum is obtained by ensuring a surplus of energy production in the first half of the calculation period and an equal amount of delivered energy in the second half. The first step of the BIPV-area optimization showed that for the actual average electricity production (164 kWh/m^2·year, as detailed in Table 1) the BIPV area varies between 427 m^2 and 540 m^2. This means that all the PV modules can be installed on the roof. Therefore, the second step of the BIPV area optimization is performed by using the mono-SI modules with the efficiency and annual production (207 kWh/m^2·year) described in Table 1. Figure 6a shows the initial investment C_I (sum of costs of building components and BIPV system) vs. the BIPV area.

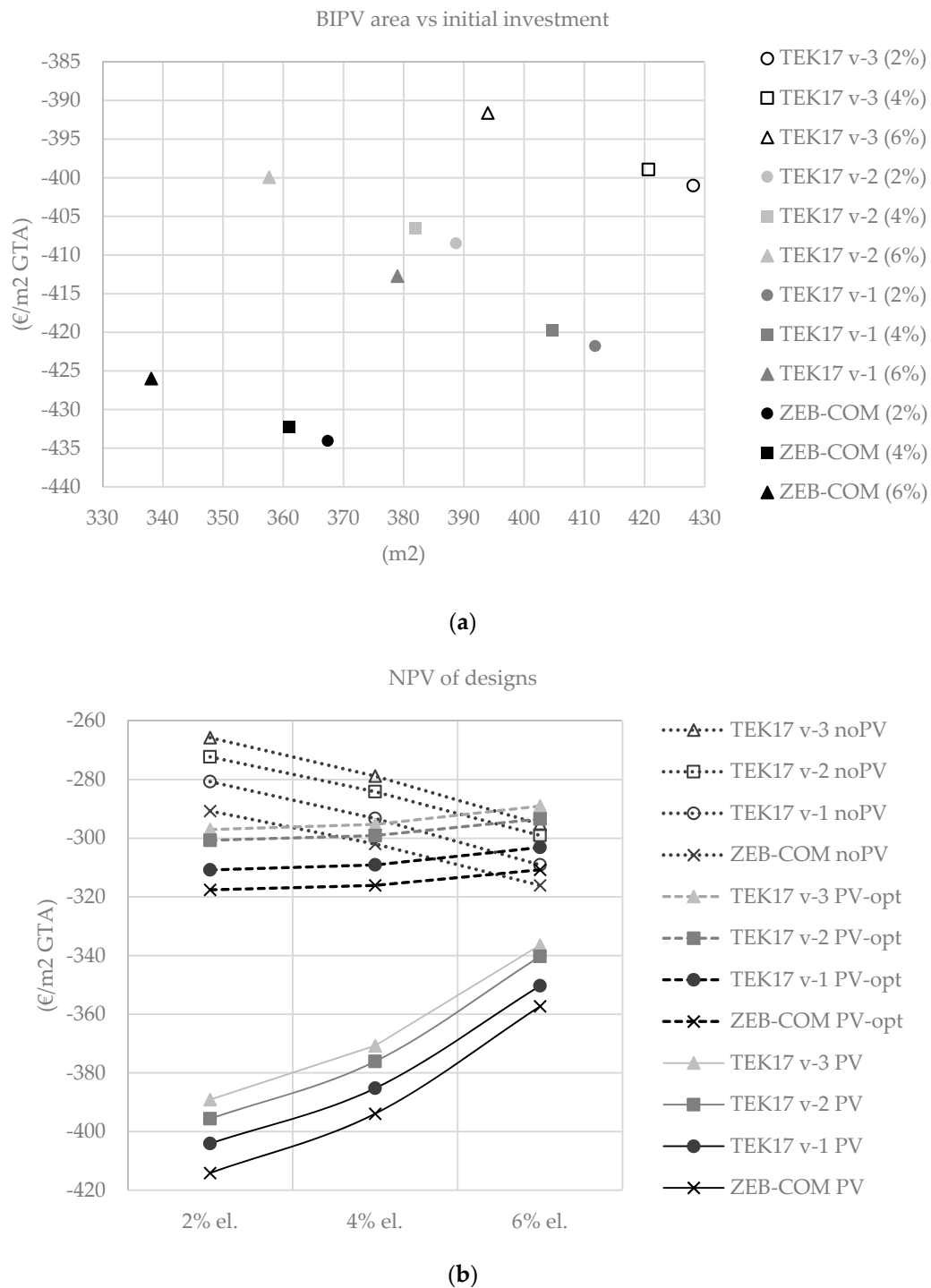BIPV area vs initial investment

(**a**)

NPV of designs

(**b**)

Figure 6. Scatter plot rendering the corresponding initial investments and BIPV areas for the four designs and three electricity price scenarios (**a**). Comparison of the NPVs between all the designs for the three electricity price scenarios (**b**).

The sum of the annual costs $C_{a,i} = 0$, and it is therefore not shown in Figure 6a. The second step of this analysis gives an optimized BIPV area which is considerably smaller, and it varies between 338 m² and 428 m², due to the higher energy yield of the BIPV on the roof. The corresponding initial investments of both the energy saving measures and of the BIPV systems vary between 426 EUR/m² and 401 EUR/m², against 651 EUR/m² of the ZEB-COM and full BIPV area (1170 m²). The BIPV areas given by the 4% electricity price scenarios are closer to those given by the 2% scenario than those given

by the 6% scenario. This is because the electricity annual price increase in the 6% scenario is higher than the 4% discount rate applied to both the purchased and sold electricity.

Figure 6b shows the NPVs of all the designs analyzed so far: with either the original BIPV area (continuous lines), or the optimized BIPV areas (dashed lines), or without BIPV (dotted lines), for the three electricity price scenarios. NPVs are calculated for a 20-year time horizon. The NPVs of the designs with optimized BIPV areas show a little increase at growing electricity price because these areas are optimized for each of the price scenarios. The difference of NPVs between corresponding designs with (dashed lines) or without (continuous lines) optimized BIPV area decreases too at increasing electricity price scenarios. This is because the optimized BIPV area is smallest and the profit of electricity selling given by the full BIPV area is highest at the 6% scenario. The difference of NPVs therefore varies between approximately 95 EUR/m^2 and 45 EUR/m^2 for corresponding designs with the 2% and 6% electricity price scenarios, respectively.

4. Discussion

The results presented in this paper show that at increasing the electricity price, the solutions with cost-optimized BIPV areas become more economically convenient than those without BIPV, as seen in Hamdy et al. [8]. By comparing the ZEB-COM designs either with the optimized BIPV system or without it (Figure 6b), the NPV of the solution with the optimized BIPV area is higher than that of the solution without the BIPV only when the yearly electricity price increase is 6%. Specifically, when the electricity price scenario changes from 2% to 6%, the NPV of the ZEB-COM design decreases by 25 EUR/m^2, whereas the NPV of the ZEB-COM design with the optimized BIPV area increases by 7 EUR/m^2.

As mentioned in Section 2.2, the variation of the building envelope airtightness from 0.3 ACH to 1.5 ACH is calculated to increase the net energy need for heating of the ZEB-COM design by 11 kWh/m^2 year. This equals to 3.7 kWh/m^2 year of delivered electricity, by using the COP of the heat pump. Given the building heated floor area of 1742 m^2 and by using the 4% yearly increase in electricity price, the additional energy cost given by the lower infiltration rate equals to EUR 13,263 after 20 years. Such an additional energy cost is to be discounted of the investment cost for the extra work needed to make the building more airtight. As a comparison, the saved investment cost given by downgrading the insulation value from the ZEB-COM design to the TEK-17 variant 3 (the design with the worst energy performance) is EUR 99,012, which is to be discounted of the additional operational energy cost of EUR 22,705 (4% increase in electricity price). In the worst-case scenario, the variation of the insulation level produces a six times larger increase in cost difference, by assuming no additional costs for increasing the building's airtightness.

The calculation of the NPV for a 20-year time horizon shows that the additional insulation level needed to improve the design from the TEK17 variant 3 to the ZEB-COM is a better choice than equipping the TEK17 variant 3 with an optimized BIPV area in the 2% electricity price scenario only (Figure 6b). For the 4% and 6% electricity price scenarios, the TEK17 variant 3 with optimized BIPV area gives higher NPVs than those of the ZEB-COM without BIPV. This confirms the findings of Niemelä et al. [10]. Moreover, as discussed by Niemelä et al. [10], energy efficiency measures aimed at reducing by a large extent the building's delivered energy (as such as those implemented in the ZEB-COM design) produce solutions that are less profitable in a 20-year time horizon. By extending the calculation period beyond 20 years, the ZEB-COM ambition level gives a higher NPV than the TEK17 variant 1 after approximately 36 years, and a higher NPV than the TEK17 variant 3 after approximately 46 years, as seen in Table 8. It may therefore be considered questionable the use of a 20-year time horizon for the economical evaluation of the ZEB Lab (and ZEBs in general), especially in relation to the GHG emission reduction goal of this building. The time horizon of the environmental impact of GHG emissions in life cycle assessment of buildings is typically 100 years. This means that the calculated saving potential of GHG emissions of the ZEB Lab is spread over a longer time than that used for its economic evaluation, which therefore highlights contradicting conclusions given by

the use of these two assessment methods. On the other hand, the use of a wider time horizon than 30 years leads to an increase in uncertainties in the calculation of the energy price scenarios and fixed interest rate. According to the guidance on the calculation of carbon emission price issued by the World Bank [36] a high-estimate and low-estimate scenarios of the future price of carbon emissions are suggested to be used in projects appraisal. For the year 2020, the carbon price is set to 40 USD/tCO$_{2e}$ and 80 USD/tCO$_{2e}$, for the low-estimate and the high estimate scenarios, respectively. By using a USD-to-EUR conversion rate at 15.09.2020 and assuming a constant electricity-to-emissions conversion factor (152 gCO$_{2e}$/kWh [14]), the difference between the cumulative carbon cost of the ZEB-COM ambition level and the TEK17 variant 3 calculated for the next 20 years, varies from 0.7 EUR/m^2 to 1.4 EUR/m^2. The increase in the NPV of the TEK17 variants compared to that of the ZEB-COM ambition level was shown to vary between 25 EUR/m^2 and 21 EUR/m^2, for the 2% and 6% electricity price scenarios, respectively. The additional carbon cost to be paid by the TEK17 variants is therefore marginal. As discussed by Arumägi and Kalamees [9], buildings with a highly efficient energy systems, as such as the ZEB Lab, gives very little space for improvement toward higher energy ambition levels, from the perspective of a short-term cost optimization.

5. Conclusions

A zero-emission office building, the ZEB LAB, is used as a test case to evaluate whether a high energy ambition level gives higher Net Present Values than that of BAU solutions. The ZEB LAB, located in Trondheim, is designed and built to compensate the building's lifecycle emissions with the use of a large array of BIPV panels, defined as the ZEB-COM ambition level. Three design alternatives are investigated by downgrading the building insulation level to the values recommended by the currently enforced Norwegian building code, the TEK17. A sensitivity analysis on the variation of the installed area of BIPV is performed to evaluate if smaller areas give better cost performances. The cost assessment is performed by using the Net Present Value method for a time horizon of 20 years and by using three electricity price scenarios.

The results of the cost analysis show that:

- All the three TEK17 variants perform better than the ZEB-COM and show higher NPVs calculated for a 20-year time-horizon.
- The ZEB-COM design becomes more profitable than the TEK 17 variants when the NPV is calculated for a time-horizon of at least 36 years.
- For any combination of the four investigated designs and three electricity price scenarios, the solutions with the BIPV gives lower NPVs calculated for a 20-year time-horizon.
- The cost-optimized BIPV areas range between 338 m^2 and 428 m^2, against the 1170 m^2 installed to reach the ZEB-COM ambition level
- The solution with optimized BIPV areas gives higher NPVs than those of the designs without BIPV for the 6% electricity price scenario only.
- The investment for increasing the insulation level produce a higher NPV for the 2% electricity price scenario only. Optimized BIPV areas gives higher NPVs for the 4% and 6% electricity price scenarios.
- The addition of price of carbon emission does not change the above results, as it produces marginal savings.
- Within the calculation frame of a 20-year time horizon, the ZEB-COM ambition level implemented in the ZEB LAB does not give cost-optimal results, in comparison to BAU solutions.

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