Energy-carbon-investment payback analysis of prefabricated envelope-cladding system for building energy renovation: Cases in Spain, the Netherlands, and Sweden

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ABSTRACT

Buildings have become a major concern because of their high energy use and carbon emissions. Thus, a material-efficient prefabricated concrete element (PCE) system was developed to incorporate construction and demolition waste as feedstock for residential building energy renovation by over-cladding the walls of old buildings. By conducting life cycle assessment and life cycle costing using the payback approach, this study aims to explore the life cycle performance of energy conservation, carbon mitigation, and cost reduction of the PCE system in three European member states: Spain, the Netherlands, and Sweden. The results show that the energy payback periods for Spain, the Netherlands, and Sweden were 20.45 years, 17.60 years, 19.95 years, respectively, and the carbon payback periods were 23.33 years, 16.78 years, and 8.58 years, respectively. However, the financial payback periods were less likely to be achieved within the building lifetime, revealing that only the Swedish case achieved a payback period within 100 years (83.59 years). Thus, circularity solutions were considered to shorten the PCE payback periods. Using secondary materials in PCE fabrication only slightly reduced the payback period. However, reusing the PCE considerably reduced the energy and carbon payback periods to less than 6 years and 11 years, respectively in all three cases. Regarding cost, reusing the PCE shortened the Swedish payback period to 29.30 years, while the Dutch and Spanish cases achieved investment payback at 42.97 years and 85.68 years, respectively. The results can be extrapolated to support the design of sustainable building elements for energy renovation in Europe.

1. Introduction

As of late, the building sector has become a primary contributor to global warming and resource depletion, in which buildings account for approximately 40% and 33% of global energy use and greenhouse gas (GHG) emissions [1]. By 2050, it is projected that the global energy consumption of buildings might double, or even triple [2]. The European Union (EU) reacted to the IPCC (Intergovernmental Panel on Climate Change)'s 2 °C target by formulating legislative goals of reducing energy use and GHG emissions for the built environment in both the short- and long-term [3].

In the EU, building sector legislature has been prioritized as it has the potential to meet certain GHG mitigation and energy-saving targets. Currently, more than 30% of buildings in the EU are more than 50 years old, and over 70% of the building stock is energy-inefficient [4]. Thus, improving the overall energy performance of both old and new buildings is necessary. However, the construction of new energy-efficient buildings does not meet the short-term GHG mitigation goals [5]. Therefore, renovating existing buildings would enable the EU to meet its 2030 goals of 32.5% energy savings and a 40% GHG emissions reduction, as compared with 1990 [3].

EU-level legislative initiatives have been introduced for building renovations. In particular, directive 2012/27/EU requires member states to establish national strategies for cost-effectively renovating more than 3% of the central government's gross building stock each year

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Abbreviations

ADR	Advanced dry recovery technology
BAU	Business-*as*-usual
CDW	Construction and demolition waste
CED	Cumulative energy demand
CRLWCA	Coarse recycled lightweight concrete aggregate
DGR	Dry Grinding & Refining system
EC	European Commission
EoL	End-of-life
EU	European Union
FRLWCA	Fine lightweight recycled concrete aggregate
GHG	Greenhouse gas
HAS	Heating-air classification system
LCA	Life cycle assessment
LCC	life cycle costing
LCEA	Life cycle energy analysis
LCCO$_2$A	Life cycle carbon emission analysis
IPCC	Intergovernmental Panel on Climate Change
PCE	Prefabricated concrete element
PCE1	Prefabricated concrete element for new building construction
PCE2	Prefabricated concrete element for existing building retrofit
RCA	Recycled concrete aggregate
RGUA	Recycled glass ultrafine admixture
URLWCA	Ultrafine recycled lightweight concrete aggregate
VEEP	European Union Horizon 2020 project VEEP

[6]. Directive 2010/31/EU set minimum energy use standards and cost-optimal levels for old building renovations [4]. Amendment 2018/844 to Directive 2010/31/EU introduced a clear target for the full decarburization of the EU's building stock by 2050. However, an investigation of 16 EU regions (covering more than 60% of the gross EU floor area) indicated that over 97% of buildings must be renovated to accomplish the EU's 2050 decarburization goal [7]. Hence, cost-efficient energy-saving solutions are necessary to support the current energy goals of the EU.

Up-scaling building renovation by mitigating the energy dissipation from building heat loss is a priority for the EU building stock [8]. Recently, an EU project, the European Union Horizon 2020 project VEEP (VEEP), developed a technological system to use recycled construction and demolition waste (CDW) to manufacture prefabricated concrete elements (PCE). These PCEs have been used to improve the thermal performance of buildings by either being constructed as an envelope of new buildings (PCE1) or by over-cladding the envelope of existing buildings (PCE2). As the life cycle performance of PCE1 has been previously evaluated [9], this study examines the performance of PCE2.

Life cycle costing (LCC) and life cycle assessment (LCA) are typical appraisal tools of life cycle management methodology [10]. An integrated implementation of LCC and LCA can provide broader insights into sustainable products and technologies [11]. Therefore, this study aims to employ LCC and LCA simultaneously to evaluate the potential of implementing VEEP PCE2 in residential buildings to save costs, conserve energy, and mitigate GHG emissions under different EU member states' climatic contexts. The results of the LCC and LCA are expressed for investment, energy, and carbon payback periods, and the applicability of VEEP PCE2 to EU residential buildings is examined. The results of this study will support policymakers in selecting cost-effective and material-efficient paths for building energy renovation in the EU.

This study is outlined as follows: Section 2 illustrates the details of the technological system and main methods; Section 3 states the results; Section 4 discusses the application potential of the PCE2 system at an EU-wide scale and the reusability of PCE2, and Section 5 presents the conclusions of the study.

2. Materials and methods

This section presents the basic materials and methods used in this study. Section 2.1 details overviews of the literature related to LCC- and LCA-based payback period methods in the field of building energy renovation, proposing a conceptual framework for an energy-carbon-investment payback period analysis. Based on this conceptual framework, Section 2.2 defines the goal and scope of the assessment system. Section 2.3 presents the life cycle environmental and economic inventory LCC and LCA, and Section 2.4 details the life cycle environmental and economic impact analysis.

2.1. Life cycle management of building energy renovation

2.1.1. Overview of life cycle energy, carbon emission, and cost analysis

As one of the main techniques for life cycle management [10], LCAs are commonly used to explore opportunities in GHG emissions mitigation and energy efficiency in the building sector [12]. Based on an LCA, the life cycle carbon emission analysis (LCCO$_2$A) and life cycle energy analysis (LCEA) specifically focus on the life cycle CO$_2$ equivalent emissions and the energy consumption of buildings, respectively.

The Building Assessment Information System [13] defines four life cycle stages for building performance assessment: production, construction process, use, and end-of-life (EoL) stages. An LCEA is usually employed to calculate the overall energy-related inputs to buildings from a life cycle perspective [14]. Analogously, an LCCO$_2$A accounts for the total CO$_2$ equivalent emission outputs from a building over different phases of its life cycle [15]. Energy [14] and GHG emissions [16] in the operation stage normally account for 80%–90% of a building's life cycle energy use and GHG emissions, followed by embodied energy and emissions, which accounts for 10%–20%. Meanwhile, the demolition energy [14] and emissions [16] are almost negligible, contributing approximately 1%.

In an LCEA and LCCO$_2$A, building materials production and building construction are often grouped into one stage. For example, studies on the LCEA [1,14,15,17] and LCCO$_2$A [1,15,16] modeled the life cycle energy and emission of three stages: (i) embodiment (manufacturing and construction), (ii) operation (operation and use), and (iii) demolition (EoL). Therefore, estimating the life cycle energy consumption and life cycle GHG emissions of buildings can be determined by summing all the energies and emissions incurred during their life cycle, as expressed in Eqs. (1) and (2):

$$Life\ cycle\ energy\ consumption = E_E + E_O + E_D, \tag{1}$$

$$Life\ cycle\ carbon\ emission = C_E + C_O + C_D, \tag{2}$$

where E_E denotes the energy consumption incurred in the embodiment phase, E_O represents the energy consumption incurred in the operation phase, E_D denotes the energy consumption incurred in the demolition phase, C_E denotes the GHG emissions incurred in the embodiment phase, C_O represents the GHG emissions incurred in the operation phase, and C_D denotes the GHG emissions incurred in the demolition phase.

Despite their popularity, it is debated whether LCEAs and LCCO$_2$As are stand-alone methodologies, a step, or indicators to be included in the life cycle inventory analysis or the life cycle impact assessment in an LCA. Chau et al. (2015) reviewed the literature regarding LCAs, LCEAs, and LCCO$_2$As and found that an LCEA focuses on energy input and an LCCO$_2$A on outputs, while an LCA considers both environmental inputs and outputs. In this manner, the LCA is an overarching environmental assessment that includes both LCEAs and LCCO$_2$As. Conversely, the

cumulative energy demand (CED) is a key index for both LCAs and LCEAs. Klöpffer [18] stated that the CED is an inventory indicator that does not rely on any assumptions. However, Frischknecht [19] explained that some assumptions are necessary to develop CED factors [20]. Instead of employing the LCEA or LCCO2A as independent methods, this study used a standard LCA, which conforms to ISO 14040 [21] and ISO 14044 [22], as an appraisal tool to explore the life cycle energy and carbon emissions of the PCE2 system.

Regarding economic assessment, LCC is a financial assessment tool that explores the costs incurred during the life cycle of a product system [23]. There are multiple cost breakdown structures for an LCC, such as life cycle-based, stockholder-based, and expenditure-based [24]. The selection of the cost breakdown structure depends on the user's goal and scope. Owing to the characteristics of a life cycle perspective, the life cycle cost of a building is usually estimated based on the building's life cycle. According to ISO 15686–5 [23], the life cycle cost of a building consists of construction costs, operation and maintenance costs, and EoL costs, as shown in Eq. (3).

$$\text{Life cycle cost} = I_E + I_O + I_D, \qquad (3)$$

where I_E represents the construction costs incurred in the embodiment stage, I_O denotes the operation and maintenance costs incurred in the operation phase, and I_D represents the EoL cost incurred in the demolition phase. External costs, such as environmental or social costs, are not considered in this study.

For the consistent application of LCAs and LCCs, the Society of Environmental Toxicology and Chemistry Europe working group defined an environmental LCC [25,26], which is not meant to consider environmental externalities, but has a methodological framework similar to a standard LCA. This study employed both an LCA and environmental LCC (hereinafter referred to as LCC) to investigate the energy and carbon reductions and economic viability of the PCE2 system.

2.1.2. Payback period method

Several systematic reviews have been conducted on LCCs [1,27–29], LCAs [1,14,15,27–33], LCEAs [14,15,27,34–37], and LCCO2As [15,38] for buildings and the building sector. These reviews demonstrated that estimating the life cycle ecological and economic performance by summing all the impacts incurred during each life cycle stage over a lifetime is the most straightforward and commonly employed method for comparing building performances.

However, in some studies, the temporal scope of the LCA was not directly defined, or the goal of a study was to explore a breakeven time, making comparison impossible. For instance, in this study, the lifespan of a PCE2 is dependent on the remaining lifetime of the building. Because the remaining building lifetime varies, due to different construction times, the temporal span of a PCE2 cannot be directly set. In this case, it would be more straightforward to evaluate the life cycle results using the payback period approach.

The payback period method is used to appraise the economic attractiveness of capital investments [39]. Despite its methodological deficiencies, a payback period is employed as a primary sieve or constraint for investment appraisal [40], representing the amount of time it takes to recover the cost of an investment, as expressed in Eq. (4) [39].

$$\text{Investment payback period} = \frac{I}{CF} = \frac{1 - (1 + IRR)^{-L}}{IRR}, \qquad (4)$$

where I is the investment outlay, CF denotes the annual cash flow, L represents the economic life, and IRR denotes the internal rate of return that makes the net present value equal to 0.

Regarding energy efficiency issues, the payback method is commonly used in energy efficiency and low-carbon projects, such as photovoltaics [41] and building energy renovation [30]. Table 1 summarizes studies related to the payback method, wherein the estimation of the energy and

Table 1
Payback period literature in building energy renovation.

Source	Topic	Area	Main findings
[49]	Net Zero Energy building with solar power	Quebec, Canada	The energy payback time is 8–11 years in the cold climate of Quebec, suggesting, with the high investment of the solar system, the financial payback may never be achieved (6–39 years).
[5]	Residential building Renovation	Finland	The carbon payback period of rebuilding new dwellings is several decades longer than that of renovating existing buildings, but; the period of renovation is 25 years less than rebuilding.
[42]	Electrochromic window	Greece	The energy payback period is 8.9 years when considering aluminum frames.
[44]	Heating energy sources	Sweden	The energy payback period of renewable heating alternatives (photovoltaic, solar thermal, and heat pump). Heat pump is the most promising option, with an energy payback period of less than 1 year.
[50]	Insulation material for exterior wall of building	Poland	The economic payback periods of these materials (up to 24 years) are much longer than the ecological payback periods (up to 4 years).
[45]	Overhang shading for campus buildings	Hong Kong, China	The energy payback period of the shading system is approximately 46 years; the carbon payback period is approximately 64 years.
[51]	School buildings refurbishment	Hong Kong, China	Mean discounted financial payback (32.1 years) is longer than carbon payback (3.9 years).
[46]	Nearly-Zero Energy-level retrofit for school building	Turin, Italy	The carbon and energy payback periods show the same trend (3–7 years); the economic payback periods (5–30 years) are higher than the environmental periods. Retrofitting related to generators presents the biggest energy-saving potential.
[52]	Rebuild of commercial building	San Francisco, California, USA	The carbon payback of a new building with no solar versus that with an existing one is approximately 7 years; a net-zero-energy building with rooftop solar is approximately 6.5 years. A full EcoIndicator99 impact

(continued on next page)

Table 1 (*continued*)

Source	Topic	Area	Main findings
			payback for a new building with no solar is 20 years; a solar net-zero building is 7 years as compared with a building with existing operation.
[53]	Highly energy-efficient house	Rural Alaska, USA	The carbon payback period of a house with a high insulation level is 3 years compared with a typical house.
[54]	House complex refurbishment	Sheffield, UK	Advanced refurbishment can reduce the carbon payback from over 160 years to less than 60 years, as compared with ordinary refurbishment. Updating from heating by waste combustion to natural gas can reduce the carbon payback from 56 – 58 years to 16 years.
[55]	Eco-Refurbishment of dwellings	Liverpool and London, UK	The carbon payback time of refurbishment is less than 7 years.
[56]	Wood-framed apartment retrofit	Växjö, Sweden	The energy payback period is less than 4 years.
[47]	Public buildings under different retrofit strategies	Brno, Czech; Gol, Norway; Plymouth, UK; Copenhagen; Denmark; Stuttgart, Germany; Vilnius, Lithuania	Regarding different retrofitting actions, the carbon payback period ranges from 0.4 years to 1.9 years; the energy payback periods are in the range of 0.4–2.1 years.
[30]	–	–	When considering all environmental impact categories, the payback period of an energy retrofit building is less than 7.5 years
[48]	Domestic hot water systems with unglazed and glazed solar thermal panels	Rome, Italy; Madrid, Spain; Munich, Germany	The energy payback of an unglazed panel system is 2–5 months and that of a glazed panel is 5–12 months. The carbon payback of an unglazed panel system is 1–2 months, while that of a glazed panel is 12–30 months. The economic payback is 9–11 years/8–13 years for systems with unglazed/glazed panels when compared with a natural gas boiler, and 3–4 years/4 years for those compared with an electric boiler.
[43]	Roof-mounted building-integrated photovoltaic (PV) system	Hong Kong, China	The energy payback time of a PV system ranges from 7.1 to 20 years; the carbon payback time is 5.2 years.

carbon payback periods are expressed by Eq. (5) (Ardente et al., 2011; Asdrubali et al., 2019; Berggren et al., 2013; Comodi et al., 2016; Huang et al., 2012; Lu and Yang, 2010; Papaefthimiou et al., 2006), and (6) [43, 45–47]:

$$Energy\ payback\ period = \frac{E_E}{E_o}, \tag{5}$$

$$Carbon\ payback\ period = \frac{C_E}{C_o}, \tag{6}$$

where E_E is the initial embodied energy, E_O is the annual operational energy saving, C_E is the initial embodied GHG emission, and C_O denotes the annual operational GHG savings.

These studies demonstrate that the payback period method is a suitable approach to handle issues related to building energy renovation as it can be used for different purposes, such as the environment, energy, and economic payback period, or as an integrated ecological payback period that includes multiple environmental impact categories. The payback method can also be modified to assess various topics, including building materials, building elements, buildings, and the area of buildings. These payback studies also manifest in energy renovation projects in which economic investment has a longer return period to return than embodied carbon emissions and energy consumption.

However, research gaps exist in the literature as studies do not consider the influence of material circularity in the EoL phase. Although the EoL impact accounts for approximately 1% of the life cycle energy and GHG emissions, utilizing secondary materials and reusing EoL products has the potential to significantly reduce the impact of the embodiment phase. Therefore, this study aims to examine cross-state cases to investigate the energy-carbon-investment payback period of the PCE2 system for building energy renovation and evaluate how material circularity influences the payback periods.

2.1.3. Methodological framework

The energy/carbon/investment payback periods herein indicate the length of time required for the cumulative cost/energy/GHG reduction from the implementation of PCE2s to equal the cost/energy/GHG incurred in the embodiment and demolition phases. Based on Eqs. (4)–(6), the energy, carbon, and investment payback periods are calculated with Eqs. (7)–(9), respectively. This study applies process-based LCA and LCC to quantify PCE2 performance in different European cities, namely, Madrid, Amsterdam, and Stockholm.

$$T_E = \frac{E_E^{PCE2} + E_D^{PCE2}}{E_O^{BAU} - E_O^{PCE2}}, \tag{7}$$

$$T_C = \frac{C_E^{PCE2} + C_D^{PCE2}}{C_O^{BAU} - C_O^{PCE2}}, \tag{8}$$

$$T_I = \frac{I_E^{PCE2} + I_D^{PCE2}}{I_O^{BAU} - I_O^{PCE2}}, \tag{9}$$

where T_E represents the energy payback period, E_E^{PCE2} denotes the embodied energy consumption for manufacturing the PCE2, E_O^{PCE2} denotes the energy demand for heating and cooling in the building operation phase after PCE2 refurbishment, E_D^{PCE2} is the energy consumption for the treatment of EoL PCE2 in the demolition phase, and E_O^{BAU} is the energy demand in the operation phase of a building with a business-*as*-usual (BAU) wall as a façade. Similarly, T_C represents the carbon payback period, C_E^{PCE2} represents the embodied GHG emission for PCE2 manufacturing, C_O^{PCE2} denotes the GHG emissions incurred in the operation phase of a building after refurbishment with PCE2, C_D^{PCE2} demonstrates the GHG emissions for treating EoL PCE2 in the demolition phase, and C_O^{BAU} denotes the GHG emissions in the operation phase of a building with a BAU wall as a façade. Finally, T_I represents the carbon payback

period, I_E^{PCE2} denotes the investment for PCE2 manufacturing incurred in the embodiment phase, I_O^{PCE2} denotes the operation costs incurred in the operation phase of a building after refurbishment with PCE2, I_D^{PCE2} denotes the cost for PCE2 EoL treatment incurred in the demolition phase, and I_O^{BAU} represents the GHG cost incurred in the operation phase of a building with the BAU wall as the façade.

The LCA in this study was outlined using the four steps determined by the ISO standards: 1) goal and scope definition, 2) life cycle inventory analysis, 3) life cycle impact assessment, and 4) results interpretation. The CED and global warming potential were considered to be impact category indicators that belong to the life cycle impact assessment step. An LCC was performed using the same four steps, as proposed by Zhang et al. (2019). The conceptual framework of this study is shown in Fig. 1. Note that the LCA focuses on energy inputs and GHG emission outputs from the system, whereas the LCC centers on the investment inputs released from the system, thereby representing the three life cycle phases in the assessment. In the embodiment phase, both virgin and recycled raw materials were incorporated into the fabrication of PCE2. In the operation phase, individual air conditioning was assumed to model the demand for household cooling. For heating energy demand, residential buildings in different member states were assumed to be equipped with different household heating systems based on the TAB-ULA database [57]. During the demolition phase, the impact of recycling and reusing PCE2 on the payback period was evaluated. Thus, this study used the payback method to investigate the energy-carbon-investment payback period of the proposed PCE2 system with the main research objective of determining what quantity of GHG mitigation, energy saving, and economic earnings from the operation phase offsets the additional inputs required in the embodiment and demolition phases.

2.2. Goal and scope definition

2.2.1. Goal and scope
The goal of this study is to compare the energy and carbon payback periods for fabricating and operating the proposed PCE2 system as an energy retrofitting strategy for existing buildings with a conventional wall as a façade compared with those with conventional walls without any retrofitting in different EU member states: Spain, Sweden, and the Netherlands. Herein, the LCEA and LCCO$_2$A building analyses included three phases: embodiment, operation, and demolition. The embodiment phase includes the manufacturing and transportation of raw materials for the fabrication of PCEs. The operation phase includes the cooling and heating needs related to the use of buildings with or without the application of PCEs. Finally, the demolition phase includes the PCE dismantling and the transport of EoL materials for either disposal or treatment. Note that the object of interest is the PCE, not the building.

The system boundary for this assessment was the geographical boundaries of each studied city. Therefore, all the productive activities during the three life cycle phases are assumed to be conducted within each state. The capital cities Madrid, Amsterdam, and Stockholm were selected as the study areas. The climates and locations of these cities are listed in Table 2.

2.2.2. Technological systems for building energy renovation
The technological system in the VEEP project involves advanced drying recovery (ADR) integrated with a heating-air classification system (HAS) to completely recycle the EoL lightweight concrete. The produced secondary coarse and fine concrete aggregate and cementitious particles were used for the production of green lightweight
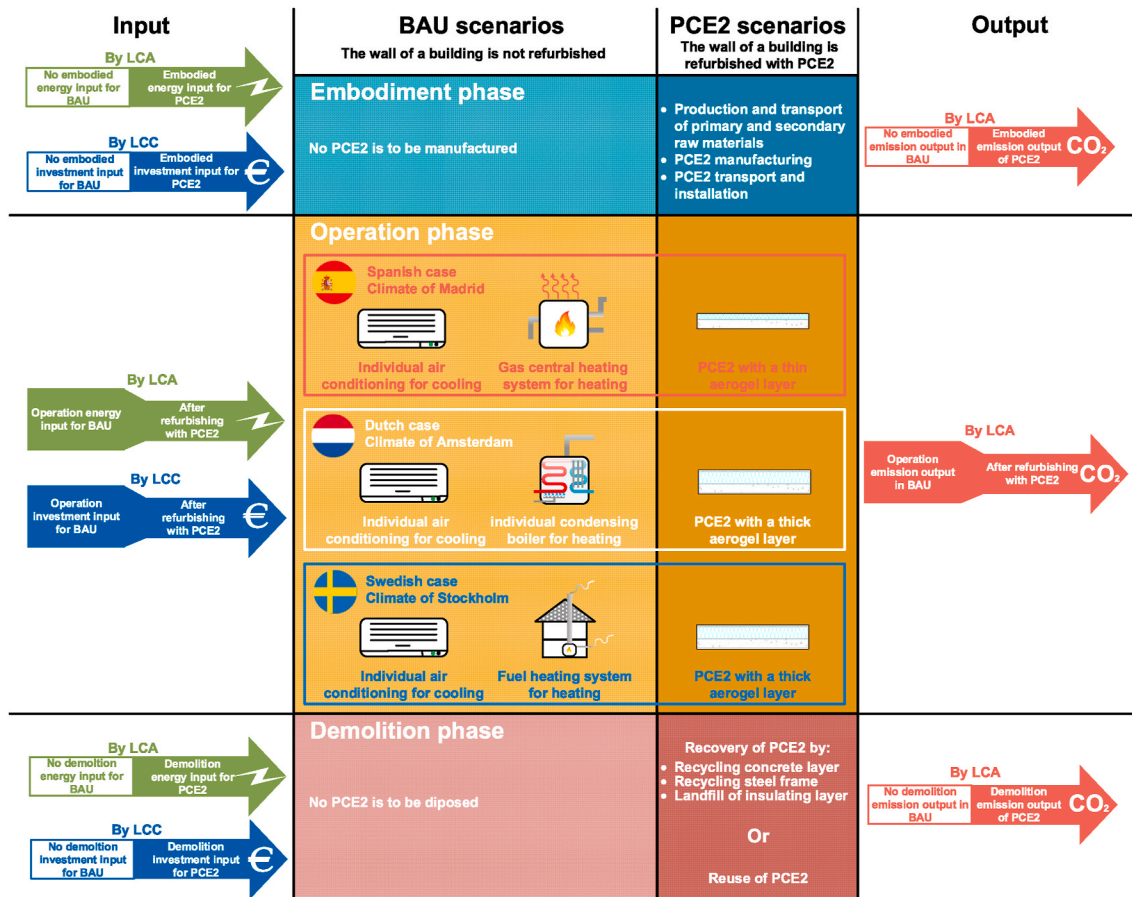

Fig. 1. Conceptual framework of the study. LCA: life cycle assessment; LCC: life cycle costing; BAU: business-*as*-usual; PCE2: prefabricated concrete element for old building refurbishment.

Table 2

Climates and locations of three case cities. The data source for information about Madrid [58], Amsterdam [59], and Sweden [60].

	Madrid, Spain	Amsterdam, the Netherlands	Stockholm, Sweden
Location in Europe	Southern Europe	Western Europe	Northern Europe
Coordinates	40°25′N, 3°43′W	52°22′N, 4°54′E	59°19′46″N, 18°4′7″E
Climate	Mediterranean climate which transitions to a cold semi-arid climate	Oceanic climate	Oceanic climate with humid continental

concrete and green aerogel in the PCE2. Furthermore, a dry grinding and refining (DGR) system was developed to reprocess glass and insulating fiber wool waste to produce secondary ultrafine admixtures to substitute cementitious materials in the concrete, such as cement and lime.

Two technological scenarios were considered herein: a BAU traditional wall and a BAU traditional wall retrofitted with different types of PCE2s. The cross-sections of the traditional wall in the BAU scenario and VEEP PCE2s for over-cladding the traditional wall are illustrated in Fig. 2. A typical façade for a residential building presented on the left of Fig. 2 was selected as a benchmark reference. Regarding the climate difference between Madrid, Amsterdam, and Stockholm, alternative structures were applied to the PCE2 designs. In particular, PCE2-a, which has a thinner aerogel layer, was employed for the Madrid case, while PCE2-b, which has a thicker aerogel layer, was implemented for the Amsterdam and Stockholm cases. The PCE2-a is 2 m long, 2 m wide and 0.08 m thick, and the PCE2-b is 2 m long, 2 m wide, and 0.12 m thick.

In the BAU scenarios, a typical traditional wall was selected as the benchmark reference for comparison with the PCE2 energy retrofitting

scenario. Because no precast concrete elements are applied in the BAU scenario, the associated GHG emissions and energy use only occur in the operation phase.

Conversely, in the PCE2 scenarios, environmental impacts are incurred throughout the entire life cycle. In the embodiment phase, secondary raw materials are incorporated into the PCE2. Integrated ADR and HAS technologies recycle EoL concrete, and DGR technology recovers glass waste. In the operation phase, dynamic thermal simulations were performed to compare the thermal performances of each scenario. A typical virtual residential apartment building was selected as a case study building for the thermal simulations. Finally, in the demolition phase, the PCE2s are dismantled and recycled. The specific features of the BAU and PCE2 scenarios are summarized in Table 3.

The functional unit for the assessment was retaining the heating and cooling comfort for 1 m² floor area through (i) passive building façades (with or without the application of VEEP PCE2s) and (ii) active heating by different heating systems and cooling by individual air-conditioning for 1 year based on the climate conditions in the Madrid, Amsterdam, and Stockholm. Based on the structure of the case study building, 1 m² of floor area requires 0.55 m² of PCE2 to over-clad the building façade.

2.3. Life cycle inventory analysis

The goal and scope definition step is followed by the life cycle inventory analysis, which further identifies the boundaries, background and foreground processes, and allocation scheme for a production system [61]. The system boundaries of the BAU and VEEP PCE2 scenarios are shown in Fig. 3. The life cycle inventory is established according to the three phases of energy use and GHG emissions. The LCA software OpenLCA 1.9, with the Ecoinvent 3.4 Cutoff database, was used for the assessment.
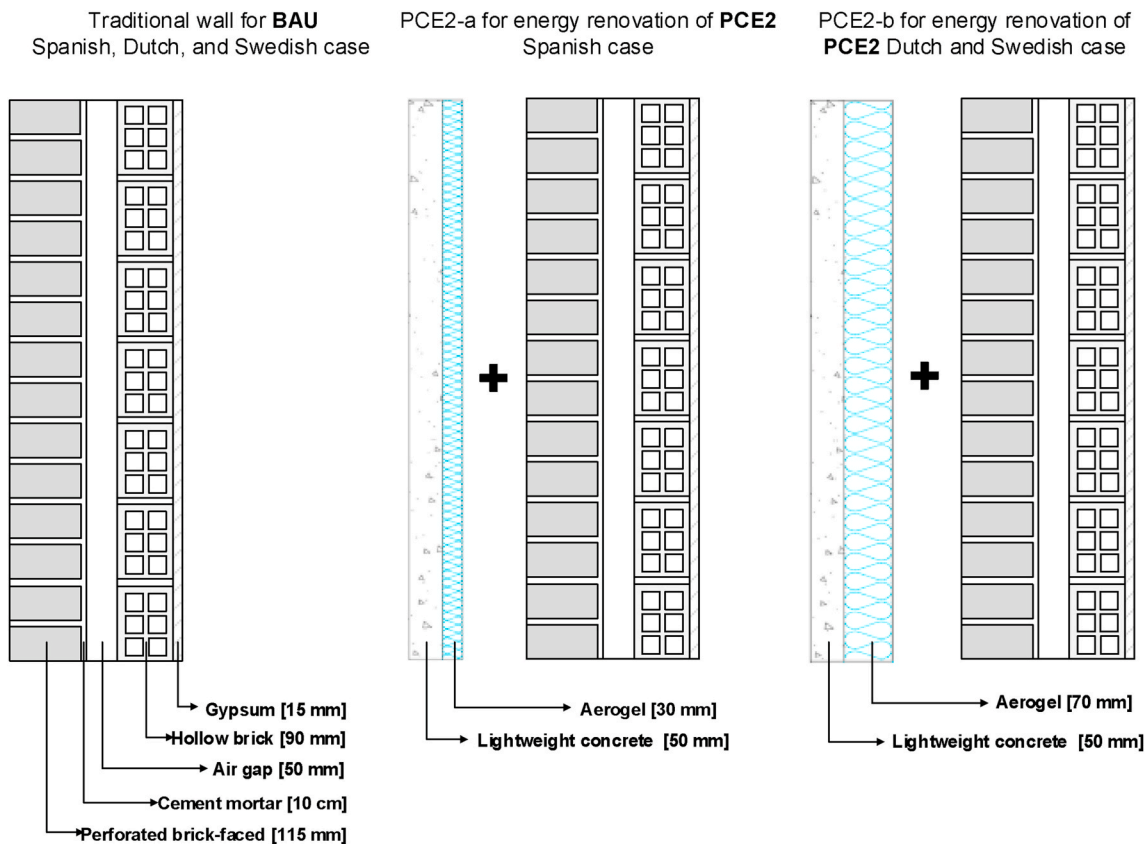

Fig. 2. Cross-section diagrams of BAU traditional wall (left), and VEEP PCE2-a (middle) to be implemented in Spain, and PCE2-b (right) to be implemented in the Netherlands and Sweden. BAU: business-*as*-usual; PCE2: prefabricated concrete element for old building refurbishment.

Table 3
Six scenarios developed based on technological and climate conditions. BAU: business-*as*-usual; PCE2: prefabricated concrete element for old building refurbishment; ES: Spanish case; NL: Dutch case; SE: Swedish case; GHG: greenhouse gas.

	Spanish case	Dutch case	Swedish case
BAU	**BAU-ES:** traditional wall of existing building under the climatic conditions of Madrid, Spain; associated investment, GHG emissions, and energy use are only incurred in the operation phase	**BAU-NL:** traditional wall of the existing building under the climatic conditions of Amsterdam, Netherlands; associated investment, GHG emissions, and energy use are only incurred in the operation phase	**BAU-SE:** traditional wall of the existing building under the climatic conditions of Stockholm, Sweden; associated investment, GHG emissions, and energy use are only incurred in the operation phase
PCE2	**PCE2-ES:** traditional wall of the existing building refurbished with PCE2-a under the climatic conditions of Madrid, Spain; associated investment, GHG emissions, and energy consumption are incurred in the embodiment, operation, and demolition phases	**PCE2-NL:** traditional wall of the existing building refurbished with PCE2-b under the climatic conditions of Amsterdam, Netherlands; associated investment, GHG emissions, and energy consumption are incurred in the embodiment, operation, and demolition phases	**PCE2-SE:** traditional wall of the existing building refurbished with PCE2-b under the climatic conditions of Stockholm, Sweden; associated investment, GHG emissions, and energy consumption are incurred in the embodiment, operation, and demolition phases

2.3.1. Embodiment phase

The carbon emissions and energy use in the embodiment phase are only incurred in the VEEP scenarios. In this phase, virgin and secondary raw material transportation and preparation, PCE2 manufacturing, and PCE2 transport and installation were determined.

Secondary raw materials were extracted from the waste stream via ADR, HAS, and DGR to fabricate the PCE2. A previous study explored the mass balance of integrated ADR and HAS technological systems for recycling both normal-weight siliceous [24] and lightweight concrete wastes [62], revealing that a larger 0–4 mm fraction is produced by processing lightweight concrete (48%) than normal-weight concrete (32%). A detailed flow chart of ADR and HAS is shown in Fig. S1 in the SI.

DGR extracts secondary raw materials from glass, mineral wool, and fiber wool waste. In this study, DGR was used to recycle glass waste to produce recycled glass ultrafine admixture as a substitute primary cement in lightweight concrete. The mass balance of the DGR system is shown in Fig. S2 in the SI. Because the amount of residue from DGR is negligible, the recycling coefficient is assumed to be 100%.

As transport has proven to be of considerable importance in CDW recycling, especially when on-site recycling occurs [24,63], the impact of transportation of recycling facilities, raw materials, PCE2s, and waste residue were considered in this study. The crusher (Keestrack Destroyer 1313), ADR, and HAS can be transported for on-site recycling. While DGR was once a stationary recycling facility, it has been optimized to process the CDW on-site. Therefore, all the recycling facilities in this study (crushing set, ADR, HAS, and DGR) were modeled as mobile. The truck travel distance from where recycling facilities are stored at the demolition site is assumed to be 20 km, and a typical building demolition project contains approximately 15 Kt of EoL concrete [24]. According to the share of EoL concrete and glass waste in the CDW by weight [64], approximately 80 tons of glass waste is generated from a typical demolition site. The impact of recycling facility transport is allocated based on the waste recycled for PCE2 manufacturing and the gross waste generated from the demolition site. The operating weights of each facility are listed in Table S1 in the SI.

In the PCE2 system, pre-crushing concrete rubble, recycling

lightweight concrete waste by ADR and HAS, and recycling glass waste by DGR are multifunctional processes. Thus, allocation is applied to distribute the environmental impact of functional flow from these multifunctional processes. The allocation method for an LCA is based on process-based allocation. The energy use and GHG emissions of multifunctional processes are both allocated via the mass-based allocation scheme, as summarized in Table S2 in the SI. Further, the detailed costs of virgin and secondary raw materials for the fabrication of PCE2 are listed in Table S3 in the SI. Pre-crushing of concrete rubble, recycling lightweight concrete waste by ADR and HAS, and recycling glass waste by DGR are multifunctional processes. Allocation is applied to distribute environmental impacts of functional flow from a multifunctional process. The allocation method for LCA is process-based allocation. The energy use and GHG emission of multifunctional processes are both allocated via the mass-based allocation scheme as presented in Table S2 in the SI. The detailed bill of virgin and secondary raw materials for fabrication of a PCE2 is presented in Table S3 in the SI. After extraction and refining, raw materials are transported to the factory to manufacture the PCE2s. It is assumed that the average truck travel distance of the recycled material is 20 km while that of virgin materials is 50 km [9]. The energy utilities related to VEEP PCE2 manufacturing are listed in Table S4 in the SI.

After fabrication, the PCE2s are transported to the construction site for installation. It is assumed that the average truck travel distance of PCE2 is 50 km [9]. The utilities and material inputs for PCE2 installation are listed in Table S5 in the SI.

2.3.2. Operation phase

Dynamic thermal simulations were conducted to quantify the energy required to maintain heating and cooling under different climate conditions. Thermal assessments at the building scale were conducted on a typical residential multi-story building in Europe, as shown in Fig. S3 in the SI.

The thermal transmittance (U-value) of the building walls varied from less than 0.2 W/(m^2·K) to more than 2.0 W/(m^2·K) depending on the construction age [65]. Thus, a typical wall (as depicted in Fig. 1) with an average level of thermal performance was selected for this case study. The thermal conductivities of the materials and components in the wall and PCE2 are listed in Table S6 in the SI. The U-values of the traditional wall before and after PCE2 refurbishment were determined in accordance with ISO 6946 [66]. The calculated U-values of each building element are listed in Table S7 in the SI.

The heating and cooling conditions considered herein are listed in Table 4. Note that the workdays and weekends were modeled with different occupation and vacancy conditions. When rooms are occupied, the temperature of the rooms is maintained at 21 °C via an individual condensing boiler for heating and at 26 °C via an individual air-conditioning for cooling. When rooms are vacant, the temperature is maintained at 18 °C via an individual condensing boiler for heating and 30 °C via an individual air-conditioning for cooling.

The annual heating and cooling distribution requirements for Madrid, Amsterdam, and Stockholm based on the dynamic thermal simulations are shown in Fig. 5. It is clear that with increasing latitude, more heating energy is required, while near the equator, more cooling energy is required. Overall, buildings (retrofitted or not) in the Netherlands and Sweden consume significantly more heating energy than those in Spain, while their cooling energy is negligible.

Based on the thermal dynamic simulations shown in Fig. 4, the annual heating and cooling demand/floor area for both the BAU and VEEP scenarios in each region is listed in Table 5. Detailed information for modeling the heating and cooling demand is provided in the SI.

2.4. Demolition phase

In the demolition phase, demolishing the VEEP PCE2s and BAU traditional walls and disposing of the BAU traditional wall were not
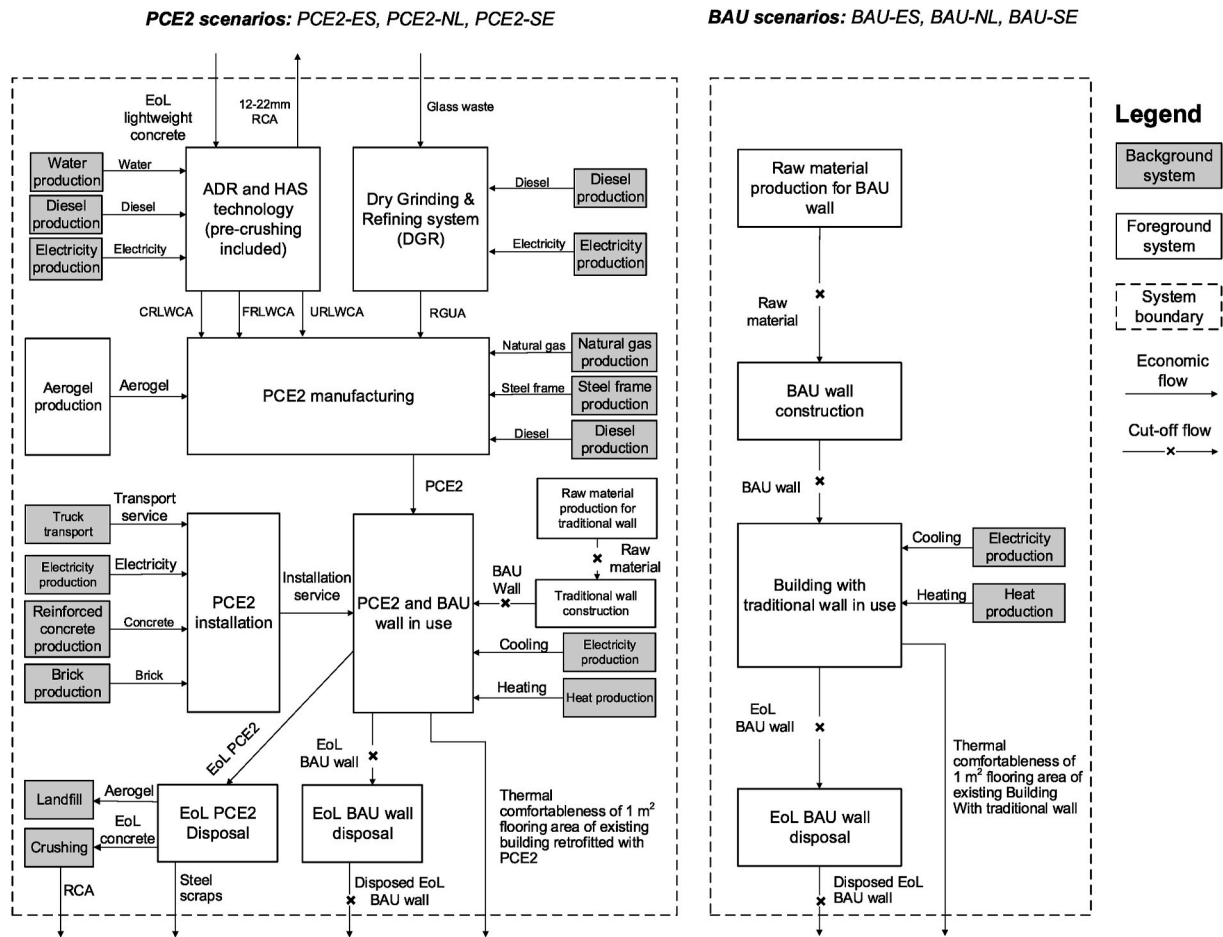
PCE2 scenarios: *PCE2-ES, PCE2-NL, PCE2-SE*   **BAU scenarios:** *BAU-ES, BAU-NL, BAU-SE*

Fig. 3. Assessment boundaries of the PCE2 (left) and BAU scenarios (right). ADR: Advanced dry recovery system; BAU: Business-*as*-usual; CRLWCA: coarse recycled lightweight concrete aggregate; DGR: Dry Grinding & Refining system; EoL: end-of-life; ES: Spanish case; FRSCA: Fine recycled siliceous concrete aggregate; FRLWCA: Fine lightweight recycled concrete aggregate; HAS: Heating-Air Classification System; NL: Dutch case; PCE2: prefabricated concrete element for building refurbishment; RCA: recycled concrete aggregate; RGUA: recycled glass ultrafine aggregate; SE: Swedish case; URLWCA: Ultrafine recycled lightweight concrete aggregate; URSCA: Ultrafine recycled siliceous concrete aggregate.

Table 4
Weekly heating and cooling conditions.

	Temperature in occupation	Temperature in vacancy
Monday	00:00 to 10:00 and 18:00 to 24:00	10:00 to 18:00
Tuesday	00:00 to 10:00 and 18:00 to 24:00	10:00 to 18:00
Wednesday	00:00 to 10:00 and 13:00 to 24:00	10:00 to 13:00
Thursday	00:00 to 10:00 and 18:00 to 24:00	10:00 to 18:00
Friday	00:00 to 10:00 and 18:00 to 24:00	10:00 to 18:00
Saturday	00:00 to 24:00	/
Sunday	00:00 to 24:00	/

considered in the assessment. Further, the constituents of the PCEs (steel frame, concrete, and aerogel) were assumed to be recycled at this stage.

Specifically, steel is treated by collecting and then selling it directly on-site, and the environmental impact of the follow-up re-melting process was not considered in the study. The EoL lightweight concrete is recycled by crushing on-site with a crusher. Disposal options for fibrous materials include landfilling or incineration [67]. The aerogel is recyclable and reusable if it remains intact. Herein, it was assumed that the aerogel was recycled by DGR on-site. The reusability of PCE2 is examined in Section 4.1. Further recycling information is provided in the SI.

2.5. Life cycle impact assessment

The impact assessment step in an LCA characterizes the inventory

results according to the target impact categories [61]. This study uses an LCA to quantify the GHG mitigation and energy saving potential of the PCE2 system. The "Global Warming (kg CO_2 eq)" from the "CML-IA, 4.4 issues, January 2015" database, and "OpenLCA LCIA methods 1.5.7," and Cumulative Energy Demand (MJ) [68] from the "OpenLCA LCIA methods 2.0.3" database were selected as impact indicators. As an individual impact indicator is sufficient to estimate each type of payback period, the weighting scheme and normalization step were not considered in the LCA.

The cost category, time value of an investment, and cost results expression are discussed in the economic impact assessment [24]. Herein, the LCC was performed from the homeowner's perspective. Therefore, the costing system only considers the real cash flows incurred by the owner, and environmental costs are excluded. Since 2020, the euro area has had a zero interest [69], which even reached a negative rate in developed areas, such as the Netherlands [62], thus, the interest rate was not considered for the payback estimation. The LCC result is expressed as the investment payback period.

3. Results

Section 3 presents the results of the embodiment, operation, and demolition phases of the LCA and LCC, which are converted into payback period in Section 3.2.
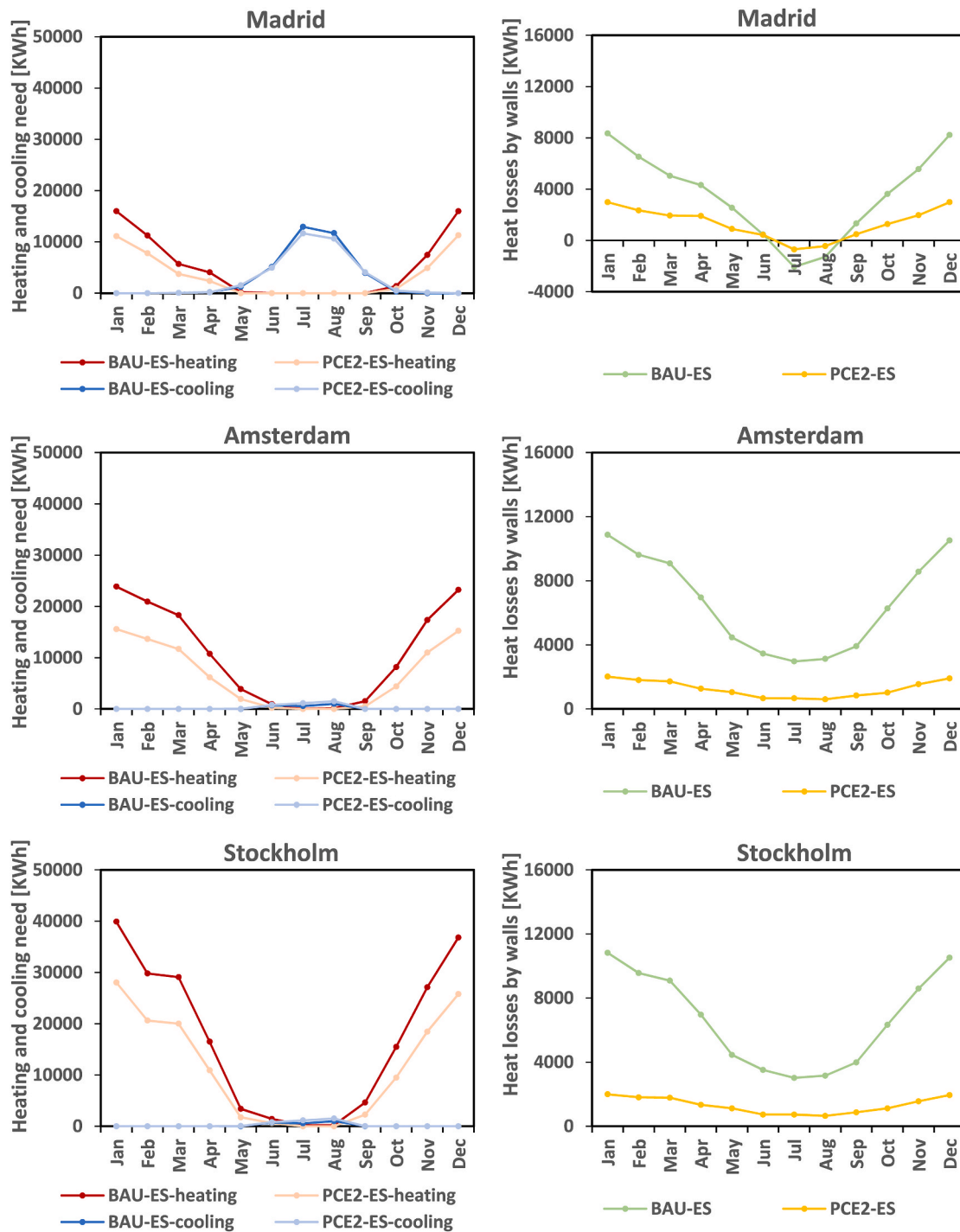
Fig. 4. Distribution of the annual heating and cooling requirements and heat loss of virtual buildings in Madrid, Amsterdam, and Stockholm. BAU, business-*as*-usual; PCE2, prefabricated concrete element for building refurbishment; ES, Madrid, Spain; NL, Amsterdam, Netherlands; SE, Stockholm, Sweden.

3.1. Environmental and economic impacts of each life cycle phase

The results of energy use, GHG emissions, and the cost in each phase of all scenarios are presented in Fig. 5. Fig. 5 (a), (b), and (c) show similar trends, revealing that energy, emissions, and costs incurred in the demolition phase are nearly negligible. This is consistent with the conclusions of previous building life cycle assessment studies. Regarding the renewability of mixed energy, non-renewable sources, especially fossil energy, are the main energy sources in every phase. In the embodiment phase, the impacts of the Spanish case are less than those of the Dutch and Swedish cases because PCE2-a uses less aerogel.

Meanwhile, in the operation phase, all three cases show that PCE2 refurbishment reduces energy use, GHG emissions, and costs. As the operation impacts are expressed in annual values, they are not directly comparable to embodiment impacts. Thus, the results are aggregated into payback periods in Section 3.2.

3.2. Energy, carbon, and investment payback period

Using Eqs. (7)–(9), the impact results were converted into payback periods. The energy, carbon, and investment payback periods of the PCE2-ES, PCE2-NL, and PCE2-SE scenarios are shown in Fig. 6. The
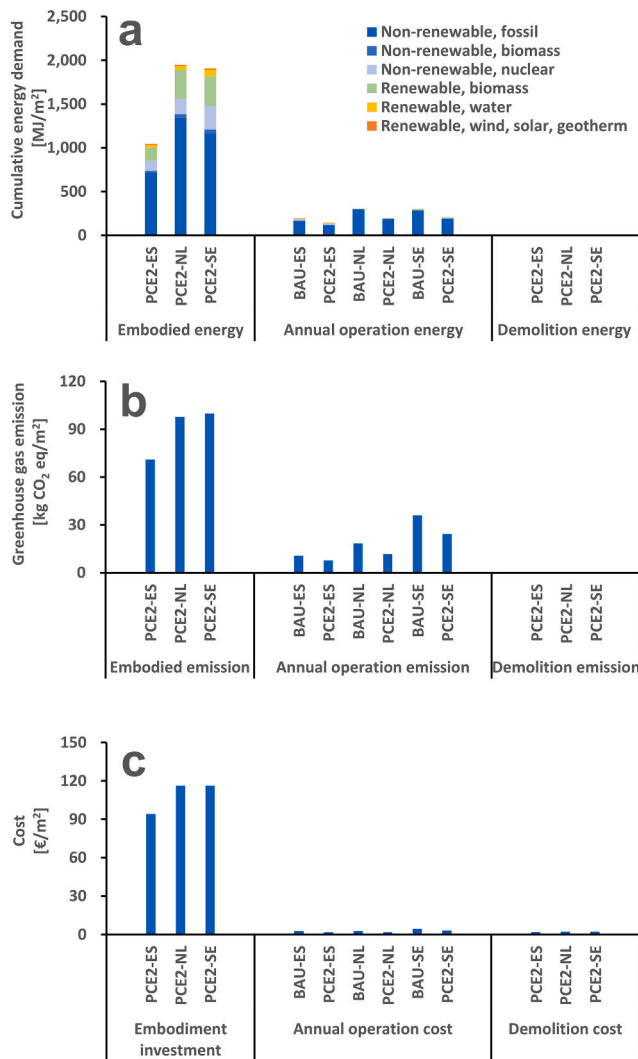
Fig. 5. (a) Cumulative energy demand, (b) GHG emissions, and (c) cost in each phase of six scenarios. BAU: Business-*as*-usual; PCE2: prefabricated concrete element for building refurbishment; ES: Spanish case; GHG: greenhouse gas; NL: Dutch case; SE: Swedish case.

Table 5
Annual heating and cooling demand/floor area for BAU and PCE2 scenarios. BAU: Business-*as*-usual; PCE2: prefabricated concrete element for building refurbishment; ES: Spanish case; NL: Dutch case; SE: Swedish case.

	BAU-ES	PCE2-ES	BAU-NL	PCE2-NL	BAU-SE	PCE2-SE
Heating need [kWh/(m²·year)]	34.95	23.73	73.36	45.99	115.69	78.19
Cooling need [kWh/(m²·year)]	19.89	18.81	1.31	1.98	1.55	1.99

differences between each energy payback period is subtle, ranging from 17.60 years for the Dutch case to 20.45 years for the Spanish case. However, disparities between the carbon payback periods are significant. The Spanish case has the longest carbon payback time of 23.33 years, the Dutch case has a middle-range payback of 16.78 years, while that in Sweden is considerably short, requiring only 8.58 years. These results indicate that the implementation of the PCE2 system in colder areas achieves shorter energy, carbon, and investment payback periods.

However, within a time span of 100 years, all the investment costs were not recouped. The Swedish scenario, which exhibited the best response, requires approximately 84 years to return the initial investment. Meanwhile, the investment payback periods of the Spanish and Dutch cases are more than 100 years, exceeding the average lifetime (120 years) of residential buildings in Europe [70]. Therefore, financial payback will probably never be achieved if the PCE2 system is implemented in the Netherlands and Sweden.

4. Discussion

This section discusses the impact of reusing PCE2s, the application potential of the PCE2 system in an EU context, and the limitations of this study.

4.1. Influence of material circularity solutions on payback periods

Although the PCE2 system has relatively short energy and carbon payback periods, its economic payback is not achievable within the building's lifetime. To make the PCE2 system more cost-effective [4,6], this section assesses how material circularity solutions, such as recycling and reuse, influence the payback periods, especially the economic payback period.

In the EoL stage of PCE2, its components (concrete layer, aerogel layer, and steel frame) are assumed to be recycled. Recycling waste provides two functions: treating waste and producing secondary material. It can be seen from the LCC and LCA results that the demolition phase barely influences the payback period estimate as compared with the embodiment phase. However, the benefits of incorporating recycled materials into the production of green concrete and aerogels are not clear. Therefore, the influence of recycling was quantified using secondary raw materials in the embodiment phase. Consequently, the payback period of implementing a PCE2 that only contains primary raw materials was calculated.

Furthermore, as a non-structural element, one prominent merit of the PCE2 system is its reusability. Reusing PCE2 is realized by applying a dismantlable connecting and anchoring system that makes it possible to disassemble an intact PCE2 for reuse. As 90% of the cost of installation is the cost of labor [62], a dismantlable connecting and anchoring system can reduce labor costs through quick installation. Successful reuse can not only prevent the generation of waste but also avoid raw material consumption in the future production of PCE2s. Therefore, the additional assessment in this section focuses on the extent to which reuse can avoid the additional PCE2 production in the embodiment phase. In this study, PCE2 reuse is modeled as 1) an avoidance of 90% of the material and energy input in the embodiment phase for PCE2 manufacturing, and 2) a reduction of the installation cost by 50% [62].

As shown in Fig. 7, using secondary materials can slightly reduce all three payback periods. However, it does not shorten the investment payback periods in the Dutch and Swedish cases to less than 100 years. Nevertheless, reusing PCE2 decreases the payback period more than recycling. With reuse, the energy payback period of the three cases can decrease from approximately 20 years to 4.11–5.99 years, and the carbon payback period can be reduced by 3–11 years for all three cases. Regarding economic impacts, when reusing PCE2, the Dutch and Spanish cases can achieve the investment payback at 42.97 years and 85.68 years, respectively. Meanwhile, the investment payback of the Swedish case can reach as low as 29.30 years.

4.2. Applicability of PCE2 system under EU context

This section evaluates the applicability of the PCE2 system in multiple EU member states. The system's energy consumption and associated costs and GHG emissions were modeled to directly relate to the U-value of building envelopes. In particular, the U-values considered were: the BAU wall (1.25 W/(m²·K)), BAU wall retrofitted with VEEP PCE2-a,
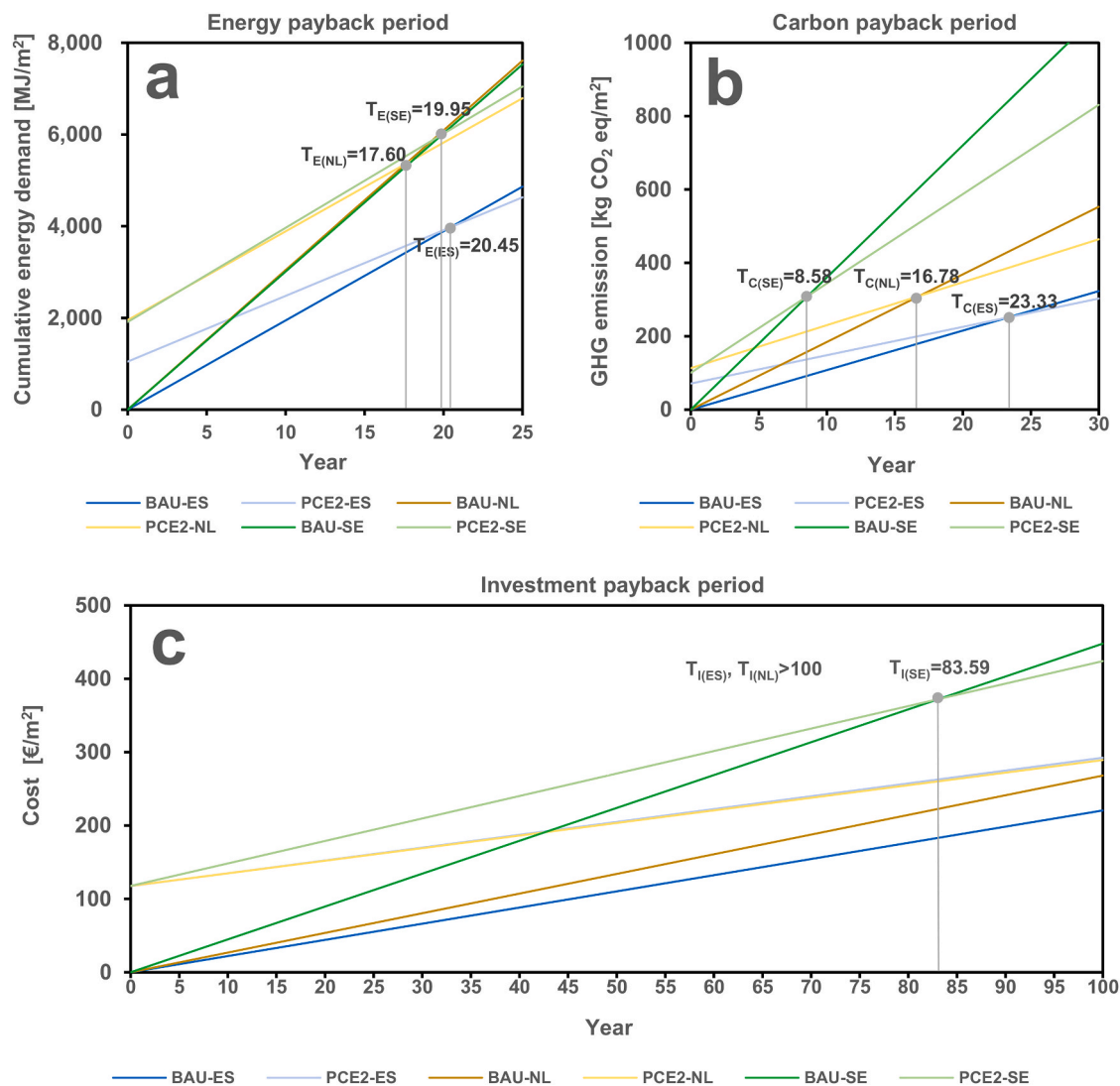
Fig. 6. (a) Energy, (b) carbon, and (c) investment payback periods for Spanish, Dutch, and Swedish cases. BAU: Business-*as*-usual; GHG: greenhouse gas; PCE2: prefabricated concrete element for building refurbishment; ES: Spanish case; NL: Dutch case; SE: Swedish case; T_E: energy payback period; T_C: Carbon payback period; T_I: investment payback period.

and the BAU wall retrofitted with VEEP PCE2-b. Each U-value was compared to the average-level building envelopes of EU building stock constructed at different times, as shown in Fig. 8.

Sandberg et al. investigated 11 European countries and found that the average lifetime of European residential buildings was approximately 120 years [70]. Thus, the potential building stock for refurbishment was considered to be constructed from 1900 to 2020. As shown in Fig. 8, building stock constructed from 1900 to 1989 accounts for 75% of the total EU building stock. This stock has a higher U-value than that of the BAU traditional wall (illustrated by gray bar) used in this study. The U-values of the PCE2s were even lower than the average U-value of the envelope of the buildings constructed after 2010, implying that the EU has a large potential market for the implementation of the PCE2 system for building energy renovation.

However, the energy required for heating accounts for the largest share (approximately 70%) of building energy consumption [65]. Considering the high importance of heating, heating demands in the BAU and PCE2 scenarios were compared with those of buildings in other EU member states that were constructed at different times, as shown in Fig. 9. In general, the energy required for heating in each member state declined over time. With PCE2 implementation, the largest energy reduction potential was associated with the refurbishment of older

buildings. In accordance with the EU's requirement for building energy efficiency, buildings constructed after 2000 require significantly less heating energy. For instance, the heating required in the PCE2-ES scenario is higher than that of a building constructed after 1980 in a continental and Atlantic climate.

Southern EU member states, such as Spain and Italy, have lower heating demands because of their milder winters. Meanwhile, heating demands in northern European countries, such as Sweden, and Norway, remain relatively stable but generally require more heating than those of southern and western European countries. Note that because the heating energy demand of households depends on many factors, such as climatic characteristics, modeling methods, efficiency of the heating system, and insulating levels of building facades, the results shown in Fig. 9 are not directly comparable. However, these results, to some degree, can demonstrate insights into the transitional trend of heating energy consumption in some EU member states and the application potential of PCE2.

4.3. Limitations and outlooks

LCA and LCC building analyses are based on multiple simplifications and assumptions. Atmaca (2016) compiled the basic assumptions in
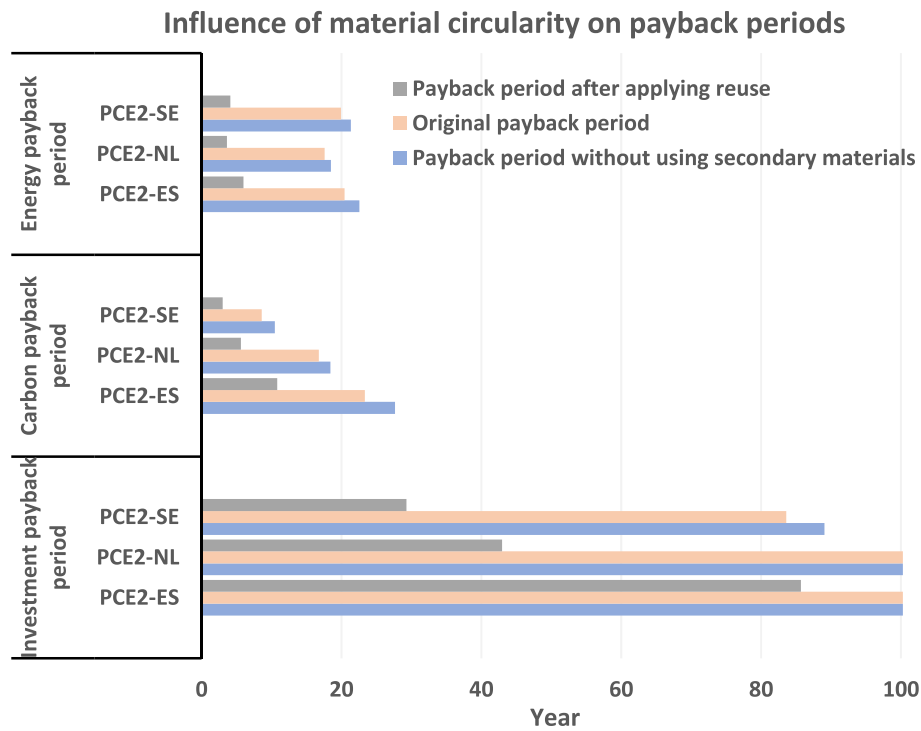
Influence of material circularity on payback periods

Fig. 7. Influence of material circularity on energy, carbon, and investment payback periods. BAU: Business-*as*-usual; PCE2: prefabricated concrete element for building refurbishment; ES: Spanish case; NL: Dutch case; SE: Swedish case.
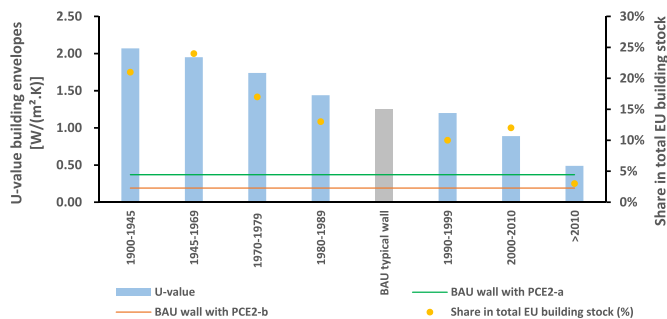

Fig. 8. EU buildings' age and average thermal transmittance for building envelopes. Data source: [7]; BAU: Business-*as*-usual; EU: European Union; PCE2: prefabricated concrete element for building refurbishment; PCE2-a: PCE2 containing a thin aerogel layer; PCE2-b: PCE2 containing a thick aerogel layer.

building LCA and LCC analyses. Other than these assumptions, the specific limitations of this study are as follows.

First, the PCE2 lifetime was determined by considering the remaining lifetime of the building to be retrofitted. Because of the variance in building lifetimes, the payback method was applied. The lifetime prolongation of a product is a common method for reducing the life cycle environmental impacts [71]. After refurbishment, the lifetime of a building is extended. However, because of the natural characteristics of the payback method [39], it failed to consider the benefits of this prolonged lifetime.

Second, PCE2 implementation in buildings constructed in different periods will result in different payback periods. For example, renovating older buildings will lead to shorter payback periods than renovating newer buildings. Herein, only one BAU traditional wall with a U-value of 1.25 W/(m²·K) was selected as the benchmark for refurbishment, which does not provide comprehensive insights into building energy renovation.

Further, this study did not consider the time value of money. As the interest rates in the European area decreased to 0% in 2020, a steady-state costing system that did not consider interest rates was employed. Nevertheless, interest rates can considerably influence the results of an LCC [26].

Finally, the payback assessment was conducted at a building element level in order to explore the environmental and economic performance of the PCE2 system. However, it is not clear if the PCE2 system can be scaled up to a regional level. For example, will EoL lightweight concrete generation be sufficient for massive building retrofitting. Thus, dynamic building stock model should be combined with life cycle management to investigate the up-scaled benefits of PCE2 implementation at a regional level.

5. Conclusions

This study combined LCA and LCC analyses to determine the energy, carbon, investment payback periods for buildings renovated with the PCE2 system in the climatic context of three EU member States: Spain, the Netherlands, and Sweden. Two technological systems were considered: the BAU traditional wall and the BAU traditional wall retrofitted with PCE2-a and PCE2-b. In addition, a dynamic thermal simulation of the energy required to heat and cool a virtual residential apartment building was conducted.

The results show that the energy payback periods of the Spanish, Dutch, and Swedish cases were 20.45 years, 17.60 years, and 19.95 years, respectively. Meanwhile, the carbon payback periods for the three cases were 23.33 years, 16.78 years, and 8.58 years, respectively. However, the financial payback periods revealed that payback was unlikely to be achieved within the lifetime of a building, and only the Swedish case reached a payback period within 100 years (83.59 years). The impacts of material circularity on the payback period of PCE2 were also evaluated. The influence of recycling was quantified using secondary raw materials in the embodiment phase. However, the results show that using secondary materials in the PCE2 system only slightly reduces the payback periods. However, reusing the PCE2 can noticeably shorten the energy and carbon payback periods to 4.11–5.99 years and 3.03–10.82 years, respectively, for all three cases. Regarding cost,
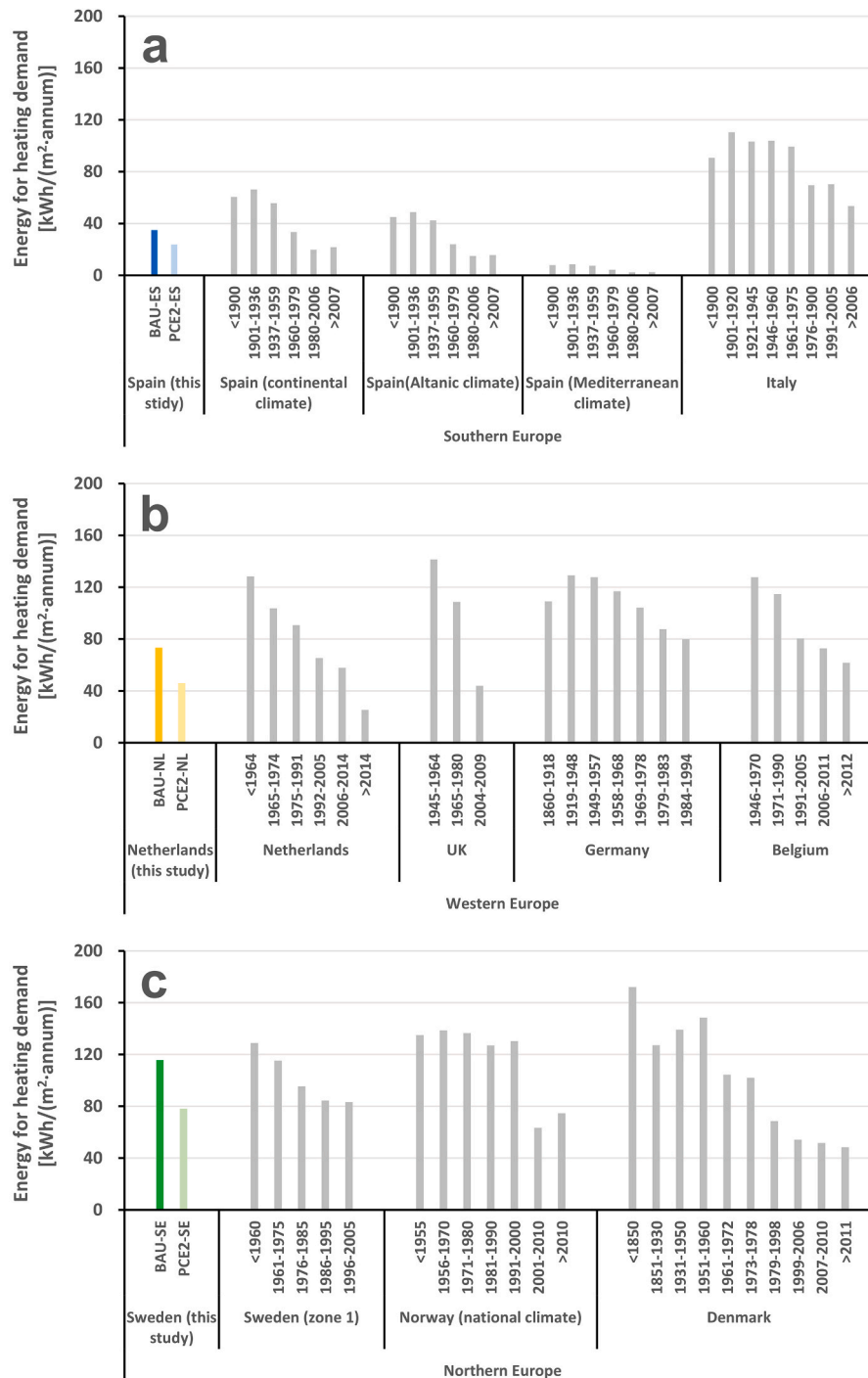
Fig. 9. Annual/floor area energy required to meet heating demand of apartment blocks by construction year in (a) southern Europe, (b) western Europe, and (c) northern Europe. Data collected from the TABULA database [57]; BAU: Business-*as*-usual; ES: Spanish case; PCE2: prefabricated concrete element for building refurbishment; NL: Dutch case; SE: Swedish case.

reusing the PCE2 reduced the payback period of the Swedish case to 29.30 years, and those of the Dutch and Spanish cases to 42.97 years and 85.68, respectively.

The applicability of VEEP PCE2 was evaluated by comparing the U-values and annual heating energy of EU buildings constructed at different times. The U-values of PCE2-a and PCE2-b were significantly lower than that of the average building envelope in the EU. Considering the lifetime, construction age, and energy performance of the EU building stock, the potential building stock for refurbishment was constructed from 1900 to 2020.

The integrated energy-carbon-investment payback analysis herein explored the life cycle stage of the PCE2 for building refurbishment. The results can be extrapolated to support design and manufacturing of sustainable building elements for building energy renovation in Europe. Further investigations will be conducted to integrate the life cycle management with the dynamic building stock model [72] address the question of region-level applicability and up-scaled ecological/financial benefits.

CRediT author statement

Chunbo Zhang: Conceptualization, Methodology, Software, Investigation, Writing - Original Draft, Formal analysis; **Mingming Hu:** Investigation, Writing - Review & Editing, Supervision; **Benjamin Laclau:** Validation, Resources, Software, Data Curation; **Thomas Garnesson:** Validation, Resources, Software, Data Curation; **Xining Yang:** Validation, Data Curation; **Arnold Tukker:** Writing - Review & Editing, Supervision.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2021.111077.

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