Towards circular and energy-efficient management of building stock: an analysis of the residential sector of the Netherlands

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Chapter 4

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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Published in Renewable and Sustainable Energy Reviews, 2021,145, 111077

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 a 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.

Keywords: life cycle assessment, life cycle costing, building energy renovation, payback, construction and demolition waste, prefabricated concrete element

Abbreviations

ADR	Advanced drying recovery
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
EER	Energy efficiency ratio
EoL	End-of-life
EPS	Expanded polystyrene
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
$LCCO_2A$	Life cycle carbon emission analysis
IPCC	Intergovernmental Panel on Climate Change
PCE	Prefabricated concrete element
PCE-new	Prefabricated concrete element for new building construction
PCE-refurb	Prefabricated concrete element for existing building retrofit
RCA	Recycled concrete aggregate
RFUA	Recycled fiber wool ultrafine admixture
RGUA	Recycled glass ultrafine admixture
URLWCA	Ultrafine recycled lightweight concrete aggregate
VEEP	European Union Horizon 2020 project VEEP

4.1 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 (Atmaca 2016b). By 2050, it is projected that the global energy use of buildings might double, or even triple (Chalmers 2014). 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 (EZK 2019).

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 (EC 2010). 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 (Säynäjoki et al. 2012). 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 (EZK 2019).

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 (EC 2012b). Directive 2010/31/EU set minimum energy use standards and cost-optimal levels for old building renovations (EC 2010). 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 (BPIE 2017). 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 (Staniaszek 2015). 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 (PCE-new) or by over-cladding the envelope of existing buildings (PCE-refurb). As the life cycle performance of PCE-new has been previously evaluated (Zhang et al. 2020a), this study examines the performance of PCE-refurb.

Life cycle costing (LCC) and life cycle assessment (LCA) are typical appraisal tools of life cycle management methodology (Hunkeler et al. 2003). An integrated implementation of LCC and LCA can provide broader insights into sustainable products and technologies (Miah et al. 2017). Therefore, this study aims to employ LCC and LCA simultaneously to evaluate the potential of implementing VEEP PCE-refurb 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 PCE-refurb 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 4.2 illustrates the details of the technological system and main methods; Section 4.2.4 states the results; Section 4.4 discusses the application potential of the PCE-refurb system at an EU-wide scale and the reusability of PCE-refurb, and Section 4.5 presents the conclusions of the study.

4.2 Materials and methods

This section presents the basic materials and methods used in this study. Section 4.2.1 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 4.2.2 defines the goal and scope of the assessment system. Section 4.2.3 presents the life cycle environmental and economic inventory LCC and LCA, and Section 4.2.4 details the life cycle environmental and economic impact analysis.

4.2.1 Life cycle management of building energy renovation

4.2.1.1 Overview of life cycle energy, carbon emission, and cost analysis

As one of the main techniques for life cycle management (Hunkeler et al. 2003), LCAs are commonly used to explore opportunities in GHG emissions mitigation and energy efficiency in the building sector (Sharma et al. 2011). Based on an LCA, the life cycle carbon emission analysis ($LCCO_2A$) and life cycle energy analysis (LCEA) specifically focus on the life cycle CO_2 equivalent emissions and the energy use of buildings, respectively.

The Building Assessment Information System (CEN 2012) 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 (Ramesh et al. 2010). Analogously, an $LCCO_2A$ accounts for the total CO_2 equivalent emission outputs from a building over different phases of its life cycle (Chau et al. 2015). Energy (Ramesh et al. 2010) and GHG emissions (Lu and Wang 2019) 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 (Ramesh et al. 2010) and emissions (Lu and Wang 2019) are almost negligible, contributing approximately 1%.

In an LCEA and $LCCO_2A$, building materials production and building construction are often grouped into one stage. For example, studies on the LCEA (Ramesh et al. 2010; Cabeza et al. 2014; Chau et al. 2015; Atmaca 2016b) and $LCCO_2A$ (Atmaca 2016b; Chau et al. 2015; Lu and Wang 2019) 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 use 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):

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

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

where E_E denotes the energy use incurred in the embodiment phase, E_O represents the energy use incurred in the operation phase, E_D denotes the energy use 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 $LCCO_2As$ 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 $LCCO_2As$ and found that an LCEA focuses on energy input and an $LCCO_2A$ 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 $LCCO_2As$. Conversely, the cumulative energy demand (CED) is a key index for both LCAs and LCEAs. Klöpffer (1997) stated that the CED is an inventory indicator that does not rely on any assumptions. However, Frischknecht (1997) explained that some assumptions are necessary to develop CED factors (Frischknecht et al. 2015). Instead of employing the LCEA or $LCCO_2A$ as independent methods, this study used a standard LCA, which conforms to ISO 14040 (ISO 2006a) and ISO 14044 (ISO 2006b), as an appraisal tool to explore the life cycle energy and carbon emissions of the PCE-refurb system.

Regarding economic assessment, LCC is a financial assessment tool that explores the costs incurred during the life cycle of a product system (ISO 2017a). There are multiple cost breakdown structures for an LCC, such as lifecycle-based, stockholder-based, and expenditure-based (Zhang et al. 2019a). 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 (ISO 2017a), the life cycle cost of a building consists of construction costs, operation and maintenance costs, and EoL costs, as shown in Eq. (3).

$$Life\ cycle\ cost\ = I_E + I_O + I_D, \tag{3}$$

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 (Ciroth et al. 2008; Swarr et al. 2011), 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 PCE-refurb system.

4.2.1.2 Payback period method

Several systematic reviews have been conducted on LCCs (Sesana and Salvalai 2013; Islam et al. 2015; Atmaca 2016b; Lu et al. 2021), LCAs (Chau et al. 2015; Ramesh et al. 2010; Vilches et al. 2017; Singh et al. 2011; Sesana and Salvalai 2013; Buyle et al. 2013; Anand and Amor 2017; Islam et al. 2015; Atmaca 2016b; Lu et al. 2021), LCEAs (D'Oca et al. 2018; Sadineni et al. 2011; Chau et al. 2015; Ramesh et al. 2010; Sesana and Salvalai 2013; Deng et al. 2014; Sartori and Hestnes 2007), and LCCO_2As (Chastas et al. 2018; Chau et al. 2015) 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 PCE-refurb 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 PCE-refurb 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 (Yard 2000). Despite its methodological deficiencies, a payback period is employed as a primary sieve or constraint for investment appraisal (Weingartner 1969), representing the amount of time it takes to recover the cost of an investment, as expressed in Eq. (4) (Yard 2000).

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

where I is the investment outlay, CF denotes the annual cash flow, L represents the economic life, and IRR denotes the discount rate 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 (Peng et al. 2013) and building energy renovation (Vilches et al. 2017). Table 4.1 summarizes studies related to the payback method, wherein the estimation of the energy and carbon payback periods are expressed by Eqs. (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) (Lu and Yang 2010; Huang et al. 2012b; Asdrubali et al. 2019; Ardente et al. 2011):

$$Energy\ payback\ period = \frac{E_E}{E_O}, \quad (5)$$

$$Carbon\ payback\ period = \frac{C_E}{C_O}, \quad (6)$$

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.

Table 4.1 Payback period literature of building energy renovation

Source	Topic	Area	Main findings
(Leckner and Zmeureanu 2011)	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).

(Säynäjoki et al. 2012)	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.
(Papaefthimiou et al. 2006)	Electrochromic window	Greece	The energy payback period is 8.9 years when considering aluminum frames.
(Berggren et al. 2013)	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.
(Dylewski and Adamczyk 2014)	Insulation material for exterior wall of a 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).
(Huang et al. 2012b)	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.
(Bull et al. 2014)	School buildings refurbishment	Hong Kong, China	Mean discounted financial payback (32.1 years) is longer than carbon payback (3.9 years).
(Asdrubali et al. 2019)	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.
(Faludi and Lepech 2012)	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 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.
(Hossain and Marsik 2019)	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.
(Schwartz et al. 2016)	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.
(Mohammadpourkarbasi and Sharples 2013)	Eco-Refurbishment of dwellings	Liverpool and London, UK	The carbon payback time of refurbishment is less than 7 years.
(Dodoo et al. 2010)	Wood-framed apartment retrofit	Växjö, Sweden	The energy payback period is less than 4 years.
(Ardente et al. 2011)	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.
(Vilches et al. 2017)	-	-	When considering all environmental impact categories, the payback period of an energy retrofit building is less than 7.5 years
(Comodi et al. 2016)	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.
(Lu and Yang 2010)	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.

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 use.

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 PCE-refurb system for building energy renovation and evaluate how material circularity influences the payback periods.

4.2.1.3 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 PCE-refurbs to equal the cost/energy/GHG incurred in the embodiment and demolition phases. Based on Eqs. (4), (5), and (6), the energy, carbon, and investment payback periods are calculated with Eqs. (7), (8), and (9), respectively. This study applies process-based LCA and LCC to quantify PCE-refurb performance in different European cities, namely, Madrid, Amsterdam, and Stockholm.

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

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

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

where T_E represents the energy payback period, $E_E^{PCE-refurb}$ denotes the embodied energy use for manufacturing the PCE-refurb, $E_O^{PCE-refurb}$ denotes the energy demand for heating and cooling in the building operation phase after PCE-refurb refurbishment, $E_D^{PCE-refurb}$ is the energy use for the treatment of EoL PCE-refurb 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, $C_E^{PCE-refurb}$ represents the embodied GHG emission for PCE-refurb manufacturing, $PCE - refurb$ denotes the GHG emissions incurred in the operation phase of a building after refurbishment with PCE-refurb, $C_D^{PCE-refurb}$ demonstrates the GHG emissions for treating EoL PCE-refurb 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, $I_E^{PCE-refurb}$ denotes the investment for PCE-refurb manufacturing incurred in the embodiment phase, $I_O^{PCE-refurb}$ denotes the operation costs incurred in the operation phase of a building after refurbishment with PCE-refurb, $I_D^{PCE-refurb}$ denotes the cost for PCE-refurb 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 facade.

The LCA in this study was outlined using the four steps determined by the ISO standards: (i) goal and scope definition, (ii) life cycle inventory analysis, (iii) life cycle impact assessment, and (iv) results interpretation. The CED and global warming potential were considered 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 Figure 4.1. Note that the LCA focuses on energy inputs and GHG emission outputs from the system, whereas the LCC focuses 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 PCE-refurb. 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 TABULA database (TABULA 2017). During the demolition phase, the impact of recycling and reusing PCE-refurb on the payback period was evaluated. Thus, this study used the payback method to investigate the energy-carbon-investment payback period of the proposed PCE-refurb 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.

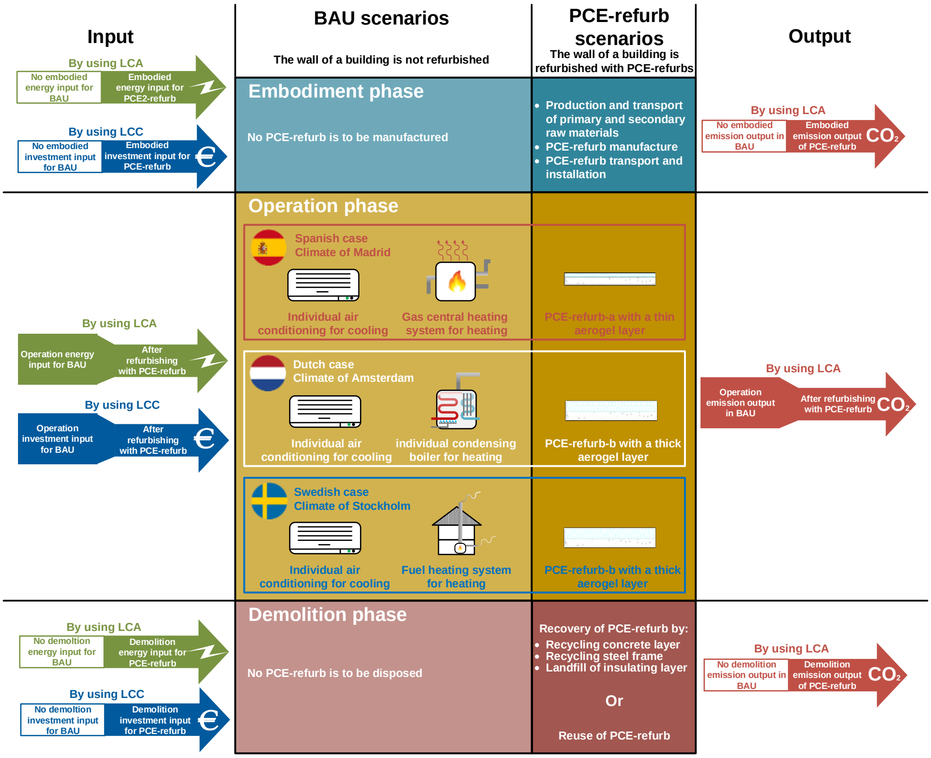

Figure 4.1 Conceptual framework of the study. LCA: life cycle assessment; LCC: life cycle costing; BAU: business-as-usual; PCE-refurb: prefabricated concrete element for old building refurbishment.

4.2.2 Goal and scope definition

4.2.2.1 Goal and scope

The goal of this study is to compare the energy and carbon payback periods for fabricating and operating the proposed PCE-refurb system as an energy retrofitting strategy for existing buildings with a conventional wall as a fa çade 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 4.2.

Table 4.2 Climates and locations of three case cities. The data source for information about Madrid (Wikipedia 2020a), Amsterdam (Wikipedia 2020b), and Stockholm (Wikipedia 2020c)

	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

4.2.2.2 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 concrete and green aerogel in the PCE-refurb. 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 PCE-refurbs. The cross-sections of the traditional wall in the BAU scenario and VEEP PCE-refurbs for over-cladding the traditional wall are illustrated in Figure 4.2. A typical façade for a residential building presented on the left of Figure 4.2 was selected as a benchmark reference. Regarding the climate difference between Madrid, Amsterdam, and Stockholm, alternative structures were applied to the PCE-refurb designs. In particular, PCE-refurb-a, which has a thinner aerogel layer, was employed for the Madrid case, while PCE-refurb-b, which has a thicker aerogel layer, was implemented for the Amsterdam and Stockholm cases. The PCE-refurb-a is 2 m long, 2 m wide and 0.08 m thick, and the PCE-refurb-b is 2 m long, 2 m wide, and 0.12 m thick.

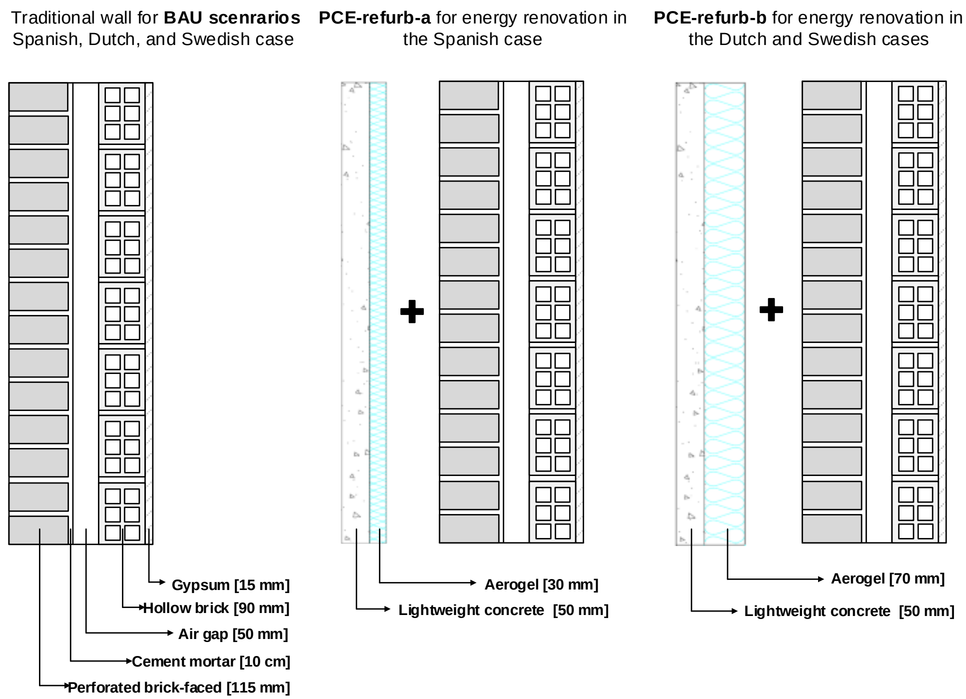

Figure 4.2 Cross-section diagrams of BAU traditional wall (left), and VEEP PCE-refurb-a (middle) to be implemented in Spain, and PCE-refurb-b (right) to be implemented in the Netherlands and Sweden. BAU: business-as-usual; PCE-refurb: prefabricated concrete element for old building refurbishment.

In the BAU scenarios, a typical traditional wall was selected as the benchmark reference for comparison with the PCE-refurb 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 PCE-refurb scenarios, environmental impacts are incurred throughout the entire life cycle. In the embodiment phase, secondary raw materials are incorporated into a PCE-refurb. 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, PCE-refurbs are dismantled and recycled. The specific features of the BAU and PCE-refurb scenarios are summarized in Table 4.3.

Table 4.3 Six scenarios developed based on technological and climate conditions. BAU: business-as-usual; PCE-refurb: 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 the 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
PCE-refurb	**PCE-ES:** traditional wall of the existing building refurbished with PCE-refurb-a under the climatic conditions of Madrid, Spain; associated investment, GHG emissions, and energy use are incurred in the embodiment, operation, and demolition phases	**PCE-NL:** traditional wall of the existing building refurbished with PCE-refurb-b under the climatic conditions of Amsterdam, Netherlands; associated investment, GHG emissions, and energy use are incurred in the embodiment, operation, and demolition phases	**PCE-SE:** traditional wall of the existing building refurbished with PCE-refurb-b under the climatic conditions of Stockholm, Sweden; associated investment, GHG emissions, and energy use are incurred in the embodiment, operation, and demolition phases

The functional unit for the assessment was retaining the heating and cooling comfort for 1 m^2 floor area through (i) passive building façades (with or without the application of VEEP PCE-refurbs) 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 m^2 of floor area requires 0.55 m^2 of PCE-refurb to over-clad the building façade.

4.2.3 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 (Guinée et al. 2001). The system boundaries of the BAU and VEEP PCE-refurb scenarios are shown in Figure 4.3. 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.

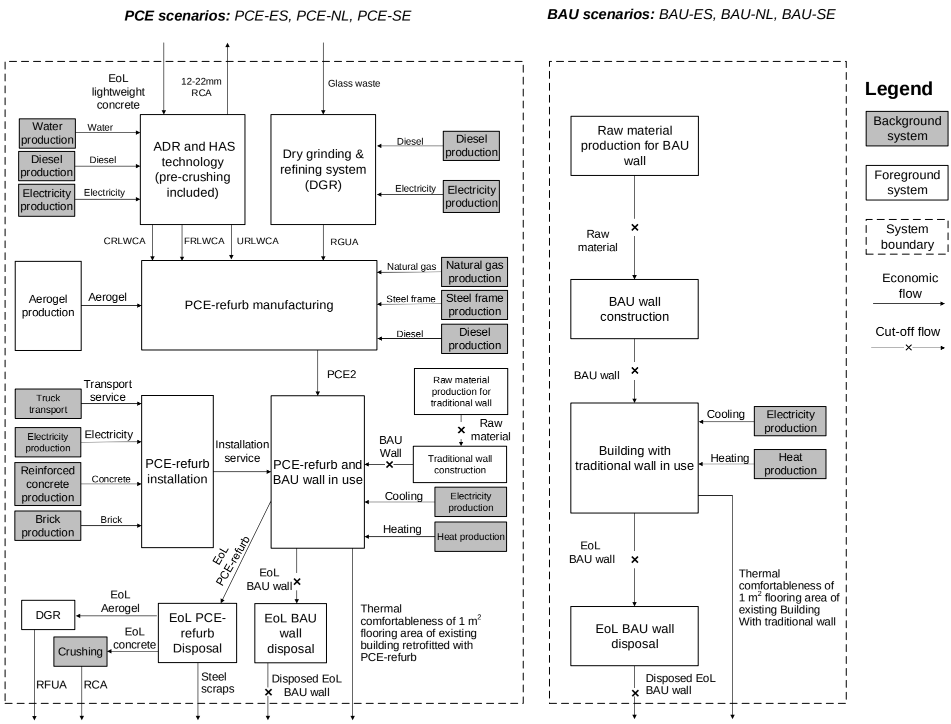

Figure 4.3 Assessment boundaries of the PCE-refurb (left) and BAU scenarios (right). ADR: Advanced dry recovery system; BAU: Business-as-usual; CRLWCA: coarse recycled lightweight concrete aggregate; DGR: Dry Grinding & Refining system; EoL: end-of-life; ES: Spanish case; FRSCA: Fine recycled siliceous concrete aggregate; FRLWCA: fine lightweight recycled concrete aggregate; HAS: Heating Air Classification System; NL: Dutch case; PCE-refurb: 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.

4.2.3.1 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, PCE-refurb manufacturing, and PCE-refurb transport and installation were determined.

Secondary raw materials were extracted from the waste stream via ADR, HAS, and DGR to fabricate the PCE-refurb. A previous study explored the mass balance of integrated ADR and HAS technological systems for recycling both normal-weight siliceous (Zhang et al. 2019a) and lightweight concrete wastes (Zhang et al. 2021a), revealing that a larger

0–4 mm fraction is produced by processing lightweight concrete (48%) than normal-weight concrete (32%). The flow chart of ADR and HAS is shown in Figure A4.1.

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 virgin cement in lightweight concrete. The mass balance of the DGR system is shown in Figure A4.2 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 (Zhang et al. 2019a, 2018), the impact of transportation of recycling facilities, raw materials, PCE-refurbs, 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 (Zhang et al. 2019a). According to the share of EoL concrete and glass waste in the CDW by weight (Zhang et al. 2020b), 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 PCE-refurb manufacturing and the gross waste generated from the demolition site. The operating weights of each facility are listed in Table A2.2 in Chapter 2.

In the PCE-refurb 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 4.4. Further, the detailed costs of virgin and secondary raw materials for the fabrication of PCE-refurb are listed in Table A4.1. 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 the 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 4.4. The detailed bill of virgin and secondary raw materials for fabrication of a PCE-refurb is presented in Table A4.2. After extraction and refining, raw materials are transported to the factory to manufacture the PCE-refurb. It is assumed that the average truck travel distance of the recycled material is 20 km while that of virgin materials is 50 km (Zhang et al. 2020a). The energy utilities related to VEEP PCE-refurb manufacturing are listed in Table A4.3.

Table 4.4 Processes with multifunctionality in the PCE-refurb scenarios

Process name	Multifunctionality category	Functional flows	Allocation coefficient
Pre-crushing process	Recycling	EoL lightweight concrete treatment	50%
		Coarse RCA (0-12mm) production	40%
		Coarse RCA (12-22mm) production	10%
ADR process	Co-production	CRLWCA production	40%
		Fine RCA (0-4mm) production	60%
HAS process	Co-production	FRLWCA production	80%
		URLWCA production	20%
DGR process	Recycling	Glass waste treatment	50%
		RGUA production	50%

After fabrication, PCE-refurb is transported to the construction site for installation. It is assumed that the average truck travel distance of PCE-refurb is 50 km (Zhang et al. 2020a). The utilities and material inputs for PCE-refurb installation are listed in Table A4.4.

4.2.3.2 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 Figure 3.5 in Chapter 3.

The thermal transmittance of the building walls varied from less than 0.2 W/(m ²K) to more than 2.0 W/(m ²K) depending on the construction age (Economidou 2011). Thus, a typical wall (as depicted in Figure 4.4) 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 PCE-refurb are listed in Table A4.5. The thermal transmittance of the traditional wall before and after PCE-refurb refurbishment were determined in accordance with ISO 6946 (ISO 2017b). The calculated thermal transmittance of each building element is listed in Table A4.6. The heating and cooling conditions considered herein are listed in Table 3.3 in Chapter 3.

The annual heating and cooling distribution requirements for Madrid, Amsterdam, and Stockholm based on the dynamic thermal simulations are shown in Figure 4.4. 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.

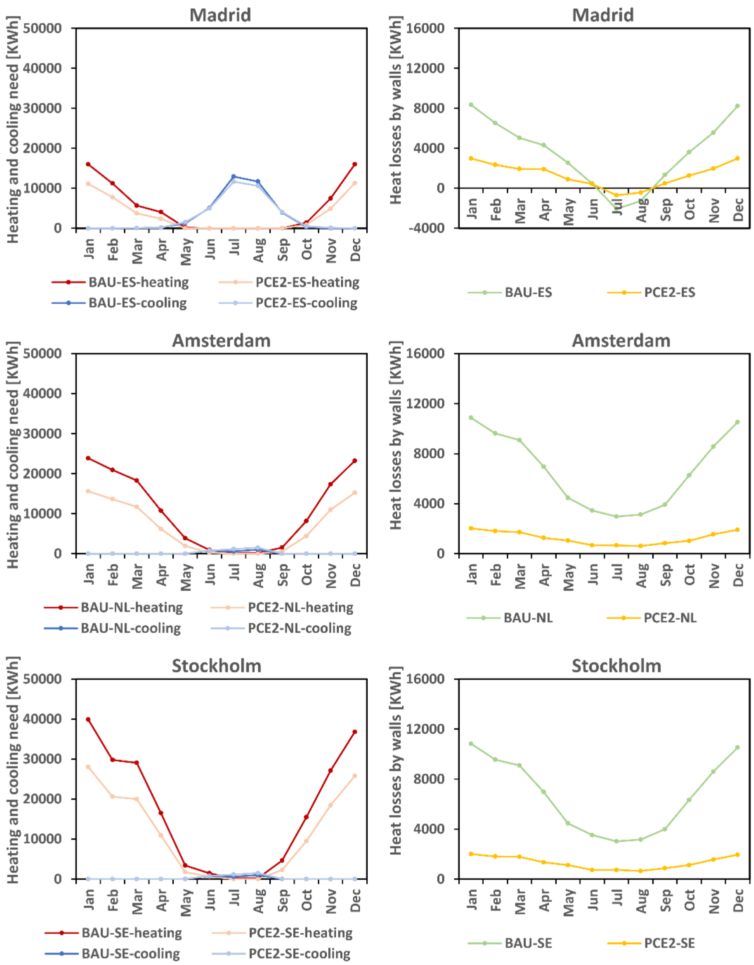

Figure 4.4 Distribution of the annual heating and cooling requirements and heat loss of virtual buildings in Madrid, Amsterdam, and Stockholm. BAU, business-as-usual; PCE-refurb, prefabricated concrete element for building refurbishment; ES, Madrid, Spain; NL, Amsterdam, Netherlands; SE, Stockholm, Sweden.

Based on the thermal dynamic simulations shown in Figure 4.4, the annual heating and cooling demand/floor area for both the BAU and VEEP scenarios in each region are listed in Table 4.5. Detailed information for modeling the heating and cooling demand is provided in Table A4.7.

Table 4.5 Annual heating and cooling demand/floor area for BAU and PCE-refurb scenarios. BAU: Business-as-usual; PCE-refurb: prefabricated concrete element for building refurbishment; ES: Spanish case; NL: Dutch case; SE: Swedish case.

	BAU-ES	PCE-ES	BAU-NL	PCE-NL	BAU-SE	PCE-SE
Heating need [kWh/(m ²year)]	34.95	23.73	73.36	45.99	115.69	78.19
Cooling need [kWh/(m ²year)]	19.89	18.81	1.31	1.98	1.55	1.99

4.2.3.3 Demolition phase

In the demolition phase, demolishing the VEEP PCE-refurbs and BAU traditional walls and disposing of the BAU traditional wall were not 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 (Karatum et al. 2018). 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 PCE-refurb is examined in Section 4.1. Further recycling information is provided in the SI.

4.2.4 Life cycle impact assessment

The impact assessment step in an LCA characterizes the inventory results according to the target impact categories (Guinée et al. 2001). This study uses an LCA to quantify the GHG mitigation and energy saving potential of the PCE-refurb 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) (Frischknecht et al. 2003) 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 (Zhang et al. 2019a). 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 zero interest (De Nederlandsche Bank 2020), which even reached a negative rate in developed areas, such as the Netherlands (Zhang et al. 2021a), thus, the interest rate was not considered for the payback estimation. The LCC result is expressed as the investment payback period.

4.3 Results

Section 4.3.1 presents the results of the embodiment, operation, and demolition phases of the LCA and LCC, which are converted into payback periods in Section 4.3.2.

4.3.1 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 Figure 4.5. Figure 4.5 (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 PCE-refurb-a uses less aerogel. Meanwhile, in the operation phase, all three cases show that PCE-refurb 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 4.3.2.

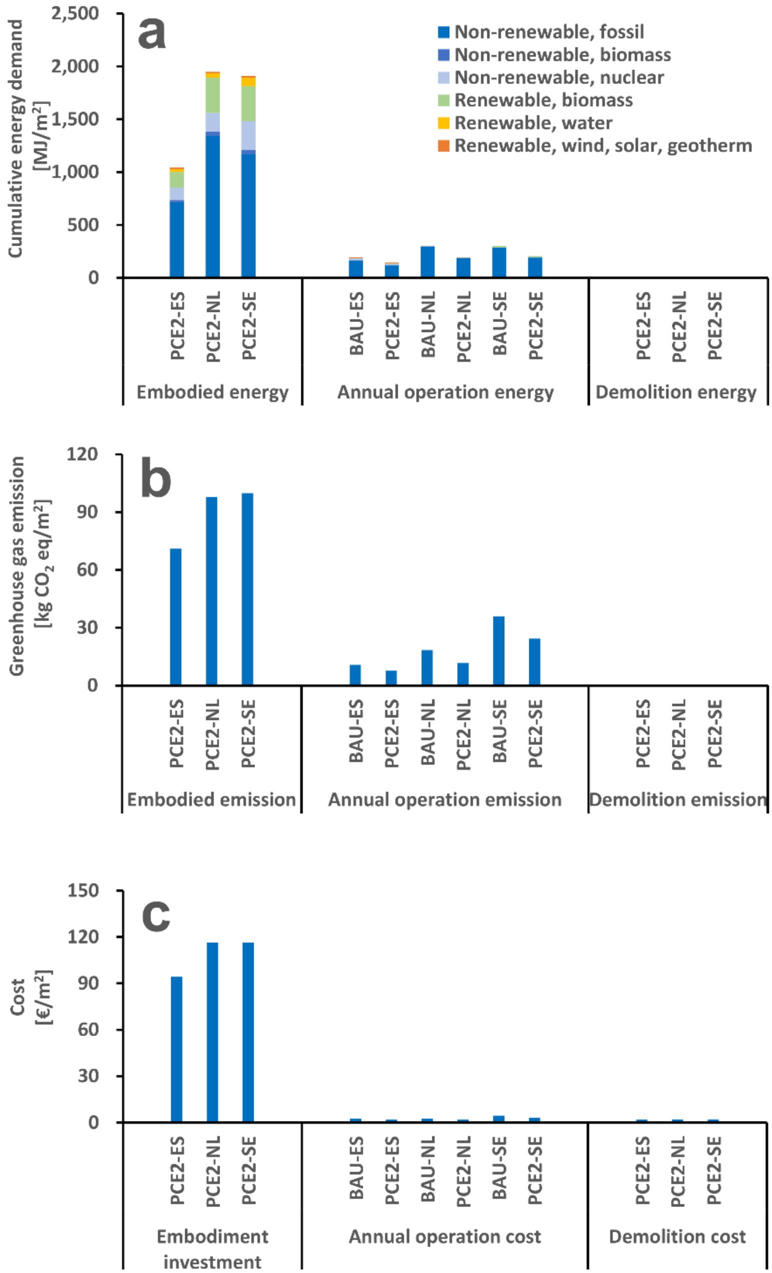

Figure 4.5 (a) Cumulative energy demand, (b) GHG emissions, and (c) cost in each phase of six scenarios. BAU: Business-as-usual; PCE-refurb: prefabricated concrete element for building refurbishment; ES: Spanish case; NL: Dutch case; SE: Swedish case.

4.3.2 Energy, carbon, and investment payback period

Using Eqs. (7), (8), and (9), the impact results were converted into payback periods. The energy, carbon, and investment payback periods of the PCE-refurb-ES, PCE-refurb-NL, and PCE-refurb-SE scenarios are shown in Figure 4.6. The differences between each energy payback period are 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 PCE-refurb 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 (Sandberg et al. 2016). Therefore, financial payback will probably never be achieved if the PCE-refurb system is implemented in the Netherlands and Sweden.

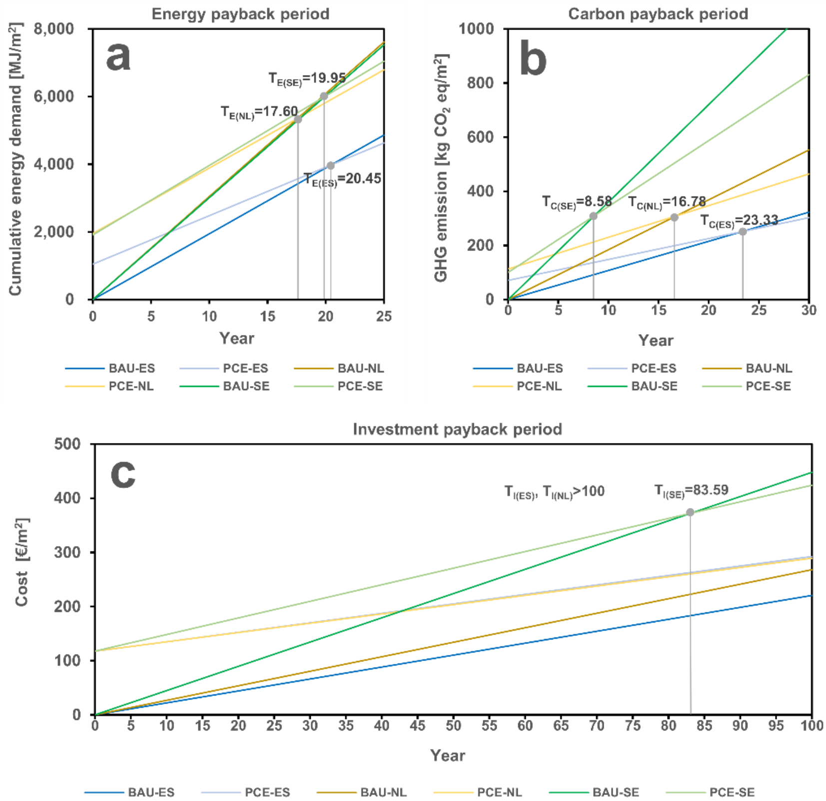

Figure 4.6 (a) Energy, (b) carbon, and (c) investment payback periods for Spanish, Dutch, and Swedish cases. BAU: Business-as-usual; PCE-refurb: prefabricated concrete element for building refurbishment; ES: Spanish case; NL: Dutch case; SE: Swedish case; T_E: energy payback period; T_C: Carbon payback period; T_I: investment payback period.

4.4 Discussion

This section discusses the impact of reusing PCE-refurbs, the application potential of the PCE-refurb system in an EU context, and the limitations of this study.

4.4.1 Influence of material circularity solutions on payback periods

Although the PCE-refurb system has relatively short energy and carbon payback periods, its economic payback is not achievable within the building's lifetime. To make the PCE-refurb system more cost-effective (EC 2012b, 2010), 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 PCE-refurb, 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 PCE-refurb that only contains primary raw materials was calculated.

Furthermore, as a non-structural element, one prominent merit of the PCE-refurb system is its reusability. Reusing PCE-refurb is realized by applying a dismantlable connecting and anchoring system that makes it possible to disassemble an intact PCE-refurb for reuse. As 90% of the cost of installation is the cost of labor (Zhang et al. 2021a), 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 PCE-refurbs. Therefore, the additional assessment in this section focuses on the extent to which reuse can avoid the additional PCE-refurb production in the embodiment phase. In this study, PCE-refurb reuse is modeled as (i) avoidance of 90% of the material and energy input in the embodiment phase for PCE-refurb manufacturing, and (ii) a reduction of the installation cost by 50% (Zhang et al. 2021a).

As shown in Figure 4.7, 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 PCE-refurb 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 PCE-refurb, 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.

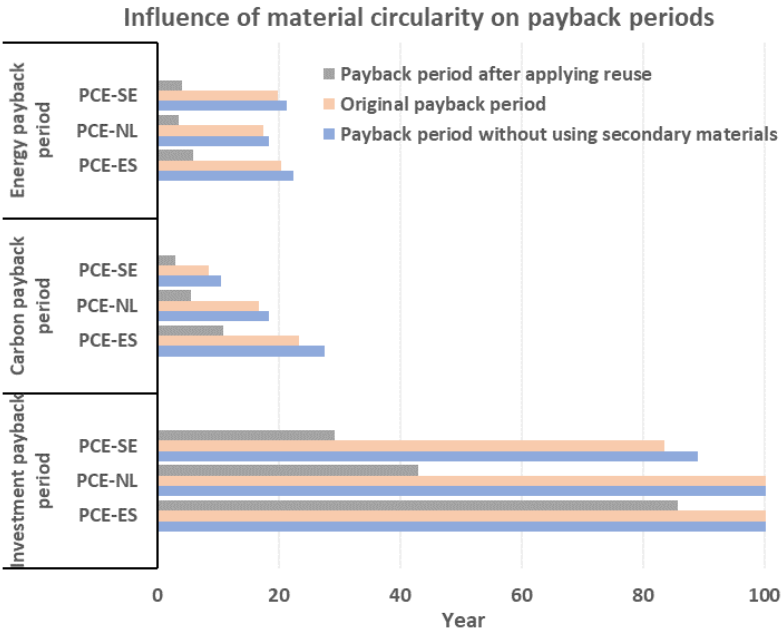

Figure 4.7 Influence of material circularity on energy, carbon, and investment payback periods. BAU: Business-as-usual; PCE-refurb: prefabricated concrete element for building refurbishment; ES: Spanish case; NL: Dutch case; SE: Swedish case.

4.4.2 Applicability of PCE-refurb system under EU context

This section evaluates the applicability of the PCE-refurb system in multiple EU member states. The system's energy use and associated costs and GHG emissions were modeled to directly relate to the thermal transmittance of building envelopes. In particular, the thermal transmittance considered were: the BAU wall (1.25 W/(m^2 K)), BAU wall retrofitted with VEEP PCE-refurb-a, and the BAU wall retrofitted with VEEP PCE-refurb-b. Each thermal transmittance was compared to the average-level building envelopes of EU building stock constructed at different times, as shown in Figure 4.8.

Sandberg et al. investigated 11 European countries and found that the average lifetime of European residential buildings was approximately 120 years (Sandberg et al. 2016). Thus, the potential building stock for refurbishment was considered to be constructed from 1900 to 2020. As shown in Figure 4.8, building stock constructed from 1900 to 1989 accounts for 75% of the total EU building stock. This stock has a higher thermal transmittance than that of the BAU traditional wall (illustrated by grey bar) used in this study. The thermal transmittance of the PCE-refurbs was even lower than the average thermal transmittance of the envelope of the buildings constructed after 2010, implying that the EU has a large potential market for the implementation of the PCE-refurb system for building energy renovation.

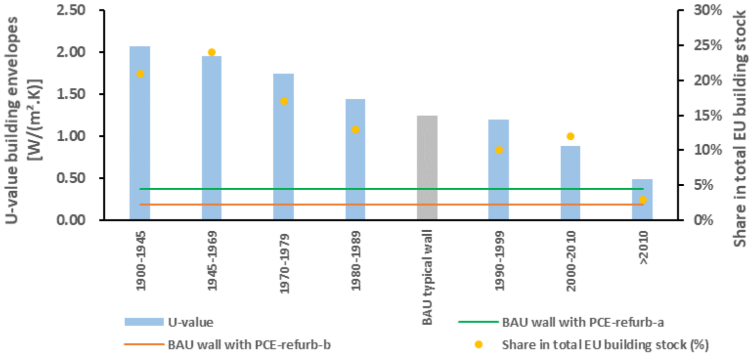

Figure 4.8 EU buildings' age and average thermal transmittance for building envelopes. Data source: (BPIE 2017); BAU: Business-as-usual; EU: European Union; PCE-refurb: prefabricated concrete element for building refurbishment; PCE-refurb-a: PCE-refurb containing a thin aerogel layer; PCE-refurb-b: PCE-refurb containing a thick aerogel layer.

However, the energy required for heating accounts for the largest share (approximately 70%) of building energy use (Economidou 2011). Considering the high importance of heating, heating demands in the BAU and PCE-refurb scenarios were compared with those of buildings in other EU member states that were constructed at different times, as shown in Figure 4.9. In general, the energy required for heating in each member state declined over time. With PCE-refurb 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 PCE-refurb-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, the efficiency of the heating system, and insulating levels of building facades, the results are shown in Figure 4.9 are not directly comparable. However, these results, to some degree, can demonstrate insights into the transitional trend of heating energy use in some EU member states and the application potential of PCE-refurb.

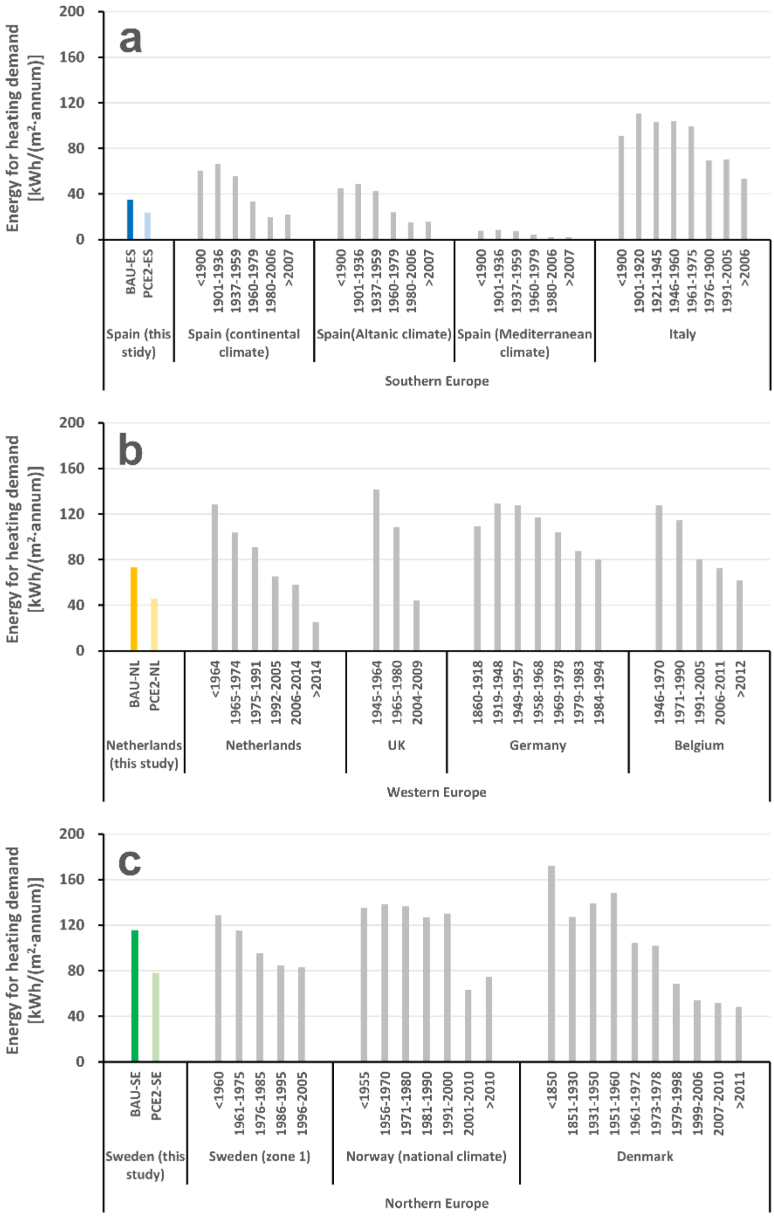

Figure 4.9 Annual/floor area energy required to meet heating demand of apartment blocks by construction year in (a) Southern Europe, (b) Western Europe, and (c) Northern Europe. Data collected from the TABULA database (TABULA 2017); BAU: Business-as-usual; ES: Spanish case; PCE-refurb: prefabricated concrete element for building refurbishment; NL: Dutch case; SE: Swedish case.

4.4.3 Limitations and outlooks

LCA and LCC building analyses are based on multiple simplifications and assumptions. Atmaca (2016) compiled the basic assumptions in building LCA and LCC analyses. Other than these assumptions, the specific limitations of this study are as follows.

First, the PCE-refurb 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 (Aguilar-Hernandez et al. 2018). After refurbishment, the lifetime of a building is extended. However, because of the natural characteristics of the payback method (Yard 2000), it failed to consider the benefits of this prolonged lifetime.

Second, PCE-refurb 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 thermal transmittance of 1.25 W/(m^2·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 (Swarr et al. 2011).

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

4.5 Conclusions

This study combined LCA and LCC analyses to determine the energy, carbon, investment payback periods for buildings renovated with the PCE-refurb 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 PCE-refurb-a and PCE-refurb-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 PCE-refurb 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 PCE-refurb system only slightly reduces the payback periods. However, reusing the PCE-refurb 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, reusing the PCE-refurb 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 PCE-refurb was evaluated by comparing the thermal transmittance and annual heating energy of EU buildings constructed at different times. The thermal transmittance of PCE-refurb-a and PCE-refurb-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 PCE-refurb for building refurbishment. The results can be extrapolated to support the design and manufacture 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 to address the question of region-level applicability and up-scaled ecological/financial benefits.

Acknowledgements

This work was supported by the European Union (grant number: 723582). Chunbo Zhang was supported by the China Scholarship Council (grant number: 201706050090). The authors also thank Arianna Amati from Rina Consulting, Ismo Tiihonen, Dr. Jaime Moreno Juez from Tecnalia, Dr. Abraham Teklay Gebremariam and Dr. Francesco Di Maio from the Delft University of Technology, Dr. Francisco Ruiz from Keey Aerogel, Frank Rens, and Eric van Roekel from Strukton BV for providing the data.

Appendix

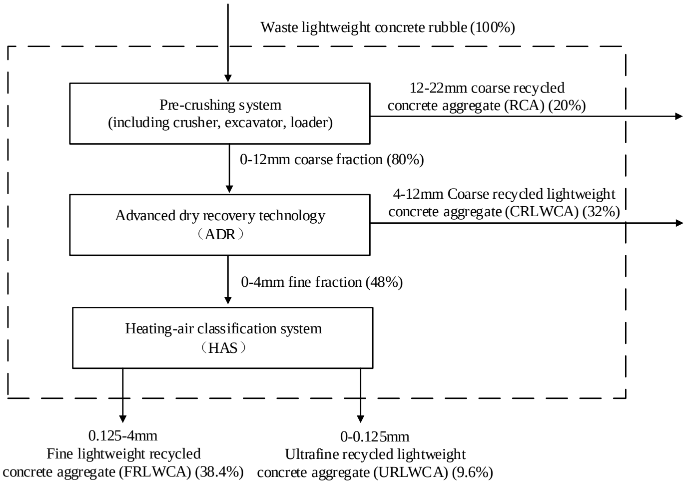

Figure A4.1 Mass balance of integrated ADR and HAS technology for recycling lightweight concrete waste

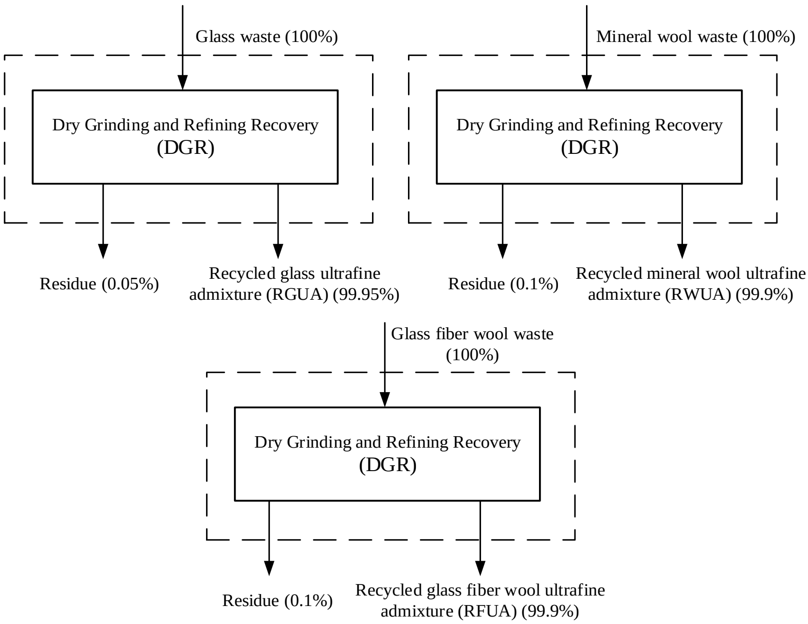

Figure A4.2 Mass balance of integrated ADR and HAS technology for recycling glass waste, mineral wool waste, and glass fiber wool waste

Table A4.1 Life cycle economic inventory

Items	Expenditure	Cost	Unit	Remark
Embodiment phase	Green lightweight concrete	93.82	€/t	The cost of green lightweight concrete for the PCE-refurb is expressed in an integrated unit cost. Data from (Zhang et al. 2021a)
	Green aerogel	10.00	€/0.01 m^2	The cost of green aerogel for the PCE-refurb is expressed in an integrated unit cost. Data from (Zhang et al. 2021a)
	Steel frame	537.00	€/t	Data from (Zhang et al. 2021a)
	Manufacturing of PCE-refurb	6.10	€/m^2	Data from (Zhang et al. 2021a)
	Installation of PCE-refurb	69.38	€/0.55 m^2	The cost incurred in the installation of 0.55 m^2 PCE-refurb for refurbishing per 1 m^2 floor area. Data from (Zhang et al. 2021a)
	Transport	0.1	€/km·t	Data from (Zhang et al. 2020a)
Operation phase	Electricity price in Spain	0.2239	€/kWh	Medium size household electricity prices in 2020 in Spain, data from the Eurostat (Eurostat 2020)
	Electricity price in the Netherlands	0.1427	€/kWh	Medium size household electricity prices in 2020 in the Netherlands, data from the Eurostat (Eurostat 2020)
	Electricity price in Sweden	0.1826	€/kWh	Medium size household electricity prices in 2020 in Sweden, data from the Eurostat (Eurostat 2020)
	Heating price in Spain	0.0360	€/kWh	Data from dataset "heat production, natural gas, at boiler modulating <100kW | heat, central or small-scale, natural gas | Cutoff, U - Europe without Switzerland" in Ecoinvent 3.4.
	Heating price in the Netherlands	0.0360	€/kWh	Data from dataset "heat production, natural gas, at boiler modulating <100kW | heat, central or small-scale, natural gas | Cutoff, U - Europe without Switzerland" in Ecoinvent 3.4.
	Heating price in Sweden	0.0382	€/kWh	Data from dataset "heat, at cogen, with supporting oil furnace 60%, 160kWe Jakobsberg, allocation exergy | heat, central or small-scale, Jakobsberg | Cutoff, U – RoW" in Ecoinvent 3.4.
Demolition phase	EoL concrete recycling	40.63	€/t	Data from (Zhang et al. 2021a)
	Aerogel recycling	75.18	€/t	Data from (Zhang et al. 2020a)
	Steel for sale	-133.12	€/t	Data from (Zhang et al. 2021a)

Table A4.2 Inventory of raw material for the fabrication per VEEP PCE-refurb. Note: For commercially confidential concerns, the exact amounts of constituents for lightweight concrete and aerogel are not given. Background process “market for transport, freight, lorry >32 metric ton, EURO3 | transport, freight, lorry >32 metric ton, EURO3 | Cutoff, U - GLO” in Ecoinvent 3.4 is selected for modeling transport of recycling facilities.

The material of the PCE	VEEP PCE-refurb-a	VEEP PCE-refurb-b	Sources of referred unit processes
Cement (CEM III/A)	/	/	Referred to “cement production, alternative constituents 6-20% | cement, alternative constituents 6-20% | Cutoff, U- Europe without Switzerland” in Ecoinvent 3.4
URLWCA	/	/	From the HAS
Lime sand	/	/	Referred to “market for sand | sand | Cutoff, U-GLO” in Ecoinvent 3.4
FRLWCA	/	/	From the HAS
CRLWCA	/	/	From the ADR
Expanded clay	/	/	Referred to “market for expanded clay | expanded clay | Cutoff, U-GLO” in Ecoinvent 3.4
Water	/	/	Referred to “market for tap water | tap water | Cutoff, U - Europe without Switzerland” in Ecoinvent 3.4
Masterglenium sky 526	/	/	Referred to “market for plasticizer, for concrete, based on sulfonated melamine formaldehyde | plasticizer, for concrete, based on sulfonated melamine formaldehyde | Cutoff, U-GLO” in Ecoinvent 3.4
Master X-Seed	/	/	Referred to “chemical production, organic | chemical, organic | global” in Ecoinvent 3.4
Sika AER 5	/	/	Referred to “chemical production, organic | chemical, organic | global” in Ecoinvent 3.4
Lime	/	/	Referred to “market for lime, packed | lime, packed | Cutoff, U - RoW” in Ecoinvent 3.4
RGUA	/	/	From the DGR
Aerogel	0.28 m^3	0.12 m^3	From VEEP aerogel production
Steel beams & welded nets	23.72 Kg	23.72 Kg	Referred to “reinforcing steel production | reinforcing steel | Europe” in Ecoinvent 3.4

Table A4.3 Energy usage related to VEEP PCE-refurb manufacturing. Note: Background process "transport, freight, lorry 3.5-7.5 metric ton, EURO3 | transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Cutoff, U - RER" in Ecoinvent 3.4 is selected for modeling transport of secondary and virgin materials.

Energy carrier	Energy usage per unit of PCE-refurb	Sources of referred unit processes
Diesel	10.98 MJ/per PCE-refurb	"market for diesel, burned in building machine | diesel, burned in building machine | Cutoff, U - GLO" in Ecoinvent 3.4
Electricity	20.20 MJ/per PCE-refurb	"market for electricity, high voltage | electricity, high voltage | Cutoff, U – NL(/ES/SE)" in Ecoinvent 3.4
Natural gas	49.38 MJ/per PCE-refurb	"natural gas, burned in gas motor, for storage | natural gas, burned in gas motor, for storage | Cutoff, U - NL(/RoW)" in Ecoinvent 3.4

Table A4.4 Energy and material input for installation of 1 m^2 PCE-refurb. Note: Background process "transport, freight, lorry 3.5-7.5 metric ton, EURO3 | transport, freight, lorry 3.5-7.5 metric ton, EURO3 | Cutoff, U - RER" is selected for the transport of PCE-refurb.

Energy and material input	Amount	Sources of referred unit processes
Electricity [kWh]	4.21	"market for electricity, high voltage | electricity, high voltage | Cutoff, U – NL(/ES/SE)" in Ecoinvent 3.4
Brick [Kg]	62.85	"sand-lime brick production | sand-lime brick | Cutoff, U - RoW" in Ecoinvent 3.4
Reinforced concrete [Kg]	125.43	"concrete production 30-32MPa, RNA only | concrete, 30-32MPa | Cutoff, U - RoW" in Ecoinvent 3.4

Table A4.5 Thermal conductivity of materials for wall of building and PCE-refurb

Material	Thermal conductivity [W/(m K)]
Aerogel	0.0157
Green light weight concrete	0.5000
Perforated brick-faced	0.6560
Cement mortar	0.8000
Air gap (5cm)	0.2780
Hollow brick	0.2430
Gypsum	0.2500

Table A4.6 Thermal transmittance of the building envelope for dynamic thermal simulation with PCE-refurb in façade. Note: The thermal transmittance of the traditional wall before and after refurbishment with PCE-refurb systems were calculated based on ISO 6946 (ISO 2017b). BAU: Business-as-usual; PCE-refurb: prefabricated concrete element for building refurbishment.

Building elements	Thermal transmittance [W/(m²K)]
Floor	3.37
Roof	0.52
Glazing	1.30
BAU traditional wall	1.25
PCE-refurb-a (with thin aerogel layer)	0.52
PCE-refurb-b (with thick aerogel layer)	0.22
BAU traditional wall retrofitting with PCE-refurb-a	0.37
BAU traditional wall retrofitting with PCE-refurb-b	0.19

Table A4.7 Background processes in Ecoinvent for modeling household heating and cooling. Note: It is assumed individual air-conditioning is applied for cooling in these three areas. Energy demand for cooling is converted into household electricity use by a seasonal energy efficiency ratio. According to Norm DIN V 18599 (DIN 2011) for individual air conditioning (>12kW), the seasonal energy efficiency ratio is around 4.7. Therefore, 1 kWh of electricity can provide 4.7 kWh of cooling demand.

Heating and cooling input	Amount (BAU/PCE-refurb) [kWh/(m²annum)]	Sources of referred unit processes in Ecoinvent 3.4
Individual air-conditioning for household cooling in Spain	4.2300/4.0000	Data from dataset “market for electricity, low voltage | electricity, low voltage | Cutoff, U – ES”
Individual air-conditioning for household cooling in the Netherlands	0.2787/0.4213	Data from dataset “market for electricity, low voltage | electricity, low voltage | Cutoff, U – NL”
Individual air-conditioning for household cooling in Sweden	0.3298/0.4234	Data from dataset “market for electricity, low voltage | electricity, low voltage | Cutoff, U – SE”
Gas central heating system for household cooling in Spain	34.95/23.73	Data from dataset “heat production, natural gas, at boiler modulating <100kW | heat, central or small-scale, natural gas | Cutoff, U - Europe without Switzerland”
Individual condensing boiler for household heating in the Netherlands	73.36/45.99	Data from dataset “heat production, natural gas, at boiler condensing modulating <100kW | heat, central or small-scale, natural gas | Cutoff, U - Europe without Switzerland”
Fuel (oil) heating system for household heating in Sweden	115.69/78.19	Data from dataset “heat, at cogen, with supporting oil furnace 60%, 160kWe Jakobsberg, allocation exergy | heat, central or small-scale, Jakobsberg | Cutoff, U - RoW” in Ecoinvent 3.4

Table A4.8 Allocation scheme of processes with multifunctionality in the demolition phase in PCE-refurb scenarios. Note: The EoL lightweight concrete with be recycled on-site to produce RCA. The aerogel is assumed to be recycled by the DGR system. For recycling EoL lightweight concrete and aerogel, only the function waste treatment is considered. Based on the mass-based allocation method, 50% of the impact of recycling is supposed to be allocated to secondary material production.

Process name	Multifunctionality category	Functional flows	Allocation coefficient	Category
Pre-crushing process	Recycling	EoL lightweight concrete treatment	50%	Target service
		RCA production	50%	Non-target product
DGR process	Recycling	Aerogel treatment	50%	Target service
		RFUA/RWUA	50%	Non-target product