Exploring the pathway from zero-energy to zero-emission building solutions: A case study of a Norwegian office building

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Abstract

This paper explores the most influential aspects regarding the environmental and economic performance of zero-energy and zero-emission buildings and proposes a pathway for transition in building solutions. A representative zero-energy office building in Norway is investigated with alternative design solutions to achieve zero-emission status i.e., the extensive use of locally generated energy through photovoltaic (PV) panels and the use of materials with low embodied emissions, such as low-carbon concrete and wood. A life cycle environmental and economic assessment is performed to evaluate specific indicators during the building life cycle: cumulative energy (CED), global warming potential (GWP), and equivalent annual cost (EAC).

The extensive use of PV panels was most effective in lowering the operational energy because it reduced the CED by about 30% compared to the building as-built. However, the extensive use of wood in the construction contributed the most to GWP reduction, with around 25% decrease compared to the building as-built. Finally, the differences in EAC were interestingly insignificant among the alternatives, with the investment costs dominating the EAC for all designs examined.

The findings of this paper emphasize that a full compensation of the life cycle GHG emissions from materials is difficult to achieve through renewable energy, even with extensive use of PV panels, especially in a low-carbon grid situation as in Norway. A pathway strategy from zero-energy towards zero-emission buildings must therefore strongly focus on the materials' embodied energy and emissions because low operational energy demand is already a regulatory priority in most countries.

Keywords: zero-energy buildings; zero-emission buildings; life cycle; environmental sustainability; economic sustainability.

1. Introduction

Buildings account for approximately 40% of the energy use and 35% of the greenhouse gas (GHG) emissions of the European Union [1]. In the recent years, new policies and regulations have been introduced to reduce the environmental impacts of building stock.

At the European level, Energy Performance of Buildings Directive (EPBD recast) 2010/31/EC [1] defined the minimal energy performance requirements for buildings and introduced the nearly zero-energy building target. In the EPBD recast, the nearly zero-energy building concept is presented to define a highly energy-efficient building, in which the nearly zero or very low energy demand is mainly covered by renewable energy technologies. The construction of nearly zero-energy buildings represents a meaningful step in reducing the environmental impacts of new buildings by leading, at the same time, to relative economic and social improvements, such as the reduction of future energy costs and the improvement of indoor well-being. The design includes effective energy saving measures with regard to both the building envelope components and the technical building systems, as well as the use of renewable energy technologies (RETs).

Several definitions and approaches to the zero-energy building target are available in the literature. Marszal et al. [2] provided a review of definitions and calculation methodologies for zero-energy buildings, aiming to facilitate the development of a consistent and standardised approach in this field. In many definitions, only the energy used during the operation of the building is considered by neglecting the energy used for material production and construction of the building and its components, i.e., the so-called embodied energy [3]. However, when shifting from standard buildings to low-energy and zero-energy buildings, the contribution of embodied energy to total energy can increase significantly, with a decrease of the operational energy importance [4-6]. Moreover, the energy savings achieved in zero-energy buildings within the annual operational energy balance usually exceed the increase in the embodied energy [7].

The zero-energy building concept is increasingly superseded by the zero-emission building concept, in which the balance is measured in terms of GHG emissions [8, 9]. The Norwegian Research Centre on Zero Emission Buildings provided a definition of zero-emission buildings based on different ambition levels regarding which life cycle stages are accounted for, in accordance with EN 15978:2011 [10] (see Figure A 1 of the Appendix). Here, ZEB-O-EQ indicates the lowest level at which the onsite renewable energy generation compensates for the emissions related to all energy use during operation (O), minus the energy use for equipment/appliances (EQ). ZEB-COMPLETE is the highest ambition level where all life cycle stages are considered [11]. To achieve the highest zero-emission level, the GHG emissions of locally generated energy from renewable sources, such as PV, solar thermal, heat pump or combined heat and power (CHP) technologies, must counterbalance the embodied emissions from materials. Therefore, moving from a zero-energy building to a zero-emission building requires not only an effort on energy-related measures but also a holistic focus on how to reduce or compensate for the embodied emissions of the materials during the entire life cycle.

The balance and the implications for the operational and embodied emissions in zero-emission buildings were analysed by Georges et al. [8]. They noted that the criterion for zero emissions in operation is easily achievable; however, an overall emission balance including both operational and embodied energy is difficult to realize and would be unobtainable in a scenario of low-carbon electricity from the grid. By analysing alternative scenarios for the CO_2 emission factor of electricity, Georges et al. highlighted the strong dependency between the emission factors and the possibility to balance embodied emissions. The GHG emissions related to the building product stage can be up to 60–75% of the total life cycle in zero-emission buildings, as noted by Kristjansdottir et al. [12]. However, the contribution of the embodied emissions can be significantly reduced by using environmentally friendly materials, such as wood, instead of concrete and steel [13]. Dokka et al. [14] suggested a combination of further reduced energy demand, high-performance thermal supply systems, reduced embodied emissions and increased PV energy generation, to achieve a higher life cycle zero-emission level.

A life cycle perspective in zero-emission building analysis would be very meaningful. However, the life cycle approach is not yet included in standards and regulations, and this makes challenging its adoption in building projects. In addition, the inclusion of the economic dimension in the context of zero-emission buildings would be noteworthy, but costs represent a key criterion commonly not examined along with energy demand and GHG emissions. As noted by Torcellini et al. [15], the market relevance and adoption of zero-energy buildings are strictly related to their cost-effective design; therefore, the energy cost savings during the operation of the buildings should be realised with little additional construction costs.

The pathway from zero-energy buildings to zero-emission buildings will require a delicate balance between further locally generated energy, focus on environmentally friendly materials, and economically viable solutions. This paper investigates this pathway further, as one of the few papers assuming a holistic perspective, and proposes the following research question: What are the most influential factors and promising strategies in a pathway from zero-energy buildings to zero-emission buildings from a life cycle environmental and economic perspective?

To address the research question, we examined an office building that was recently built in a Nordic context with the main objective of fulfilling the nearly zero-energy target during the use stage. We explored how such a building could have been realised aiming at the life cycle zero-emission target, by either extensive use of low-carbon construction materials, such as wood, or PV panels or a combination of both approaches.

The remainder of the paper is organized as follows. Section 2 describes the methodological approach for performing the environmental and economic assessments and presents the case study, along with input data and assumptions. Sections 3 and 4 illustrate results and findings, followed by a critical discussion. Finally, Section 5 presents conclusions and suggestions on possible future developments of the research.

2. Materials and methods

The methodological approach adopted in this paper comprises in the performance of specific environmental and economic analyses for a representative nearly zero-energy building project in Norway. This includes analysis of the primary energy[1] in terms of cumulative energy demand (CED), the life cycle GHG emissions in the form of global warming potential (GWP), and the life cycle cost defined as equivalent annual cost (EAC). In the following subsections, the case building is presented, together with the input data and the assumptions for the analyses performed.

2.1 Study object

The study object is a three-floor office building located in Bergen, which was completed in 2015 for the Norwegian Defence Estates Agency (NDEA) as a nearly zero-energy building. It also represents a pilot project for the Norwegian Research Centre on Zero Emission Buildings and was conceived with the ZEB-O-EQ ambition level; i.e., the GHG emissions of the building operation, excluding the technical equipment (computers, appliances, etc.), should mainly be compensated by renewable energy generation. See Figure A1 in the Appendix.

Several measures for improving the building energy efficiency are implemented in the building as-built. The load-bearing system is based on low-carbon concrete and hollow-core slabs, and the building envelope is highly insulated and tight. In particular, the external walls have a wood frame with 300 mm glass wool insulation and aluminium façade plates. The roof is primarily made of a hollow core slab and 450 mm of expanded polystyrene (EPS) insulation, whereas the ground floor consists of a reinforced concrete slab with 250 mm of extruded polystyrene (XPS) insulation and 50 mm of EPS. The windows have an aluminium frame and a triple glazing, with two low-e coatings and argon filling. The heating, ventilation and air conditioning (HVAC) system includes demand-controlled ventilation with heat recovery and a geothermal heat pump. The latter covers 90% of the building heating demand. Finally, a grid-connected PV system is installed on the roof to generate onsite renewable energy. Excess energy generated by the PV system is delivered to the local electricity grid for use in other buildings. The case building is shown in Figure 1, and the main geometric features of the building are summarized in Table 1.

Figure 1. Picture of the building.
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Source: https://www.forsvarsbygg.no/no/nyheter/nyhetsarkiv-eldre-nyheter/2013/kilowattkutteren-pa-haakonsvern/.

Table 1. Main geometric features of the study object.

Description	Value
Total number of floors (-)	3
Gross internal floor area (m^2)	2,035
Heated volume (m^3)	7,108
External wall area (m^2)	1,126
Roof area (m^2)	683
Window and external door area (m^2)	290

Four alternative design solutions for the building were analysed in this paper. Alternative 1 denotes the as-built building representing the zero-energy solution. Alternative 2 represents one likely promising pathway towards a life cycle zero-emission building, with extensive use of wood, which is a well-known low-carbon construction material. This alternative adopts wood in the load-bearing system, floors, roof, façade cladding, and windows. Other material amounts are the same as in Alternative 1. In particular, the external walls of Alternative 2 are the same as in Alternative 1 except the cladding, which is made of wood in this case. The roof consists of a wood frame with 500 mm glass wool insulation, whereas the ground floor is the same as in Alternative 1. Finally, the windows have a wood frame and a triple glazing, with two low-e coatings and argon filling. The wood structures were roughly dimensioned by using information and indications available from SINTEF Byggforsk [16], based on several standards, such as [17, 18]. Furthermore, a certain amount of concrete was not replaced for structural reasons e.g., in the concrete walls surrounding the stairs and elevator. The HVAC system of Alternative 2 was assumed to be the same as that in Alternative 1. Alternative 3 represents another likely promising pathway in which the life cycle zero-emission ambitions are attempted through the extensive use of renewable energy from PV panels. The building envelope and the HVAC system are the same as in Alternative 1, with the only addition of PV panels on the southern façade, to complement the PV panels on the roof characterising the as-built solution. Note that only the PV panels were included in the material inventory of the LCA analyses, whereas the PV support system was neglected. Finally, Alternative 4 represents a combined pathway towards a life cycle zero-emission building, with extensive use of both low-carbon construction materials such as wood and renewable energy from PV panels. Alternative 4 is basically a combination of Alternative 2 and Alternative 3, where the building envelope and the HVAC system are the same as in Alternative 2, with the only addition of PV panels on the southern façade as in Alternative 3. Table 2 summarizes the main features of the four alternatives analysed.

Table 2: Main building components of the alternatives analysed.

	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Load-bearing system	Low carbon concrete and steel	Glued laminated wood	Low carbon concrete and steel	Glued laminated wood
Slab on ground	Concrete, 250 mm of XPS and 50 mm of EPS	Concrete, 250 mm of XPS and 50 mm of EPS	Concrete, 250 mm of XPS and 50 mm of EPS	Concrete, 250 mm of XPS and 50 mm of EPS
Floors	Hollow-core slab	Wood structure	Hollow-core slab	Wood structure
External walls	Wood frame with 300 mm glass wool and aluminium façade plates	Wood frame with 300 mm glass wool and wood façade plates	Wood frame with 300 mm glass wool and aluminium façade plates; PV panels	Wood frame with 300 mm glass wool and wood façade plates; PV panels
Windows	Aluminium frame and triple glazing	Wood frame and triple glazing	Aluminium frame and triple glazing	Wood frame and triple glazing
Roof	Hollow-core slab and 450 mm of EPS	Wood structure with 500 mm of glass wool	Hollow-core slab and 450 mm of EPS; PV panels	Wood structure with 500 mm of glass wool; PV panels

Note that the features of the building envelope components influencing the energy performance in Alternative 2, Alternative 3, and Alternative 4 were adjusted to have the same thermal transmittance (U-value) as in Alternative 1. The external walls of all alternatives have the same layers except for the cladding, which, as previously mentioned, does not contribute to the wall thermal transmittance. The ground floor is the same in all alternatives because the concrete layer was also kept in Alternative 2 and Alternative 4, which is characterized by wooden materials; the roofs in Alternative 1 and Alternative 3 are the same, whereas the wooden roof solution in Alternative 2 and Alternative 4 has the same U-value as in the other alternatives. As concerns the thermal mass contribution of different building materials in the analysed alternatives, note that Alternative 1 and Alternative 3 have the same concrete-based horizontal partitions, while Alternative 2 and Alternative 4 have wood-based horizontal partitions, but all alternatives have the same acoustic suspended ceiling for horizontal partitions and roof. Finally, the external walls and the ground floor have, in all alternatives, the same material layers contributing to the thermal mass. The windows were assumed to have the same U-value in all alternatives, neglecting the possible U-value increase due the argon leakage over time. Furthermore, the overall additional thermal losses due to areas and junctions of the building envelope with a higher heat transfer were accounted through the thermal bridge coefficient. This coefficient was assumed to be the same in all alternatives because the project must fulfil a maximal value defined in the Norwegian passive house standard (NS 3701:2012 [19]). Note that the façade PV support system was assumed to be fastened to the cladding of the external walls without affecting the thermal properties of the building, as the cladding was outdistanced from the rest of the wall layers by a ventilated air cavity.

The thermal properties of the building envelope for the building case in all alternatives are shown in Table 3.

Table 3. Thermal properties of the building envelope for the study object.

Description	Value
External walls, U-value (W/m^2/K)	0.12
Roof, U-value (W/m^2/K)	0.09
Ground floor, U-value (W/m^2/K)	0.08
Windows and external doors, average U-value (W/m^2/K)	0.85
Average thermal bridge per floor area (W/m^2/K)	0.03
Air leakage, 50 Pa (1/h)	0.40

2.2 Data collection

In this paper, we wanted to explore the elements of a pathway where the study object could comply with the ambitious ZEB-OM zero-emission level (see Figure A 1), with system boundaries that include the embodied emissions from materials for construction and replacements, in addition to the total operational energy. Information on the quantities of the materials used for realizing the building was extracted from building information model (BIM) files available in the project. Missing data were calculated through available technical drawings and other information from contractors and NDEA. Further assumptions were made in accordance with similar case studies [13, 14]. Technical building systems were only partially included in the material inventory because there was no information available in the project's BIM files. In particular, the building system components considered were the heat pump, the ventilation system and the hot water tank. Other components of the HVAC system, such as pipes, radiators, together with components of the electric and lighting system, were not included in the material inventory. This modelling choice does not influence the results because these systems are the same for all alternatives, and their materials provide a low contribution to the total building environmental impacts [13, 14].

The building lifespan was set to 60 years, and the functional unit of the analysis was considered as 1 m^2 of gross internal floor area, which is measured to the internal face of the external walls, including partitions, shafts, and stairwells. Henceforth, the term 'floor area' is used to refer to the gross internal floor area of the building.

2.3 Cumulative energy demand

The CED indicator was computed by means of the CED method [20], as expressed in Eq. (1).

$$CED = \sum_i EE_i m_i + \sum_n OE_n e_n \tag{1}$$

where *CED* is the cumulative energy demand over the building life cycle [kWh]; EE_i is the embodied primary energy in material/construction product i used for building construction and maintenance [kWh/kg]; m_i is the mass of material/construction product *i* [kg]; OE_n is the primary energy factor of energy carrier *n* [$\mathrm{kWh_{primary}/kWh_{delivered}}$ i.e., $\mathrm{kWh_p/kWh_d}$]; and e_n is the operational delivered energy[2] of energy carrier *n* [kWh].

The building model was run in the LCA software program SimaPro 8.1.1 [21], and the attributional modelling approach was used, with the 'Allocation, recycled content' model available in Ecoinvent database 3.1. The 'unit processes' data library was used together with transforming activities mostly characterized by the geographic location 'Europe (RER)'.

The energy demand for building material manufacture was assessed through information mainly taken from the Ecoinvent database. Only in Alternative 1, the information on low-carbon concrete and hollow core blocks was derived from Environmental Product Declarations (EPDs) [22], referring to such products as available in the project. Replacement measures during the building lifespan were assumed for certain building components, based on information from the EN 15459 standard [23] and SINTEF Byggforsk [24]. Table A 1 of the Appendix illustrates the inventory of the materials used in all alternatives, whereas Table A 2 shows the main replacements occurring during the building lifespan. Information about the monthly energy use for space heating, domestic hot water (DHW), lighting and electric appliances, together with the monthly electricity generation by the PV panels, was available from the project documentation. In particular, the energy delivered to the building and generated by the PV system was assessed by means of the software program SIMIEN [25] and the PVGIS tool [26], respectively. SIMIEN is a dynamic building simulation tool based on the calculation method described in the Norwegian standard NS 3031:2014 [27], which complies with the European standard EN 15265:2007 [28]. Table A 3 and Table A 4 in the Appendix show the main input data for the building simulation model and the PV system design. The European electricity mix assessed in the Ecoinvent 3.1 database [29] was used for the electricity imported from the grid (10.99 MJ/kWh).

For the use stage impacts, electricity is the only energy carrier, and the term ‘OE· e’ of Eq. (1) was calculated through Eq. (2), as by Kristjansdottir et al. [9].

$$OE \cdot e = \sum_{j=1}^{60} \sum_{m=1}^{12} \left\{ El_{PV,m}(j) \cdot CED_{PV} + \left[El_m(j) - El_{PV,m}(j) \right] \cdot CED_{grid} \right\} \cdot I_m + El_m(j) \cdot CED_{PV} \cdot (1 - I_m) \quad (2)$$

where j is a year during the building lifespan; m is a month in the year; $El_{PV,m}$ is the monthly electricity generated by the PV system [kWh]; El_m is the monthly need for delivered electricity [kWh]; CED_{PV} and CED_{grid} are the CED values of the PV system and grid electricity, respectively; and I_m is a binary variable, with: $I_m = 1$ if $El_m > El_{PV,m}$ and $I_m = 0$ otherwise.

Note that a constant value of the CED for the PV system and the grid was assumed over the 60-year building lifespan. Furthermore, owing to large seasonal variations in PV energy generation, a monthly perspective was applied to the energy balance. This led to different impact factors for the electricity generated by the PV system and the electricity imported from the grid [9]. Therefore, the PV system impacts were allocated to the building use stage as kWh of primary energy per kWh of generated electricity over the estimated service lifetime. Because the electricity generated by the PV system can be higher than that required by the building in certain months of the year, the CED of the use stage energy export, CED_{export}, was calculated through Eq. (3):

$$CED_{export} = \sum_{J=1}^{60} \sum_{m=1}^{12} \left[El_{PV,m}(j) - El_{m}(j) \right] \cdot \left[CED_{PV} - CED_{grid} \right] \cdot (1 - I_{m}) \qquad (3)$$

The zero-energy building hence receives an energy credit if the grid CED is higher than the PV system CED; otherwise, it receives an energy load.

2.4 Global warming potential

The ReCiPe method [20] was used to assess the GWP indicator, as expressed in Eq. (4).

$$GWP = \sum_{i} GWP_{i} m_{i} + \sum_{n} GWP_{n} e_{n} \qquad (4)$$

where *GWP* is the GWP during the building life cycle [CO_2 eq.]; GWP_i is the GWP of material/construction product *i* used for building construction and maintenance [kg CO_2 eq./kg]; m_i is the mass of material/construction product i [kg]; GWP_n is the GWP of energy carrier n [kg CO_2 eq./kWh]; and e_n is the operational delivered energy of the carrier *n* [kWh].

The building model was run in SimaPro 8.1.1 LCA software as for the CED indicator calculation. Furthermore, the hierarchist perspective of the ReCiPe method was applied, with a time horizon of 100 years for GWP of the emissions occurring during the life span of the building. The material's embodied GHG emissions were calculated by combining information from the Ecoinvent 3.1 database and chosen geographically relevant EPDs, as for the CED indicator calculation. The same assumption for building materials and replacement measures made for the CED analysis hold for the GWP analysis. The GHG emissions related to the monthly energy use, for all purposes noted in section 2.3, were assessed through the Ecoinvent 3.1 database. For the use stage impacts, electricity is the only energy carrier, and the term 'GWP· e' of Eq. (4) is calculated through Eq. (5).

$$GWP \cdot e = \sum_{j=1}^{60} \sum_{m=1}^{12} \{El_{PV,m}(j) \cdot GWP_{PV} + [El_m(j) - El_{PV,m}(j)] \cdot GWP_{grid}\} \cdot I_m + El_m(j) \cdot GWP_{PV} \cdot (1 - I_m) \quad (5)$$

where GWP_{PV} is the GWP of the PV system with constant value assumed over the 60-year building lifespan. GWP_{grid} is the GWP of the grid electricity. The European electricity mix defined in the standard NS 3720 [29, 30] was used for the electricity delivered from the grid (estimated as 0.136 kg CO_2 eq./kWh, as an average value for the period 2015-2075).

Finally, the GWP_{export} associated with the difference between the electricity generated by the PV system and that required by the building in certain months of the year, was calculated using Eq. (6):

$$GWP_{export} = \sum_{j=1}^{60} \sum_{m=1}^{12} [El_{PV,m}(j) - El_m(j)] \cdot [GWP_{PV} - GWP_{grid}] \cdot (1 - I_m) \quad (6)$$

Note that a neutral CO_2 balance was adopted for wood products, where neither CO_2 sequestration nor CO_2 emissions from combustion are considered. Such an assumption was adopted because only the product, replacement, and use stages were assessed, so the whole life cycle of materials, inclusive of the end-of-life, was not part of the scope of this study.

2.5 Equivalent annual cost

The EAC indicator was assessed through a life cycle costing (LCC) analysis over a calculation period equal to the building lifespan, 60 years. LCC allows assessment of the total costs of projects during a period of time, involving certain relevant economic factors and discounting future costs [31]. EAC was calculated as shown in Eq. (7).

$$EAC = NPC \cdot a(n) \tag{7}$$

where *EAC* is EAC [NOK/y]; *NPC* is the net present cost related to the duration of the calculation period and refers to the starting year of the calculation [NOK]; and *a(n)* is the annuity factor depending on the number of years of analysis, n.

NPC was calculated as shown in Eq. (8).

$$\mathrm{NPC} = C_0 + \sum_{i=1}^{\tau} \frac{C_{f,i}}{(1+r)^i} \tag{8}$$

where C_0 is the initial investment cost [NOK]; and $C_{f,i}$ is the future cost at year i (including annual energy cost and periodic replacement cost) [NOK]; τ is the duration of the calculation period; and r is the real discount rate [%]. The annuity factor was calculated according to Eq. (9)

$$a\,(n) = \frac{r}{1-(1+r)^{-n}} \qquad (9)$$

The following cost categories were assessed: investment costs, including building material provision and assembly; replacement costs, including building component substitution; and energy costs, including the cost of electricity over the building operation. Note that the investment costs also include the PV system cost i.e., the roof PV system for Alternatives 1 and 2 and the roof/façade PV system for Alternative 3. The investment and replacement costs were assessed through the available project documentation and the Norwegian Price Book [32]. The price of the electricity imported from the grid was considered as 0.9 NOK/kWh, which is the average price over the last five years in Norway, whereas the price of the electricity exported to the grid was considered as 0.3 NOK/kWh [33].

The annual operational energy cost, EC, was calculated as expressed in Eq.(10).

$$EC_{year} = \sum_{m=1}^{12}[\,(El_m - El_{PV,m}) \cdot EC_{grid} \cdot I_m - (El_{PV,m} - El_m) \cdot EC_{PV} \cdot (1 - I_m)] \qquad (10)$$

where EC_{year} is the annual operational energy cost [NOK/y]; $El_{PV,m}$ is the monthly electricity generated by the PV system [kWh/month]; El_m is the monthly need for delivered electricity [kWh/month]; EC_{grid} is the cost of the electricity imported from the grid [NOK/kWh]; EC_{PV} is the cost of the electricity sold to the grid [NOK/kWh]; and I_m is a binary variable, with $I_m = 1$ if $El_m > El_{PV,m}$ and $I_m = 0$ otherwise.

All costs were computed with the value-added tax (VAT) included, and future costs were actualised to the starting year of calculation through the real discount rate, r, which initially was set equal to 4%, as in NS 3454:2013 [34]. At the time of the calculations, the exchange rate was 1 Euro = 9.0 NOK.

2.6 Sensitivity analyses

Sensitivity analyses were executed to test the robustness of the indicator results in relation to the uncertainty of certain input parameters. The analyses were performed by assessing the sensitivity ratio (SR), which represents the fraction of the relative change in the result over the relative change in a given input parameter [35], as shown in Eq.(11).

$$SR = \frac{\Delta\, result}{initial\, result} \Big/ \frac{\Delta\, parameter}{initial\, parameter} \tag{11}$$

SR represents the ratio between two relative changes. If a parameter has an SR of 0.5, this implies that when its value is increased by 10%, the final result is increased by 5%.

Previous studies have demonstrated the sensitivity of the zero-energy/emission building performance to the electricity mix as well as the environmental impacts of the PV system [8, 9, 12]. Furthermore, the influence of the electricity and PV panel costs in the life cycle cost calculations was already revealed by Marszal et al. [36]. Therefore, the following parameters were selected for the sensitivity analysis: i) different electricity mix for the electricity imported from the grid in the use stage, ii) increase in GWP and CED values for PV panels, iii) increase in electricity price (exported and imported), and iv) increase in the PV panel cost. An overview of the sensitivity parameters is given in Table 4. In particular, in Table 4, the parameters denote the variables whose sensitivity was tested; the baseline settings are the inputs used in the initial analyses; the new settings denote the new inputs used for each parameter in the sensitivity analyses. Note that the variation of the new settings from the baseline settings is indicated in parentheses for each parameter. The Norwegian electricity mix was examined to determine the impacts of the parameter electricity mix. The impacts of the electricity mix in terms of CED were derived from the Ecoinvent database, while the impacts in terms of GWP were derived from the standard NS 3720. The 100% increase for the PV panel impacts was decided based on higher possible values, as shown by Kristjansdottir et al. [12]. Moreover, the increase in the cost of the electricity imported/exported from/to the grid was defined based on the trend in recent years, as shown by Statistisk sentralbyrå [33]. Finally, the increase in the cost of PV panels was defined according to Norconsult Informasjonssystemer and AS Bygganalyse [32].

Table 4. Main assumptions for the sensitivity analyses performed.

Parameters	Baseline settings	New settings
Electricity mix impacts	European electricity mix: 3.1 kWh_p/kWh_d and 0.136 kg CO_2 eq./kWh	Norwegian electricity mix: 1.2 kWh_p/kWh_d and (baseline -62%) 0.018 kg CO_2 eq./kWh (baseline -83%)
PV panel impacts	0.29 kWh_p/kWh_d (Alternatives 1-2); 0.28 kWh_p/kWh_d (Alternative 3-4) 0.068 kg CO_2 eq./kWh (Alternatives 1-2); 0.066 kg CO_2 eq./kWh (Alternative 3-4)	0.43 kWh_p/kWh_d (Alternatives 1-2) (baseline +50%); 0.42 kWh_p/kWh_d (Alternative 3-4) (baseline +50%); 0.102 kg CO_2 eq./kWh (Alternatives 1-2) (baseline +50%); 0.098 kg CO_2 eq./kWh (Alternative 3-4) (baseline +50%).
Electricity costs	Imported from the grid: 0.85 NOK/kWh Exported to the grid: 0.30 NOK/kWh	Imported from the grid: 1.27 NOK/kWh (baseline +50%) Exported to the grid: 0.45 NOK/kWh (baseline +50%)
PV panel costs	25 NOK/kWh	50 NOK/kWh (baseline +100%)

3. Results

3.1 Cumulative energy demand

Figure 2 illustrates the CED indicator results, including the net total values and the contribution from all life cycle stages. Table A5 of the Appendix illustrates the annual energy demand balance of the four alternatives in the use stage, in terms of delivered energy. Note that real data for the electricity generation and use in the first year of building operation were available, so a comparison between actual and simulated results was possible. The actual electricity generated by the PV system was approximately 1% higher than the simulation results; in contrast, the real delivered energy, excluding the PV system energy, was nearly 8% higher than the simulated value. However, the simulated values were adopted for all alternatives as Alternatives 2, Alternative 3 and Alternative 4 were hypothetical cases.

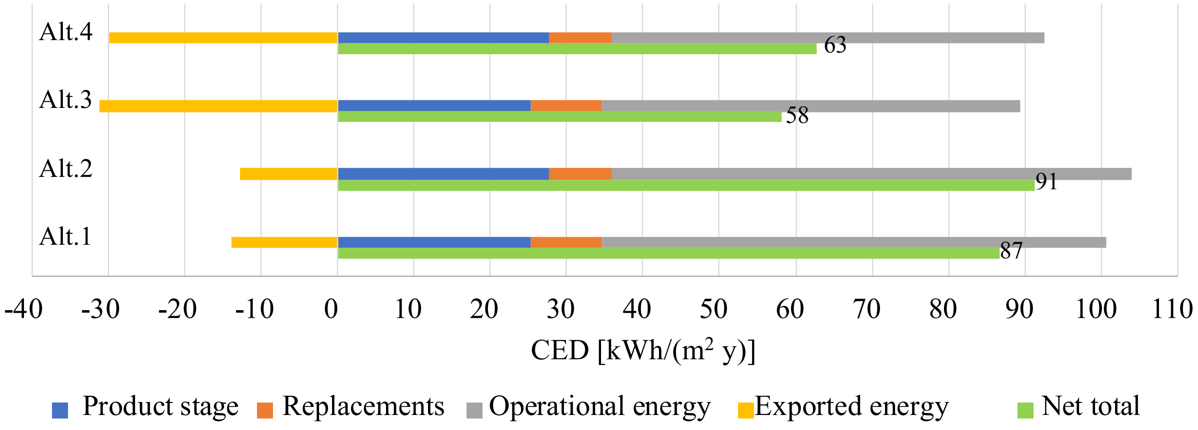

Figure 2. Cumulative energy demand results for the four alternatives, normalised by years of building lifespan and floor area.

The results confirm that a pathway strategy of more extensive use of PV, including the involvement of southern façades, leads to the lowest CED for the net operational energy (operational energy plus exported energy). In particular, the value for the net operational energy in Alternative 3 is around 60% lower than for Alternatives 1 and 2, while the net operational energy in Alternative 4 is about 50% lower than for Alternatives 1 and Alternative 2. The CED of the operational energy represents 76%, 75%, 94%, and 90% of the net total CED for Alternatives 1, Alternative 2, Alternative 3 and Alternative 4, respectively. The CED associated with the product stage represents 29%, 30%, 43%, and 44% of the total CED for Alternatives 1, Alternative 2, Alternative 3 and Alternative 4, respectively. Replacements constitute a less significant share of the total CED namely, 11% for Alternative 1, 9% for Alternative 2, 16% for Alternative 3, and 13% for Alternative 4, with contributions mainly from external walls, internal walls, and floors.

3.2 Global warming potential

The GWP indicator results during the building life cycle are shown in Figure 3, including the net total values and the contribution from the life cycle stages.

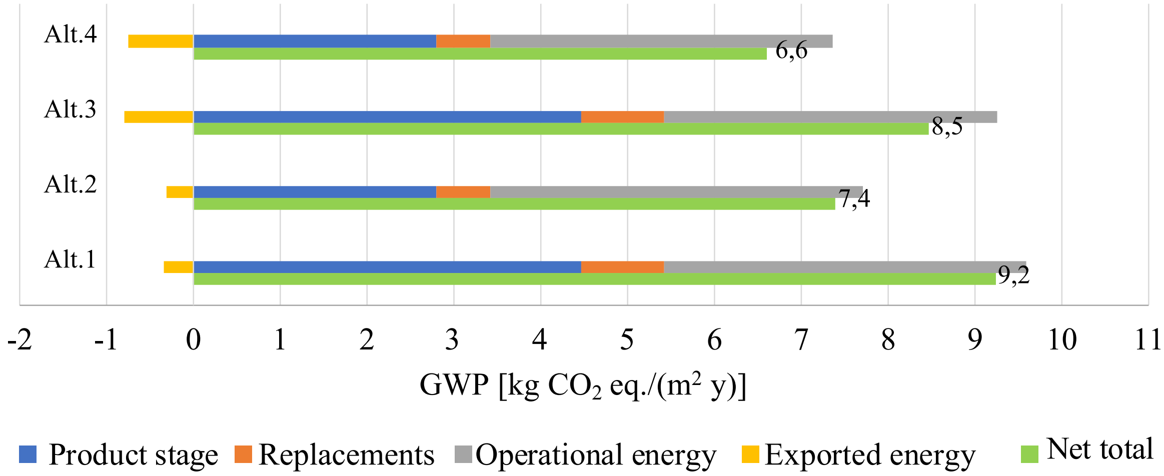

Figure 3. GWP results for the four alternatives, normalised by years of building lifespan and floor area.

Alternative 4 shows the lowest GWP value, and the difference from the as-built case is approximately a 30% reduction. The four alternatives differ mainly in the product and replacement stages, where Alternative 2 and Alternative 4 have approximately

40% lower emissions than the other alternatives. The GWP associated with the operational energy is 45%, 58%, 45%, and 60% of the net total GWP for Alternative 1, Alternative 2, Alternative 3, and Alternative 4 respectively. However, the share of the exported energy of the net total GWP is 4% for Alternative 1, 4% for Alternative 2, 9% for Alternative 3, and 11% for Alternative 4. Interestingly, the increased portion of the exported energy from PV panels compensates only partially for the emissions from the product stage. This is due to the rather low CO_2 -intensity of the European electricity mix, which is defined in NS 3720 considering the objective of nearly-zero emissions by 2050. The above results underscore the strong importance of good material choices in a pathway strategy towards zero-emission buildings.

3.3 Equivalent annual cost

The EAC indicator results are shown in Figure 4, including the net total values and the contribution from the main cost categories analysed. All alternatives show comparable EAC values, where investment costs clearly dominate, whereas replacement and operational energy costs are minor contributors.

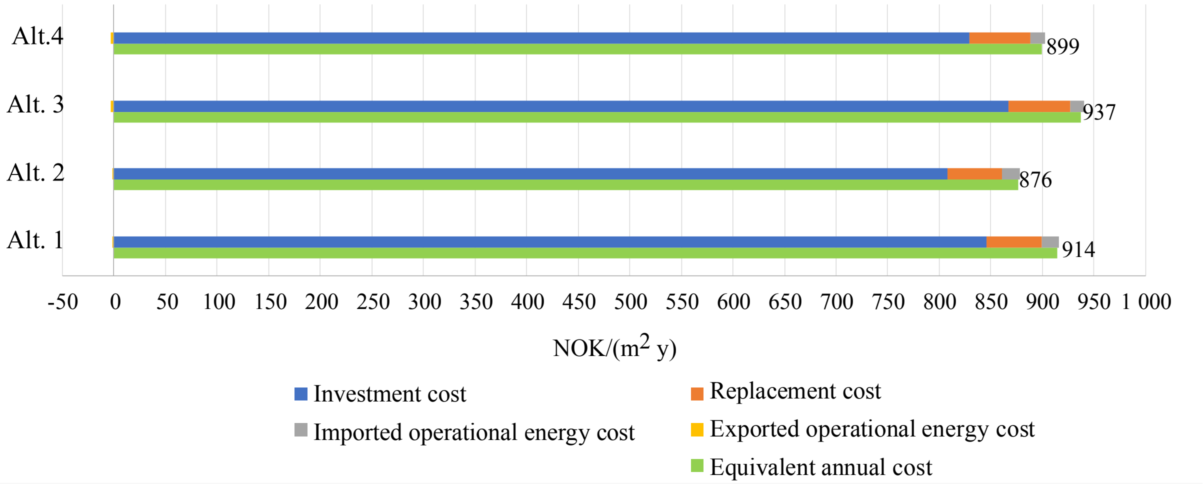

Figure 4. Equivalent annual cost results for the four alternatives, split by cost categories and normalised by years of building lifespan and floor area.

The extensive use of wood in Alternative 2 allows the investment cost to be reduced by 5% compared to Alternative 1, whereas the addition of PV panels in Alternative 3 leads to an increase in the investment costs of 3% compared to Alternative 1. The extensive use of wood in Alternative 4, together with the addition of PV panels, leads to a reduction in the investment costs of 2% compared to Alternative 1. Furthermore, the net operational energy cost of both Alternative 3 and Alternative 4 is around 20% lower than that of Alternatives 1 and Alternative 2.

These results point to the dominant role of investment costs and thereby to the importance of design solutions to keep low such costs, in a pathway strategy towards zero-emission buildings.

3.4 Sensitivity analyses

The sensitivity ratio (SR) results are shown in Table 5 for the three main indicators analysed in this research, CED, GWP, and EAC. SR results refer to the chosen parameters that were tested with new settings and compared with the baseline settings, as illustrated in Table 4 in section 2.6.

Table 5. Sensitivity ratio (SR) results for different indicators and parameter changes in the four alternatives analysed.

Indicator	Parameter change	Alternative 1	Alternative 2	Alternative 3	Alternative 4
CED	CED with Norwegian electricity mix	0.510	0.520	0.225	0.260
	CED of PV +50%	0.206	0.187	0.565	0.508
GWP	GWP with Norwegian electricity mix	0.213	0.285	0.069	0.110
	GWP of PV +50%	0.285	0.364	0.317	0.415
EAC	Cost of electricity imported from grid +50%	0.018	0.054	0.031	0.117
	Cost of electricity exported to grid +50%	−0.002	−0.002	−0.004	-0.004
	Cost of PV panels +100%	0.061	0.063	0.061	0.064

High SR values are achieved for CED and GWP in Alternatives 1 and 2, owing to the CO_2 -intensity and primary energy difference of the electricity mix under a Norwegian and European context. Alternatives 1 and 2 are, in fact, characterized by a high amount of electricity imported from the grid and a less significant contribution of exported electricity than Alternative 3 and Alternative 4. In particular, when using the Norwegian electricity mix the CO_2 credits that the building receives from the exported energy becomes loads, and the contribution of the operational energy decreases. Therefore, the lack of compensation of the GHG emissions from materials through the extensive use of PV panels becomes even more evident in a low-carbon grid situation as in Norway.

The increase in the GWP and CED of the PV panels also has a meaningful effect on the SR for the four alternatives, especially in Alternative 3 and Alternative 4, owing to the higher number of PV panels used. The increase in the cost of the electricity imported/exported slightly affects the SR values, and this is due to the low contribution of the energy costs to the life cycle costs. Finally, the increase in the cost of PV panels leads to negligible SRs owing to the small share of the PV panels in the total material cost.

4. Discussion

All the examined alternatives show a low delivered energy during the use stage owing to the high-performance envelope and technical building systems. Considering the current European legislation requirements, Alternative 3 achieves the lowest level of operational primary energy during the use stage, covered mostly by locally generated renewable energy. The embodied energy from the material production and replacement in all alternatives is approximately 40-50% of the total energy during the life cycle. This is comparable with the findings in analyses of other low-energy buildings [37]. Looking at the entire building life cycle, Alternative 3 continues to show the lowest primary energy value due to the high contribution of the operational and the exported energy to the total life cycle energy.

Considering the zero-emission target, the additional PV panels in Alternative 4, together with the extensive use of wood, leads to the lowest GWP value in the use stage, which is approximately 30% lower than in Alternative 1. Both Alternative 3 and Alternative 4 benefit from the low GHG emissions in the delivered energy and from the energy credits of the exported energy. However, from a life cycle perspective, Alternative 2 and Alternative 4 present lower total GWP than Alternative 3, owing to the lower emissions in the product stage. The energy generated by the PV panels in Alternative 3 cannot alone fully compensate for the higher emissions from building materials. This result is consistent with the findings in similar studies [9, 38]. Therefore, the combined solution as presented in Alternative 4 is the closest to the life cycle zero-emission building definition, ZEB-OM, and this is due to the very low embodied emissions of the wood materials together with the low net operational energy owing to the extensive use of PV panels. The sensitivity analysis confirms that the electricity mix is very significant for the results. When high-carbon electricity is used, the compensatory effect of the PV panels on the GHG emissions increases and vice versa.

To examine the material contribution more closely, Figure 5 shows the distribution of the embodied GHG emissions of materials for the four alternatives, considering the product stage.

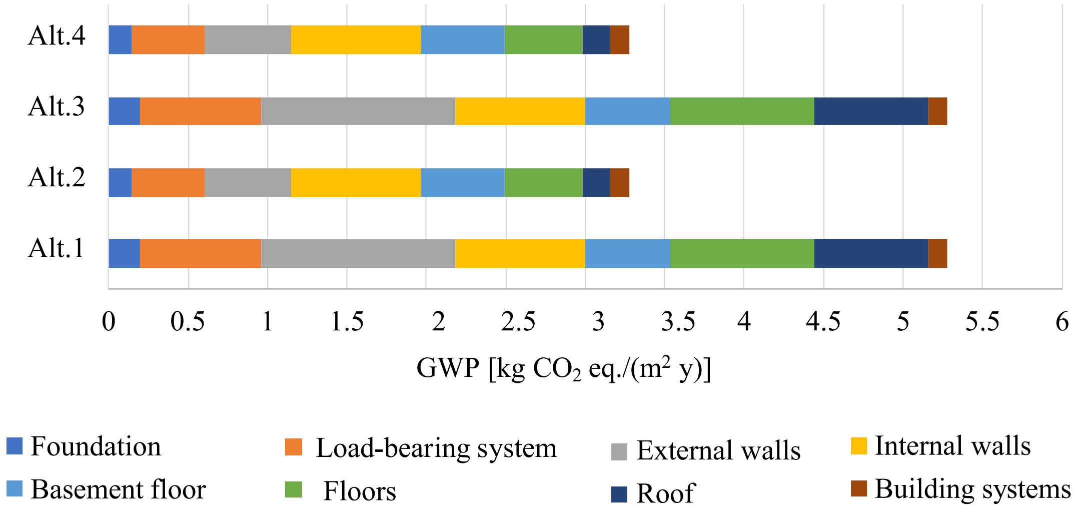

Figure 5. Global warming potential for the product stage in the four alternatives, split by building components and normalized per floor area and years of building lifespan.

Alternative 2 and Alternative 4 have the lowest GWP associated with the material production and replacement, approximately % lower than Alternative 1 and Alternative 3. The highest differences among the four alternatives are found in the roof, external walls, and floors, where the use of wood for the main component materials leads to a significant decrease in the GHG emissions. In particular, the use of wood materials in Alternative 2 and Alternative 4 allows GWP to be reduced compared to the as-built solution by −76%, −56%, −47% and −40%, for the roof, external walls, floors, and load-bearing system, respectively. These findings point to the importance of choosing building materials with low emission factors, particularly in building components with a high material demand, in terms of mass. Such a choice is therefore an important element in a pathway strategy towards zero-emission buildings. The results show that in the study object, many building components contribute significantly to the overall emissions.

The alternative showing the lowest EAC during the use stage is Alternative 3, owing to the highest amount of exported electricity; see Figure 4. From a life cycle perspective, the EAC values for the four alternatives are comparable. Alternative 2 exhibits slightly lower values, mainly due to the reduced material cost of wood compared to steel and concrete. The material cost appears to be the most influential contribution to EAC during the building life. Therefore, the results highlight the importance of an economic analysis at the early design stage of zero-emission buildings to achieve the emission target alongside the economic efficiency. The results are in accordance with similar studies [39, 40]. However, LCC analyses are very case specific, and the results may vary owing to different assumptions.

The research question posed in the introduction aimed to investigate the most influential factors and promising strategies in a pathway from zero-energy buildings to zero-emission buildings from a life cycle environmental and economic perspective. Figure 6 shows the normalised values for the four alternatives considering CED, GWP, and EAC in the life cycle of the building.

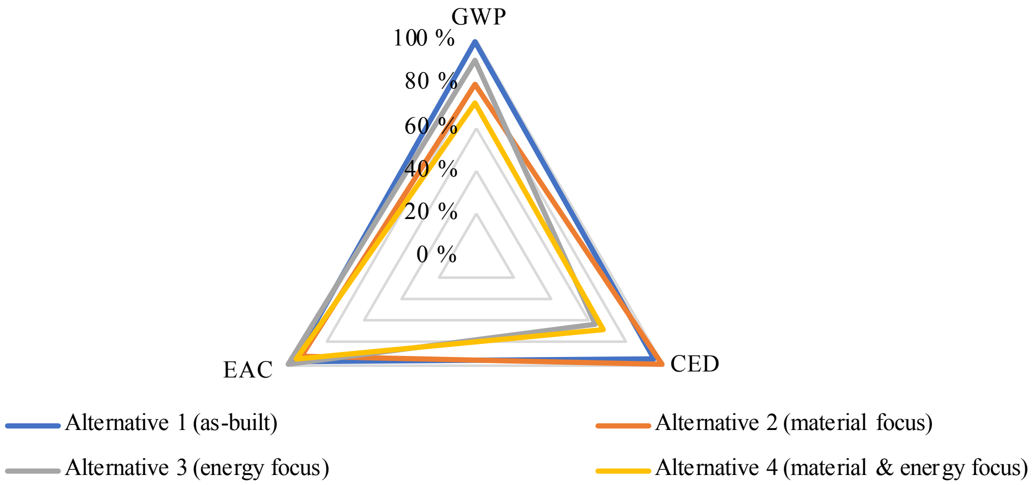

Figure 6: Radar plot showing normalised values for the life cycle CED, GWP, and EAC of the four analysed alternatives. Values are normalised against the highest values for each indicator.

Based on the analyses performed in this paper, the choice of materials appears to be one of the key factors to address when investigating a pathway for the transition in building solutions. Renewable energy generation lowers the CED as seen in Figure

6, but the energy generated is simply not high enough to compensate for the embodied GHG emissions from the building materials. A strategy focused only on energy savings is therefore not sufficient for a transition from a zero-energy to zero-emission building solution. This is an interesting finding and is especially important in areas with low-carbon energy from the grid, as in the Nordic countries. Although the use of wood instead of low-carbon concrete can lead to marginally higher embodied energy values, this choice can significantly reduce the embodied emissions of the building materials, thus lowering the total GWP. Interestingly, the study confirms that material substitution can be achieved with comparable or even slightly lower investment costs.

A strategy focused on both material and energy saving solutions, as in Alternative 4, shows an improvement in the GWP results, with an approximately 30% decrease in the GHG emissions compared to the case building (Alternative 1). However, this solution is also quite far from being a real zero-emission solution from a life cycle perspective. In addition, such a strategy would lead to a 30% lower life cycle energy demand compared to building as built, but 8% higher than the concrete-based alternative with extensive use of PV panels (Alternative 3), owing to the slightly higher embodied energy of timber materials than the concrete ones.

These findings demonstrate the key role of the material selection and the corresponding embodied material emissions for the reduction in GHG emissions and emphasises the importance of a proper material strategy when designing a zero-emission building, regardless of the use of local renewable energy.

5. Conclusions

This paper investigates several elements in a pathway strategy for the transition from zero-energy to zero-emission building solutions from a life cycle environmental and economic perspective. A representative nearly zero-energy office-building project in Norway was used as a study object by considering alternative design solutions in addition to the as-built design. The effects of low-carbon materials versus photovoltaic (PV) panels on the life cycle greenhouse gas (GHG) emissions, energy use, and costs were the primary focus areas.

It is common knowledge that a zero-energy target is mainly achieved by high attention to design solutions for energy efficiency and use of onsite energy generation. Such a strategy will also be an important element in a pathway towards zero-emission buildings, particularly in situations with a high-carbon electricity mix in the power grid. However, to reduce the life cycle emissions even more, an extended focus on local energy generation or a more proactive preference for using low-emission materials in major building components is required. The findings of this paper point towards the need for a stronger strategic emphasis on the embodied energy and emissions of materials than what is common today for a successful transition from the zero-energy to the zero-emission building target. Attention should also be given to novel design solutions and specific building components to encompass emission reduction because the operational energy demand is already a common priority area.

The results of this paper concern a typical building constructed in a Nordic country as zero-energy or zero-emission buildings. The study object is presently in use and well documented, so the alternatives analysed represent realistic predictions of what can be achieved in terms of materials and energy use for this kind of building. In addition, the performed sensitivity analysis allows a further comparison of the results to other contexts and assumptions, such as assuming different cost conditions and surplus PV power exported to the grid to replace power according to the Norwegian electricity mix.

However, certain limitations should be considered when generalising the results. The life cycle analyses were conducted according to defined system boundaries, excluding some life cycle stages, such as installation activities, material transport, and end-of-life. The information from the Ecoinvent database for materials may not be completely representative of the Norwegian context. Time-dependent impact assessments of carbon sequestration from wood products were not considered, and this could affect the embodied emission/energy. The environmental footprint of cementitious materials is rapidly decreasing, which will reduce the positive impact of using wood. Site-specific use of information on embodied material emissions from environmental product declarations (EPD) is therefore preferable, when available. Finally, the cost analysis performed in this paper does not consider all possible costs occurring during the life cycle, such as those related to the operation of the construction site and maintenance throughout the use stage, which are different for concrete or wooden structures. In addition, material prices may not completely reflect market prices for investment costs.

Future research could include an advanced refinement of the energy component. Seasonal variations in the generation profiles for the electricity from the grid could therefore be subject to analysis, as well as the technological developments due to increased shares of low-carbon energy technologies in the power system. The inclusion of further life cycle stages in the examination, such as end-of-life, would also be of interest for defining a broader picture of the environmental and economic impacts. Finally, the use of the approach of this research in other zero-energy and zero-emission building projects would allow a portfolio of comparable projects to be built, contributing to a possible future consensus of such analyses in this field.

Endnotes

[1] Energy from renewable and non-renewable sources that has not undergone any conversion or transformation process [1].

[2] Energy flowing from the grid or a supply system to buildings, specified per energy carrier in kWh/y or kWh/(m^2y). This is the energy imported by the building [41]. The conversion from delivered to primary energy for different energy carriers can be made through specific factors, expressed in $kWh_{primary}/kWh_{delivered}$.

Acknowledgement

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References

[1] European Parliament, Council of the European Union, Directive 2010/31/EU. Energy performance of buildings (recast), 2010.
[2] A.J. Marszal, P. Heiselberg, J.S. Bourrelle, E. Musall, K. Voss, I. Sartori, A. Napolitano, Zero Energy Building – A review of definitions and calculation methodologies, Energy and Buildings 43(4) (2011) 971-979.
[3] P. Hernandez, P. Kenny, From net energy to zero energy buildings: Defining life cycle zero energy buildings (LC-ZEB), Energy and Buildings 42(6) (2010) 815-821.
[4] I. Sartori, A.G. Hestnes, Energy use in the life cycle of conventional and low-energy buildings: A review article, Energy and Buildings 39(3) (2007) 249-257.
[5] T. Ramesh, R. Prakash, K.K. Shukla, Life cycle energy analysis of buildings: An overview, Energy and Buildings 42(10) (2010) 1592-1600.

[6] G.A. Blengini, T. Di Carlo, The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings, Energy and Buildings 42(6) (2010) 869-880.
[7] B. Berggren, M. Hall, M. Wall, LCE analysis of buildings – Taking the step towards Net Zero Energy Buildings, Energy and Buildings 62 (2013) 381-391.
[8] L. Georges, M. Haase, A.A.M. Wiberg Houlihan, T.F. Kristjansdottir, B. Risholt, Life cycle emissions analysis of two nZEB concepts, Building Research & Information 43(1) (2015) 82-93.
[9] T.F. Kristjansdottir, N. Heeren, I. Andresen, H. Brattebø, Comparative emission analysis of low-energy and zero-emission buildings, Building Research & Information (2017) 1-16.
[10] European Committee for Standardization, EN 15978, Sustainability of construction works - Assessment of environmental Performance of Buildings - Calculation Method, 2011.
[11] S.M. Fufa, R.D. Schlanbusch, K. Sørnes, M. Inman, I. Andresen, A Norwegian ZEB Definition: Guideline, ZEB Project report 29, 2016.
[12] T.F. Kristjansdottir, C.S. Good, M.R. Inman, R.D. Schlanbusch, I. Andresen, Embodied greenhouse gas emissions from PV systems in Norwegian residential Zero Emission Pilot Buildings, Solar Energy 133 (2016) 155-171.
[13] T.B. Hofmeister, T. Kristjansdottir, B. Time, A.A.M. Houlihan Wiberg, Life Cycle GHG Emissions from a Wooden Load-Bearing Alternative for a ZEB Office Concept ZEB Project report 20, 2015.
[14] T.H. Dokka, T.F. Kristjansdottir, B. Time, S.E. Mellegård, M. Haase, J. Tønnesen, A zero emission concept analysis of an office building, ZEB Project report 8, 2013.
[15] P. Torcellini, S. Pless, M. Leach, A pathway for net-zero energy buildings: creating a case for zero cost increase, Building Research & Information 43(1) (2014) 25-33.
[16] SINTEF Byggforsk, Byggforskserien, Byggdetaljer, 2017. https://www.byggforsk.no.
[17] Standard Norge, NS-EN 1991-1-1:2002+NA:2008, Eurocode 1: Actions on structures. Part 1-1: General actions. Densities, self-weight, imposed loads for buildings, 2002.
[18] Standard Norge, NS-EN 1995-1-1:2004+A1:2008+NA:2010, Eurocode 5: Design of timber structures. Part 1-1: General common rules and rules for buildings, 2004.
[19] Standard Norge, NS 3701:2012, Criteria for passive houses and low energy buildings - Non-residential buildings, 2012.
[20] R. Frischknecht, N. Jungbluth, H.-J. Althaus, C. Bauer, G. Doka, R. Dones, R. Hischier, S. Hellweg, S. Humbert, T. Köllner, Y. Loerincik, M. Margni, T. Nemecek, Implementation of Life Cycle Impact Assessment Methods. Ecoinvent report No. 3, v. 2.0, Swiss Centre for Life Cycle Inventories, Dübendorf, 2007
[21] PRé Sustainability, SimaPro Classroom, version 8.1.1, 2016.
[22] International Organization for Standardization, ISO 14025, Environmental labels and declaration - Type III environmental declarations - Principles and procedures, 2006.
[23] European Committee for Standardization, EN 15459, Energy performance of buildings - Economic evaluation procedure for energy systems in buildings, 2007.
[24] SINTEF Byggforsk, Intervals for maintenance and replacement of building parts, 2010. https://www.byggforsk.no/dokument/3312/intervaller_for_vedlikehold_og_utskifting_av_bygningsdeler.
[25] ProgramByggerne, SIMIEN, SIMulation of Indoor climate and ENergy use (Version 6.0), 2016.
[26] Joint Research Centre, Photovoltaic Geographical Information System (PVGIS). Geographical Assessment of Solar Resource and Performance of Photovoltaic Technology, 2001.
[27] Standard Norge, NS 3031:2014, Calculation of energy performance of buildings - Method and data, 2014.

[28] European Committee for Standardization, EN 15265:2007, Energy performance of buildings - Calculation of energy needs for space heating and cooling using dynamic methods - General criteria and validation procedures, 2007.
[29] G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz, B. Weidema, The ecoinvent database version 3 (part I): overview and methodology, The International Journal of Life Cycle Assessment 21(9) (2016) 1218-1230.
[30] Standard Norge, NS 3720:2018, Method for greenhouse gas calculations for buildings, 2018.
[31] International Organization for Standardization, ISO 15686-5, Buildings and constructed assets - Service-life planning - Part 5: Life-cycle costing, 2008.
[32] Norconsult Informasjonssystemer and AS Bygganalyse, Norsk prisbok 2016.
[33] Statistisk sentralbyrå, Electricity prices, 2017. https://www.ssb.no/energi-og-industri/statistikker/elkraftpris.
[34] Standard Norge, NS 3454:2013, Life cycle costs for construction works - Principles and classification, 2013.
[35] J. Clavreul, D. Guyonnet, T.H. Christensen, Quantifying uncertainty in LCA-modelling of waste management systems, Waste Management 32(12) (2012) 2482-95.
[36] A.J. Marszal, P. Heiselberg, R. Lund Jensen, J. Nørgaard, On-site or off-site renewable energy supply options? Life cycle cost analysis of a Net Zero Energy Building in Denmark, Renewable Energy 44 (2012) 154-165.
[37] P. Chastas, T. Theodosiou, D. Bikas, Embodied energy in residential buildings-towards the nearly zero energy building: A literature review, Building and Environment 105 (2016) 267-282.
[38] T. Lützkendorf, G. Foliente, M. Balouktsi, A.H. Wiberg, Net-zero buildings: incorporating embodied impacts, Building Research & Information 43(1) (2014) 62-81.
[39] A.J. Marszal, P. Heiselberg, Life cycle cost analysis of a multi-storey residential Net Zero Energy Building in Denmark, Energy 36(9) (2011) 5600-5609.
[40] M. Kapsalaki, V. Leal, M. Santamouris, A methodology for economic efficient design of Net Zero Energy Buildings, Energy and Buildings 55 (2012) 765-778.
[41] I. Sartori, A. Napolitano, K. Voss, Net zero energy buildings: A consistent definition framework, Energy and Buildings 48 (2012) 220-232.

Appendix

	A1-A3: Product stage			A4-A5: Construction stage		B1-B7: Use stage							C1-C4: End-of-life				D: Benefits and loads
	A1: Raw material supply	A2: Transport to manufacturer	A3: Manufacturing	A4: Transport to construction site	A5: Installation in the building	B1: Use	B2: Maintenance (incl. transport)	B3: Repair (incl. transport)	B4: Replacement (incl. transport)	B5: Refurbishment (incl. transport)	B6: Operational energy use	B7: Operational water use	C1: Deconstruction/Demolition	C2: Transport to end-of-life	C3: Waste processing	C4: Disposal	D: Reuse, recovery, recycling
ZEB - O-EQ											▨ *						
ZEB - O											▨						
ZEB - OM	▨	▨	▨						▨ **		▨						
ZEB - COM	▨	▨	▨	▨	▨				▨ ***		▨						
ZEB - COME	▨	▨	▨	▨	▨				▨		▨		▨	▨	▨	▨	
ZEB - COMPLETE	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	

* Does not include operational energy of electric equipment.

** Does not include transport to building site (A4), installation in the building (A5) or end-of-life treatment of the replaced materials.

*** Does not include end-of-life treatment of the replaced materials.

Figure A 1. Ambition levels for the Norwegian Research Centre on Zero Emission Building, according to the system boundary of NS-EN 15978: 2011.
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Table A 1. Material inventory for all alternatives analysed.

Building element	Main component	Main materials	Process in Ecoinvent 3.1 or EPD source	Quantity		
				Alternative 1	Alternative 2	Alternative 3
Foundation	Plinths	Concrete	EPD: Betong B35 M45, Voss Cementvarefabrikk	52.54 m^3	39.94 m^3	52.54 m^3
		Reinforcing steel	Reinforcing steel {RER}|production| Alloc Rec, U	5,682.70 kg	4,171.66 kg	5,682.70 kg
Load-bearing system	Pillars	Concrete	EPD: Betong B35 M45, Voss Cementvarefabrikk	25.99 m^3		25.99 m^3
		Reinforcing steel	Reinforcing steel {RER}|production| Alloc Rec, U	4,158.96 kg		4,158.96 kg
		Wood	Glued laminated timber, for indoor use {RER}|production| Alloc Rec, U		6.62 m^3	
		Nail plates	Steel, low-alloyed {RER}| steel production, converter/electric, low-alloyed | Alloc Rec, U		942.21 kg	
	Beams	Concrete	EPD: Betong B35 M45, Voss Cementvarefabrikk	59.23 m^3		59.23 m^3
		Reinforcing steel	Reinforcing steel {RER}|production| Alloc Rec, U	9,476.64 kg		9,476.64 kg
		Wood	Glued laminated timber, for indoor use {RER}|production| Alloc Rec, U		28.14 m^3	
		Nail plates	Steel, low-alloyed {RER}| steel production, converter/electric, low-alloyed | Alloc Rec, U		942.21 kg	
	Walls	Concrete	EPD: Betong B35 M45, Voss Cementvarefabrikk	118.16 m^3	118.16 m^3	118.16 m^3
		Reinforcing steel	Reinforcing steel {RER}|production|Alloc Rec, U	8,271.40 kg	8,271.40 kg	8,271.40 kg
External walls	Internal finish	Gypsum	Gypsum plasterboard {CH}|production|Alloc Rec, U	15,422.40 kg	15,422.40 kg	15,422.40 kg
	Studs	Wood	Sawnwood, softwood, kiln dried, planed {RER}| production |Alloc Rec, U	159.89 m^3	159.89 m^3	159.89 m^3
	Insulation	Glass wool	Glass wool mat {CH}| production|Alloc Rec, U	10,205.26 kg	10,205.26 kg	10,205.26 kg
	Air barrier	Polyethylene	Polyethylene, high density, granulate {RER}| production |Alloc Rec, U	315.90 kg	315.90 kg	315.90 kg
	Cladding	Aluminium	Aluminium, primary ingot {UN-EUROPE} production|Alloc Rec, U	2,942.46 kg		2,942.46 kg
		Polyethylene	Polyethylene, high density, granulate {RER}| production |Alloc Rec, U	3,056.33 kg		3,056.33 kg
		Wood	Sawnwood, softwood, kiln dried, planed {RER}| production | Alloc Rec, U		21.39 m^3	
		Primer	Alkyd paint, white, without solvent, in 60% solution state {RER}| production |Alloc Rec, U		53.63 kg	

Internal walls	Finish	Gypsum	Gypsum plasterboard {CH}|production|Alloc Rec, U	17,533.60 kg	17,533.60 kg	17,533.60 kg
		Ceramic tiles	Ceramic tile {CH}| production | Alloc Rec, U	5,342.10 kg	5,342.10 kg	5,342.10 kg
	Insulation	Glass wool	Glass wool mat {CH}| production|Alloc Rec, U	2,087.60 kg	2,087.60 kg	2,087.60 kg
	Plates	Glass	Flat glass, uncoated {RER}| production | Alloc Rec, U	58,350.00 kg	58,350.00 kg	58,350.00 kg
	Studs	Wood	Sawnwood, softwood, kiln dried, planed {RER}| production |Alloc Rec, U	19.19 m^3	19.19 m^3	19.19 m^3
Basement floor	Insulation	Polystyrene	Polystyrene, extruded {RER}| polystyrene production, extruded, CO$_2$ blown | Alloc Rec, U	3,900.50 kg	3,900.50 kg	3,900.50 kg
			Polystyrene foam slab {RER}| production | Alloc Rec, U	1,008.75 kg	1,008.75 kg	1,008.75 kg
	Vapor barrier	Polyethylene	Polyethylene, high density, granulate {RER}| production | Alloc Rec, U	807.00 kg	807.00 kg	807.00 kg
	Supporting slab	Concrete	Betong B35 M45, Voss Cementvarefabrikk	67.25 m^3	67.25 m^3	67.25 m^3
		Reinforcing steel	Reinforcing steel {RER}|production| Alloc Rec, U	5,380.00 kg	5,380.00 kg	5,380.00 kg
	Flooring	Ceramic tiles	Ceramic tile {CH}| production | Alloc Rec, U	5,365.00 kg	5,365.00 kg	5,365.00 kg
		Rubber	Synthetic rubber {RER}| production | Alloc Rec, U	1,813.35 kg	1,813.35 kg	1,813.35 kg
Floors	Supporting slab	Hollow-core blocks	EPD: Hulldekke-element 265, Nobi Voss AS	1,314.50 m^2		1,314.50 m^2
		Wood	Sawnwood, softwood, kiln dried, planed {RER}| production | Alloc Rec, U		51.55 m^3	
			Particle board, for indoor use {RER}| production | Alloc Rec, U		28.92 m^3	
			Fibreboard, soft {Europe without Switzerland} | fibreboard production, soft, from wet & dry processes | Alloc Rec, U		47.32 m^3	
	Insulation	Glass wool	Glass wool mat {CH}| production | Alloc Rec, U		8,996.42 kg	
	Flooring	Ceramic tiles	Ceramic tile {CH}| production | Alloc Rec, U	6,670.00 kg	6,670.00 kg	6,670.00 kg
		Rubber	Synthetic rubber {RER}| production | Alloc Rec, U	3,832.62 kg	3,832.62 kg	3,832.62 kg
	Ceiling system	Glass wool	Glass wool mat {CH}| production | Alloc Rec, U	3,098.70 kg		3,098.70 kg
		Steel	Steel, low-alloyed {RER}| steel production, converter/electric, low-alloyed | Alloc Rec, U	1,408.50 kg		1,408.50 kg
		Gypsum	Gypsum plasterboard {CH}| production | Alloc Rec, U		12,303.72 kg	

<table>
<tr><td>Roof</td><td>External finish</td><td>Bitumen</td><td>Bitumen adhesive compound, cold {RER}| production | Alloc Rec, U</td><td>5,805.50 kg</td><td>5,805.50 kg</td><td>5,805.50 kg</td></tr>
<tr><td></td><td>Insulation</td><td>Polystyrene</td><td>Polystyrene foam slab {RER}| production | Alloc Rec, U</td><td>4,589.76 kg</td><td></td><td>4,589.76 kg</td></tr>
<tr><td></td><td></td><td>Rock wool</td><td>Rock wool {CH}| production | Alloc Rec, U</td><td>3,175.95 kg</td><td></td><td>3,175.95 kg</td></tr>
<tr><td></td><td></td><td>Glass wool</td><td>Glass wool mat {CH}| production | Alloc Rec, U</td><td></td><td>4,946.32 kg</td><td></td></tr>
<tr><td></td><td>Vapor barrier</td><td>Polyethylene</td><td>Polyethylene, high density, granulate {RER}| production |Alloc Rec, U</td><td>126.36 kg</td><td>126.36 kg</td><td>126.36 kg</td></tr>
<tr><td></td><td>Supporting slab</td><td>Hollow-core blocks</td><td>EPD: Hulldekke-element 265, Nobi Voss AS</td><td>683.00 m^{2}</td><td></td><td>683.00 m^{2}</td></tr>
<tr><td></td><td></td><td>Wood</td><td>Sawnwood, softwood, kiln dried, planed {RER}| production | Alloc Rec, U</td><td></td><td>29.04 m^{3}</td><td></td></tr>
<tr><td></td><td></td><td></td><td>Particle board, for indoor use {RER}| production | Alloc Rec, U</td><td></td><td>10.93 m^{3}</td><td></td></tr>
<tr><td></td><td>Ceiling system</td><td>Glass wool</td><td>Glass wool mat {CH}| production | Alloc Rec, U</td><td>2,128.17 kg</td><td></td><td>2,128.17 kg</td></tr>
<tr><td></td><td></td><td>Steel</td><td>Steel, low-alloyed {RER}| steel production, converter/electric, low-alloyed | Alloc Rec, U</td><td>967.35 kg</td><td></td><td>967.35 kg</td></tr>
<tr><td></td><td></td><td>Wood</td><td>Sawnwood, softwood, kiln dried, planed {RER}| production | Alloc Rec, U</td><td></td><td>1.98 m^{3}</td><td></td></tr>
<tr><td></td><td></td><td>Gypsum</td><td>Gypsum plasterboard {CH}| production | Alloc Rec, U</td><td></td><td>6,392.88 kg</td><td></td></tr>
<tr><td>Windows</td><td>Frame</td><td>Aluminium</td><td>Window frame, wood-metal, U=1.6 W/m^{2}K {RER}| production | Alloc Rec, U</td><td>51.67 m^{2}</td><td></td><td>51.67 m^{2}</td></tr>
<tr><td></td><td></td><td></td><td>Window frame, wood, U=1.5 W/m^{2}K {RER}| production | Alloc Rec, U</td><td></td><td>51.67 m^{2}</td><td></td></tr>
<tr><td></td><td>Glazing</td><td>Glass</td><td>Flat glass, coated {RER}| production | Alloc Rec, U</td><td>4,316.27 m^{2}</td><td>4,316.27 m^{2}</td><td>4,316.27 m^{2}</td></tr>
<tr><td></td><td></td><td></td><td>Flat glass, uncoated {RER}| production | Alloc Rec, U</td><td>2,158.13 m^{2}</td><td>2,158.13 m^{2}</td><td>2,158.13 m^{2}</td></tr>
<tr><td>Doors</td><td></td><td>Wood</td><td>Door, inner, wood {RER}| production | Alloc Rec, U</td><td>221.49 m^{2}</td><td>221.49 m^{2}</td><td>221.49 m^{2}</td></tr>
<tr><td></td><td></td><td>Wood/ aluminium</td><td>Door, outer, wood-aluminium {RER}| production | Alloc Rec, U</td><td>39.79 m^{2}</td><td>39.79 m^{2}</td><td>39.79 m^{2}</td></tr>
<tr><td></td><td></td><td>Wood/ glass</td><td>Door, outer, wood-glass {RER}| production | Alloc Rec, U</td><td>8.1 m^{2}</td><td>8.1 m^{2}</td><td>8.1 m^{2}</td></tr>
<tr><td>PV, roof</td><td></td><td></td><td>Photovoltaic panel, single-Si wafer {RER}| production | Alloc Rec, U</td><td>414 m^{2}</td><td>414 m^{2}</td><td>414 m^{2}</td></tr>
<tr><td>PV, façade</td><td></td><td></td><td>Photovoltaic panel, CIS {DE}| production | Alloc Rec, U</td><td></td><td></td><td>280 m^{2}</td></tr>
<tr><td>Heat pump</td><td></td><td></td><td>Heat pump, brine-water, 10kW {CH} |production| Alloc Rec, U</td><td>1p</td><td>1p</td><td>1p</td></tr>
<tr><td>DHW boiler</td><td></td><td></td><td>Hot water tank, 600 l {CH} |production| Alloc Rec, U</td><td>1p</td><td>1p</td><td>1p</td></tr>
<tr><td>Ventilation system</td><td></td><td></td><td>Ventilation system production, central, 1 x 720 m3/h, steel ducts, with earth tube exchanger {CH}|production| Alloc Rec, U</td><td>1p</td><td>1p</td><td>1p</td></tr>
</table>

[*] p=unit

Table A 2. Replacement measures for all alternatives analysed.

Replacement measure	Alternative 1	Alternative 2	Alternative 3
Replacing windows every 40 years	x	x	x
Replacing external doors every 40 years	x	x	x
Replacing roof covering every 30 years	x	x	x
Replacing flooring every 30 years	x	x	x
Replacing PV panels on roof every 30 years	x	x	x
Replacing PV panels on façade every 30 years			x
Replacing aluminium façade plates every 40 years	x		x
Replacing wooden façade plates every 50 years		x	
Replacing ventilation system components every 30	x	x	x
Replacing heat pump every 20 years	x	x	x
Replacing hot water tank every 20 years	x	x	x

Table A 3. Main input data for the building model in the energy simulations.

Parameter	Value
Outdoor temperature (°C)	Dynamic, Bergen climate from meteonorm.com
Indoor temperature during operation time (°C)	21
Indoor temperature outside of operation time (°C)	19
Internal gains from occupants (W/m^2)	4
Internal gains from lighting (W/m^2)	4
Internal gains from electric appliances (W/m^2)	5
Lighting power density (W/m^2)	4
Electric appliance power density (W/m^2)	5
Domestic hot water (DHW) power density (W/m^2)	0.8
Heating, DHW, lighting, electric appliance yearly operation hours	3120
People yearly occupation hours	3120
Mechanical air flows, operation time (m^3/h/m^2)	6
Mechanical air flows, outside operation time (m^3/h/m^2)	1
Mechanical ventilation heat exchanger efficiency (%)	85
Heat pump COP (-)	3

Table A 4 . Main features of the PV system.

Cell technology (-)	Mono-Si for PV panels on roof CIGS for PV panels on façade
Total panel area, roof (m^2)	414
Total panel area, façade (m^2)	280
Slope PV panels, roof (°)	11
Slope PV panels, façade (°)	90
Azimuth PV panels, roof (°)	90-270 (west-east)
Azimuth PV panels, façade (°)	0 (south)
Module efficiency, roof (%)	20
Module efficiency, façade (%)	14
Peak power, roof (kWp)	85
Peak power, façade (kWp)	39

Table A 5. Delivered energy breakdown during annual operation of the four alternatives, normalized by the gross internal floor area

	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Space heating (kWh/m^2)	3.4	4.1	3.4	4.1
Domestic hot water (kWh/m^2)	2.0	2.0	2.0	2.0
Ventilation (kWh/m^2)	1.4	1.4	1.4	1.4
Fan and pumps (kWh/m^2)	6.9	6.9	6.9	6.9
Lighting (kWh/m^2)	12.4	12.4	12.4	12.4
Electric appliances (kWh/m^2)	15.5	15.5	15.5	15.5
Total annual delivered energy (kWh/m^2)	41.6	42.2	41.6	42.2
PV system energy generation (kWh/m^2)	27.2	27.2	37.3	37.3
Net annual delivered energy (kWh/m^2)	14.4	15.1	4.3	4.9

We declare to have no conflicts of interest to disclose and we confirm that this work is original and has not been published elsewhere, nor is it currently under consideration for publication elsewhere. Furthermore, all copyright permissions have been obtained.

Sincerely,
Roberta Moschetti,
Helge Brattebø,
Magnus Sparrevik.