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RESEARCH AND ANALYSIS

Life cycle greenhouse gas emission and cost analysis of prefabricated concrete building façade elements

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Abstract

Buildings are responsible for approximately 36% of carbon emissions in the European Union. Besides, gradual aging and a lack of adaptability and flexibility of buildings often lead to destructive interventions, resulting not only in higher costs but also in a large amount of construction and demolition waste (CDW). Recently, an innovative system (Ref. VEEP project) has been developed to recycle CDW for the manufacturing of energy-efficient prefabricated concrete elements (PCE) for new building construction. By applying life cycle costing (LCC) and life cycle assessment (LCA), this study aimed to determine whether the use of VEEP PCE leads to lower carbon emission and lower associated costs over the life cycle of an exemplary four-story residential building in the Netherlands than a business-as-usual (BAU) PCE scenario. This paper provides a case study on the alignment and/or integration of LCA and LCC in an independent and a combined manner (via monetization). This study examines how the internalization of carbon emission and discount rate will affect the final life cycle costs over a 40-year life span. The simulation results show that the key to economic viability and environmental soundness of VEEP PCE is to reduce production cost and to optimize the thermal performance of the novel isolation material Aerogel; internalization of external cost monetarizes the environmental advantage thus slightly expands the cost advantage of low carbon options, but leads to larger uncertainty about the LCC result.

KEYWORDS
building façade, construction and demolition waste (CDW), industrial ecology, life cycle assessment, life cycle costing, prefabricated concrete element

1 | INTRODUCTION

There is a wide agreement that future economic growth must be driven by greater energy-efficiency. The European Union (EU)'s current housing stock is thermally poor, and national energy performance standards are relatively weak when benchmarked against international best practice. Buildings are responsible for approximately 40% of energy consumption and 36% of CO_2 emissions in the EU (EC, 2014a). Currently, about 35% of the EU's buildings are over 50 years old and almost 75% of the building stock is energy-inefficient, while the yearly renovation rate is only 0.4–1.2%, depending on the country (EC, 2014a). The European building industry needs new technologies, products and materials to minimize that energy dependence. More renovation of buildings can lead to significant energy savings, potentially reducing the EU's total energy consumption by 5–6% and lowering CO_2 emissions by about 5% (EC, 2018). One of the key strategies for cutting the energy consumption of buildings through renovation is scaling up the use of novel technologies for highly efficient thermal insulation of a building's envelope (Morrissey & Horne, 2011).

At the same time, one of the largest solid waste streams is construction and demolition waste (CDW). The European Commission (EC) has identified CDW as a priority stream because of the large amounts that are generated and their high potential for reuse and recycling (EC, 2011). In

2005, the EU-27 member states generated approximately 461 million metric tons of CDW, and the generation volume is expected to reach 520 Mt in 2020 (excavated material excluded) (EC, 2011). Therefore, by 2020, the Waste Framework Directive (2008/98/EC) requires EU member states to take any necessary measures to prepare a minimum of 70% of CDW (by weight) for reuse, recycling, and other material recovery, including the use of non-hazardous CDW for backfilling (EC, 2008).

The Netherlands has noticeable performance over CDW management. Nearly 98% of the CDW generated in the Netherlands can be recycled, which is more than in the other member states (EC, 2012). End-of-life (EOL) concrete represents 40% of CDW in the Netherlands, and 100% of this stream is recycled, with more than 97% of it being used in road construction as road base material (Hu, Di Maio, Lin, & Van Roekel, 2012). While road construction is expected to remain stable, there is a need for shifting from traditional recycling approaches to novel recycling and recovery solutions. In particular, the fine fraction (0–4 mm), which constitutes roughly 40% of the recycled concrete, is often downcycled because its incorporation into new concrete still faces technical barriers (Lotfi, Eggimann, Wagner, Mróz, & Deja, 2015). Also, some minor (e.g., glass) and emerging (e.g., mineral wool) CDW streams, currently accounting for about 0.7% of the total CDW generation, are expected to grow until 2030 as a consequence of the European regulations on building energy efficiency and building retrofitting (EC, 2014b). In global terms, no technological and business solutions have yet been found for recycling those emerging CDW streams, which so far are mostly landfilled. Thus, more advanced and appropriate solutions should be developed to ensure the effective and efficient use of natural resources and to mitigate the associated environmental and economic impacts.

More and more businesses in the construction sector, as well as governments and even consumers are seeking eco-products which are not only financially viable but also bring in environmental, and even social benefits (Zhang, Oo, & Lim, 2019b). Also, new products need to meet upcoming challenges concerning climate change and lower carbon footprints, resource depletion and shortages, increasing restrictions on the use of toxic substances, lower embodied energy and best positioning in competitive markets. Over the last few years, novel technologies have been developed aiming to guarantee high-quality recycled raw material for use in new construction products, thereby closing the loops in the manufacturing of concrete and insulation material. In Europe, an innovative and integrated technological system called VEEP (www.veep-project.eu) was designed and developed for the massive retrofitting of the built environment, aiming at cost-effectively recycling CDW and reducing building energy consumption. VEEP's core technologies include advanced drying recovery (ADR), heating-air classification system (HAS), and dry grinding and refining (DGR), which provide the scientific-technological basis for new green concrete recipes containing high levels of upgraded CDW recycled materials. With VEEP, CDW will contribute at least 75% of the total weight of the new concrete, and at least 10% of cement will be replaced by recycled supplementary cementitious CDW materials. VEEP also allows for higher resource efficiency in the novel multilayer precast concrete elements (PCE) for new building envelopes, through the combination of concrete and superinsulation material manufactured by using recycled CDW materials as raw materials.

In view of the need for eco-efficient thermal insulation materials for renovating a building's envelope, it is of great significance to explore the environmental impact and cost-effectiveness of VEEP PCE as building façade. Hence, the main research question of the present study was "Is the use of concrete façade elements containing secondary materials more economic and environmental advantageous than the use of elements that are only made of primary material?" This study aimed to answer this question by comparing the economic costs and GHG emissions of two types of PCEs, one of which is made of both virgin and secondary raw material from the VEEP technological recycling system, the other being a conventional PCE with only virgin material. The comparison was based on an integrated life cycle assessment (LCA) conforming to ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b) and life cycle costing (LCC) based on the SETAC's definition (Hunkeler, Lichtenvort, Rebitzer, & Ciroth, 2008; Swarr et al., 2011). Critical life cycle phases of both PCEs are analyzed, including raw material production, manufacturing, in-use, and EOL disposal. This research selects a four-story residential building as a case study under the climatic conditions of Amsterdam, not only focusing on the environment-cost issue in practice but also trying to better integrate the LCA and LCC for comprehensive life cycle sustainability assessment.

Following the Introduction section, Section 2 presents a brief overview of LCC studies in calculation of internal and external costs with LCA, Section 3 describes the methods and materials, Section 4 presents the results and interpretation, and Section 5 presents the conclusions.

2 | LITERATURE REVIEW

Many traditional costing systems fail to consider a whole range of costs, and LCC has been suggested as a popular way of solving this problem. The LCC has been developed by the Rand corporation after the Second World War (Novick, 1959). The major difference between the traditional costing system and LCC is that the LCC approach comprises an expanded life cycle perspective, and thus includes not only investment costs, but also operational costs and sometimes even EOL costs. It also requires a more precise definition of the functional unit. One obvious merit of LCC is the identification of factors which have the largest contribution to the total life cycle costs of a project (Korpi & Ala-Risku, 2008). The application of LCC has expanded to many areas, such as waste management (Martinez-Sanchez, Kromann, & Astrup, 2015), ship production (Utne, 2009), packaging (Albuquerque, Mattos, Scur, & Kissimoto, 2019), energy system (Ristimäki, Säynäjoki, Heinonen, & Junnila, 2013; Zakeri & Syri, 2015), and building (Kneifel, 2010; Marszal & Heiselberg, 2011; Sterner, 2000). Because LCC is able to provide a significantly better assessment of the long-term effectiveness of a project than alternative economic methods that focus only on first costs or on operation-related costs in the short run, LCC is particularly suitable for evaluating the building design alternatives that satisfy a required level of building performance (Fuller & Petersen, 1995). LCC is vaguely defined by the building and construction assets standard ISO15686-5 (2008) as a technique which enables comparative cost assessments to be made over a special period of time. LCC can address a period of analysis that covers the entire life cycle or selected stages or periods of interest. Sterner (2002) estimated the life cycle costs of residential dwellings including construction costs, operation costs and maintenance costs. Morrissey and Horne (2011) apply an integrated thermal modeling and life cycle costing approach to an extensive sample of dominant house designs to investigate life cycle costs (material preparation costs, operational energy costs, disposal costs) in Melbourne. Marszal and Heiselberg (2011) evaluated the life cycle costs (investment costs, operation & maintenance costs, replacement costs, and demolition costs) of a multistory residential net-zero energy building in Denmark.

Besides the obvious costs of production activities, all processes involved in the life cycle may induce environmental impact costs, as they consume resources, emit greenhouse gasses and generate waste, which, however, most time are not considered in traditional LCC. It thus leads to environmentally unjustified decisions. It has been augured that LCC was not originally developed to calculate environmental costs, the expansion of the system boundaries of LCC to cover costs of more lifecycle stages does not automatically include all environmental costs. Therefore, it does not make LCC an environmental accounting tool just because it contains the words "life cycle" (Gluch & Baumann, 2004).It was suggested to view LCC as a tool for financial assessment, which has potential to align with the life cycle environmental assessment for a more comprehensive evaluation but unable to explore environmental externalities issue stand-alone. But the alignment is challenging because an LCA considers the overall environmental perspective so no stakeholder is taken as the reference, while an LCC need consider not only what the total costs is but also who the costs bearers are, for example, being the consumer, the producer or the society. To highlight the interlinked environmental and economic issues, the Society of Environmental Toxicology and Chemistry (SETAC) defined the methodology "environmental LCC" (Hunkeler et al., 2008). The term "environmental" in environmental LCC needs some explanation. The LCC focuses on a complete array of real cash flows, so it is not restricted to environmental costs, and it does not address hypothetical externalities (Heijungs, Settanni, & Guinée, 2013). Environmental LCC only includes internal costs and external costs expected to be internalized in the near future, such as carbon emission costs in Europe (Hunkeler et al., 2008). The adjective "environmental" refers to the fact that the economic analysis has been made in a way that is consistent with that of the environmental analysis which largely follows ISO 14040.

In recent decades, there has been an increasing volume of literature on combining LCA and LCC to simultaneously explore the environmental and economic impacts of product and technology systems (Miah, Koh, & Stone, 2017). For example, a combined LCA and LCC method was applied in CDW management studies, such as EOL concrete management in Malaysia (Mah, Fujiwara, & Ho, 2018), municipal solid waste management in Beijing (Yang, Zhou, & Xu, 2008) and in Tianjin (Zhao, Huppes, & van der Voet, 2011), and CDW management in Trondheim (Bohne, Brattebø, & Bergsdal, 2008). Projects aimed at energy conservation in buildings are other excellent examples of applying LCC and LCA to determine whether it is financially acceptable to trade higher initial capital investment for reduction of energy costs and environmental impact in the operational stage. Kneifel (2010) studied the carbon emissions and life cycle costs (construction costs, operational energy costs, maintenance costs, and disposal costs) of 12 new commercial buildings in the US to measure their energy efficiency. Islam, Jollands, Setunge, Ahmed, and Haque (2014) compared the environmental impacts and life cycle costs (construction, operation and maintenance, and disposal costs) of 5 alternative wall assemblage techniques for typical houses in Australia. Trigaux et al. (2013) used a combined LCC and LCA approach to assess different housing renovation scenarios. Dong, Kennedy, and Pressnail (2005) used life cycle environmental and economic analysis to explore when it is better to retrofit a building as opposed to demolishing and rebuilding it. Although the combined LCA and LCC approach is increasingly used, the explanation power of the method is still hampered by the longstanding methodological inconsistencies between LCC and LCA, especially regarding the consideration of: a) stakeholders/cost-bearers' perspective and b) the factor of time. Recently, the study of Zhang et al. (2019a) proposed an LCA-LCC analysis framework, suggesting an "economic impact assessment" step, which can be used to explore the impacts on various cost-bearers and periods in time. This study built upon the LCA-LCC analysis framework proposed in Zhang et al. (2019a)and explored the potential to harmonize LCA and LCC on stakeholders' perspective by internalizing the foreseeable environmental costs: carbon emission costs, and on the factor of time by considering "discounting" effects. Through a comparative LCA of PCE panels, this study provides a Dutch case for global issues with respect to CDW generation, GHG emission, and energy efficiency in the construction domain. As the evaluation includes a use phase of 40 years, it provides an excellent opportunity to investigate the effects of "discounting" on the harmonization of LCA and LCC methods in a combined study.

3 | METHODS

3.1 | Goal and scope definition

3.1.1 | Goal

The goal of this study was to determine the financial effects and carbon mitigation of manufacturing and using the innovative VEEP PCE as façade for a new building in comparison to those of manufacturing and using conventional PCE.

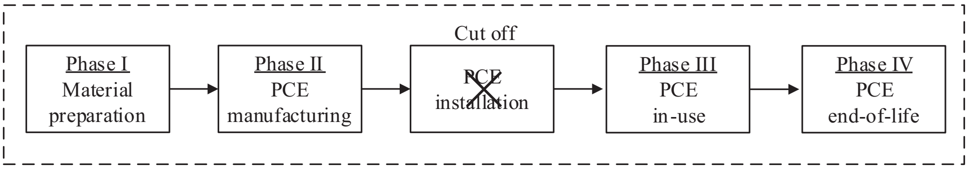


FIGURE 1 Scope of this study
Note: PCE represents prefabricated concrete element.

3.1.2 | Scope and scenarios

Normally there are five processes in the life cycle of PCE: material preparation; manufacturing; installation; in use; disposal. It is assumed that there is no difference between VEEP PCE and traditional PCE in installation, thus the installation phase will not be taken into account in this study. The life cycle that is considered in this study comprises four phases: (a) material preparation, (b) PCE manufacturing, (c) PCE in use, and (d) PCE disposal, as shown in Figure 1. Two scenarios are assessed in the study: *VEEP* and *BAU*. In both scenarios, PCE will be manufactured to improve the energy efficiency of a building. The differences are that PCE from BAU uses virgin material and conventional insulation material, whereas in the VEEP scenario, secondary raw material and the novel insulation material aerogel will be incorporated in PCE.

3.1.3 | Description of the VEEP system

VEEP ADR and HAS technologies

The combined innovative ADR technology and HAS was developed for the simultaneous cost-effective production of high-quality coarse and fine recycled concrete aggregates from concrete waste for green concrete production and green aerogel production. Siliceous concrete waste will be studied in this study. Given that selective demolition and sorting are common practice in the Netherlands, it is assumed that concrete waste fed into ADR and HAS does not contain residue. In this study, EOL siliceous concrete waste is considered as the target concrete waste for recycled concrete aggregate (RCA) production and recycled concrete ultrafine aggregate (RCUA). The details of ADR and HAS were described in a previous study (Zhang et al., 2019a).

VEEP DGR technology

Evolved VEEP dry grinding recovery (DGR) technology is currently a stationary recycling equipment which can produce secondary raw material: recycled glass ultrafine aggregate (RGUA) and recycled fiber ultrafine aggregate (RFUA), with an average purity level higher than 90%, from emerging building glass waste (GW) and insulating mineral fiber wool waste (FWW). These waste materials will first be precrushed by a mobile hammermill when larger amounts of material are processed. Materials are fed three times through the hammermill to achieve a suitable particle size. The whole process is sealed by a small vacuum in the hammermill feeding opening so that no dust or particles can escape from the process. From the hammermill, the milled material is transported pneumatically through a cyclone separator to the collecting bag. Recycled mineral microfibers and ultrafine cementing particles (particle sizes lower than 200 microns) are obtained from this process in order to hopefully incorporate these silica-rich particles effectively into new concrete formulations and aerogel composites for the subsequent manufacture of panels.

VEEP aerogel production

While the BAU scenario involves the use of the conventional insulating material EPS, the VEEP project includes the development of a green cost-effective aerogel using secondary raw materials from CDW. The production of this aerogel relies on the integration of the following steps: (a) low-cost water-glass-based precursor production by using silica-containing CDW recycled materials such as 2–4 mm RCA, RGUA, or RFUA; (b) gasification; (c) higher efficient multisolvent low-temperature supercritical drying. Aerogels can be manufactured in different forms: monolithic, powder, blankets, granules, and so forth. In the VEEP project, the chosen strategy for preparing aerogel composites is the employment of fibers during the sol-gel step. The fibers will contribute the mechanical performance to the silica-based aerogel materials, allowing the use of the aerogel in the novel PCE. However, since the VEEP green aerogel is still under development, the present assessment uses lab-scale data. Additionally, due to concerns about business confidentiality, the details of the data will not be disclosed in this study.

VEEP PCE production

The VEEP green recipe concrete contains secondary material, including RCA and RCUA from ADR and HAS, RGUA and RFUA from DGR. VEEP PCE will be manufactured using the VEEP concrete and the aerogel EPS, as well as rebar cages and welded nets.

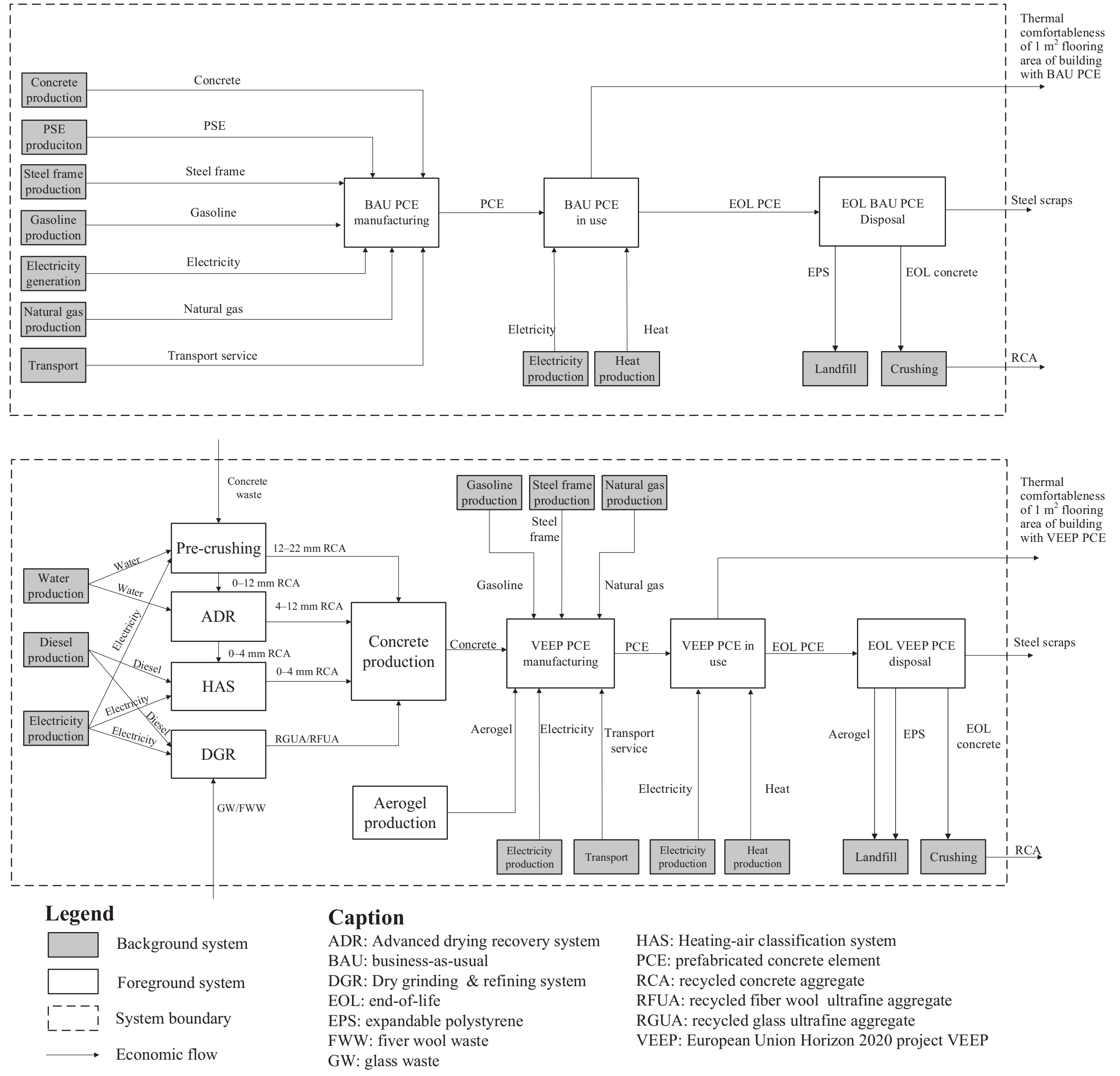


FIGURE 2 System boundaries for the BAU scenario (above) and the VEEP scenario (below)
Note: BAU represents business-as-usual PCE technological scenario; VEEP represents VEEP technological PCE scenario.

3.1.4 | Functional unit

Principally, the same functional unit at the system level will be defined for the LCA and LCC. The functional unit selected for this study was maintaining the thermal comfortableness of 1 m^2 flooring area of a building with the application of a PCE façade and active heating and cooling for 40 years based on reference scenarios. In both scenarios, it is assumed that the required building façade per 1 m^2 of flooring area amounts to 0.55 m^2 of PCE.

3.2 | Inventory analysis

The LCA software OpenLCA 1.9 was selected to perform the LCA analysis as an assessment instrument with a database of Ecoinvent 3.4 (Allocation, cut-off by classification). For the LCC study, Microsoft office 2016 Excel was used to investigate the main contributions of costs. System boundaries of the two scenarios are shown in Figure 2. Details of the two scenarios are described as follows:

3.2.1 | Environmental inventory

The environmental inventory has been carried out for the BAU and VEEP scenarios and organized into four phases: *Material preparation, PCE manufacturing, PCE in-use and Disposal of PCE* as defined in goal and scope definition (Figure 1). We will discuss these topics below.

Material preparation

In the Material preparation phase, the raw material for the PCE manufacturing will be prepared, including concrete materials (aggregate, cement, additive, and so forth), thermal insulation material, rebar Cages, and welded nets. In the BAU scenario, only primary raw material was used, while the VEEP PCE used both primary and secondary raw material. As the transport of raw material does matter in urban mining studies (Zhang et al., 2018), the transport costs of virgin material and recycled material are considered. The details of the inventory analysis of material preparation for both scenarios are presented in Appendix 1 in Supporting Information S1.

PCE manufacturing

In the PCE manufacturing phase, a family of ribbed panels is selected for both scenarios in order to reduce the consumption of concrete, reduce the weight of the panel, and improve the thermal performance of the panel. VEEP PCE is a sandwich panel with higher insulation properties due to the material green aerogel and higher contents of secondary raw material from CDW. The BAU PCE taken as the reference is also in the form of a sandwich panel with the same stratigraphy but manufactured from traditional concrete (benchmark siliceous concrete produced without the use of secondary raw material) and expandable polystyrene (EPS) as the insulation layer. The sandwich panels will be manufactured with those materials in the material preparation phase in the plant and will then be transported to the construction site. The components and structure of both PCEs and the inventory data for manufacturing the PCEs are presented in Appendix 2 in Supporting Information S1.

PCE in use

In the PCE in-use phase, dynamic thermal simulation (DTS) was performed to compare the thermal performances of the two concrete façade elements. The selected case study building was a typical residential building in the capital of the Netherlands, Amsterdam (52.30N, 4.76E, a climate zone with cool summers and mild winters). The life span of the prefabricated building is assumed to be 40 years. For the climate zone of Amsterdam, the cooling need is rather low. However, to reflect the entire thermal performance of the application of the two PCEs, this study did take the cooling need into account along with the heating need. DTS at building scale were carried out on a virtual residential multistory building. The details of how DTS was conducted are presented in Appendix 3 in Supporting Information S1.

Disposal of PCE

When the target building enters its EOL stage, the building will be demolished, and the PCEs will be deconstructed from the building in structurally intact condition and will be further dismantled manually in situ. A novel anchoring and connection system was applied to the VEEP PCE. Dismountable internal epoxy connectors were set between concrete layers, which enable the PCE itself as well as the constituents inside the PCE to be disassembled more easily. Due to a lack of data, the impact of dismantling the PCE from the building and of disassembling the PCE is currently not considered. Steel, concrete and insulation materials were separated from each other. The inventory data for PCE disposal is shown in Appendix 4 in Supporting Information S1.

3.2.2 | Economic inventory

To align to the environmental analysis, the economic inventory has been carried out for the BAU and VEEP scenarios and organized into the same four phases as defined in goal and scope definition (Figure 1). While, different from the environmental assessment, the economic assessment considers the stakeholders' perspective. It distinguishes the costs with clear cost bears, being producers' costs or consumers' costs, from those without clear cost bears, being society's costs. The former is termed as internal costs, which can be inventoried by monitoring real transactions. However, internal private costs include transfer payments to governments, such as payment for emission allowances in the European Union Emissions Trading System (EU ETS). The transfer payments are currently not discussed in this study. Moreover, the latter are termed as external costs, following the scope defined in environmental LCC (Hunkeler et al., 2008) only the "external costs expected to be internalized," which in this study only the carbon emission costs are inventoried.

Internal costs

The economic inventory of the internal costs relies on the physical flows associated with the product system, which are the same as defined in the environmental inventory. Cost structure was broken down in this section based on the four defined phases. The geographic scope of the study is the Netherlands, where the field data of the case study were collected. Relevant cost data were collected and expressed in € (euro). The analysis takes as reference Netherlands as the geographical reference area for the price background, and all cost categories are expressed in €. The details of cost data and its sources are presented in Appendix 5 in Supporting Information S1.

External costs

The external costs was inventoried for the carbon emissions of the BAU and VEEP systems. In 2003, a scheme of greenhouse gas emission allowances was established under the EU ETS. Larger European firms must deliver carbon allowances equal to their emissions, and it can buy or sell carbon allowances that it needs or does not need. The carbon emission costs rose to its highest level in more than a decade in Europe, surpassing 20€ a metric ton, and it has been predicted that prices will rise to 35 or 40€ a metric ton on average from 2019 to 2023, with market rates possibly reaching 50€ in the winters of 2021 and 2022 (Morison & Hodges, 2018). The EU ETS does not affect all companies it covers in the same way because of the differences in their reliance on energy and in their production methods (Duggan, 2015). Along with this trend, the external costs related to GHG emission might be directly internalized to relevant actors in the future. In this study, the CO_2 costs was seen the “external costs expected to be internalized ” which was defined in the environmental LCC (Hunkeler et al., 2008). The details of the monetization information are presented in Appendix 5 in Supporting Information S1.

3.3 | Impact assessment

3.3.1 | Environmental impact assessment

Climate change poses a fundamental threat to habitats, species, and people’s livelihoods (Liu et al., 2017). Recent studies have identified a near-linear relationship between global mean temperature change and cumulative GHG emissions (Friedlingstein et al., 2014). For LCA, this study explores the potential of the VEEP PCE for greenhouse gas emission mitigation. Global warming (kg CO_2 eq) from CML-IA version 4.4 issues in January 2015 was selected as the sole impact indicator, thus normalization and weighting scheme were not necessary.

3.3.2 | Economic impact assessment

According to the environmental LCC guidebook, there is no need to make an impact assessment for LCC. The life cycle costs of a product are expressed in monetary units which are already comparable, thus there is no threshold and a lower cost is always better (Swarr et al., 2011). However, for a better interpretation of the economic results, (Zhang et al., 2019a) proposed to add an economic impact assessment step in the LCC analysis, which intends to answer three questions: (a) how will the life cycle cost be categorized? (b) how will the moment of incurring costs and benefits in time be considered? (c) how will the final costs value be expressed? In this study, the economic impact assessment has been implemented according to (Zhang et al., 2019a). While answering these questions, this study intended to explore the potential of sensibly using “external costs” to harmonize LCA and LCC on stakeholders’ perspective, and the factor of time by investigating the effects of “discounting.”

First, the costs are categorized according to the life cycle stages of the PCE, thus, the life cycle costs are estimated as in Formula (1):

$$\mathrm{LCCs} = C_{\mathrm{I}} + C_{\mathrm{II}} + C_{\mathrm{III}} + C_{\mathrm{IV}} + E \tag{1}$$

where LCCs is life cycle costs; C_{I} is internal costs incurred in the material preparation phase; C_{II} is internal costs incurred in PCE the manufacturing phase; C_{III} is internal costs from PCE in the in-use phase; C_{IV} is internal costs from PCE in the EOL phase. E is the external costs related to GHG emission. The external costs of carbon emission was added to the LCCs to demonstrate to what extent it would affect the economic viability.

Second, the discounting effect is investigated. A controversial issue is the discount rate applied to actualize external costs (Arrow et al., 2014; Portney & Weyant, 2013; Weitzman, 2011). Whether a study should use a discount rate and if so, which rate, is highly dependent on the study’s defined goal and scope. However, according to the LCC guide book *Environmental Life Cycle Cost* published by SETAC (Hunkeler et al., 2003), environmental LCC usually is a steady-state method, as is the complementary LCA, and discounting the final result of environmental LCC specification is not consistent nor easily carried out and is therefore not recommended. However, in this study, the life span of the prefabricated building is assumed to be 40 years, and therefore the discount rate has to be considered even though it may not be consistent. In this study, the discount rate is only used for heating and cooling costs, while the costs in the material preparation phase and the PCE manufacturing phase will not be discounted, nor will the GHG emission costs. Islam, Jollands, and Setunge (2015) reviewed building-related LCC studies with consideration of the time value of money and found that discount rates ranged from 2% to 8% worldwide, and from 2.5% to 4% in Europe. Moore and Morrissey (2014) found that the discount rate was usually significantly lower in developed countries. Thus, a range of (2%, 4%) is selected for this Dutch case study and the median value 3% is set as the discount rate for calculation. The financial result will be expressed as a net present value (NPV) in Euro. The costs incurred in the material preparation and PCE manufacturing stage was regarded as NPV directly, whereas the costs incurred in the in-use stage of the PCE was regarded as annual costs (A) which were transferred into NPV according to Formula (2).

$$\mathrm{NPV} = A\left[\frac{1}{i}\quad\frac{1}{i(1+i)^{n}}\right] \tag{2}$$

Where A is annual energy cost; i is discount rate; n is building Life span, 40 years. For LCA, discounting of environmental impacts is seldom performed.

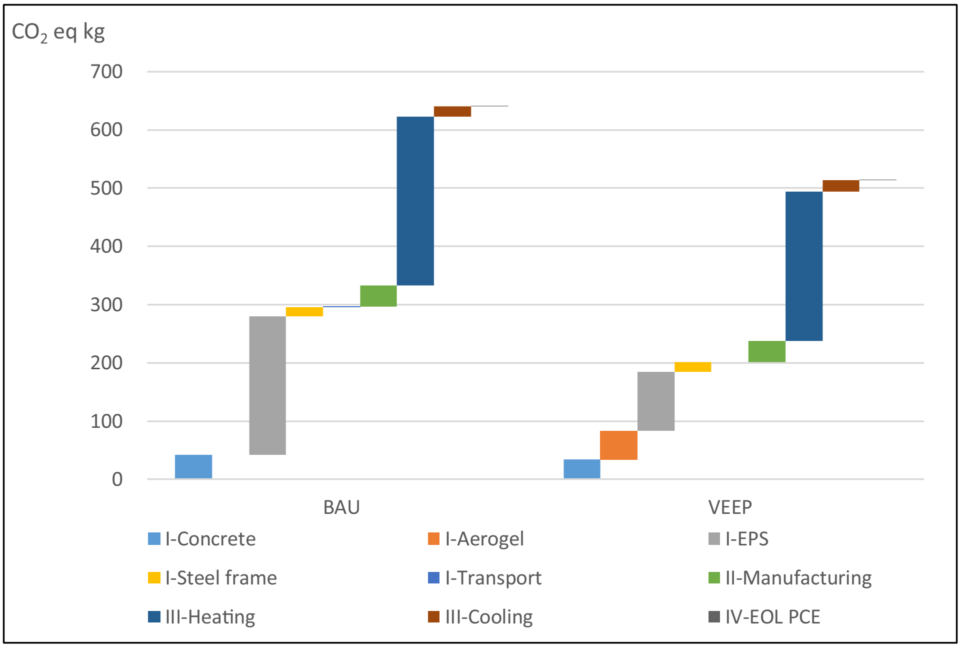


FIGURE 3 Life cycle GHG emission of BAU PCE (left) and VEEP PCE (right)
Note: EPS represents expandable polystyrene; BAU represents business-as-usual PCE technological scenario; VEEP represents VEEP technological PCE scenario; EOL represents end-of-life. Underlying data used to create this figure can be found in Supporting Information S1.

4 | RESULTS INTERPRETATION AND DISCUSSION

The primary results of the LCA and LCC analysis are presented separately along with the contribution analysis, followed by a sensitivity analysis and an uncertainty analysis.

4.1 | Contribution and comparison analysis

4.1.1 | Life cycle environmental impact

The Life cycle environmental impacts of the 40-year life cycle of the VEEP PCE and BAU PCE are summarized in Figure 3. The GHG emissions of both scenarios have the same distribution trends. For the BAU scenario, the life cycle GHG emission is mainly due to gas for heating in the in-use phase and to EPS production in the material preparation stag, amounting to 45% and 37%, respectively. For the VEEP scenario, the largest portion of GHG is from heating, which accounts for 50% of the total GHG emission. The second largest portion (20% for EPS and 10% for green aerogel, respectively) is due to the production of insulation material in the material preparation phase.

To compare,

- In the VEEP scenario, life cycle GHG emission is 19% lower than in the BAU scenario, 13% of which results from the production of aerogel to substitute EPS and 5% of which is due to savings on energy for heating.
- Due to the climate zone of Amsterdam, the cooling need is negligible.
- The VEEP scenario and the BAU scenario have similar distributions of life cycle GHG emissions. The transport costs of raw materials are negligible in both scenarios (less than 1%). In both scenarios, the GHG emissions resulting from the production of insulation material and energy for heating account for more than 80% of the life cycle GHG emission.

4.1.2 | Life cycle costs

The LCC results on the 40-year life cycle of the VEEP PCE and the BAU PCE are summarized in Figure 4, which presents the internal costs in four life cycle stages and the external CO$_2$ costs. In terms of external costs, the carbon costs of the VEEP scenario was 21% lower than the carbon costs of the BAU scenario (discounting is not performed). The discussion below does not consider the CO$_2$ costs.

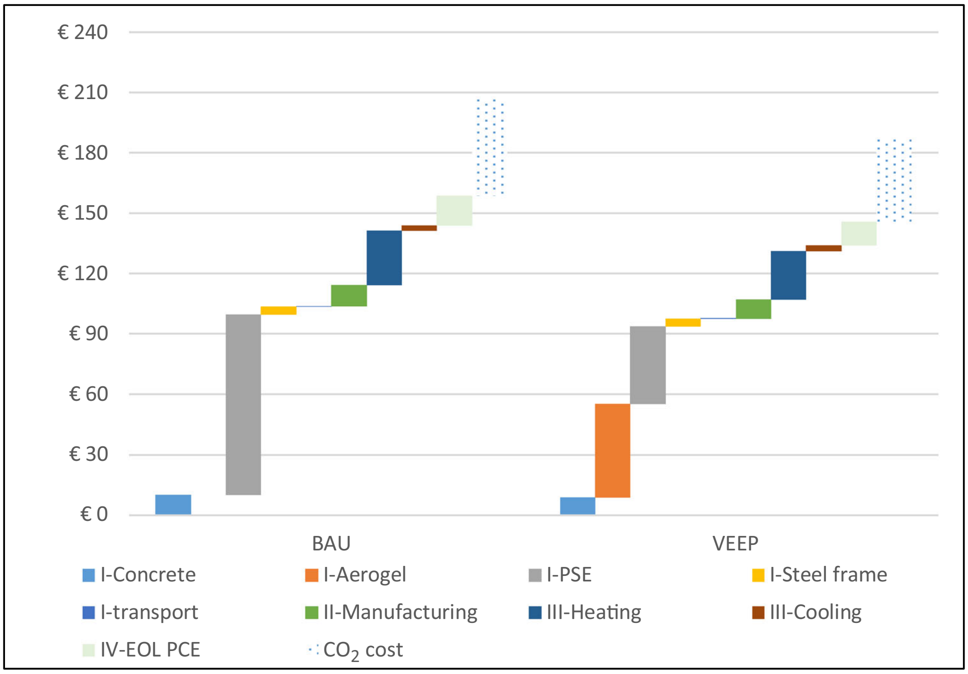


FIGURE 4 Life cycle costs of BAU PCE and VEEP PCE
Note: EPS represents Expandable polystyrene; BAU represents business-as-usual PCE technological scenario; VEEP represents VEEP technological PCE scenario; EOL represents End-of-life. Underlying data used to create this figure can be found in Supporting Information S1.

The LCCs of the BAU PCE are around 160 €/0.55m^2. The costs of the material preparation phase (65%) and the in-use phase (19%) together account for more than 80% of the LCCs. The largest cost component for the BAU scenario is EPS, which makes up 86% of the material preparation cost and 56 % of the LCCs. In the PCE in-use phase, more than 90% of the energy costs is due to energy required for heating.

For the VEEP scenario, the LCCs of VEEP PCE is about 146 €/0.55m^2. The costs of the material preparation phase account for 67 % of the LCCs, and 18 % of the LCCs result from the in-use phase. The largest cost component is the insulating material: aerogel and EPS contribute 32% and 26% to the LCCs, respectively. In the PCE in-use phase, 89% of the energy costs is due to energy required for heating.

To compare (CO_2 costs excluded):

- VEEP PCE does not have an obvious economic advantage over the BAU scenario: the LCCs of VEEP PCE are 8% lower than those of BAU PCE;
- The VEEP PCE and BAU PCE have a similar distribution of life cycle costs. Transport costs of raw materials are negligible in both scenarios (less than 1%).
- In both scenarios, the biggest cost component is the insulating material, accounting for more than 50% of the LCCs;
- For the building chosen for the case study and the climate of Amsterdam, the cooling costs are negligible.

4.2 | Sensitivity analysis

To better understand how the CO_2 costs would affect the LCC results in reality, we assumed scenarios in which CO_2 costs is directly borne by relevant actors and is seen as an internal costs in the LCCs. In this case, the discount rate is applied to the CO_2 costs which was allocated to each phase accordingly. We established two new scenarios, BAU-ex and VEEP-ex, which do consider the CO_2 costs. Cumulative cost curves of the four scenarios are projected in Figure 5. If CO_2 costs are considered, the cost reduction performance of VEEP-ex (compared to BAU-ex) is slightly better than VEEP (compared to BAU).

The robustness of these scenarios was first verified by means of a sensitivity analysis. As explained in the contribution analysis, energy for heating and the production of insulation materials (including EPS and aerogel) contributed more than 70% to the LCCs and life cycle carbon emission of both PCEs. Therefore, the variables listed in Table 1 that were related to heating and insulation materials were considered in the sensitivity analysis.

The sensitivity analysis was conducted to identify the sensitivity of the 8 factors by decreasing 10% of each factor. The results of the sensitivity analyses of four the scenarios are depicted in a radar plot in Figure 6. The BAU and BAU-ex scenarios are the most sensitive to EPS price (−5.62%

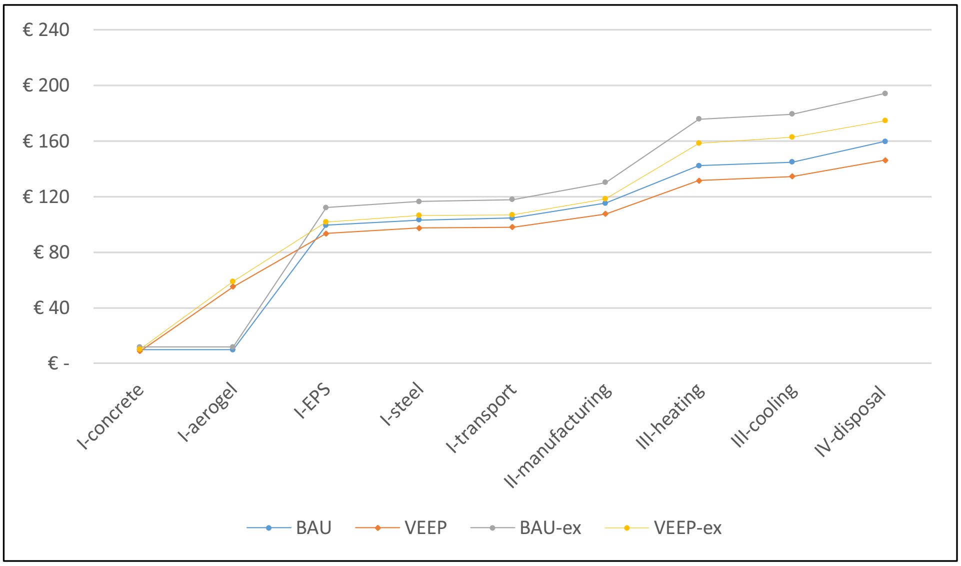


FIGURE 5 Cumulative life cycle costs of four scenarios: BAU, VEEP, BAU-ex, VEEP-ex

Note: EPS represents expandable polystyrene; BAU represents business-as-usual PCE technological scenario; VEEP represents VEEP technological PCE scenario; BAU-ex represents BAU PCE scenario taking into account the external costs; VEEP-ex represents VEEP PCE scenario taking into account the external costs; EOL represents end-of-life. Underlying data used to create this figure can be found in Supporting Information S1.

TABLE 1 Factors for robustness analysis

Code	Factors	Value	Range of uncertainty
f_1	Discount rate	3.00%	(2%, 4%)[a]
f_2	Natural gas price [€/kWh]	0.04	0.04 ± 5%[b]
f_3	Aerogel cost [€/0.01 m^3]	12.06	± 15%[c]
f_4	EPS price [€/metric ton]	1,290.00	1,290.00 ± 5%[b]
f_5	CO_2 monetary indicator for construction phase [€/kg CO_2 eq]	0.045	(0.023, 0.09)[d]
f_6	CO_2 monetary indicator for in-use phase [€/kg CO_2 eq]	0.11	(0.055, 0.22)[d]
f_7	CO_2 monetary indicator for EOL phase [€/kg CO_2 eq]	0.14	(0.070, 0.280)[d]
f_8	BAU/VEEP heating need [kWh m^{-2}·per year]	29.25/24.65	29.25± 5%/24.65± 5%[b]

Abbreviations: EPS, expandable polystyrene; BAU, business-as-usual PCE technological scenario; VEEP, VEEP technological PCE scenario; EOL, end-of-life.

[a] As mentioned in Section 3.3.2.

[b] For those LCI data that do not have a source of uncertainty range, a single standard error range of ±5% for the LCI data was selected in this study, which is seen as an accepted assumption regarding the uncertainty of LCI data (Huijbregts et al., 2003).

[c] Data from the VEEP project internal report D3.3 released on May 2019 "Pilot Manufacturing Line (plus report describing integration of systems, optimization of operating conditions, and validation of the Pilot Line)."

[d] From literature (De Nocker & Debacker, 2017).

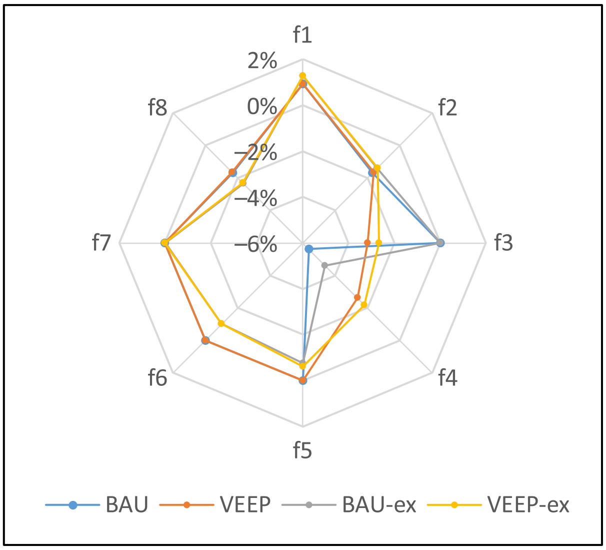
and −4.62%, respectively). VEEP and VEEP-ex are slightly less sensitive to EPS price (−2.62%) but most subject to aerogel price (−3.17% and −2.66%, respectively). Both the BAU and the VEEP scenario are relatively less sensitive to gas price, heating need, and especially to discount rate. As for the BAU-ex and the VEEP-ex scenario, the graph shows that they basically present the same trend to sensitivity as BAU and VEEP, respectively. Due to an additional portion of costs added to the LCCs in the BAU-ex and VEEP-ex scenario, shifts in the per unit price of natural gas, aerogel, EPS, and so forth, have relatively smaller effects on these LCCs than on the LCCs of the BAU and VEEP scenarios. By contrast, sensitivity to the discount rate and heating need increases in the BAU-ex and VEEP-ex scenario.

4.3 | Uncertainty analysis

The factors which were evaluated in the sensitivity analysis were also selected for the uncertainty analysis. The value ranges of those factors are determined by a variety of sources, as shown in Table 1. Value of those factors was assumed a uniform distribution varying from minimum to

FIGURE 6 Sensitivity analysis of relevant factors in the BAU and VEEP scenarios (each factor decreased by 10%)

Note: BAU represents business-as-usual PCE technological scenario; VEEP represents VEEP technological PCE scenario; BAU-ex represents BAU PCE scenario taking into account the external costs; VEEP-ex represents VEEP PCE scenario taking into account the external costs. Underlying data used to create this figure can be found in Supporting Information S1.



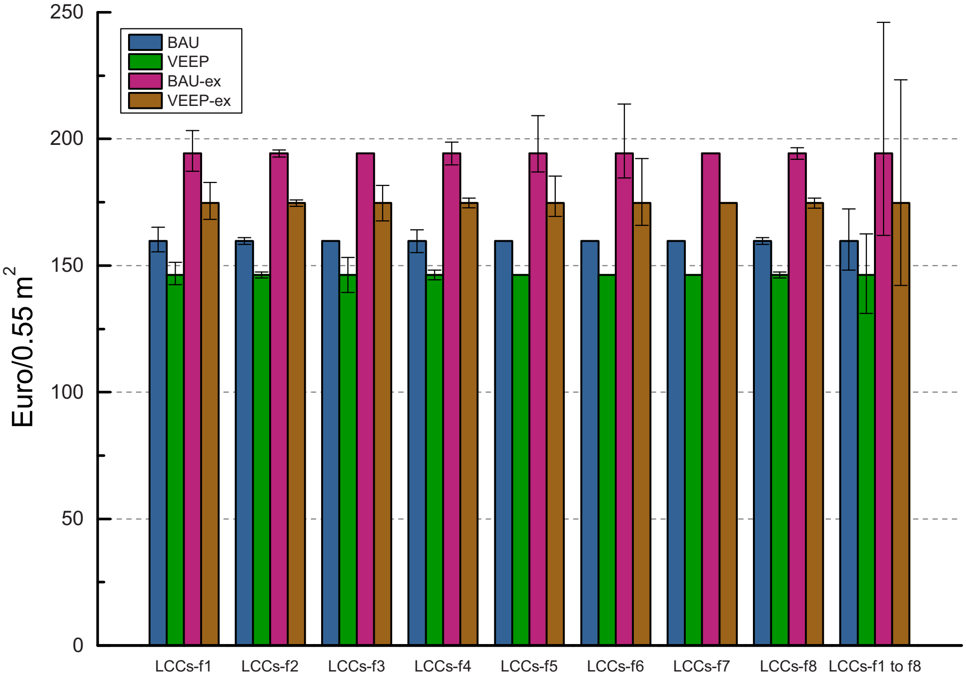


FIGURE 7 Uncertainty analysis of the LCCs: Cohort LCCs-f1 to LCCs-f8 present the extent to which the fluctuation of the factors affects the uncertainty of the LCCs respectively; cohort LCCs-f1 to f8 show the summarized uncertainty of LCCs when considering all factors

Note: BAU represents business-as-usual PCE technological scenario; VEEP represents VEEP technological PCE scenario; BAU-ex represents BAU PCE scenario taking into account the external costs; VEEP-ex represents VEEP PCE scenario taking into account the external costs; LCCs represents life cycle costs. Underlying data used to create this figure can be found in Supporting Information S2.

maximum value. To what extent the fluctuation of the factors in separation and in combination affecting the LCCs is shown in Figure 7. Generally, scenarios included externality, BAU-ex and VEEP-ex, have a wider range of uncertainty which mainly results from the monetary indicators. For the BAU and VEEP scenario, the largest uncertainty stems from the price fluctuation of the insulation material. Additionally, the selection of the discount rate would create large uncertainty to the internal costs and even larger to the external costs. The higher discount rate is, to more degree the VEEP system's economic advantage will be diminished. Since the EOL costs of four scenarios is negligible, the uncertainty of monetary indicator for the EOL phase barely affects the LCCs.

4.4 | Discussion of results

Previous studies (Dissanayake, Jayasinghe, & Jayasinghe, 2017; Dong et al., 2005; Islam et al., 2014; Ottelé, Perini, Fraaij, Haas, & Raiteri, 2011; Wan Omar, Doh, Panuwatwanich, & Miller, 2014) assessed the economic and environmental performance of wall assemblage in buildings. However, it is impossible to validate the outcomes of this particular case study by comparing to other studies, because LCA and LCC studies of residential building façades vary considerably in terms of functional units, assumptions, database, wholesale price index, and system boundaries. Additionally, they vary in building typology and life span, local climate, and inclusion or exclusion of maintenance. Results from the analysis of contribution, sensitivity, and uncertainty are further discussed in this section.

At a certain degree of uncertainty, the VEEP PCE system only shows a slightly higher performance in an economic and environmental comparison with BAU PCE. A few points that were not considered in the robustness analysis need to be mentioned. First, in the VEEP system the production costs and environmental impacts of the secondary raw materials recovered from CDW was estimated using a mass-based allocation method. The prices used in the case study reflect only the Dutch market situation under current environmental regulations and resource conservation policies. Applying VEEP technologies in other regions with different market and policy situations may increase or decrease the potential economic advantages of VEEP scenarios. Second, since green aerogel is under development, it is not financially viable yet, nor did it obviously improve the thermal performance of VEEP PCE at a pilot scale. However, Aerogel is key to the further optimization of the VEEP PCE system. This study assumed a conservative thermal conductivity value of 0.0157 W m^{-1} K^{-1}, while the target thermal conductivity of VEEP aerogel is equal to 0.012 W m^{-1} K^{-1}. If this requirement is satisfied, the U value of VEEP PCE will be below 0.17 W m^{-2} K^{-1}). Besides, in the EOL PCE disposal phase, this study assumed that aerogel was landfilled, whereas in future, the aerogel blankets can be fully recycled as feed for the VEEP process together with the CDW. Moreover, this study did not yet take into account the development of a novel anchoring system that will enable more convenient destruction and dismantling of VEEP PCE. Third, including external CO_2 costs in LCC increases financial advantages of low-carbon options, indicating a government could use policy tools to propagate the use of low-carbon products by raising environmental taxes or emission fees. Finally, while previous research found that the LCC approach is sensitive to changes in discount rate (Islam et al., 2015), this study found that LCC is in fact sensitive to the wide range of possible discount rates, which can be doubled from one country to another. A high discount rate can take the edge off economic advantages of the VEEP system, flipping the evaluating results from country to country.

5 | CONCLUSION

This paper presents an integrated environmental LCC and LCA study exploring to which extent the life cycle costs and environmental impact of building envelopes can be reduced by applying a VEEP PCE system containing secondary material instead of a BAU PCE. LCA was used to estimate the GHG emission during the main life cycle phases of both PCEs, while LCC were calculated to examine the systems' financial costs in parallel with LCA. To explore how externality will affect the PCEs' economic feasibility, the GHG emission was internalized via monetary indicators, leading to two additional scenarios, BAU-ex and VEEP-ex.

The final results show that the life cycle GHG emission of the VEEP scenario is 19% lower than that of the BAU scenario, and the majority of the carbon mitigation results from the production of green aerogel as a substitute for the conventional insulation material EPS. However, from the economic perspective, the LCCs of the VEEP PCE are only 8% lower than those of the BAU scenario. If externality is considered, the difference in LCCs is slightly larger, amounting to 10% in favor of VEEP PCE, but this also leads to greater uncertainty. In the VEEP scenario, about 32% of the LCCs result from aerogel production, but aerogel does not present an obvious advantage in energy saving for VEEP PCE in the in-use phase.

Sensitivity analysis and uncertainty analysis were carried out to understand the robustness of the results obtained. In the BAU scenario, the conventional insulation EPS was shown to be relatively costly, and the economic viability of BAU PCE is considerably subject to its market price. For VEEP PCE, the green aerogel was shown to be one of the main cost stressors. As it is under development, currently it does not show a noticeable economical advantage over EPS, nor does it show a better thermal performance than EPS. From the environmental perspective, however, green aerogel is preferable to EPS, since production per unit of aerogel can mitigate the emission of GHG by more than half compared to production per unit of EPS by weight.

It is necessary to note some limitations of the present study. First, due to a lack of data, this study omitted the impact of the PCE installation phase, the impact of dismantling the PCEs and the recyclability of the two insulation materials in the disposal phase. However, if we had been able to include these aspects, the results would have been even more favorable for VEEP, because theoretically, the detachable design of the VEEP PCE system will lead to less time for installation and dismantling, thus lower installation and dismantling costs than traditional PCE.

Second, to reduce the uncertainty from monetization to some point, GHG emission was selected as the sole environmental impact indicator. However, other impact categories, such as resource depletion can be also significant in CDW management.

Third, the DTS was conducted using different insulating materials in the PCEs on the condition that both PCEs maintain the same thickness. However, other potential scenarios could be established to compare the BAU and VEEP scenarios from multiple angles, such as choosing two PCEs that use the same insulation or PCEs with the same U value.

Fourth, due to the limitations of the OpenLCA software, partial sensitivity and uncertainty analysis were performed.

Last but not least, the controversial issues monetization and discounting in an integrated LCC-LCA study have not been completely solved. On the one hand, the discount rate was inconsistently applied to LCC and LCA, and to each cost component of LCC. On the other hand, in BAU-ex and VEEP-ex scenarios, external cost was internalized thus a market related discount rates were applied. However, issue on discount rate for social cost including real externalities is much more complex, which is not discussed in the study.

Nevertheless, this combined LCA and LCC study on the PCE case explored the potential to resolve the inconsistence between the two analytical methods, on stakeholders' perspective and the factor of time, by including external costs and discounting. The study shows that to support sensible decision making, a systematic method to standardize the treatment on to be internalized external costs specify the discounting scheme should be developed for the combined use of LCA and LCC. These factors will be examined in our future studies.

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CONFLICT OF INTEREST

The authors have no conflict to declare.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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