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Life cycle analysis of GHG emissions from the building retrofitting: The case of a Norwegian office building

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ABSTRACT

Through a systematic study, this paper conducted a life cycle assessment (LCA) consisting of evaluation of both embodied and operational emissions of different building retrofitting scenarios for a typical office building, located in Norway. LCA analysis was performed via the OneClick LCA tool. The emissions associated with the operational energy use were evaluated for both the reference and optimized building energy models developed in the IDA-ICE models from our previous studies. These models included two different HVAC systems: an all-air (AA) system equipped with a demand control ventilation (DCV) and a hydronic system with the radiator space heating (RSH) and a constant air volume (CAV) ventilation system. The findings showed that, through retrofitting measures, the net total emissions could be reduced up to 52%, from 1336–637 kg carbon dioxide equivalent (CO_2-eq)/m^2, which was achieved for the life cycle cost (LCC) optimal scenario equipped with the AA system. The share of operational energy use (B6) in the total CO_2-eq emissions was around 77% for the reference case, whereas it was around 43–46% for the retrofitting scenarios. The most embodied CO_2-eq emitted stages of the LCA through retrofitting concerned the product stage (19–23%), transport to construction site (24–31%), and the end-of-life service (around 25%). The findings confirmed that it was more environmentally friendly to further re-insulate the other parts of the building envelope instead of ground floor, as the latter retrofitting scenario was accompanied with a large increase of embodied emissions.

1. Introduction

According to the Intergovernmental Panel on Climate Change (IPCC), the global temperature has risen by roughly 1 °C since the industrial age, because of human actions. It is also expected that the temperature will increase further, by 1.5 °C, if the current situation is prolonged [1]. Greenhouse gas (GHG) emissions are considered to be one of the main sources for the climate change, and there has been already introduced a GHG abatement curve in order to maintain the global temperature rise below 2 °C by 2030 [2].

It has been reported that around 30–40% of global CO_2 emissions are produced in the building stock [3]. Since the 80–90% of the existing buildings will still be in operation in 2050 [4,5], it is apparent that building retrofitting would substantially mitigate the total GHG emissions in the building sector. Building retrofitting has been broadly studied to cope with the climate change issue, but to achieve the target of EU's Policy, the renovation rate should further increase [6]. According to Statistics Norway (SSB), the amount of CO_2 emissions in non-residential buildings, which form the largest part of building stock in Norway (around 58%), has decreased around 39% from 2015 to 2019 due to improvement of building energy performance [7]. However, there must be additional attention to this matter if the goal is to reach a carbon neutral level in Norway by 2030. Retrofitting towards the zero energy buildings (ZEB) signifies a purposeful step in this regard, resulting in reduction of forthcoming buildings energy use. The retrofitting process can include renovation measures with regard to building envelope and façade, technical system, and utilization of renewable energy technologies [8–10]. Furthermore, there are several ZEB definitions and some of them only focus on the energy use during building operation and ignore the energy utilized for the production and manufacturing of material and systems when shifting to ZEB level, or so

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Nomenclature

Roman symbols

AA	all-air
CAV	constant air volume
CHP	combined heat and power
CO_2	carbon dioxide
CO_2-eq	carbon dioxide equivalent
COP	coefficient of performance
DCV	demand control ventilation
EU	European union
EPD	environmental performance deceleration
GHG	greenhouse gas
GSHP	ground source heat pump
GWP	global warming potential
HVAC	heating, ventilation, air conditioning system
IPCC	intergovernmental panel on climate change
LCA	life cycle assessment
LCC	life cycle cost
n_{50}	airtightness (1/h)
nZEB	nearly zero energy building
PH	passive house
PV	photovoltaic
RSH	radiator space heating
ZEB	zero energy building

Greek symbols

ψ	normalized thermal bridge (W/(m^2·K))

called embodied energy [11,12]. The concepts of the zero energy building and embodied energy have proposed the idea to replace the former concepts by the zero emission building and embodied emissions, in which the balance is applied in terms of GHG emissions [13,14]. In this regard, to reach the greatest level of the zero emission building in the retrofitting process, it is necessary to conduct a life cycle assessment (LCA) on how to compensate the embodied emissions of additional materials during the whole life cycle. The balancing can be done using the GHG emissions of produced energy from renewable sources such as the use of solar energy via photovoltaic (PV) panels [15].

A broad range of embodied CO_2 emission from buildings has been reported in literature. De Wolf et al. [16] signified this by analyzing the data obtained from over 200 buildings and the results showed that the amount of building embodied CO_2 emission equivalent (CO_2-eq) varies in the range of 150–600 kg CO_2-eq/m^2 per year of building lifetime. Simonen et al. [17] state also a significant change of buildings' contribution in CO_2-eq emissions, which is in the range of 10–1082 kg CO_2-eq/m^2 per year by evaluating 1150 buildings. These variations are pointed out regarding several parameters such as building type, materials, geometry, and other design variables. So far, several studies on the life cycle assessment (LCA) of GHG emissions related to both new and refurbished buildings have already addressed the impact of the aforementioned parameters. Some of them consider only the building use phase, but others also consider the other stages of building life cycle including the production, construction, and end-of-life.

Asdrubali et al. [18] evaluated the energy use and carbon payback time of different retrofit scenarios for a school building in Northern Italy. They applied the LCA method for calculating environmental impact of the building for lifetime of 50 years. Their findings show that a cost optimal case, in which the total specific building energy use was around 70 kWh/m^2.year, had a carbon payback time around 3.2 years. Opher et al. [19] conducted a LCA, using OneClick LCA tool, to assess the embodied emissions associated with the renovation of an existing building. By assuming a 60-year lifetime, the results show that the installation of renewable energy systems and the raised concrete floor are responsible for 31% and 26% of the embodied CO_2-eq. Rodriguez et al. [20] assessed the embodied carbon emissions associated with the mechanical, electrical, and plumbing systems (MEP) in an office building in the Pacific Northwest, USA and Canada. Various heating, ventilation, and air conditioning (HVAC) systems such as variable air volume (VAV) air handling unit (AHU), parallel fan terminals, water-source heat pump, dedicated outdoor air system, variable refrigerant flow, and energy recovery ventilator were evaluated. The results showed that the embodied carbon estimates ranged from 40 to 75 kg CO_2-eq/m^2 for MEP. García-Sanz-Calcedo et al. [21] quantified the embodied carbon of HVAC systems installed in healthcare centers in the region of Extremadura, Spain. The results showed that the embodied carbon considering a 15-year lifetime of HVAC installations, is around 48.95 kg CO_2-eq/m^2. This was equivalent to the CO_2 emitted for 2.3 years in the operation phase. Ylmén et al. [22] investigated the embodied and operational carbon emissions from HVAC systems in an office building in Sweden and the results showed that 38 kg CO_2-eq/m^2 was emitted in the production phase and 100 kg CO_2-eq/m^2 in the operation phase. Shuo [23] analyzed the embodied emissions associated with three different HVAC installations, including a VAV system, a chilled beam system, and an underfloor air distribution in an office building in Australia. The total embodied carbon emission was reported 21.01 kg CO_2-eq/m^2, 42.70 kg CO_2-eq/m^2, and 9.2 kg CO_2-eq/m^2, respectively. Kiamili et al. [24] performed a detailed LCA for HVAC systems based on building information modelling (BIM) of a newly built office building in Switzerland. The results indicated that the embodied impact of HVAC systems was in the range of 15–36% of the total embodied impact of office buildings. However, Medas et al. [25] indicated that recurring embodied carbon of MEP from 30 years of maintenance and replacement might be much larger than the initial embodied carbon.

Moschetti et al. [26] investigated alternative design solutions for a zero energy office building, located in Norway, in order to achieve a zero emission one. The building model was run using SimaPro tool, and the results revealed that it was difficult to totally balance the life cycle GHG emissions from materials by renewable energy, even with widespread use of PV panels, and hence the embodied emissions from the materials should come into the sharp focus. Piccardo et al. [27] conducted the LCA of a retrofitted building to passive house level. They considered various scenarios including using covering different building materials and different electricity production cases. They pointed out that a careful choice of building materials might result in maximum 68% reduction of the net CO_2-eq in the retrofitted building than in the reference case, notably when selecting the wood material for building frames. Chen et al. [28] presented a multi-criteria evaluation approach for retrofit of a residential building to reduce the primary energy, global costs, payback period and the CO_2 emission. Regarding the environmental impact, an CO_2-eq factor, corresponding to the emissions from different GHGs generated only during building operation, was considered on the time frame of 100 years. The results showed the CO_2-eq can drop up to 10.4 kg CO_2-eq/m^2 in the case of applying extensive retrofits of building envelope and use of renewable measures. Pal et al. [29] proposed a LCA optimization approach to find the carbon-cost optimal solutions in terms of both operational and embodied CO_2 emissions. The results showed that when the carbon optimal solution was the matter of concern, the contribution of carbon embodied emissions in the LCA process was 39%, while in the cost optimal solution, its share was 28% in the LCA. Kristjansdottir et al. [30] studied the feasibility of achieving a zero emission building level, in terms of the life cycle energy and the material emission balance, through redesigning a single family pilot building located in Norway, which was constructed based on previous concept of zero greenhouse gas emission building [31,32]. The findings revealed that the embodied emissions can be compensated up to 60% using the new model. However, an optimization framework is necessary to reach the balance of the life cycle energy and material emissions. Llantoy et al. [33] developed a comparative LCA by focusing on different building insulation materials including polyurethane, extruded polystyrene, and mineral wool. The results showed that although all insulation materials demonstrated a net positive benefit over 55 year's lifetime, the highest environmental impact was corresponding to the polystyrene insulation material and the lowest one was for the mineral wool. Echarri-Iribarren et al. [34] proposed a Life Cycle Construction Assessment of Envelopes (LCCA-e) method for analysis of constructive improvements derived from the application of ceramic panels and aluminum in a building façade located in Spain. The results showed 65.6% and 67.7% reduction in the global energy resources (GER) and global warming potential (GWP) indicators in the production phase and a reduction of these indicators by 87.1% and 86.8% respectively in the complete LCA. Chang et al. [35] performed a life cycle energy assessment of several academic buildings in Singapore. Their findings showed that 90% of the total life cycle energy is due to operational energy while the remaining 10% is from embodied energy. Sierra-Pérez et al. [36] used an integrated life cycle and thermal dynamic simulation assessment to identify the adequacy of each renovation alternative regarding the post-renovation energy performance of a commercial building, located in Spain. Their method included an evaluation of using a renewable insulation material in a low-energy building, especially a particular cork solution. The results showed that the renovation process of the low energy building results in an increase in the embodied impacts in the building, mainly for the large amount of insulation material. Furthermore, adopting cork did not fit the requirements for competing with the common non-renewable insulation materials as it did not lead to a better environmental performance in buildings. Luo and Chen [37] established a LCA of a residential building in different areas and the results showed that the amount of CO_2 emissions in server cold area and hot summer and warm winter area are the largest and the smallest, respectively. Wrålsen et al. [38] studied the LCA of retrofitting a residential building block from 1960s to nearly Norwegian passive house standard level over a 30 years period. The results of upgrading showed that all environmental impact categories reduced around 56–96% compared to the reference case, and the carbon payback period was 1.09 year. Shirazi and Ashuri [39] carried out a systematic LCA comparison of different retrofit measures and their associated payback time for a single family residential building. The investigation results showed that the foundation wall insulation significantly contributed to the carbon and smog potential for the building constructed before 1970s. The replacement of windows and the HVAC system had the next highest environmental impact. However, for after 1970s, HVAC replacement had the highest contribution to the carbon and smog potential.

Some studies focused on the uncertainty of parameters, methods, and scenarios in LCA process as it is a long-time frame process and there might be significant changes in building fabric features, occupancy behavior, climate changes, and etc. Zhang et al. [40], in a comparative case study, investigated the uncertainty in the LCA of a building case study by adopting deterministic and stochastic approaches. The first term is basically defined as the emissions, which are equal to the quantity product and the associated emission factor of the analyzed process [41]. The second approach could be applied by Monte Carlo simulations by considering the data samples generation as the main technique, which necessitates the dissemination of input data [42]. The results showed that the uncertainty in the input parameters could lead the ratio of standard deviation to the results sample mean, which was in accordance with the deterministic results, to be obtained around 0.51. Zhang et al. [43] also carried out a similar investigation to quantify the uncertainties in LCA of building CO_2-eq emissions when applying different parameter, methods, and modelling. The methods included process based method [44,45], input-output analysis [46,47], and hybrid method [48,49]. LCA results of two residential buildings showed that selection of methods could significantly affect the CO_2-eq emissions. Furthermore, regarding parameter uncertainty, the input-output analysis could result in substantial errors, and hybrid techniques were suggested in the emission evaluation instead. Goulouti et al. [50] applied a systematic method to investigate the uncertainties of life service of building components through a stochastic approach. This method was applied for LCA calculation of a multi-family house. Moreover, a comprehensive sensitivity analysis was applied. The results showed that the main influential building elements on the uncertainty of LCA replacement stage were external insulation, windows, roofing, flooring, internal layout, and ceiling covering, respectively.

As the aforementioned studies showed, in the building retrofitting context, applying new materials introduces extra embodied emissions although the impacts associated with the energy use are reduced. Furthermore, LCA is a proper tool to analyze the resulting shifting between the increased embodied emissions and the reduced impacts associated with the energy use from an environmental standpoint. Therefore, in this paper, we conducted a feasibility study through adapting a cradle to grave method to assess the environmental impacts associated with GHGs generated due to applying extra/new materials and systems, and the resulting reduction of building energy use, by applying several retrofit measures for a typical and existing Norwegian office building. The main aim and novelty of this study was to identify the environmental impacts associated with the aforementioned retrofit measures applied in two different HVAC scenarios: (1) radiator space heating (RSH) system with constant air volume (CAV) and (2) all-air (AA) system equipped with a demand control ventilation (DCV) system. Due to complexity of the building simulation modeling, the building energy models corresponding to these scenarios were taken from our previous studies [8,51]. In addition, the aim was to find an optimal set of design solutions contributing to achieve a zero emission building level with regard to these HVAC scenarios.

The rest of the paper is organized as follows. Section 2 introduces the case building study and its characteristics, LCA specifications for analysis of embodied emissions connected to building materials and components, and emissions related to the operational energy use both for the reference building and the retrofitting scenarios. Furthermore, the building LCA tool and its properties are described in this section (see Fig. 1). Section 3 presents the results obtained from the LCA tool and discuss and interpret the CO_2-eq emissions produced in different scenarios and stages of the building life cycle. Finally, Section 4 summarizes the conclusions and findings of this study and suggests a framework for future work.

2. Method, building description, and tools

In this study, the LCA method was adopted to obtain science based information about the environmental impact of different retrofit measures of an office building built in the 1980s, in terms of GHG emissions ($kgCO_2 - eq/m^2_{floor\ area}$), implemented according to the Norwegian standard NS 3720 [52]. This reference is based on the European LCA standard EN 15978 [53] and is used for calculation of GHGs in buildings. The functional unit was considered as one square meter of heated floor area ($m^2_{floor\ area}$) over a service lifetime of 60 years [54]. The GHGs were based on the Kyoto basket gases weighted by their global warming potential (GWP) and aggregated to give total greenhouse gas emissions in terms of CO_2-eq [55]. In the first stage, we conducted energy simulations using the building model and the optimized scenarios applied in our previous work [8]. In this respect, we updated the building technical system and envelope characteristics in the building Indoor Climate and Energy (IDA-ICE) simulation software [56] to comply with the Norwegian building regulation TEK 87. Afterwards, we calculated the CO_2-eq, using OneClick LCA, for various retrofit scenarios in different phase of the building life cycle.

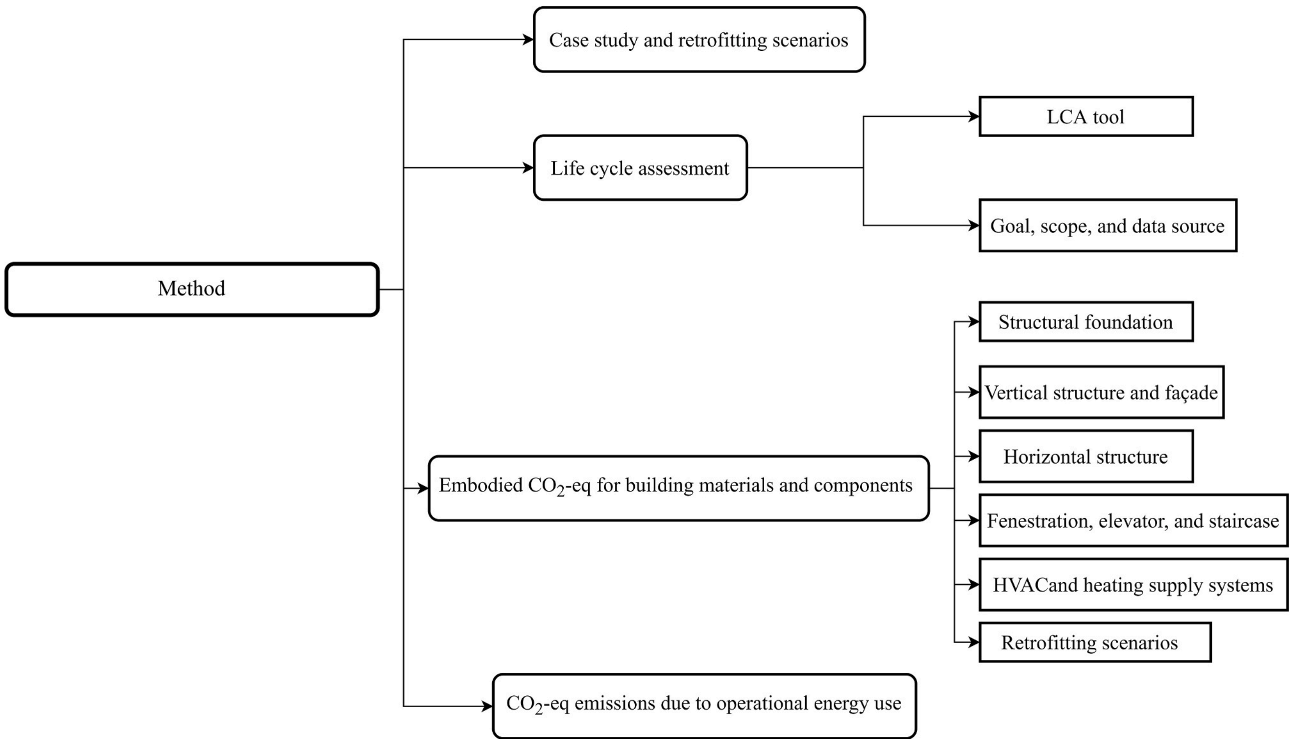

Fig. 1. Method and different stages of LCA process.

2.1. Case study and retrofitting scenarios

The case building that was simulated and analyzed in this study was a building model representing a typical and existing office building configuration located in Norway (Fig. 2). As shown in Fig. 2 (a) and (b), two office buildings, built on 1965 and 2015, have similar rectangular geometry and consist of combination of single and landscape offices. The considered building model in this study was an existing building from 1980 that was already applied in our previous studies [8,51]. The reference building properties were selected according to the Norwegian building regulation TEK 87 describing the characteristics of the typical existing Norwegian office buildings in the same time frame [57], as the majority of office buildings in Norway were built in the 1980s [7]. All data related to the building's area, volume, and energy use were obtained from the IDA-ICE model in our previous study [8] and were used as a basis for the greenhouse gas calculations in the LCA tool.

The building had a compact square design with a total internal volume of 9062 m^3 and a total floor area of 2940 m^2. Details about the building system and services can be found in the previous work [51] and the most important building properties are given in Table 1.

In addition, four retrofitting scenarios were considered based on the models in our previous work [8]:

Table 1
Properties of the building mass used in the energy simulation and LCA analyses.

Building component	Values
Gross volume (m^3)	10 200
Net volume (m^3)	9062
Gross area (m^2)	3000
Useable area (m^2)	2940
Heated area (m^2)	2290
Number of floors	3
Roof and Floor area (m^2)	1000
External wall gross area (m^2)	1326
External wall net area (m^2)	1025
Window area (m^2)	280
Exterior doors (m^2)	21

- The first and second scenarios models were designed based on the Norwegian Passive House (PH) standard NS 3701 for non-residential buildings [58]. The difference between the two scenarios was the


(a) (b) (c)

Fig. 2. (a) FN office building located in Arendal, which was built in 1965 and renovated in 2006 (b) An office building located in Bergen, which was completed in 2015 for the Norwegian Defence Estates Agency (NDEA) as a nearly zero energy building (nZEB) (c) Considered office building configuration modelled in the energy simulation software in our previous studies [8,51].

type of HVAC system in the zones. RSH and CAV ventilation system were used in the first scenario (the same HVAC system as the reference building) while the AA system was applied in the second scenario [8].

- The two other scenarios were the optimized models achieved in the previous work [8]. The optimized models were designed so that the minimum life cycle cost (LCC) of retrofit measures were reached while the building energy use for space heating and cooling did not exceed the requirements defined in the Norwegian PH standard NS 3701. Furthermore, a thermal comfort constraint was also considered in these cases. The difference between two scenarios was the type of space heating and cooling systems. The RSH system was adopted in the third scenario whereas AA system, was applied in the fourth scenario.

It should be noted that the space heating and cooling system in the reference building and first and second scenarios was the RSH system.

The minimum requirements for the building envelope and glazing properties for the reference building (TEK 87) and the PH cases, and the building envelope properties for two other retrofit scenarios were selected based on the previous work [8], are shown in Table 2.

2.2. Life cycle assessment

2.2.1. LCA tool

OneClick LCA was used for the LCA by taking into account the Norwegian standard NS 3720 [59]. It is a standardized web-based platform specifically designed for LCA of construction projects and contains EPDs [60], completed together with upstream data from well-established commercial LCA databases. It includes twelve third-party certifications and complies with more than 30 certifications and standards for the life cycle assessment, including NS 3720 [59]. Data points used in our life cycle analysis were mainly Norwegian EPDs for Norway or Nordic countries. In cases where none of the aforementioned standard were accessible in the database, data from other countries were used. It should be noted that this tool uses qualitative data input meaning that the user selects an option from a given list, i.e. the modules and indicators to be considered, the building substructure type, as well as pre-established scenarios for construction and end-of-life. It facilitates the data inputs, especially in the early stages of design, when exactly information is not yet available. However, one of the downsides of qualitative inputs is the "black box" approach that does not allow the user to modify or access the parameters considered. Moreover, the tool does not calculate the operational energy use, however, it allows the user to input this information, as well as the electricity and fuel grid.

2.2.2. Goal, scope, and data source

Fig. 3 illustrates all the life cycle stages for building constructions. In this study, we focused the LCA on the building GHG emissions, calculated in terms of CO_2-eq, from four main stages, i.e. production of materials, construction phase, operation stage, and the end-of-life (filled green and red boxes). The first stage included extraction of raw materials, transport of them to the production site, and production (A1-A3).

Table 2
Building envelope and glazing properties reported in the previous work.

Building component	TEK 87	PH	RSH_LCC	AA_LCC
External wall U-value (W/(m^2·K))	≤0.3	≤0.1	0.12	0.12
Roof U-value (W/(m^2·K))	≤0.2	≤0.08	0.18	0.08
Floor towards ground U-value (W/(m^2·K))	≤0.3	≤0.08	0.18	0.18
Windows/doors U-values (W/(m^2·K))	≤2.4 (doors, ≤ 2)	≤0.8	0.8	0.8
ψ (W/(m·K))	≤0.13	≤0.03	0.03	0.03
n_{50} (1/h)	≤4	≤0.6	0.6	0.6

The second stage encompassed transportation of materials/components to the construction site, construction, and installation work (A4-A5). The embodied emissions related to the operation of the building included renovation and replacement of building materials and components during the use of the building (B2–B5). The embodied emissions in the last phase covered the demolition, transportation, waste processing, and disposal (C1–C4). The life service period for the retrofitted building and the reference case study was assumed to be 60 years [54, 61]. In addition, the life service for various products in this study was selected based on the product information provided by the manufacturer and it available in the LCA tool. The emissions associated with the operational energy use (B6) were calculated based on the energy simulations performed by considering the details of retrofitting scenarios from our previous studies [8,51]. In fact, IDA ICE was used as a platform to compute the energy performance of the models, and that data was used in One Click LCA to compute the emission in the energy use. It should be pointed out that the reuse, recovery, and recycling potential of materials/components (phase D) were not taken into account due to considering a cut-off system modelling approach, implying that the avoided burdens of the recyclable materials were not modelled throughout the way to where they recycled to new production.

For the retrofitting process, we adopted the same framework as in Fig. 3, but considering a refurbished process instead of a new building construction. This infers that the inputs for materials and components of the LCA model were only associated with the retrofit measures and not to the entire building in the retrofitting scenarios. Furthermore, the database used for the greenhouse gas calculations at different life cycle stages in the LCA tool are shown in Table 3.

In the product stage (A1-A3), the quantity of materials and technical information of the building structural foundation, which mostly concerned the reference building, were obtained from the archive for the Norwegian Building Research Series for the office buildings constructed in the 1980s [57].

2.3. Embodied CO_2-eq for building materials and components at different scenarios

The material/component quantities, types, and their corresponding CO_2-eq emissions for the building structural foundation, vertical structures and facade, horizontal structures, and building HVAC and heating supply systems were described only for the reference building, according to the TEK87 code (see Fig. 2 c). For the retrofit scenarios, only the quantity and the emissions associated with the extra building materials and components were considered. Therefore, in the following sections, the quantity and CO_2-eq emissions of the materials used for the aforementioned building components are firstly described for the reference building and afterwards only the changes due to retrofitting are mentioned. It should be noted that the life service for building foundation, and vertical and horizontal structures was considered permanent if otherwise it was mentioned.

2.3.1. Structural foundation

The building materials used in the structural foundation are shown in Table 4. These materials were never replaced, considered with permanent lifetime in all scenarios, and their quantities were calculated per building gross area. The frost insulation was specified according to the Norwegian building instructions and was calculated for the externally insulated concrete with the maximum frost amount of 35 000 h°C [62].

2.3.2. Vertical structure and façade

Table 5 shows the list of all materials' quantity and their corresponding CO_2-eq emissions used in the vertical structures and façade. The insulation materials were mineral wool class 36, which were selected according to the archive for the Norwegian Building Research Series in 1987 [63]. For the material calculation of load-bearing vertical structures, the same calculation principles were used as proposed for the

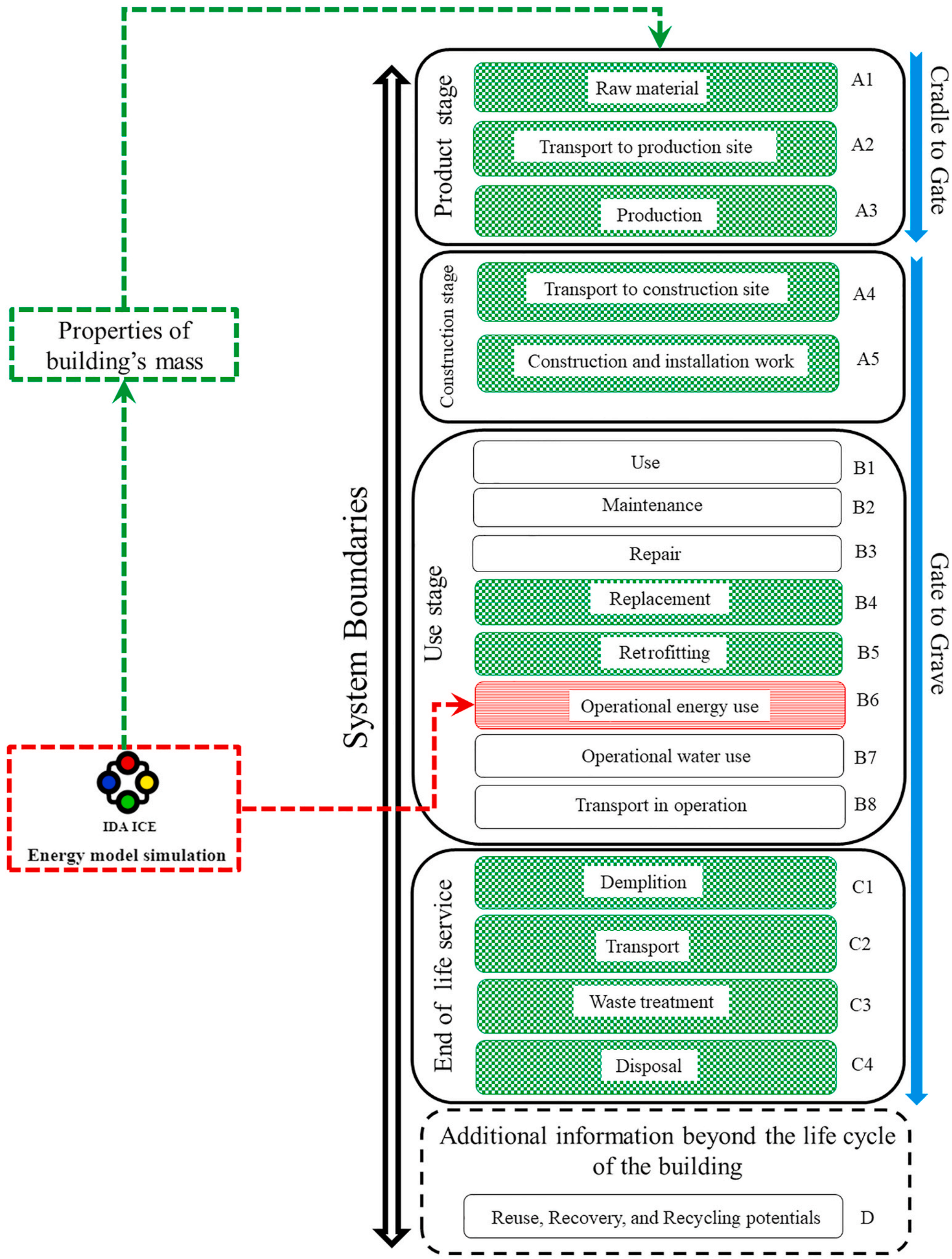

Fig. 3. Entire building life cycle stages according to NS 3720 [52]. In color: those considered in the boundaries of LCA in the present study. (green): Stages assessed through the LCA tool database. (red): Those evaluated using the optimized building energy models taken from our previous studies [8,51]. (white box) Those not considered in this study. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

reference buildings in the Carbon Designer tool. Furthermore, the interior walls were assumed to be composed of 25% concrete walls and 75% timber frame. In addition, a layer of water-based interior paint was added to all interior walls in the calculation.

2.3.3. Horizontal structure

The quantities and corresponding CO_2-eq emissions of the materials used in the horizontal structure of the reference building are shown in Table 6. The components of the horizontal structure such as roof, floors and floor separators were set to be constructed of concrete.

2.3.4. Fenestration, elevator, and staircase

Table 7 shows an overview of the quantities and the corresponding CO_2-eq emissions of the materials used in the windows, stairs, elevators, and doors. The considered material quantities corresponded to stairs with 11 m height and one elevator shaft. As there was no available window or door type with U-value of 2.4 W/(m^2.K) in the OnceClick LCA library, a generic two-layer windows with wooden/aluminum frame were used instead, because it had the same material impact on the CO_2-eq emissions as those had in 1987. The same assumptions were adopted in selecting the type of doors.

2.3.5. HVAC and heating supply systems

The HVAC system in the reference building consisted of a generic constant air volume system for cooling and heating of ventilation air and the RSH system. The materials used for the ventilation system were due to duct work and machinery. The materials used in the radiators or the RSH system were due to hydronic heating distribution system, as shown

Table 3
Data sources used for different LCA stages.

LCA stage	Source/assumption
Material quantities in production stage (A1-A3)	Quantities and material types were entered manually in the LCA tool based on the requirements for the reference building case and retrofit scenarios.
Transport of material to the production site (A4)	Automatic regional transport scenarios were used representing typical transport distances. If there was no data for the materials, the LCA's Norwegian default distance was used. The vehicles' type used for transportation was modelled using the available database, so that the maximum capacity of the vehicles nearly matches the transported mass.
Construction and installation work (A5)	Emission from waste materials associated with the construction and installation work was calculated based on the available standard values for each individual product.
Replacement and retrofitting (B4–B5)	Estimated lifetime was based on typical values for each material. Maintenance and repairs were omitted from the assessment as the materials were assumed to be replaced at the end of their technical life.
Operational energy use (B6)	Emissions from energy use were calculated based on the findings from building energy simulations and optimization in our previous study [8].
End-of-life service (C1–C4)	Emissions in connection with the end-of-life service were calculated according to the default scenarios in the tool representing the typical procedures for different types of material in accordance with the requirements in the Norwegian standard NS 3720.

Table 4
Materials' quantity and CO_2-eq emissions for the ground foundation.

Component	Source	Quantity	CO_2-eq (kg/m^2)
Foundation	Base plate, 0.3 m generic concrete	225 m^3	28
	Reinforced steel	18 750 kg	
	Gravel products	78 7500 kg	
Frost insulation	EPS80	39 m^3	0.8

in Table 8.

The systems were based on the generic available environmental products in the LCA tool and represented the average quantity of the materials for the performance criteria determined for the building gross area around 3000 m^2. The electric boiler was sized to cover the total building heating demands. However, there are still large uncertainties regarding the data sources used in the LCA tool since the available data may not be accurate or can be specific to the investigated system.

2.3.6. Retrofitting scenarios

In the retrofitting scenarios, only the additional materials, with corresponding CO_2-eq emissions, to the aforementioned building materials were taken into account. In the scenarios where the re-insulation of building envelope and façade was essential, a completely new construction component was replaced. This was performed to have a correct calculation of the life cycle assessment, so that the replacement of component was taken into consideration. In this respect, for example, the floor was replaced and the outer layer of asphalt in the roof was replaced in order to re-insulate these building components with additional insulation. All the building envelope components including floor, roof, and exterior walls were re-insulated with Glava Extrem 32 in the LCA tool.

Table 9 shows the quantity of extra materials and the associated emissions. In the PH scenarios (RSH_PH and AA_PH) the extra materials

Table 5
Materials' quantity and CO_2-eq emissions for vertical structure and facade.

Component	Source	Quantity	CO_2-eq (kg/m^2)
Exterior wall made of concrete	Wooden studwork	118.9 m^2 × 148 mm	26
	Mineral wool insulation	906.1 m^2 × 150 mm	
	wind barrier	1025 m^2 × 9 mm	
	Generic concrete for external wall	1025 m^2 × 200 mm	
	Reinforced steel	17 425 kg	
Exterior cladding (external wall)	Fiber cement board cladding	1025 m^3	1.5
Concrete columns (support systems)	Generic mixed concrete	56 203 kg	4
	Reinforced steel	4662 kg	
Internal concrete wall with reinforcement and filler	Mortar wall	960 m^2 × 1 mm	9
	Generic mixed concrete	480 m^2 × 150 mm	
	Reinforced steel	6120 kg	
Timber framed wall and 100 mm steel stud with mineral wool insulation (internal walls)	Plaster cast 13 mm	2 × 1440 m^2	7
	Structural steel profiles	3984.5 kg	
	Mineral wool insulation boards	1440 m^2 × 100 mm	
Interior paint (internal walls)	Water-based interior paint (lifetime 15 years)	514.4 kg	0.3

Table 6
Materials' quantity and CO_2-eq emissions for horizontal structure.

Component	Source	Quantity	CO_2-eq (kg/m^2)
Floor towards ground	EPS insulation	1000 m^2 × 80 mm	39
	Generic concrete	1000 m^2 × 300 mm	
	Vapor barrier in plastic	1000 m^2 × 0.2 mm	
	Reinforced steel	27 000 kg	
	Mineral wool insulation	1000 m^2 × 3 mm	
Floor separator: hollow core slab with mineral wool insulation	Generic hollow core slab	1940 m^2 × 265 mm	43
	Generic concrete	1940 m^2 × 50 mm	
	Reinforced steel	4306.8 kg	
	Mineral wool insulation	1940 m^2 × 20 mm	
Floor paint	Epoxy floor painting	2940 m^2 × 0.1 mm	0.7
Floor covering	Linoleum covering (lifetime 30 years)	2000 m^2 × 2.25 mm	0.8
External roof: Compact concrete	EPS insulation and Mineral wool insulation boards	1000 m^2 × 180 mm	33
	Vapor barrier plastic	1000 m^2 × 0.2 mm	
	Generic concrete	1000 m^2 × 200 mm	
	Reinforced steel	28 000 kg	
Roof membrane (external roof)	Double layer of asphalt roof membrane (lifetime 60 years)	1000 m^2 × 3,5 mm	4

were chosen to meet the standard requirements. The RSH_LCC and AA_LCC scenarios were based on the previous work [8], where the requirements were obtained from the LCC optimized solutions. The HVAC

Table 7
Materials' quantity and CO_2-eq emissions for fenestration, elevator, and stairs.

Component	Source	Quantity	CO_2-eq (kg/m^2)
Stairs	Generic concrete	6.6 m^3	0.8
	Reinforced steel	658.4 kg	
Elevator shaft	Generic concrete	19 m^3	2
	Reinforced steel	1897.4 kg	
External doors	Steel door (lifetime 30 years)	12.6 m^2	0.7
	Steel garage door (lifetime 30 years)	8.4 m^2	
Internal doors	Wooden interior door (lifetime 30 years)	44 units	1.9
	Wooden double door (lifetime 30 years)	13.2 m^2	0.6
	Emergency door (lifetime 30 years)	6.15 m^2	0.1
Windows	Two-layer window with wooden/ aluminum frame (lifetime 30 years)	280 m^2	12

Table 8
Materials' quantity and CO_2-eq emissions for HVAC system and central heating system.

Component	Source	Quantity (kg)	CO_2-eq (kg/m^2)
Ventilation system	Generic ventilation system (lifetime 50 years)	8250	55
Heating system	Radiator heating system (lifetime 30 years)	10 755	18
Electric boiler	Electric boiler, 280 kW (lifetime 22 years)	3558	8

system in the RSH_PH and RSH_LCC was the same as the reference building but with new waterborne radiators. In the AA_PH and AA_LCC the HVAC system was replaced by an AA system to cover space heating, space cooling, and ventilation air needs. In that case, the ventilation control method was changed to DCV.

To investigate the effect of different insulation materials, the same requirements for the building envelope characteristics should be considered. Therefore, we considered the U-value requirements for the Norwegian PH standard NS 3701 [58]. The reason was that the PH standard required the thickest insulation layers associated with largest CO_2-eq emissions. Table 10 shows the overview of which products were assessed, and whether Norwegian EPDs were used. In the cases where the desired product and EPD were not found in the software, generic products were used instead, such as cellulose insulation.

Since a German product was used for the VIP insulation, the transportation distance to the construction site was set to 1160 km. Furthermore, the transportation distance to the construction site was considered 1000 km for Polyurethane foam due to use of a Finnish product. Otherwise, a standard Norwegian value was used for the transportation of other insulation materials to the construction site.

Furthermore, as the aim of the retrofitting was to reach a nZEB level, two types of PV were used, namely Monocrystalline and Polycrystalline. Similar to the comparison of CO_2-eq emissions for different insulation materials, the energy use for the PH standard was used as the criterion to balance the total delivered energy to the building and to calculate the necessary area of PV panels, which was calculated based on the method reported in Ref. [51]. The required area was obtained around 1500 m^2 and 1800 m^2 for Monocrystalline and Polycrystalline cells, respectively. The efficiency of these two types of PV cells was estimated based on typical figures for commercial PV panels. To allow these types of panels to be comparable in terms of CO_2-eq emission, a manufacturer that produced both types of panels were chosen, which is a Dutch manufacturer. Furthermore, the lifetime of PV cells was considered 30 years and their degradation rate neglected in this study.

2.4. CO_2-eq emissions due to operational energy use

GHG emissions due to operational energy use were calculated based on the delivered energy to the building and emission factors for electricity and district heating in accordance with NS 3720 [52]. Regarding the CO_2-eq factor related to the electricity production and transportation, 0.13 kg CO_2-eq/kWh was assumed based on production mix approach in the electricity supply (EU28 + Norge) with an expected average over 60 years and starting point based on the average for the last

Table 9
Extra materials' quantity and CO_2-eq emissions for different retrofitting scenarios.

Component	Materials	RSH_PH		AA_PH		RSH_LCC		AA_LCC	
		Quantity	CO_2-eq (kg/m^2)	Quantity	CO_2-eq (kg/m^2)	Quantity	CO_2-eq (kg/m^2)	Quantity	CO_2-eq (kg/m^2)
Extra insulation for external wall	Glava Extrem 32	1 025m^2 × 215 mm	4.6	1 025m^2 × 215 mm	4.6	1 025m^2 × 160 mm	3.5	1 025m^2 × 160 mm	3.5
New exterior façade (external wall)	Fiber cement board cladding	1 025m^2	4.3	1 025m^2	4.3	1 025m^2	4.3	1 025m^2	4.3
Extra insulation of the floor towards ground	Glava Extrem 32	1 000m^2 × 240 mm	116	1 000m^2 × 240 mm	116	1 000m^2 × 20 mm	111	1 000m^2 × 20 mm	111
	Generic concrete	1 000m^2 × 300 mm		1 000m^2 × 300 mm		1 000m^2 × 300 mm		1 000m^2 × 300 mm	
	Plastic vapor barrier	1 000m^2 × 0.2 mm		1 000m^2 × 0.2 mm		1 000m^2 × 0.2 mm		1 000m^2 × 0.2 mm	
	Armouring	27 000 kg		27 000 kg		27 000 kg		27 000 kg	
	Mortar	1 000m^2 × 3 mm		1 000m^2 × 3 mm		1 000m^2 × 3 mm		1 000m^2 × 3 mm	
	Epoxy floor paint	1 000m^2 × 0.1 mm		1 000m^2 × 0.1 mm		1 000m^2 × 0.1 mm		1 000m^2 × 0.1 mm	
Extra insulation of the roof	Glava Extrem 32	1 000m^2 × 240 mm	17.5	1 000m^2 × 240 mm	17.5	1 000m^2 × 20 mm	12.9	1 000m^2 × 240 mm	17.5
	Double layer of asphalt roof membrane	1 000m^2 × 3.5 mm		1 000m^2 × 3.5 mm		1 000m^2 × 3.5 mm		1 000m^2 × 3.5 mm	
	Plastic vapor barrier	1 000m^2 × 0.2 mm		1 000m^2 × 0.2 mm		1 000m^2 × 0.2 mm		1 000m^2 × 0.2 mm	
Window	Triple glazing, lifetime 30 years	280m^2	34	280m^2	34	280m^2	34	280m^2	34
External door	Existing doors were replaced by sliding door for use in exterior wall, lifetime 30 years	12.6m^2	4	12.6m^2	4	12.6m^2	4	12.6m^2	4
New hydronic system	For RSH_PH, and RSH_LCC, lifetime 30 years	10 755 kg	52	NA	NA	10 755 kg	52	NA	NA

Table 10
Required quantity of various insulation materials and their corresponding CO_2-eq emission to satisfy Norwegian PH standard.

Insulation product	Norwegian EPD	Quantity	CO_2-eq (kg/m^2)
Glass wool: Glava Extreme 32	Available	Roof and floor: 2 × 1000m^2 × 240 mm External wall: 1025m^2 × 215 mm	5
Rock wool: Rockwool-REDair Plate	Available	Roof and floor: 2 × 1000m^2 × 248 mm External wall: 1025m^2 × 221 mm	24
EPS80: EPS-group, EPS80	Available	Roof and floor: 2 × 1000m^2 × 285 mm External wall: 1025m^2 × 255 mm	17
VIP insulation, Vacuum VIP	Not available	Roof and floor: 2 × 1000m^2 × 53 mm External wall: 1025m^2 × 47 mm	121
Cellulose insulation	No EPD[a]	Roof and floor: 2 × 1000m^2 × 278 mm External wall: 1025m^2 × 248 mm	2.6
Polyurethane foam	No EPD[b]	Roof and floor: 2 × 1000m^2 × 173 mm External wall: 1025m^2 × 155 mm	12.2
XPS, Sundolitt XPS	Available	Roof and floor: 2 × 1000m^2 × 255 mm External wall: 1025m^2 × 230 mm	30

[a] A Norwegian generic model was selected.
[b] A Finnish generic was used.

3 years [52,64]. The EU28 mix is a global power producer and the result of cooperation between the countries of the EU, where the goal is to reduce greenhouse gas emissions related to the production of electricity [64].

The CO_2-eq factor for district heating was selected 0.0138 kg CO_2-eq/kWh, which was based on the public data from Norwegian District Heating Fellowship [65]. Additionally, we compared the CO_2-eq for various types of energy supply system for heating. Four scenarios including district heating, a ground source heat pump (GSHP), electric boiler, and a combination of GSHP and electric boiler were considered. In order to find the necessary electricity required by the GSHP, a COP of 2.5 was considered for the GSHP [66]. In the hybrid scenario, the GSHP covered 60% of the heating demand and the rest was covered by the electric boiler. It should be mentioned that the embodied emissions related to the district heat distribution and the GSHP were selected based on the available data source for Norway in 2019, which were equal to 9.23 kg CO_2-eq/kW and 59.0 kg CO_2-eq/kW, respectively.

3. Results and discussions

In this section, the obtained results from the LCA tool are presented for both the reference case and the retrofitting scenarios. In this regard, the CO_2-eq emissions from different stages of building life cycle for the reference building are elaborated. Afterwards, the retrofitting scenarios are compared with the reference cases in terms of CO_2-eq during the whole building life span and the CO_2-eq payback period is discussed. In the third section, the CO_2-eq emissions for different insulation materials and various heating supply systems are described. In the fourth section, the CO_2-eq emissions for nZEB cases are presented.

3.1. CO_2-eq emissions for reference building

The amount of CO_2-eq emissions related to various stages of the building life cycle for the reference building is presented in Fig. 4. The overview of the building life cycle shows that most of emissions, around 77%, was due to building operational energy use (B6), calculated based on the building energy simulation model in our previous study [51]. Furthermore, the product stage (A1-A3) stood for 16% of the total emissions, and the lowest emissions, around 1%, were related to transport to construction site (A4) and the end-of-life service (C1–C4). This implies the importance of improving the energy performance of the existing buildings as it leads to significant reductions in the building energy use and the corresponding CO_2-eq emissions.

Analyzing the embodied CO_2-eq emissions of materials shows that decks stood for the largest amount of the embodied CO_2-eq emissions, around 83 kg/m^2, and the stairs generated the lowest amount, approximately 3 kg/m^2 see Fig. 5. A Large part of CO_2-eq emissions for HVAC installations was related to the replacement and retrofitting stage, because the service life of the ventilation system, the eating system, and the electric boiler was estimated at 50, 30 and 22 years respectively and must be, therefore, replaced during the life of the building (60 years). It was also pointed out in Ref. [25] that the embodied emissions corresponding to the periodical maintenance of the HVAC system could be larger than the initial embodied emissions. However, the total production of materials (A1-A3) formed the largest source of emissions from the life cycle stages, with 73% of the total embodied emissions.

Fig. 6 shows the CO_2-eq emissions associated with 10 resources in the building that have the largest environmental impact in the reference building. The finished concrete was the largest driving source of the CO_2-eq emissions in all stages of building life cycle except the replacement and retrofitting, where the ventilation system was the most CO_2-eq emitted component. Overall, the finished concrete and ventilation system produced around 44% and 21% of the total embodied emissions in the entire life cycle stages. However, the minimum embodied CO_2-eq emissions were generated by the EPS insulation materials due to poor insulation quality of the reference building.

3.2. Environmental impacts of retrofitting scenarios

Fig. 7 shows the total CO_2-eq emissions for the reference building and retrofitting scenarios for the lifetime of 60 years. An obvious decrease of CO_2-eq emissions was obtained in the retrofitting scenarios, around 68% and 73% for the RSH and the AA scenarios respectively, mostly due to significant energy savings achieved by applying retrofitting measures. It should be noted that the emissions associated with the building operational energy use were calculated based on the reference and the optimized building energy models in our previous studies [8, 51]. Less CO_2-eq reduction in the cases with the RSH system was, firstly, due to the heating distribution network for radiators, which did not exist in the cases with the AA system, and secondly, because of the DCV in the AA system assisted in higher reduction of the building energy use than CAV ventilation in the RSH system. Although, due to the utilization of extra materials, the embodied CO_2-eq emissions increased in the retrofitting scenarios compared to the reference case, around 12–19%, the reduction of CO_2-eq emissions was much bigger in the operational stage. Accordingly, the share of operational energy use (B6) in the total CO_2-eq emissions was around 77% for the reference case whereas it was obtained around 43–46% for the retrofitting scenarios, and 54–57% of total emissions were due to embodied emissions of extra materials. In Ref. [38] it was also shown that applying the building retrofit measures could reduce the corresponding environmental impacts by 56–96% for a residential building in Norway, where the largest reduction was due to renovation of energy supply in addition to building envelope retrofitting. Overall, the AA_LCC produced the least CO_2-eq emissions, around 354 kg CO_2-eq/m^2, among all studied scenarios, owing to less materials used in the product stage together with less emissions generated in the operational energy use stage. It should be emphasized that the share of embodied CO_2-eq emissions related to material usage in the RSH and AA scenarios may vary depending on how these systems are implemented and installed.

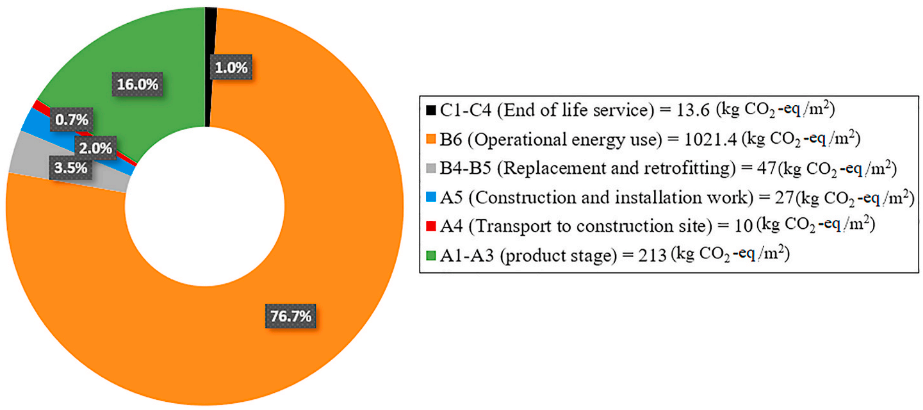

Fig. 4. Total CO_2-eq emissions related to various stages of the building life cycle.

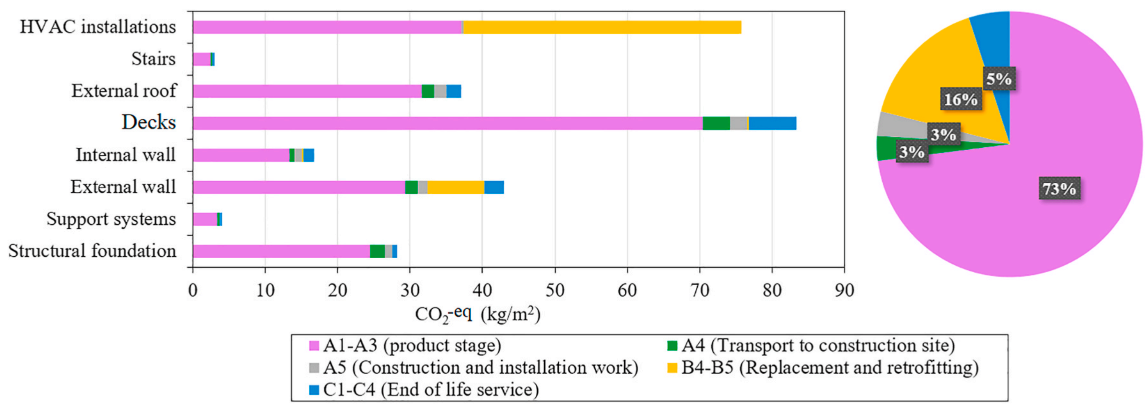

Fig. 5. Embodied CO_2-eq emissions of the materials in the reference building.

To further compare the embodied emissions for the reference building and retrofitting scenarios, the CO_2-eq emissions associated with different building component and materials are shown in Fig. 8. The change in the insulation thickness of the building envelope, together with replacement of various types of windows were the differences between the retrofitting scenarios. The cases equipped with AA system generated less emission related to HVAC installations. In this regard, the minimum embodied CO_2-eq emissions from materials were produced for the AA_LCC case.

Although HVAC installation generated almost the largest embodied CO_2-eq emissions among all building components and materials for all the five cases, which was mainly due to replacement (B4–B5), the largest increase in the embodied emissions, due to retrofitting, was associated with the re-insulation of the ground floor. Furthermore, to maintain the ceiling height the same as that in the reference building, due to re-insulation of floors, the ground floor had to be replaced. This retrofit measure is not only costly and time consuming, but also turned out to have a considerable impact on the total CO_2-eq emissions in the LCA analysis as it involves new pouring of concrete. It should be noted that the share of produced emissions in the operational energy use which was only corresponding to re-insulation of the ground floor should also be considered to find out if this retrofit measure could compensate for the large associated embodied emissions. However, it could have been more appropriate, from an environment perspective, to further re-insulate the other parts of the building envelope instead of ground floor. It can be also observed in Fig. 8 that the emissions associated with retrofitting of the exterior walls and the roof were considerably lower compared to the ground floor.

To obtain a comprehensive LCA of retrofit scenarios, the CO_2-eq payback time was used for the studied cases, as shown in Fig. 9. It is an important indicator for finding the retrofit scenarios which have the best environmental performance in the building lifetime and determines how long it would take before the lower emissions from energy use will offset greenhouse gas emissions in connection with retrofitting. In this respect, the retrofitting scenarios were compared to the reference building, spread over a 60-year period.

In Fig. 9, the embodied emissions related to all building's life cycle stages, except the replacement, have been considered at the beginning of the lifetime period, while the emissions related to the operational energy use were successively added over the building lifetime. As the results demonstrated, the CO_2-eq payback times for the AA_LCC and RSH_LCC scenarios were almost the same and equal to 3.9 years, followed by the AA_PH and RSH_PH scenarios with CO_2-eq payback times equal to 4.6 and 5.1 years, respectively. These payback periods were obtained without considering the retrofitting of the building energy supply system and changing the energy supply could shorten the CO_2-eq payback period. A case in this point was stated in Ref. [38], where retrofitting of building envelope along with changing the energy supply system resulted in a CO_2-eq payback period 1.09 years for a residential building in Norway. Overall, considering both the carbon payback times and the total CO_2-eq emissions generated at various stages of the building life cycle, the AA_LCC had the best environmental performance among all retrofitting scenarios. It should be noted that these retrofitting scenarios are not the most environmentally friendly solutions and are already based on our previous LCC optimization study [8]. Nevertheless, they can provide worthwhile information about the environmental impacts associated with the cost-efficient solutions for the buildings in cold climate.

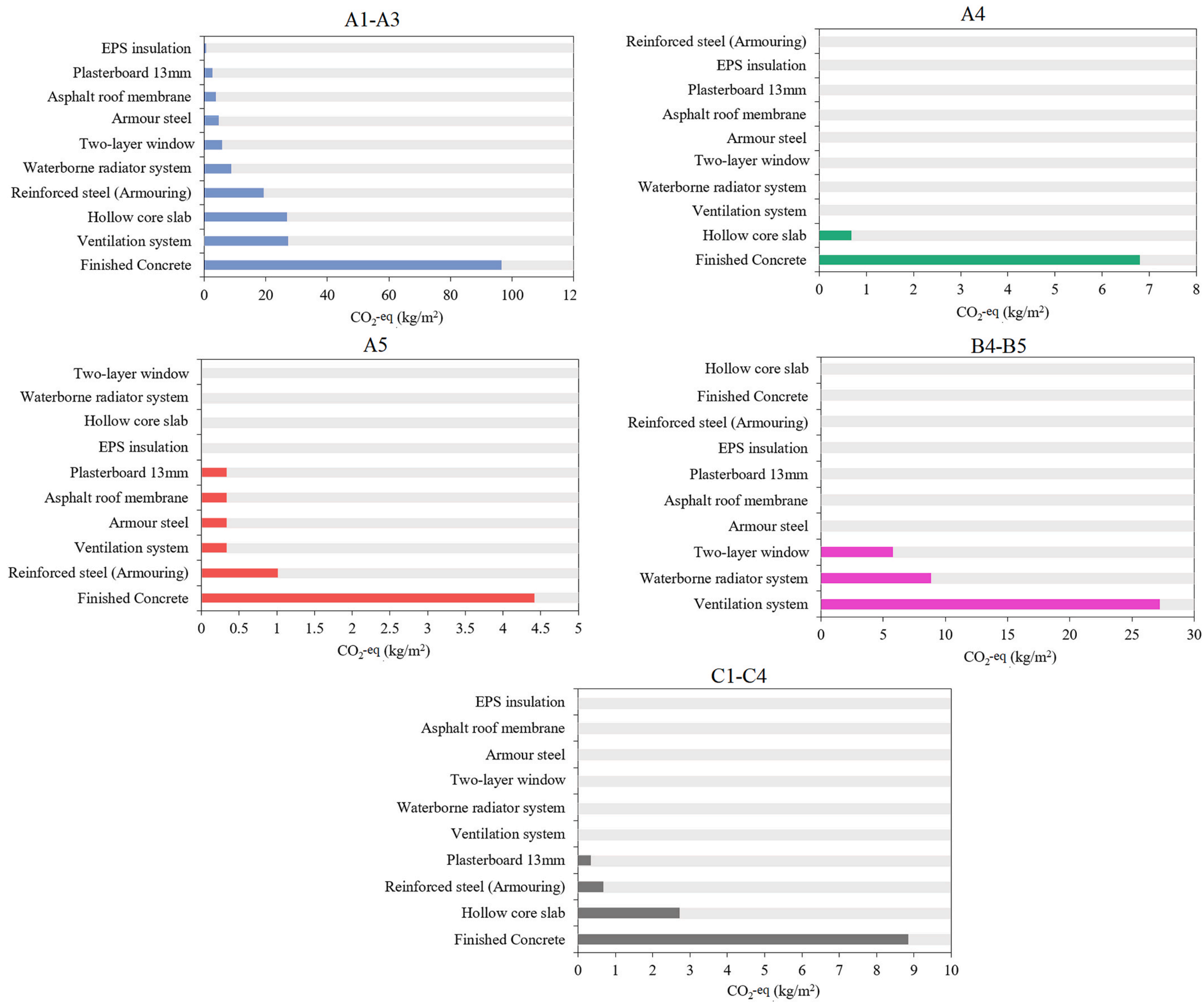

Fig. 6. Ranking of embodied CO_2-eq emissions of different building materials in various life cycle stages for the reference building.

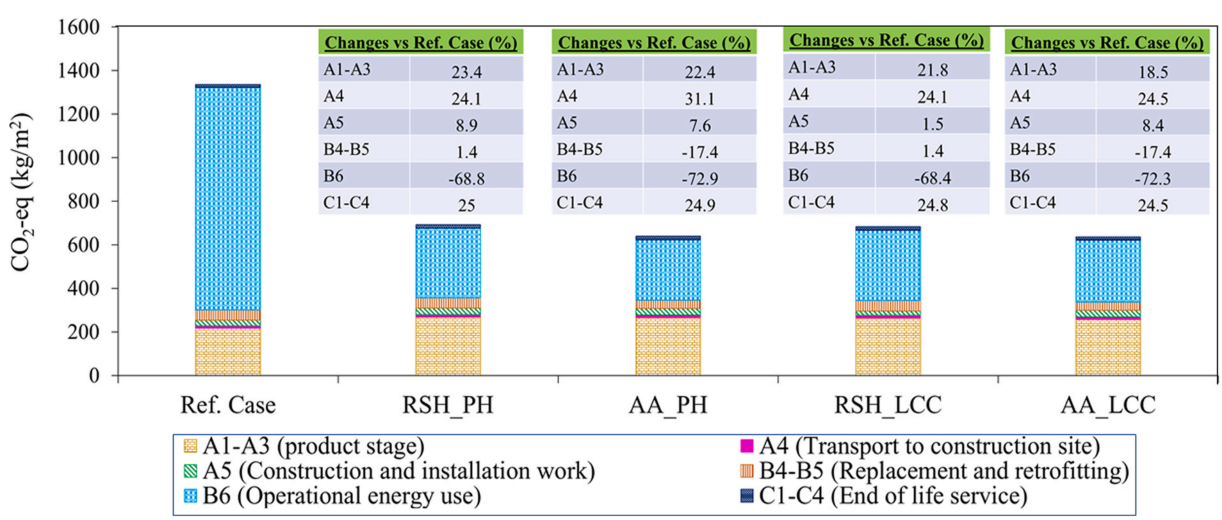

Fig. 7. Total CO_2-eq emissions related to various stages of the building life cycle for the reference building and retrofitting scenarios.

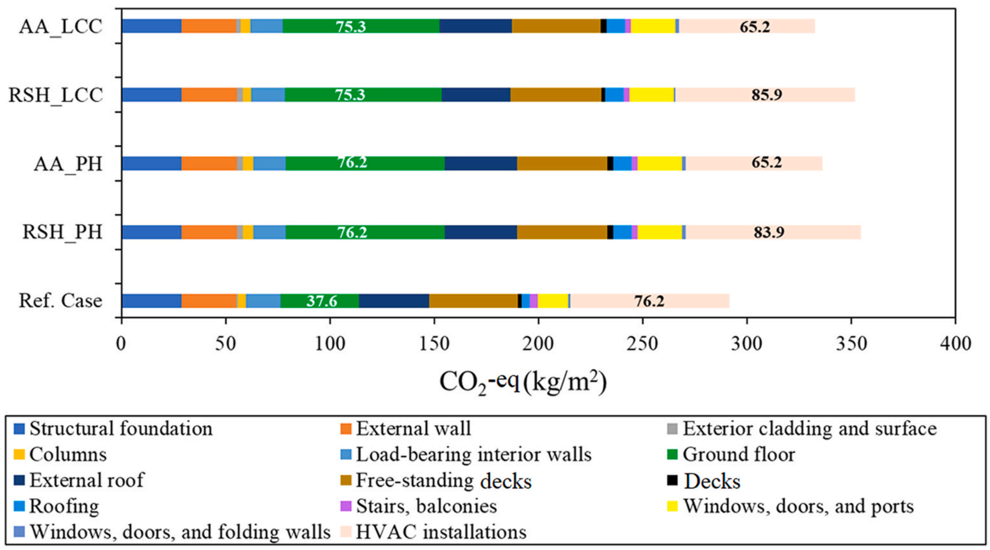

Fig. 8. Embodied CO_2-eq emissions from materials for the reference building and the retrofitting scenarios.

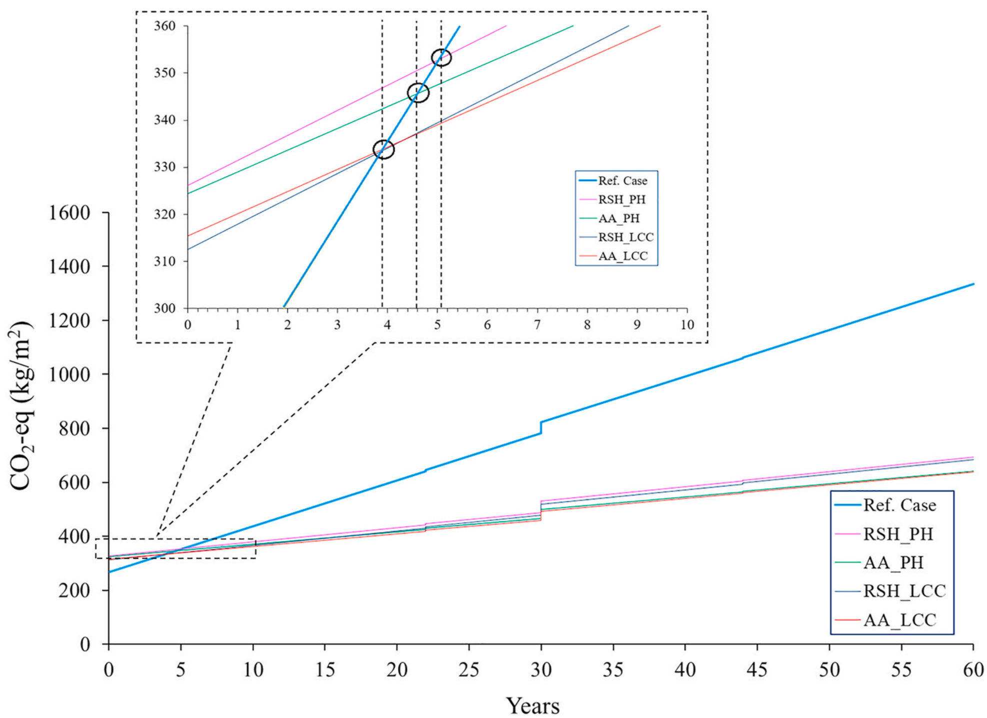

Fig. 9. Time plot of CO_2-eq for the reference case and different retrofit scenarios.

3.3. Environmental impacts of various insulation materials and heating supply systems

To investigate the carbon life cycle impact of various heating supply systems and insulation materials, the RSH_PH case was considered as a case study, since the environmental impact of the type of insulation and heating supply system would be the same for all the scenarios.

Fig. 10 shows the CO_2-eq emissions related to the four supply heating systems described in section 3.4. The emissions include only the environmental impacts related to the operational energy use and the embodied emissions for installation of heating supply systems.

As Fig. 10 shows, the district heating systems resulted in the minimum CO_2-eq emissions among all the considered systems, in terms of embodied CO_2-eq emissions corresponding to the materials and those associated with the operational energy use. The reason was that the electricity was supplied to the heating systems by considering the EU28 mix supply scenario in which 49% of the power production sources is from fossil fuels, having a large effect on greenhouse gas emissions. It was also pointed out in Ref. [67] that the district heating may reduce the CO_2-eq more than other supply systems. The reduction amount still depends on the source of the district heating system, as reported in Ref. [68] that the district heating provided by CHP plants competes with other forms of heat generation such as heat pumps. Furthermore, the hybrid system did not show better environmental performance than the GSHP because the electricity source was the EU28 mix. However, it could be an interesting alternative if the boiler was supplied by renewable sources and if the Norwegian electricity mix, which has much lower CO_2-eq impact than the EU28 mix, was used to drive the GSHP.

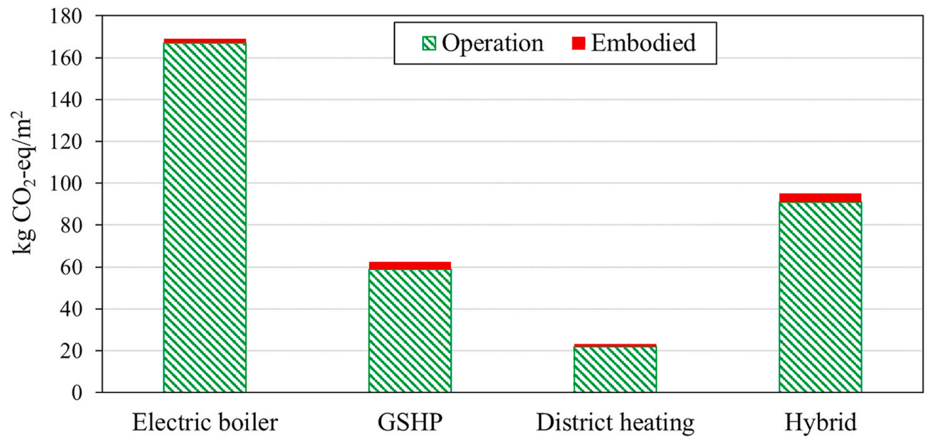

Fig. 10. CO_2-eq emissions associated with various types of heating systems for the RSH_PH case.

This analysis could be a further research in this area.

The total embodied CO_2-eq emissions of the entire building corresponding to various insulation materials are shown in Fig. 11. Using VIP and Glass wool insulation materials led to maximum and minimum CO_2-eq emissions among all types of insulation materials, respectively. The high CO_2-eq emissions were mostly associated with the product stage (A1-A3) and end-of-life service (C1–C4). However, Cellulose insulation material resulted in the minimum CO_2-eq emissions in the product stage. Although VIP is not an Eco-friendly product, it is still a desirable insulation material in rehabilitation projects with little space for extra insulation materials.

It should be noted that the choice of insulation material will always depend on the type of building, type of building components, climate conditions at the location, and the thickness and positioning of the insulating material. Environmental impact, heat resistance, and area to be insulated will be factors that come into play. For example, it was found in Ref. [30] that by using a strip foundation of low carbon concrete with glass wool insulation and a timber construction, a considerable reduction of embodied emissions in terms of CO_2-eq is achieved, around 40%, for a zero emission single family house located in Norway. However, it was reported that retrofitting a Swedish residential building with glass wool insulation along with other materials such as aluminum-framed windows and aluminum cladding results in trivial saving in CO_2-eq [27]. The cost of insulations also plays an important role in the assessment of various insulation materials. For instance, it was reported in Ref. [69] that Cellulose insulation shows the best overall performance for the considered areas of applications (energy, environmental, economic) in a residential building in Ireland. Nevertheless, each investigation regarding the environmental impacts of insulation materials may provide worthwhile information about the environmental and economic aspects of them in various conditions.

3.4. *CO_2-eq emissions for nZEB scenario*

As mentioned in Section 3.3.5, the nZEB scenario was achieved by installing PV panels to balance the total delivered energy to the building. The environmental impacts of two types of PV panels were studied for the RSH_PH scenario, as shown in Fig. 12.

Although Monocrystalline resulted in less material usage (smaller PV panel areas) to reach nZEB level, due to its higher efficiency than Polycrystalline, it generated more CO_2-eq emissions than Polycrystalline, especially in the product stage and replacement and retrofitting see Fig. 12(a). This was due to extra Czochralski process in the production of the Monocrystalline PV panels. In addition, in both cases, the replacement and retrofitting stood for more than 49% of CO_2-eq emissions production. Fig. 12(b) shows that installing the PV panels to balance the delivered energy use for RSH_PH led to increase of embodied emissions around 11% and 6% when applying the Monocrystalline and the Polycrystalline, respectively. However, the emissions related to the operational energy use, accounting for 50% of total emissions in RSH_PH, were decreased resulting in approximately 39% and 44% net reduction of CO_2-eq emissions in the nZEB 2 and nZEB 1 scenarios,

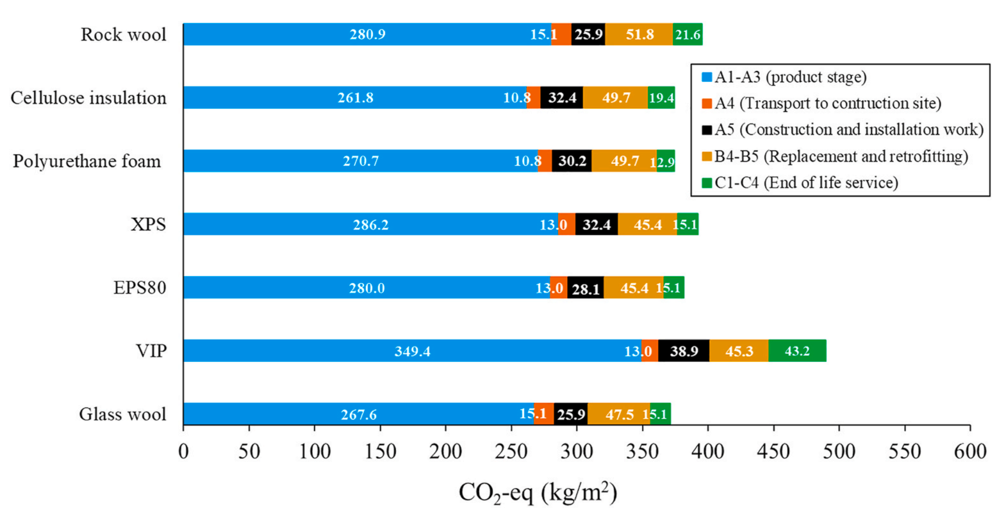

Fig. 11. Total building embodied CO_2-eq emissions associated with using various types of insulation materials for the RSH_PH case.

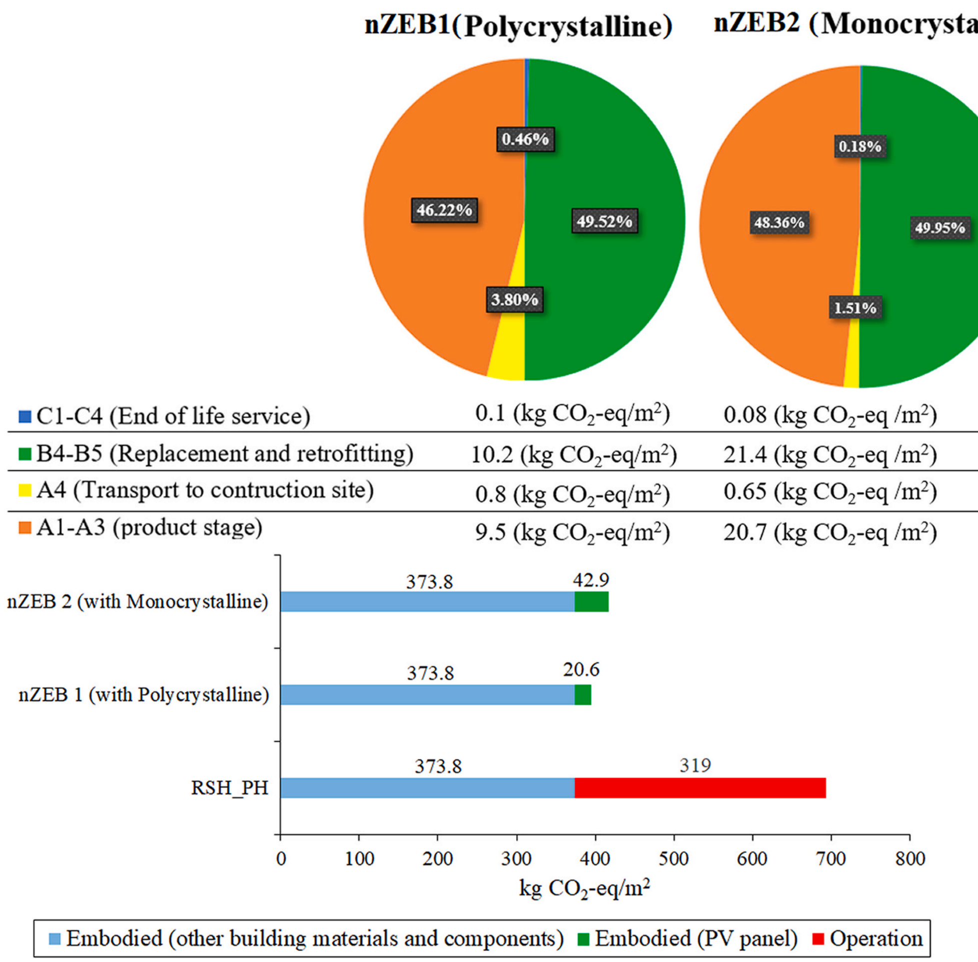

Fig. 12. (a) CO_2-eq emissions for two types of PV panels to reach nZEB level and (b) total CO_2-eq emissions for the RSH_PH and two nZEB cases.

reactively.

Fig. 13 shows the time profile of CO_2-eq emissions for the RSH_PH case and the two nZEB scenarios over the lifetime period 60 years. As it can be observed, the nZEB 1 had carbon payback time around six years while, the payback time was obtained around 12 years for the nZEB 2 scenario.

Comparing the results obtained in Figs. 12 and 13 shows that the case with the Polycrystalline PV panels had better performance than the Monocrystalline ones in terms of environmental impact even though with a larger PV area, around 20%, was needed for the Polycrystalline PV panels to reach nZEB level. However, the high efficiency and space saving make Monocrystalline PV panels attractive on the market, as there is often limited installation space.

4. Conclusions

This paper investigated a detailed LCA of various retrofit scenarios, in terms of CO_2-eq, for a typical existing office building built in Norway

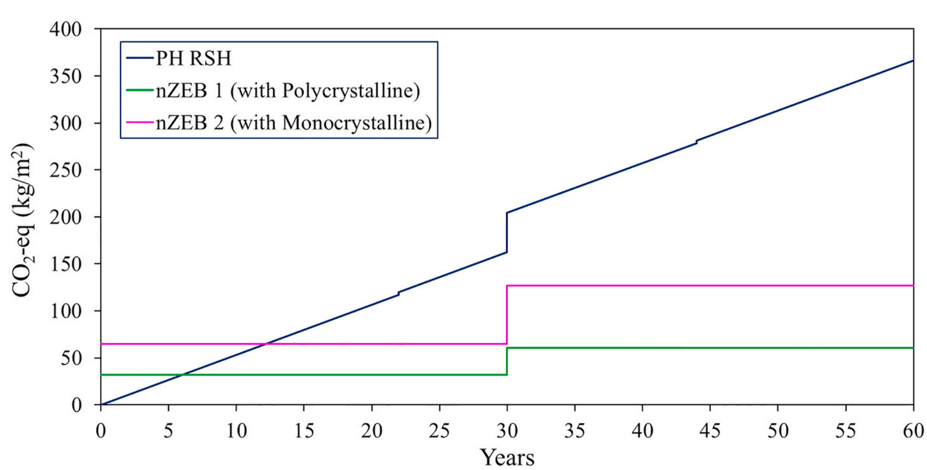

Fig. 13. Time plot of CO_2-eq for the RSH_PH and two nZEB cases.

in 1987, by assuming a 60-years lifetime for both the existing and the retrofitted buildings. The alternative design solutions for different scenarios were based on the optimized building energy models obtained in our previous studies. These alternatives were accordingly based on the Norwegian passive house standard and a LCC optimization study. Furthermore, in the retrofitting scenarios, two different HVAC systems including the AA with a DCV system and the RSH system equipped with a CAV ventilation system were taken into consideration. The LCA was conducted using OneClick LCA tool by considering the national Norwegian standard NS 3720. Analysis of the reference building showed that around 77%, 1021.4 kg CO_2-eq/m^2, of the total GHG emissions were due to building energy use and the 23% were attributed to the embodied emissions of building materials and components, of which 16%, 213 kg CO_2-eq/m^2, of embodied emissions were related to product stage in the building life cycle. The most carbon emitted materials in this respect were finished concrete and the ventilation system components. Applying the retrofit measures increased the embodied emissions for different retrofit scenarios owing to use of extra materials, their transport to construction site, and the end-of-life service, and they were accounted for around 18–23%, 25–31%, and around 25%, respectively. However, the reduction of CO_2-eq emissions associated with the operational energy use, which were calculated around 69–73%, overweighted the embodied CO_2 emissions of the extra materials. Among all the retrofitting scenarios, the LCC optimized case with the AA system (AA_LCC) showed the best performance in terms of environmental impact, so that the total CO_2-eq emissions were decrease from 1336 kg CO_2-eq/m^2, in the reference case, to 637 kg CO_2-eq/m^2 in the AA_LCC scenario. The reason was that this scenario showed better energy performance with less material use, due to omitting radiators for heating, which resulted in less embodied and operational CO_2-eq emissions compared to other retrofitting scenarios. Looking at the CO_2-eq payback times of retrofitting scenarios, the LCC scenarios had shorter return period, around 3.9 years, than the PH scenarios. In addition, we assessed the GHG emissions associated with adopting various heating supply system and insulation materials. The results confirmed that the district heating system generated the minimum emissions related to operational energy use and the embodied emissions for the heating supply systems, while the Glass wool and cellulose insulation led to minimum embodied emissions related to building materials. Eventually, the GHG missions associated with the two nearly zero energy (nZEB scenarios) corresponding to use of the Polycrystalline and the Monocrystalline PV panels showed a considerable reduction, around 39–44%, of the total CO_2-eq emissions compared to the PH case with the RSH system. Although the material usage for the Monocrystalline PV panels was less than the Polycrystalline ones, due to higher efficiency, the extra Czochralski process in the production of Monocrystalline resulted in higher embodied emissions for nZEB case for the Monocrystalline PV panels. Therefore, based on the LCA for the retrofitting scenarios in terms of CO_2-eq emissions, the AA_LCC scenario taking advantage of the Glass wool insulation material, the district heating supply system, and the Polycrystalline PV panels could be considered as a potential retrofitting solution greatly contributing to achieve a ZEB level. Nevertheless, they can provide worthwhile information about the environmental impacts associated with the cost-efficient solutions for the buildings in cold climate. Furthermore, the data sources used in this LCA work may include some uncertainties arising from inaccuracy of available data or their dependency on the specific analyzed systems and inaccuracy of parameters modelled in this study.

To finish, let us recall that the scenarios investigated in our study was limited to the Norwegian passive house standard and a LCC optimization model obtained in our previous work. As a cost-effective model may not fully represent the most environmentally friendly solutions for building retrofitting, it would be very interesting to focus on ZEB level by broad use of low CO_2-eq emission materials and those having negative embodied carbon in the construction phase such trees and short-term crops. Alternatively, an extensive use of renewable energy sources such as PV panels, biomass combined heat and power (CHP), etc. Can also be considered to compensate both the embodied and operational emissions during entire building life cycle. It would be worth finding out which approach is more efficient because if, for example, a scenario of low carbon electricity grid is considered, it would be more difficult to achieve a zero emission level through extensive use of PV panels. However, a combination of LCC and LCA would give a more practical perspective in achieving a zero emission level.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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