Industrial Ecology Master Thesis

Leiden University & TU Delft

Comparative LCA and Cost Assessment of Cross Laminated Timber, Traditional Concrete, and Geopolymer Concrete in Dutch Housing

By

Lukas klein Goldewijk

02-07-2025

Supervised by:

Robert Istrate | Leiden University – 1st supervisor

Stijn Brancart | TU Delft – 2nd supervisor

Jasper Drost | Sweco

Preface

Writing this preface marks the completion of my Industrial Ecology master's thesis, and with it, the end of my time as a student draws near. After seven years of studying, I am excited to finally put my knowledge into practice and contribute to sustainable change.

Throughout my broad and interdisciplinary sustainability studies, I especially enjoyed this thesis project, which allowed me to delve deeper into the field of environmental impact assessment within the construction sector. I am grateful to have learned more about this crucial industry, where environmental challenges also create opportunities to drive the transition towards a circular and biobased built environment. After six months of research, I look forward to continuing my journey in this sector.

I would like to greatly thank my academic supervisors, Robert Istrate (Leiden University) and Stijn Brancart (TU Delft), for their invaluable guidance and inspiration throughout this project. I would equally like to thank Jasper Drost, my supervisor at Sweco, for his support, advice, and good humour along the way. Conducting my research at Sweco made this experience even more rewarding, and I am thankful to have been surrounded by a team of like-minded circular economy enthusiasts.

Lukas klein Goldewijk, Leiden, July 2025

Abstract

The Netherlands faces the dual challenge of addressing a severe housing shortage while reducing the environmental burden of construction. It is therefore vital to identify building materials with the lowest life cycle impacts while remaining economically viable. Although timber products like cross laminated timber (CLT) have been compared as alternatives to traditional concrete, few studies have jointly assessed their environmental and economic performance or compared them directly with geopolymer concrete (GPC). This study presents a cradle-to-grave Life Cycle Assessment (LCA) and cost analysis for two common Dutch housing types: row houses and mid-rise apartment buildings. Each typology was evaluated with three structural materials: ordinary Portland cement concrete (OPC), GPC, and CLT.

The CLT designs showed the best environmental performance in 12 (row house) and 13 (apartment) out of 16 impact categories, including climate change and all eutrophication- and toxicity- related categories. However, CLT material costs were 7% higher for row houses and 90% higher for apartments compared to OPC. GPC performed worse than OPC in most categories due to the impacts of conventional alkali activators, but using silica fume instead of sodium silicate could reduce GPC impacts, excluding use phase, by up to 38%. Design optimization and end-of-life reuse of CLT and concrete also substantially lowered impacts across all cases. Moreover, sand-limestone was identified as driver of environmental impacts and economic costs in all concrete building designs.

Further research is needed into alternative activators for GPC and the environmental impacts of sand-lime stone, a widely used Dutch building material. Policies such as life cycle impact standards for new housing, environmental taxes on building materials, and stricter operational energy regulations are crucial to support a transition to low-impact housing construction in the Netherlands.

Table of Contents

List of Abbreviations

Abbreviation	Full Name
AAB	Alkali-Activator Binder
BENG	Bijna Energie Neutrale Gebouwen (Nearly Energy Neutral Buildings)
CBS	Centraal Bureau voor Statistiek (Central Bureau of Statistics)
CaO	Calcium Oxide
CLT	Cross Laminated Timber
EF	Environmental Footprint
EoL	End-of-Life
FA	Fly Ash
FU	Functional Unit
GFA	Gross Floor Area
GGBFS	Ground Granulated Blast Furnace Slag
GPC	Geopolymer Concrete
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
MPG	Milieuprestatie Gebouwen (Environmental Performance of Buildings)
NaOH	Sodium Hydroxide
OPC	Ordinary Portland Cement concrete
RC	Reinforced concrete
SC REN EN	Scenario Renewable Energy
RVO	Rijksdienst voor Ondernemend Nederland (Netherlands Enterprise Agency)
SC EoL	Scenario End-of-Life
SC OPT	Scenario Optimization
SC SUS GPC	Scenario Sustainable Geopolymer Concrete
SM	Supplementary Material

1. Introduction

The Netherlands faces a severe housing deficit, which has prompted the ambitious national target of creating 100,000 new dwellings annually till 2030 (Rijksoverheid, n.d.). At the same time, the Dutch construction sector accounts for 50% of the country's material use (Bruinsma et al., 2021), and drives environmental impacts, accounting for 35% of the country's CO2eq emissions (Circle Economy, 2025). To meet the new housing objectives while reducing construction's environmental burden, identifying and implementing sustainable solutions to construct and operate buildings is crucial. In the Netherlands, the electricity grid rapidly decarbonizes and new houses are built with increasingly efficient energy systems (RVO, 2022), causing environmental impacts of building usage to drop (Abed et al., 2022). Construction materials however remain a large driver of the sector's environmental impacts and are therefore focused on in this study (Hart et al., 2021).

Construction's high material demand primarily comes from its extensive use of traditional concrete, or ordinary Portland cement concrete (OPC), the dominant material in most load-bearing structures (D'Amico et al., 2021). However, OPC production is highly energy-intensive and contributes about 8% of global CO_2 emissions (Monteiro et al., 2017). Moreover, combustion of fossil fuels to meet the high temperature requirements of the cement production process emits particulate matter and other pollutants linked to respiratory diseases and cancer, while also causing resource depletion and acidification (Habert et al., 2020). This study therefore investigates the potential of substituting OPC with alternative materials—cross laminated timber (CLT) and geopolymer concrete (GPC)—for housing construction in the Netherlands.

CLT is an engineered wood product gaining attention as a renewable material capable of replacing reinforced concrete in structural applications (Abed et al., 2022; D'Amico et al., 2021; Tokede et al., 2022). CLT exhibits excellent mechanical properties, durability, and suitability for both low- and high-rise buildings (D'Amico et al., 2021). GPC is an alternative to OPC in which traditional cement—the primary contributor to OPC's environmental impacts—is replaced by industrial byproducts, such as ground granulated blast furnace slag (GGBFS) or fly ash (FA) (Monteiro et al., 2017).

Life Cycle Assessment (LCA) is a well-established method for assessing and comparing the environmental impacts of buildings constructed with alternative materials. It accounts for impacts across the full life cycle of a product, thereby avoiding burden shifting to overlooked life cycle stages (Guinee, 2002). In addition to environmental performance, economic feasibility is a key factor influencing the scalability of alternative construction materials such as CLT and GPC. Although these materials have the potential to reduce the environmental burden of housing construction, their large-scale adoption depends on their cost competitiveness with conventional materials such as OPC. To assess this economic dimension, a cost assessment is conducted alongside the LCA.

By jointly evaluating the environmental and economic performance of OPC, GPC, and CLT, this study aims to generate actionable insights to support a transition toward more sustainable construction practices in the Dutch housing sector. The remainder of this thesis is structured as follows: Chapter 2 reviews the selected building materials and existing literature on building LCAs. Chapter 3 presents the case study building and explains the research methodology. Chapter 4 discusses the results of the LCA and the cost assessment, which are further interpreted in Chapter 5. Finally, Chapter 6 concludes with a summary of key findings and recommendations.

2. Context

This section explains fundamental concepts relevant to this study, reviews existing literature on CLT and concrete alternatives, and identifies research gaps based on reviewed literature.

2.2. Traditional concrete (OPC)

Concrete has been used as construction material since the Romans and it is the most consumed material on Earth after water (Monteiro et al., 2017). According to Monteiro et al. (2017), annual global concrete consumption is estimated at 30 billion tonnes. Its high strength, durability and diverse moulding possibilities, along with its relatively cheap production costs, have made it the dominant constituent of load-bearing structures (Assi et al., 2018). The predominantly used concrete is OPC, which consists of aggregates, gravel, water and cement (Munir et al., 2023). Cement is a calcium-oxide (CaO) containing powder that, when brought into contact with water, produces hydration products that glue the concrete components together as a hardened material (Monteiro et al., 2017). Cement is the main driver of OPC's high environmental burden, accounting for approximately 7-9% of global CO2 emissions, due to its high energy intensity and carbon release during its chemical formation (Abed et al., 2022; Monteiro et al., 2017).

2.1. Geopolymer concrete (GPC)

GPC is an alternative to OPC that uses waste products from industry as binding agents instead of Portland cement (Assi et al., 2018). Geopolymer cement can be manufactured from aluminate silicate containing materials, such as FA and GGBFS, which are byproducts from the coal and steel industry respectively (Monteiro et al., 2017). These amino silicates are the precursor materials which—upon contact with an activation fluid—polymerize and become the binding agent that replace ordinary cement. The activation fluid consists of alkali activators such as sodium hydroxide (NaOH) and sodium silicate (Collivignarelli et al., 2020). Existing studies highlight that GPC exhibits higher mechanical and durability performance compared to OPC, while its production is associated with 20-50% lower carbon emissions (Collivignarelli et al., 2020). Additionally, it presents a solution to valorise high volumes of waste from the coal and steel industries (Almutairi et al., 2021).

2.2. Cross laminated timber (CLT)

CLT is an engineered wood product that was first developed in Germany in the 1990, and has been extensively researched since (Abed et al., 2022). CLT is produced by glueing timber boards, generally softwoods such as pine and spruce, at 90 degrees angles on top of each other (W. Dong et al., 2021; Younis & Dodoo, 2022). It has received substantial research and industry attention since it exhibits higher mechanical performance than sawn timber, enabling its use in a higher variety of applications, such as load-bearing structures (Abed et al., 2022). Due to its strength and durability, it presents an alternative of renewable origin for OPC in construction. Compared to OPC, CLT can achieve substantially lower greenhouse gas emissions. Due to biogenic carbon uptake during tree growth, CLT even functions as carbon sink during its service life (Duan et al., 2022). Although this carbon storage is temporary, it may aid slowing down climate change, giving more time to develop more permanent solutions (Duan et al., 2022).

2.3. Literature Review

LCA has been widely applied in the building sector, with an extensive body of research focusing on the environmental impacts of CLT (Younis & Dodoo, 2022). Table 1 provides an overview of 11 LCA studies that compare CLT buildings to a functionally equivalent reference building, consisting of reinforced concrete (RC) in all cases except Allan & Phillips (2021), which used a steel structure as reference. Note that this is a non-exhaustive overview, since no systematic literature review was conducted. To complement the insights derived from the 11 reviewed LCA case studies, findings from previous systematic literature reviews on LCAs applied to CLT construction have also been taken into account (Balasbaneh & Sher, 2024; Tupenaite et al., 2023; Younis & Dodoo, 2022).

Although some comparative LCA studies considered concrete in which a fraction of cement was substituted by industrial by-products such as FA and GGBFS, no study included cement-free OPC alternatives such as GPC. Most studies explore case study buildings in North-America or China. However, building practices may strongly vary between countries and regions—for instance due to differences in seismic activity, climatological conditions, and building regulations (Younis & Dodoo, 2022). Therefore, generalizability of these results to other countries is limited.

The majority of reviewed studies focuses on climate change impacts or only a small selection of impact categories including climate change. All studies report a reduction of climate change impacts of CLT buildings compared to the conventional benchmark. Andersen et al. (2022) and Ryberg et al. (2021) are the most complete studies in terms of impact category coverage, considering 18 mid-point impact categories. They found a better environmental performance of the CLT building in 11 and 10 out of the 18 categories respectively.

Furthermore, nearly all studies focus on mid-rise or high-rise residential and office buildings, with the exceptions being the gymnasium studied by Y. Dong et al. (2020) and the public library studied by Tokede et al. (2022). There seems to be a lack of studies investigating low-rise residential buildings, which may differ in terms of load-bearing structure compared to higher-rise buildings (Younis & Dodoo, 2022).

Tokede et al. (2022) is the only study that extended the environmental analysis with an economic perspective, by applying life cycle costing (LCC). However, the study is limited by its cradle-to-gate focus, consideration of only 3 impact categories, and focus on a public library in Australia, which may differ strongly in terms of bill of materials and use stage compared to other building types, such as residential and office buildings (Tokede et al., 2022).

Previous literature reviews on mass timber building LCAs also underline that quantitative environmental assessments of circular economy pathways, such as reuse and recycling of EoL materials, remain underexplored (Balasbaneh & Sher, 2024; Tupenaite et al., 2023).

Table 1. Non-exhaustive overview of previous studies that conducted a LCA to compare the environmental performance of CLT buildings to buildings with reinforced concrete or steel structure.

Authors	Scope	Location	Impact categories	Case study	Benchmark structure	Economic perspective
(Andersen et al., 2022)	Cradle-to-grave	Norway	18	5- and 8-storey residential buildings	RC (OPC)	No
(Duan et al., 2022)	Cradle-to-grave	China	1 (CC)	11-storey residential building	RC (OPC)	No
(Tokede et al., 2022)	Cradle-to-gate	Australia	3	Public library	RC (OPC)	Includes life cycle costing
(Ryberg et al., 2021)	Cradle-to-grave	Greenland	18	4-storey residential building	RC (OPC)	No
(Allan & Phillips, 2021)	Cradle-to-grave, excluding use stage	US	6	5- and 12-storey residential buildings	Steel	No
(Liang et al., 2020)	Cradle-to-site	US	5	12-storey mixed office-residential building	RC (OPC)	No
(Y. Dong et al., 2020)	Cradle-to-grave	China	1 (CC)	gymnasium	RC (OPC)	No
(Pierobon et al., 2019)	Cradle-to-gate	US	5	8-storey office building	RC (OPC)	No
(Liu et al., 2016)	Cradle-to-grave	China	1 (CC)	7-storey residential building	RC (OPC)	No
(Darby et al., 2013)	Cradle-to-grave, excluding use stage	England	1 (CC)	8-storey residential building	RC (OPC)	No
(Robertson et al., 2012)	Cradle-to-gate	Canada	11	12-storey office building	RC (OPC)	No

2.4. Knowledge gap

Despite the extensive body of literature comparing the environmental impacts of CLT and traditional reinforced concrete buildings, there is a significant gap in studies that compare GPC and CLT. GPC is increasingly recognized for its superior environmental and technical performance (Almutairi et al., 2021; Assi et al., 2018; Monteiro et al., 2017), yet its environmental performance in structural application compared to CLT has not been assessed yet using LCA. Moreover, 9 out of 11 reviewed comparing articles miss environmental impact categories, indicating that comprehensive LCAs are lacking. Also, there is a lack in studies that incorporate both an environmental and economic perspective in the comparison of CLT buildings to alternatives. Furthermore, none of examined studies focus on the Netherlands, and an analysis of low-rise housing – a very common building typology in the Netherlands – remains largely unassessed. Finally, existing literature reviews identify an overall lack in studies that address alternative EoL pathways for mass timber products such as CLT.

Addressing these gaps is essential for the construction sector, as it could reveal key trade-offs between OPC, GPC and CLT in load-bearing structures from an environmental and economic perspective. Such insights could support policymakers and industry stakeholders aiming to meet pressing housing demand in the Netherlands while balancing environmental and economic concerns.

3. Methodology

3.1. Research questions

The main research question (main-RQ), that aims to fill the mentioned research gap, is as follows:

Main-RQ: What are the environmental and economic implications of replacing OPC as main structural material with CLT or GPC for low-rise and mid-rise housing in the Netherlands?

The main research question is divided into the following sub-research questions (sub-RQs):

Sub-RQ1: How do the life cycle environmental impacts differ among low-rise and mid-rise housing in the Netherlands built with OPC, GPC, or CLT?

Sub-RQ2: What are the life cycle environmental hotspots of low-rise and mid-rise housing in the Netherlands built with OPC, GPC or CLT?

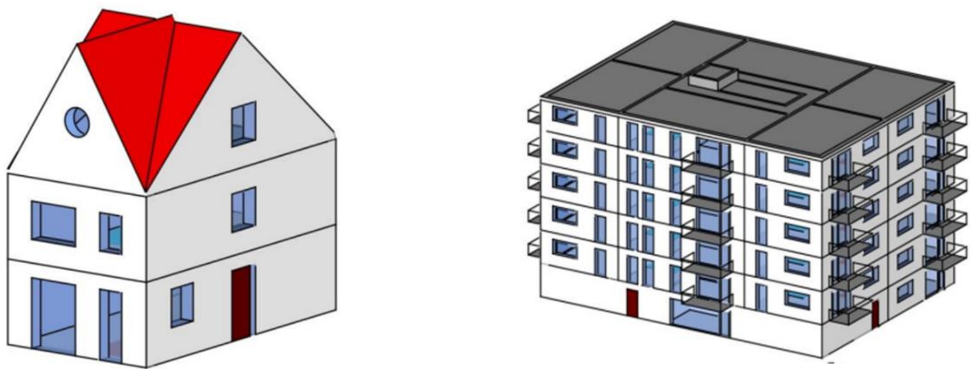
Sub-RQ3: What are the environmental impacts of alternative EoL scenarios for CLT and concrete for low-rise and mid-rise housing in the Netherlands built with OPC, GPC or CLT?

Sub-RQ4: What are material costs for low-rise and mid-rise housing in the Netherlands built with OPC, GPC or CLT?

3.2. Case study buildings

The study considers three different structures (CLT, GPC, and OPC) for two building typologies (row houses and apartment buildings), resulting in six case study buildings. Hereafter, the alternative buildings are named row house CLT; row house GPC; row house OPC; apartment building CLT, apartment building GPC, and apartment building OPC. See figure 1 for a visualization of the two building typologies. Note that all three versions for one building typology have the same appearance, as they have the same outer-envelope. Building designs were taken from BCI Gebouw (2025), a licensed platform that modelled several building archetypes that are frequently build in the Netherlands.

All row houses have a gross floor area (GFA) of 173 m2 and the apartment buildings have a GFA of 3773 m2, resulting in an average GFA per apartment building dwelling of 114 m2 as there are 33 dwellings per apartment building. Moreover, all case study buildings have an expected lifespan of 75 years (BCI Gebouw, 2025). The row houses have 3 floors and the apartment buildings 6 floors. A floor height of 2.6 meters is assumed, in accordance with the minimum specified in Dutch building regulations (Appolloni & D'Alessandro, 2021).



(A) (B)

*Figure 1. Visualization of the two housing typologies frequently built in the Netherlands and focused on in this study. Building **A** represents the row house and building **B** the apartment building (BCI Gebouw, 2025).*

The study examines six building elements that differ between typologies: foundation, floors, load-bearing walls, non-load-bearing walls, insulation, and roofs. Material quantities for each element were derived using data from (BCI Gebouw, 2025), which provides a list of material components, such as concrete floors and CLT walls, along with material intensities (e.g., kg/m or kg/m2) of those specific building components. These intensities were multiplied by the respective lengths or surface areas of the building components per case study building to estimate material quantities. In cases where BCI did not specify material types or quantities of a building component—such as for timber frame inner walls, roofs, and sand-lime stone walls—material intensities were estimated based on typical Dutch construction practices. SM 1 shows the building components and material intensity calculations.

BCI's classification of building components was maintained for consistency throughout the LCA. The resulting material quantities were grouped per building element and normalized by the GFA of each case study building, yielding material intensities in kg/m2 GFA per building element. Total material intensities at the building level were then computed by summing material quantities across all elements. A detailed breakdown of calculations is provided in SM 1.

3.3. Life Cycle Assessment (LCA)

Environmental impacts of the case study buildings are evaluated using LCA methodology, according to ISO 14040 standards, which involves the following phases: (1) Goal and Scope definition; (2) life cycle inventory analysis (3) impact assessment, and (4) interpretation (International Organization for Standardization, 2006). The section below covers all four phases.

3.3.1. Goal and Scope definition

The goal phase in LCA defines the study's purpose, intended use of results and target audience. The LCA's scope defines the systems' function and boundaries, discussing which processes and flows are included in the study and which are omitted (Guinee, 2002).

Goal

The goal of this LCA is to quantify and compare the environmental impacts of load-bearing structures build in the Netherlands made of CLT, GPC and OPC. The results of the LCA are intended to support informed decision-making for design and construction companies as well as for policy workers in the area of sustainable construction materials, supporting the development of a lower-environmental impact and more circular building sector.

Scope

The function of the system under consideration is providing floor area, in line with how a building's function is defined by Fishman et al. (2024). To enable fair comparison of the alternative buildings, the environmental impacts are all expressed in terms of a functional unit (FU)— a key concept in LCA that quantitatively defines the use of the product system under consideration (Guinee, 2002). This study defines its FU as the use of 1 m2 GFA of a dwelling in the Netherlands over a period of one year.

The study performs an attributional LCA, meaning that the considered product system is based on current supply chains, using average market data (European Commission, 2010). Moreover, the LCA is cradle-to-grave, considering the impacts of all building life cycle stages, including material extraction to building end-of-life (EoL). Maintenance and repairs are not considered within the system boundaries, due to a lack of reliable data on maintenance schemes especially for CLT structures, as CLT is a relatively new construction material (Younis & Dodoo, 2022). Operational water use, waste water, and other wastes generated during building use are also not included in the system boundaries, as they are difficult to accurately quantify and considered outside of the study's scope. Moreover, construction emissions—for instance particulate matter emissions due to on-site material handling—are not considered, as they are complex to estimate and negligible compared to whole life cycle impacts (Sandanayake et al., 2019).

For timber products such as CLT, the LCA accounts for temporary biogenic carbon storage at the inventory level. However, biogenic carbon is not translated into environmental impact categories, and therefore does not influence the calculated environmental impact results of the case study buildings that incorporate timber components. The rationale is that although carbon is sequestered in biomass during tree growth, this carbon is typically released back into the atmosphere at the end of the product's life—e.g., through incineration or decomposition (Younis & Dodoo, 2022). Extending the lifetime of timber components, for instance through reuse at the building's EoL, may result in a portion of the biogenic carbon remaining sequestered beyond the original building's lifespan. This potential influence on environmental impacts is further addressed in the discussion section.

The LCA considers materials for the load-bearing structure (foundation; load-bearing walls, floors), as well as for the non-load-bearing walls, roofs and insulation, as those are the primary building elements that differ in terms of materials per alternative structure. Building elements that are similar for all alternatives within a building typology, such as doors, facades, windows and electrical appliances are omitted from the analysis, as is common for comparative LCAs (Ryberg et al., 2021). Moreover, buildings were modelled over a 75 years lifetime, in line with the description by (BCI Gebouw, 2025). Figure 2 visualizes the product system, showing all flows and processes included in the study's system boundary. Note that processes are divided into foreground process (inputs and outputs compiled by the author); and background processes (data obtained directly from the LCI database Ecoinvent).

To ensure that data are temporally consistent and align with current construction practices in the Netherlands, LCI data were primarily sourced from publications released after 2020 with a specific focus on the Dutch context. In cases where such data were unavailable, European sources were used as a secondary option, followed by global average data as a last resort. Moreover, the database Ecoinvent v3.9.1: cut-off by classification, was used as LCI data source for all background processes, and the product systems were modelled using openLCA v2.2. In line with recommendations by the European Commission, the Environmental Footprint (EF) v3.0 was used for impact assessment (Pant et al., 2019), considering all 16 mid-point impact categories.

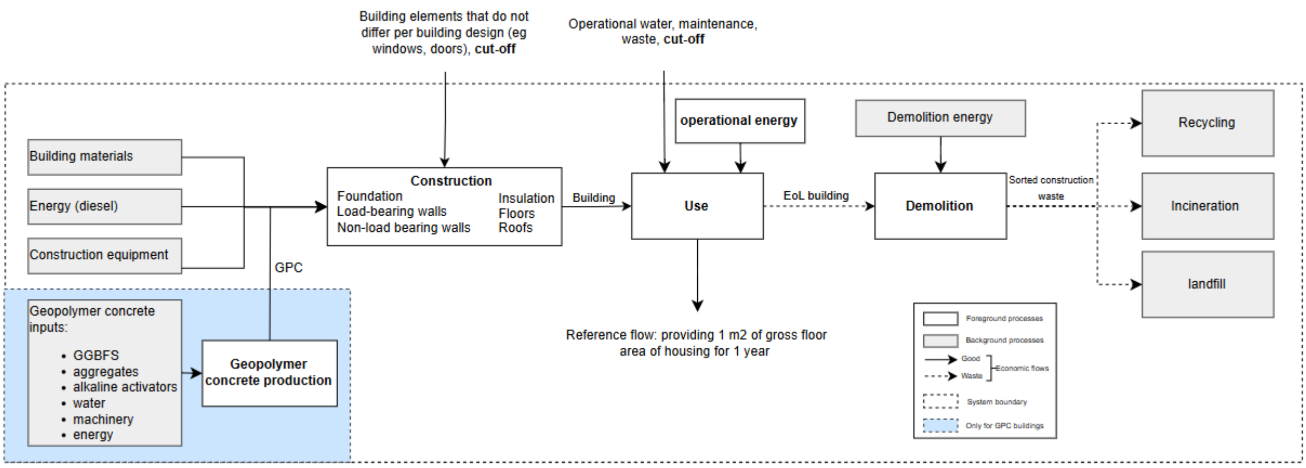


Figure 2. Schematic overview of the considered system for the case study buildings.

3.3.2. Life cycle inventory analysis

The life cycle inventory (LCI) analysis phase involves the compilation and quantification of all the inputs and outputs of the product system. The foreground processes are discussed per building life cycle stage. The reader is referred to SM 1 for more details regarding data sourcing and processing.

3.3.2.1. Materials production stage

The production of building materials was modelled using LCIs from the Ecoinvent database, except for GPC, as no datasets were available. Ecoinvent LCIs represent the whole supply chain—including transportation—required to provide a certain product, and account for all environmental flows, i.e. emissions to and extractions from the natural environment. For instance, the used LCI of CLT represents European average production of CLT—from initial forestry management and timber harvesting to wood processing and finishing of CLT panels. The used LCI for OPC represents global average production, from extraction and processing of raw materials, such as gravel and cement, to the production of ready-mix concrete.

Several GPC mixes exist, varying mostly in their precursor material, which is the material which – upon alkaline activation – becomes the primary binding agent that replaces common Portland cement in GPC (Almutairi et al., 2021). The two most common precursor materials described in literature are GGBFS and FA (Almutairi et al., 2021; Amran et al., 2020). This study used GGBFS as precursor material, as GGBFS-based GPC can cure at ambient temperature, whereas FA-based GPC mixes often require heat curing (Zannerni et al., 2020). As the GPC is cast at the building site, ambient curing is advantageous. Since GPC exhibits higher strength and durability than OPC, it was assumed GPC could replace OPC without altering the building design (Verma et al., 2022).

The study based its GPC ingredient mix on data provided by Al-Shathr et al. (2018), see table 2. The energy use for GPC production was estimated at 60 MJ of diesel/m3 GPC, based on the energy required for mixing conventional OPC, as reported by De Herde & Evrard (2005). Note that other energy inputs, such as electricity use for lighting of the concrete production site, were omitted from the analysis. It was further assumed that GPC production requires similar capital infrastructure as OPC production, specifically a concrete mixing facility. The capital input for GPC was therefore modelled using the Ecoinvent LCI for a concrete mixing factory, consistent with the approach used for OPC.

Following the principle of mass conservation, the production waste of GPC was estimated by subtracting the mass of 1 m3 of GPC output (2,420 kg) from the total mass of inputs specified in table 2 (2,513 kg), resulting in approximately 93 kg of waste per m3 GPC. This waste was assumed to consist of 50% concrete wastewater, which is contaminated water generated during the various steps of concrete production, and 50% solid GPC waste. For transportation to the construction site, GPC was assumed to follow the same logistics as OPC concrete. The Ecoinvent waste treatment and transport processes used in this study are detailed in SM 1.

Table 2. List of ingredients to produce 1 m3 of GPC (Al-Shathr et al., 2018). SM 1 further details used Ecoinvent processes for each flow.

Flow Name	**Amount**	**Unit**
Sand	650	kg
Gravel	1200	kg
GGBFS	400	kg
Tap water	146	kg
Plasticiser, for concrete, based on sulfonated melamine Formaldehyde	12	kg
Sodium silicate	69	kg
Sodium hydroxide, solid pellets	36	kg
Total mass inputs	2513	kg

3.3.2.2. Construction stage

Construction of the case study buildings was assumed to be carried out using diesel-powered cranes (Gu et al., 2021). Construction energy use was estimated based on crane diesel consumption, as described by equation 1 (Gu et al., 2021). The calculated diesel consumption (in litres) was converted to MJ using the energy density reported for the Netherlands (CBS, 2024). SM 1 presents construction energy calculations. Note that other forms of construction energy, such as energy for other machinery than cranes, building finishing, and temporary worker residences, were not considered in the analysis.

$$\text{Fuel(L)} = 0.000037\text{Mh} + \frac{\text{M}}{500} + 0.83 \tag{1}$$

- M=mass of materials being lifted (kg), using the total material mass excluding construction losses.
- h=height to which materials are lifted (m), assumed to be half the building height.

Material losses during construction are expected to be minimal (<1%) for prefabricated components or materials requiring little on-site processing, such as CLT and sand-lime stone (Andersen et al., 2022; Hart et al., 2021). For concrete that is cast on-site, this loss is substantially larger, estimated at 5%. This is due mostly to over ordering of ready-mix concrete. Excess material is usually discarded, as it cannot be reused at the building site (Hart et al., 2021). Consequently, a 5% material loss was assumed for both OPC and GPC during on-site casting. No construction waste was assumed for other materials. Note that this estimate does not include prefabricated concrete—including aerated concrete blocks—as those elements do not require on-site concrete casting.

3.3.2.3. Use stage

A lifespan of 75 years was assumed for all case study buildings, based on building descriptions provided by BCI Gebouw (2025). Operational energy was divided into electricity and thermal energy (heating/cooling).

Electricity consumption was estimated using CBS data on the average annual electricity use of existing row houses and apartment dwellings in the Netherlands (CBS, 2025). Furthermore, electricity use was assumed to be consistent across alternative structures within each building typology, in line with findings from Andersen et al. (2022). The Dutch low-voltage grid was assumed as electricity source.

For thermal energy, new housing in the Netherlands must comply with BENG regulations (RVO, 2024). These regulations specify the maximum annual energy use for heating and cooling that a dwelling may use per m2 GFA, considering different dwelling typologies. As no data on thermal energy use for new housing was found, the official BENG limits for thermal energy use were used as proxies for the GPC and OPC buildings: 55 kWh/m2/year for row houses and 65 kWh/m2/year for apartment buildings (Rijksoverheid, 2025). This represents a conservative estimate, as actual thermal energy use is likely to be lower than the regulatory maximum. As new housing in the Netherlands may not have a natural gas connection, it was assumed that 75% of thermal energy is provided by air-water heat-pumps and 25% by district heating, in line with current construction practices in the Netherlands (RVO, 2022). District heating is provided by a European average market mix, including biomass incineration and fossil-fuel driven heat generation.

Andersen et al. (2022) found that CLT building exhibit superior thermal performance compared to conventional concrete buildings. Specifically, they report thermal energy use of 49.9 kWh/m2/year for a CLT apartment building and 63.9 kWh/m2/year for a comparable concrete structure (Andersen et al., 2022). Based on this relative difference, it was assumed that the improved thermal performance of CLT also applies to the CLT row houses and apartment buildings in this study. The ratio of CLT-to-concrete thermal energy use reported by Andersen et al. (2022) was applied to the BENG limits to estimate thermal energy consumption for the CLT alternatives. A complete overview of all calculations and assumptions related to use-stage energy consumption is provided in SM 1.

3.3.2.4. End-of-life stage

At the end of their lifespan, the buildings are demolished and their constituent materials are sorted on-site, in accordance with Dutch regulations (IPLO, n.d.). The sorted waste streams are then transported to appropriate waste treatment facilities, modelled using corresponding Ecoinvent LCIs, see SM 1. Waste from screed, aerated concrete, and OPC/GPC was aggregated and classified as concrete waste, while waste from CLT, plywood, and structural timber was aggregated as waste wood.

Demolition energy was estimated based on the diesel consumption of demolition machinery, using material-specific demolition energy provided by Duan et al. (2022), table 3 presents an overview. As no demolition energy data was available for wood types other than CLT, screed floors, and sand-lime stone, the demolition energies for CLT, concrete block, and cement respectively were assumed to serve as suitable proxies. SM 1 further details the calculations. Note that other forms of energy consumed during the demolition and sorting process were excluded from the analysis for simplification and since demolition machinery accounts for the majority of energy consumption (Duan et al., 2022).

Table 3. Overview of demolition energy per material, based on fuel consumption of demolition machinery (Duan et al., 2022).

Material demolished	**Demolition energy, diesel (MJ/kg)**
Reinforce concrete	0.0612
Concrete	0.0437
Cement	0.0437
Gypsum plaster	0.0359
Concrete Block	0.0359
Particleboard	0.0359
CLT	0.0359

In this study, LCIs from the Ecoinvent database are used to model EoL treatment of materials. Many of these EoL processes involve recycling, which serves a dual function: treating waste and producing a secondary product with economic value (e.g. recycled steel or heat from incinerated CLT). Ecoinvent applies the cut-off allocation approach by default to address this multifunctionality. This approach allocates all upstream environmental burdens to the primary product, while the recycled product is considered burden-free for, aside from the impacts of the recycling process itself. As a result, no environmental benefits from avoided virgin production are included in the environmental impact calculation, aligning with the polluter-pays principle.

3.3.3. Impact assessment

Impact assessment is the phase in LCA that quantifies and interprets the environmental impacts of a product system, based on LCI results (Guinee, 2002). Environmental flows associated with the reference flow are classified into impact categories such as climate change and acidification. For example, CH_4 and CO_2 emissions are assigned to the climate change category. These flows are converted into a common unit (e.g., CO_2-equivalents) through characterisation, using characterization factors. The resulting characterised flows are summed per impact category to produce a total, such as total radiative forcing for climate change (Guinee, 2002). **Error! Reference source not found.**4 presents a list of all 16 considered impact categories and their abbreviations.

Table 4. PEF impact categories and their abbreviations.

Abbreviation	Full name
AD	acidification
CC	climate change
ECT	ecotoxicity: freshwater
ER_NR	energy resources: non-renewable
ET_F	eutrophication: freshwater
ET_M	eutrophication: marine
ET_T	eutrophication: terrestrial
HT_C	human toxicity: carcinogenic
HT_NC	human toxicity: non-carcinogenic
IR	ionising radiation: human health
LU	land use
MR_MM	material resources: metals/minerals
OD	ozone depletion
PM	particulate matter formation
POF_HH	photochemical oxidant formation: human health
WU	water use

3.3.4. Interpretation

Interpretation is the phase in LCA that analyses the outcomes of the LCI and impact assessment phases and provides recommendations for improving the environmental performance of the system under consideration (Guinee, 2002). As part of the interpretation, a sensitivity analysis was performed to assess how changes in key modelling assumptions influence the outcomes of the LCA. Three aspects are considered: (1) improved material efficiency in the load-bearing structure, (2) the use of more sustainable GPC, and (3) alternative EoL pathways for CLT and concrete.

Optimizing material use

The building material results showed high impact contributions of the materials present in the load-bearing structure: that is the foundation, walls and floors. Increasing the material efficiency of load-bearing structures therefore seems a promising way to promote the environmental performance of the case study buildings. Enhancing material efficiency can occur by (1) optimizing building materials (Mayencourt & Mueller, 2019) and (2) optimizing structural designs (Afzal et al., 2020; Elkabany et al., 2020; Todinov, 2024).

As illustration of the first strategy, research into CLT panels showed that through improved design, panels can be developed that require 20% less materials while maintaining their original quality (Mayencourt & Mueller, 2019). Regarding the second strategy, structural optimization programs are rapidly evolving that enable light-weight designs with similar performance, for instance by aggregating multiple building elements into a single component that has the same load-bearing capacity but a lower material mass (Todinov, 2024).

To explore the effects of increased material efficiency, I modelled an explorative scenario in which the use of materials for the foundation, walls and floors decreases by 20%. Specifically, these materials are CLT, concrete, rebar, sand-lime stone and sand-lime stone mortar. The waste at building EoL for these buildings was also reduced accordingly.

More sustainable GPC

The impact of GPC seems to be driven largely by the use of the alkali-activated binders (AABs) sodium hydroxide (NaOH) and sodium silicates (Bamshad & Ramezanianpour, 2024).

Three strategies to reduce the environmental impact of GPC are identified: (1) improving the sustainability of AAB production (e.g. by using renewable energy), (2) optimising the GPC mix to reduce the quantity of AABs required (Romadhon et al., 2022), and
(3) substituting conventional AABs with alternative materials, particularly industrial by-products (Mendes et al., 2021).

This scenario explores the third strategy, due to its dual benefit of reducing GPC-related impacts while also valorising industrial waste. Several waste-derived activators have been examined in the literature, including glass waste, sugarcane dust, and silica fume (Mendes et al., 2021). In this scenario, sodium silicate is replaced by silica fume—a by-product of the silica industry—as it only requires limited pre-processing (Mohapatra et al., 2022). According to Muehleisen (2021), silica fume can substitute sodium silicate in GPC while only requiring 55% of the mass. The baseline GPC mix requires 69 kg sodium silicate, which is thus replaced by 31 kg silica fume under the sustainable GPC scenario.

Alternative EoL pathways

The third scenario investigates alternative end-of-life (EoL) treatments for CLT and concrete (both OPC and GPC). In the baseline model, CLT is assumed to be incinerated at the end of the building's life, resulting in the loss of a material with high reuse potential (Passarelli, 2018; Younis & Dodoo, 2022). Given the expected increase in future recycling rates, an alternative scenario was developed in which CLT is reused and concrete is processed into aggregates for concrete production.

Passarelli (2018) explored the potential to reuse entire CLT panels in new buildings and found them highly suitable for reuse. During the extraction and refurbishment process, however, approximately 27% of the panels were lost. This study adopts the same loss rate. Due to the presence of glue between timber layers, recycling of the CLT loss fraction is limited (Nguyen et al., 2023). Therefore, the CLT unsuitable for reuse is assumed to be incinerated. This is modelled using Ecoinvent LCI data for waste wood treatment in the Netherlands, in which 97% of the wood is incinerated and the remaining 3% is landfilled.

Considering the 27% loss rate, 73% of CLT panels are assumed to be successfully refurbished into secondary CLT suitable for reuse in construction. As such, the production of 1 m3 of secondary CLT requires 1.37 m3 of waste CLT input. The energy consumption for secondary CLT production was based on electricity use for panel finishing during primary CLT production, amounting to 31.75 kWh per m3 of CLT (Chen et al., 2019).

Although CLT has only been in use since the 1990s and its long-term durability remains uncertain, engineered timber elements may last over 200 years (Migoni Alejandre et al., 2024). However, it is likely that secondary CLT has a shorter service life than primary CLT. To reflect this, a substitution factor of 0.5 is applied, meaning that 1 m3 of secondary CLT replaces 0.5 m3 of primary CLT.

In the Netherlands, approximately 95% of EoL concrete is currently downcycled, primarily for use in road foundations and site elevation (C. Zhang et al., 2020). However, recycling concrete into secondary aggregates for use in new concrete is technically feasible and may reduce environmental impacts (C. Zhang et al., 2020). While secondary aggregates generally have lower quality than primary aggregates (Wang et al., 2021), recent technological developments are rapidly improving their performance. Given these rapid developments and the long time span before the case study building reaches EoL, it is assumed that secondary aggregates can fully substitute primary aggregates with a substitution factor of 1. Therefore, 1 kg of recycled concrete is assumed to displace 1 kg of gravel. The energy requirement (diesel) for concrete recycling is based on the Ecoinvent process for reinforced concrete recycling, see SM 1.

An overview of the life cycle inventory (LCI) data for the EoL scenario is provided in SM 1. Note that the environmental benefit of CLT reuse and concrete recycling is accounted for by crediting the system under consideration with the avoided production of primary CLT and gravel respectively. In contrast, the baseline model does not include any credits for avoided production, as described under section 3.3.2.4. However, the avoided production approach was applied in the EoL scenario to enable quantification of the benefits of reuse and recycling as EoL strategies.

3.4. Cost Assessment

To complement the environmental assessment of the case study buildings with an economic perspective, material costs were assessed and used to calculate a material cost price per m2 GFA per case study building. Market prices were sourced from literature or supplier websites, considering market prices for the Netherlands when available, otherwise using European or global average price data. Note that for all materials, except GPC, material prices were found and converted to €/kg. SM 1 provides further details on the material cost calculations. Additionally, non-material construction costs of the six case study buildings—for instance of labour and machinery—were assessed qualitatively using literature.

The market price of GPC was estimated by breaking it down into three components: material costs, non-material production costs, and profit margin. Material costs were calculated using ingredient prices from market reports and supplier websites, multiplied by the quantities required per 1 m3 of GPC. Non-material production costs and average profit margin per 1 m3 OPC were based on data from Zayed et al. (2005), which include costs for the batch plant, truck mixer, and overhead. It was assumed these values are comparable for GPC and OPC. Since the data from Zayed et al. (2005) dates to 2005, values were adjusted for inflation to 2025 levels using an average annual inflation rate of 2.38% over the past 20 years (Ycharts, 2025). See SM 1 for detailed calculations.

4. Results

4.1. Building Materialization

Figure 3 shows the material intensity results for the six case study buildings. It suggests that CLT buildings are more material-efficient than their concrete counterparts, particularly in the case of row houses. The CLT apartment building, however, requires a significantly higher material mass per m2 than the CLT row house, mainly due to increased concrete use. This indicates that from a material intensity perspective, CLT is more efficient for low-rise structures like row houses than for larger apartment buildings.

For the GPC and OPC designs, total material intensities per m2 are comparable between row houses and apartment buildings. However, the composition of materials differs notably: sand-lime stone account for approximately 52% of the row houses' mass and only 22% for the apartment buildings. Apartment buildings in turn have a higher concrete intensity. Still, sand-lime stone constitute a significant share of the material intensity for GPC and OPC row houses and apartment buildings, reflecting the high use of the material in Dutch building construction (BouwTotaal, 2025; Esposito et al., 2018).

Overall, concrete constitutes a significantly larger portion of the mass in all apartment buildings compared to row houses. This is likely due to the greater structural demands of high-rise buildings, which require more reinforced concrete per m2 of gross floor area, particularly for elements such as foundations and floors.

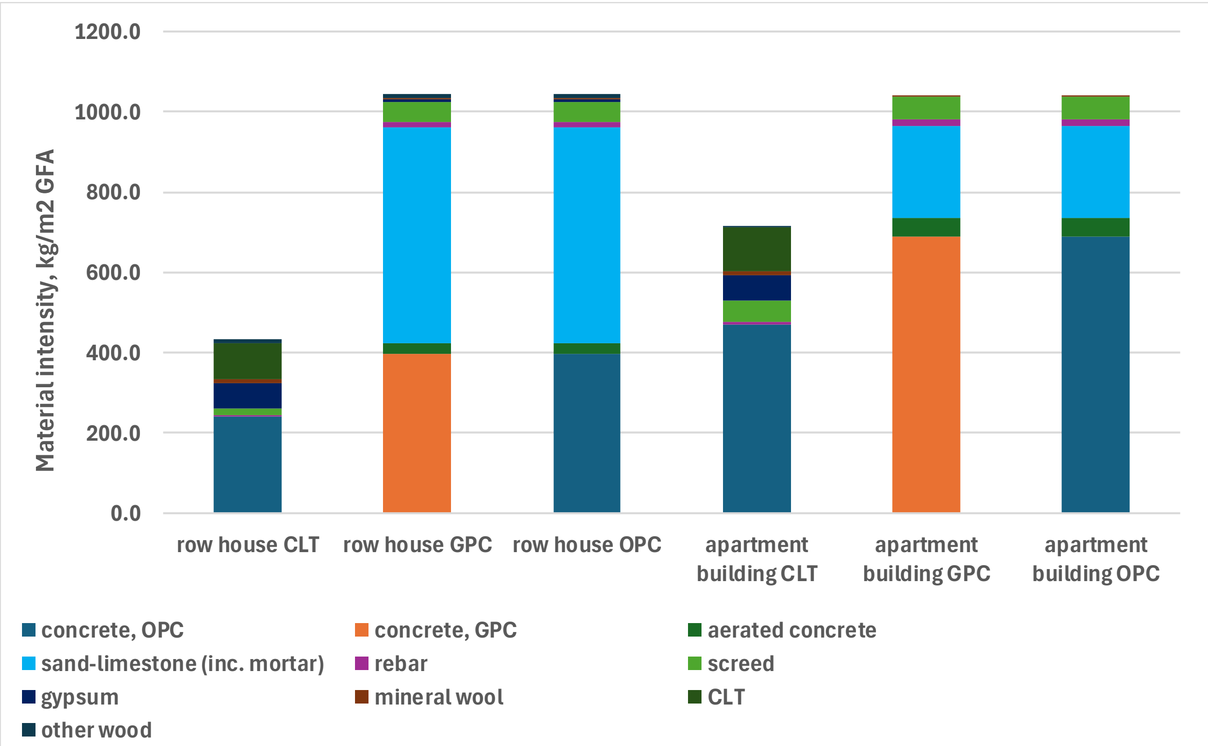


Figure 3. Material breakdown showing material types and quantities per m2 gross floor area (GFA) for all six case study buildings.

4.2. Environmental impact assessment

4.2.1. Life cycle environmental impacts

Figure 4 presents the total life cycle impact assessment results. Impacts are presented relative to the case with the highest impact, indicated as 1. The GPC alternative shows the highest impacts across most categories for both row houses and apartment buildings, although the difference with OPC is generally minor. In terms of climate change impacts, the OPC buildings show the highest results: the OPC row house has approximately 21% higher impacts than the CLT row house, while the OPC apartment building has around 16% higher impacts than its CLT counterpart.

The CLT row house has the lowest impact in 13 out of 16 categories, and the CLT apartment building in 12 out of 16; showing an impact reduction of 5-27% relative to the worst performing case, depending on the category. The most notable exception is land use, where the CLT row house and apartment building show approximately 3 and 4 times higher impacts, respectively, compared to their OPC and GPC counterparts. This is caused mainly by CLT's high timber demand, requiring a large forestry area.

The environmental performance of OPC and GPC buildings is largely similar. The GPC row house performs worse than OPC in 8 of 16 categories, and the GPC apartment building in 9 of 16. Both alternatives perform equally in 3 categories, indicating that GPC has a slightly worse overall performance than OPC. However, the relative differences between the two concrete options are small, ranging from 0-14%, depending on the category.

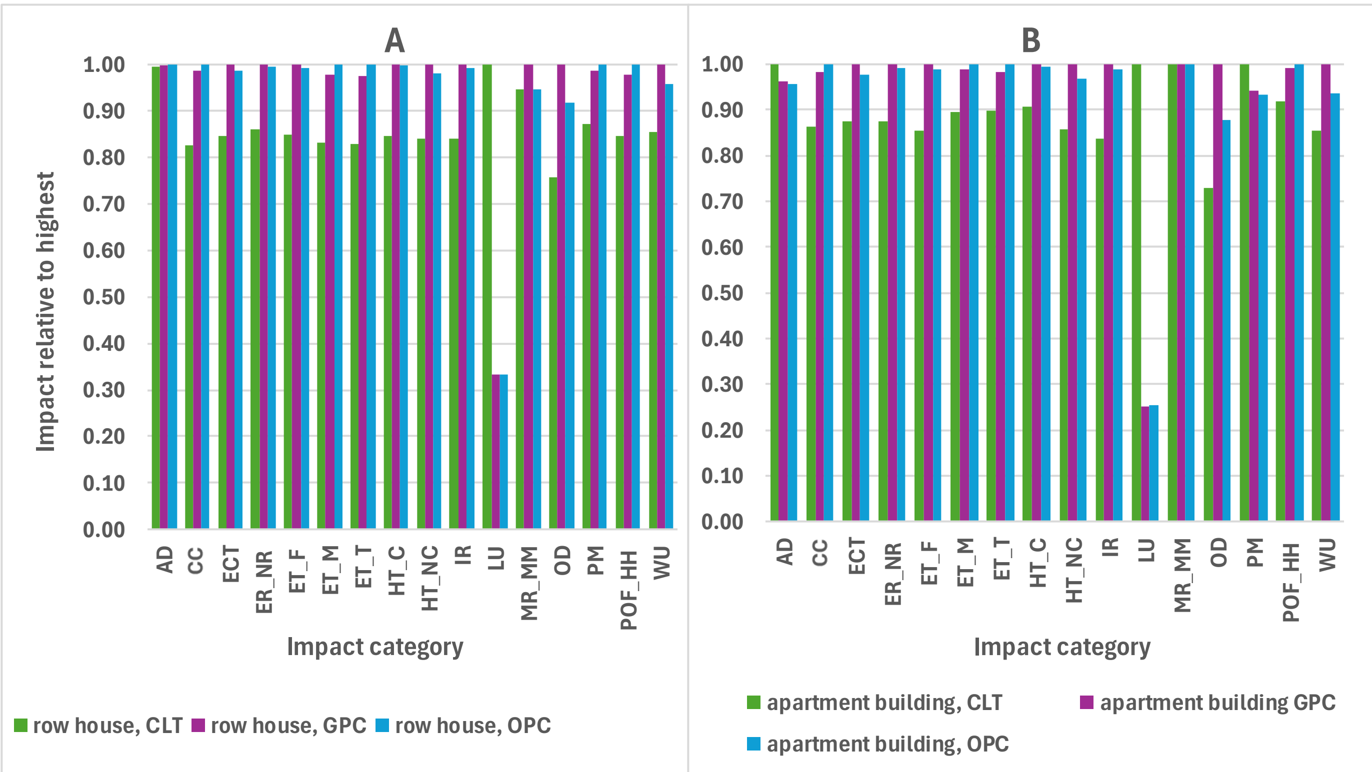


*Figure 4. Full life cycle environmental impact results for the row houses (**A**) and apartment buildings (**B**).*

4.2.2. Contribution analysis

Figure 5 shows the contribution of life cycle stages to total impacts for the CLT row house and OPC apartment building. Only these two buildings are shown as trends are similar across all case study buildings. For both, the use stage dominates nearly all impact categories, contributing 60-99%, depending on the category. The exception is land use for the CLT row house, for which materials contribute 81%. Again, this is driven by CLT's high timber use, requiring a large forestry area. Use stage impacts are driven by thermal energy for heating/cooling and electricity for appliances and lighting. Their dominant contributions can be explained as use stage energy is consumed year-on-year over the buildings' life time (75 years), while impacts by materials production, construction, and EoL are only incurred once and distributed over the buildings' life time.

*Figure 5. Contributions of life cycle stages to total environmental impacts for the OPC apartment building (**A**) and the CLT row house (**B**).*

Materials production is the second largest contributor, contributing on average 12% for the OPC apartment building and 18% for the CLT row house across all categories. Construction and end-of-life (EoL) stages contribute minimally. An exception is the CLT row house, where EoL drives about 20% of acidification impacts. Leaching of acidic wastewater generated during waste gypsum treatment explains these impacts (Ju et al., 2023); this contribution is especially high for the CLT row house as the CLT buildings have a high gypsum use for fire safety (Allan & Phillips, 2021).

The baseline model uses Ecoinvent LCI data on average electricity and heat production in the Netherlands. Since the Dutch energy sector is rapidly decarbonizing to meet the increasingly stringent environmental regulations (RVO, 2022), the model may overstate the environmental impacts of the use stage. To explore the implications of a more renewable energy system on the use stage impacts, a renewable energy scenario was developed. This scenario assumes electricity is provided through a mix of wind (89% offshore, 11% onshore) and solar PV (50%

central, 50% decentral), based on the **Entso-E: Distributed Energy** scenario (Sijm, 2024). Thermal energy is supplied by a mix of electric heat pumps using the renewable electricity mix (75%) and district heating using heat from municipal waste incineration (25%), based on reports on the Dutch heat transition (Hoogervorst, 2017; RVO, 2022). SM 1 further shows the calculations for the scenarios.

Figure 6A shows the change in impacts of the use stage, when comparing the renewable energy scenario to the baseline scenario. As this is almost identical across all 6 case study buildings, only the average is shown. Use stage impacts decrease on average by 63% under the renewable energy scenario, with non-renewable energy resources displaying the largest decrease of 98%.

Metals and minerals is the only category that increases, showing an increase of 10% relative to baseline. This is likely due to the high resource intensity of renewable energy infrastructure. Note that LCI data from Ecoinvent (v3.9.1) were used to model these technologies. Since these datasets may not fully reflect recent technological improvements, the actual future impacts are likely lower than those modelled.

As use stage impacts decline, materials production becomes more significant. Figure 6B shows this shift for apartment building OPC, representative of all cases, with materials' contribution to climate change impacts rising from ~13% to nearly 50%. This underscores the need to address material-related impacts in a decarbonizing energy system. Note that only the use stage was adjusted in the renewable scenario, though material production impacts would likely be impacted as well as a result of greener energy.

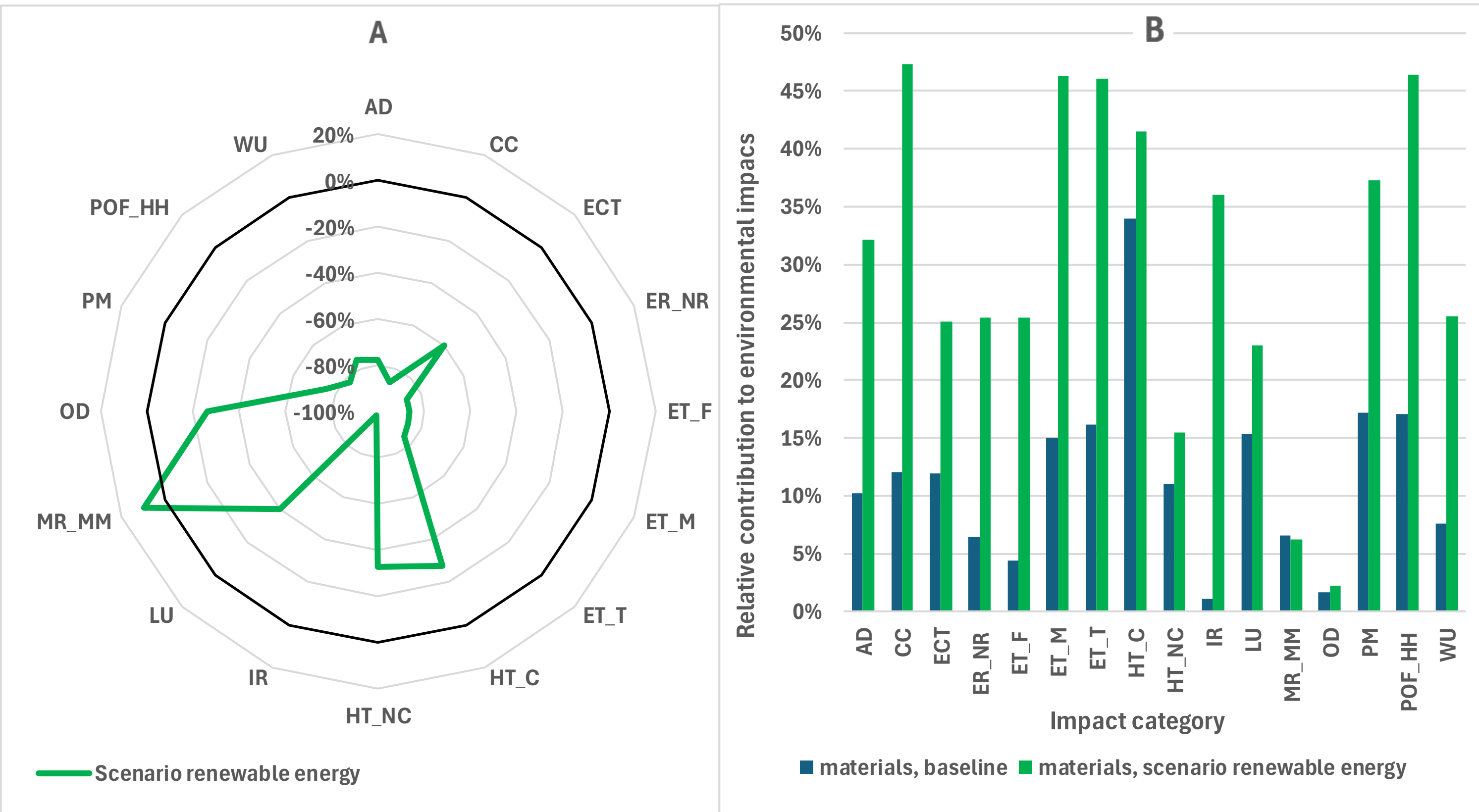


*Figure 6. (**A**) Average change in environmental impacts during the use stage when shifting from the baseline to the renewable energy scenario. (**B**) Contribution of material production to the total environmental impacts for the OPC apartment building.*

4.2.3. Impacts of building materials

The previous contribution analysis highlighted that—under a renewable energy scenario—the relative contribution of materials to environmental impacts rises significantly, compared to the baseline model. Therefore, this section further explores environmental impacts related to building materials, discussing total building material impacts, impacts per building element, and impacts per building material.

4.2.3.1. Total material level

Figure 7 shows the environmental impacts of materials per case study building. The overall pattern aligns with the full life cycle assessment of section 4.2.1. and is therefore not discussed in detail. However, a key difference is that the CLT apartment building performs worse than its OPC and GPC counterparts in 10 out of 16 categories when considering materials alone. Also, the gap in performance between GPC and OPC increases for both building types. Across all impact categories, the GPC row house shows on average 42% higher impacts and the GPC apartment building 67% higher impacts than their OPC counterparts.

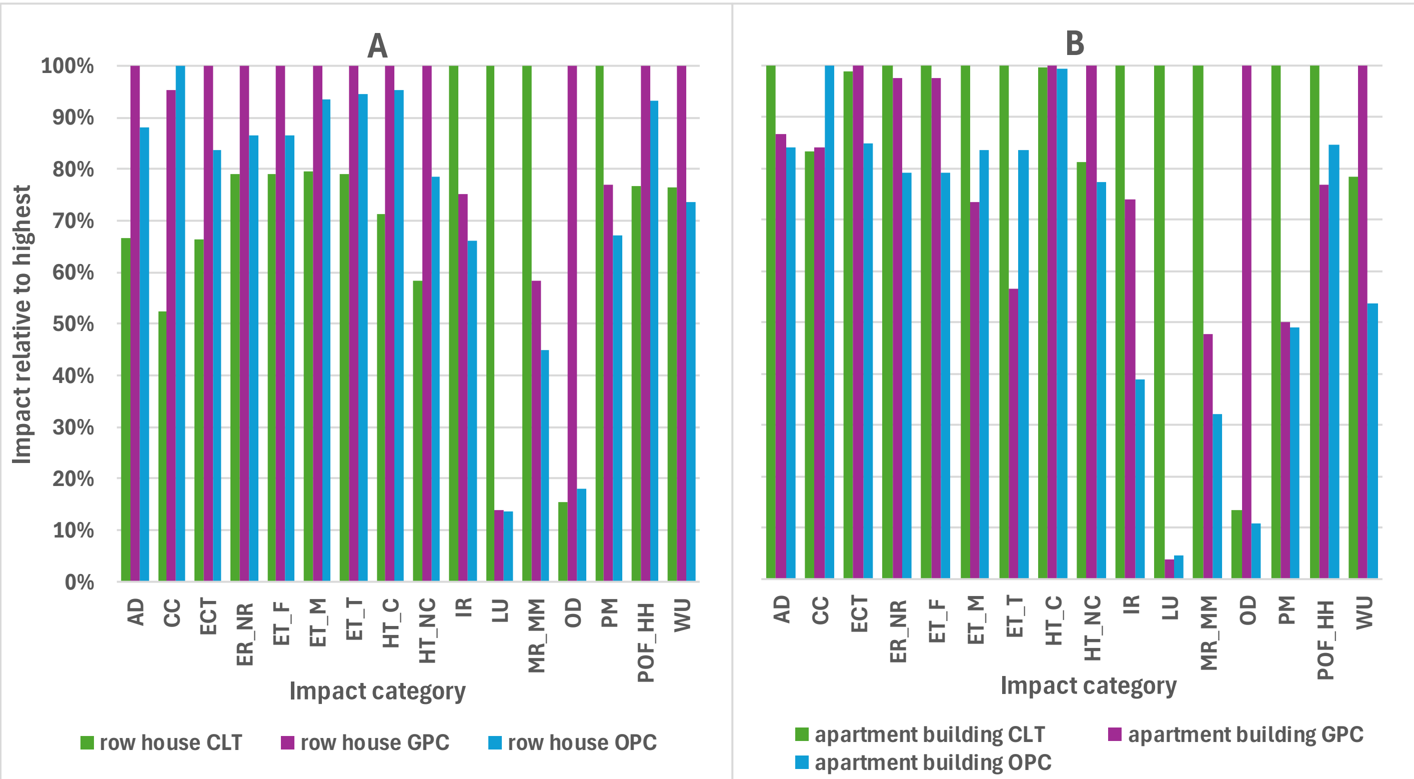


*Figure 7. Environmental impacts of material production for the row houses (**A**) and apartment buildings (**B**).*

4.2.3.2. *Building element level*

Figure 8 presents the environmental impacts of the building materials aggregated per building element.

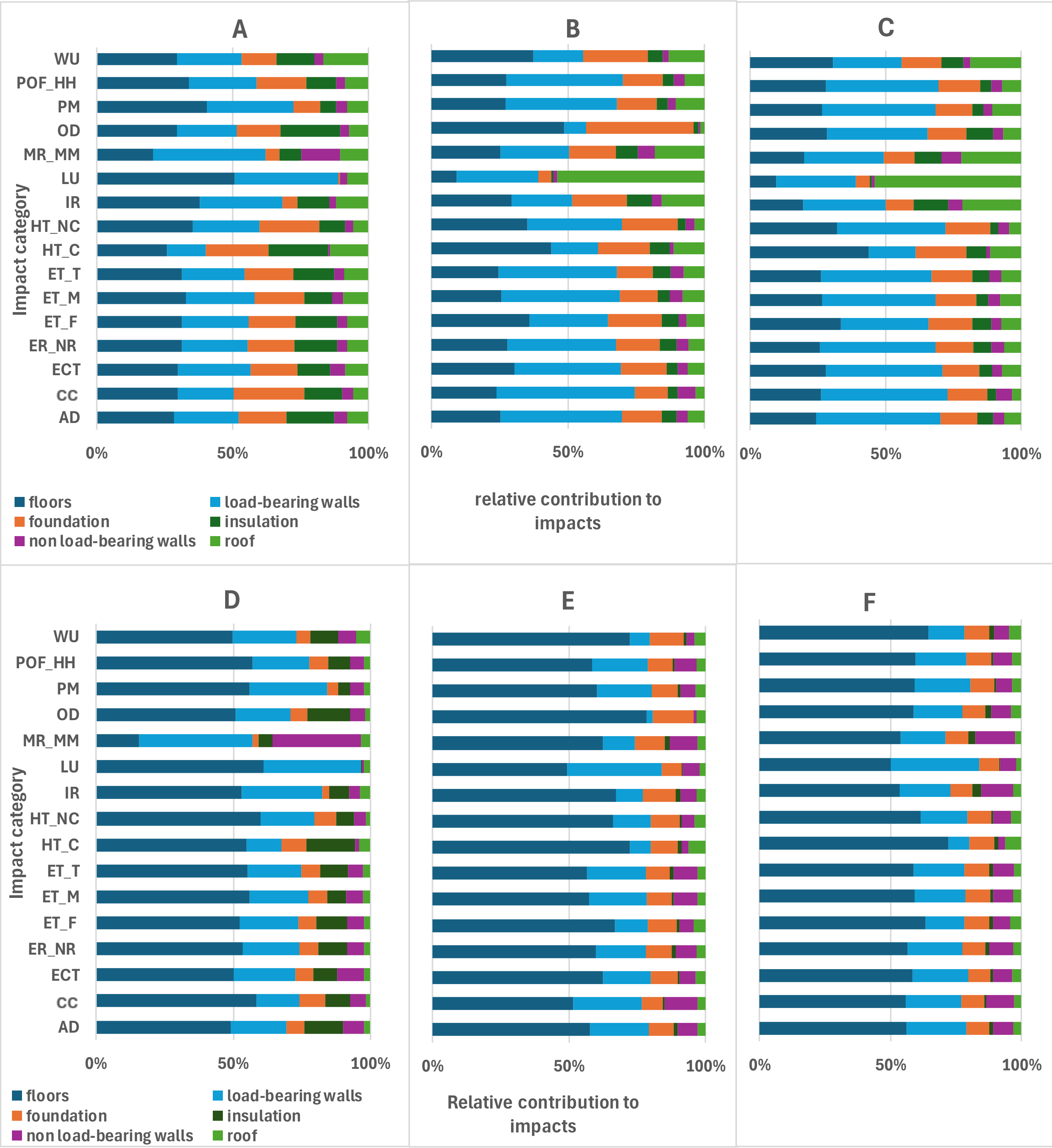


*Figure 8. Environmental impacts of building materials segmented by building element for the CLT row house (**A**), GPC row house (**B**) OPC row house (**C**); CLT apartment building (**D**), GPC apartment building (**E**) and OPC apartment building (**F**).*

The general pattern within each building type appears consistent. For row houses, the floors, load-bearing walls, and foundation—which are the main load-bearing elements—together account for 44-98% of the impacts, depending on the category. In apartment buildings, the floors are the primary contributors to impacts followed by the load-bearing walls, contributing respectively 49-72% and 7-41%, depending on the category.

Figure 8 shows that the foundation contributes significantly less to total impacts in apartment buildings compared to row houses. Row houses have three storeys, while apartment buildings have six. Although the foundation of an apartment building is larger to support the greater load, its relative impact is smaller. This is because the environmental impacts of floors and load-bearing walls scale with the number of storeys, while the foundation is built only once. As a result, the repeated structural elements dominate the total impact in apartment buildings.

When comparing material alternatives within building typologies, insulation has a significantly greater impact in CLT buildings than in their concrete counterparts. This is likely due to the more extensive use of insulation materials in the interior walls of CLT structures—specifically in timber-frame walls (row house CLT) and gypsum board walls (apartment building CLT). In contrast, the concrete buildings use aerated concrete blocks for interior walls, which do not incorporate insulation materials.

4.2.3.3. Separate material level

Figure 9 presents the climate change impacts per building material across the case study buildings. A key observation is that the CLT row house clearly outperforms its concrete counterparts, while this difference is smaller between the CLT and concrete apartment buildings. Sand-lime stone is the dominant contributor to climate change impacts in the GPC and OPC row houses, exceeding the combined impact of concrete and rebar. In apartment buildings, sand-lime stone still contributes significantly to the GPC and OPC impacts, though to a lesser extent than in the row houses.

Overall, the climate change impact per GFA is lower for the GPC and OPC apartment buildings compared to their respective row house variants. As previously shown in figure 3, the total material intensity of OPC and GPC row houses and apartment buildings is similar. However, row houses use more sand-lime stone, while apartment buildings have a higher intensity of reinforced concrete (concrete and rebar). This substitution appears beneficial regarding climate change performance for the apartment buildings.

For CLT buildings, the apartment variant has a substantially higher climate change impact than the row house. This is primarily due to the greater concrete use in the CLT apartment building, as also shown in figure 3, while the use of other materials remains approximately similar. The material impact contributions data for the other impact categories are presented in SM 2. These are not discussed further, as the trends are largely similar to those observed for climate change.

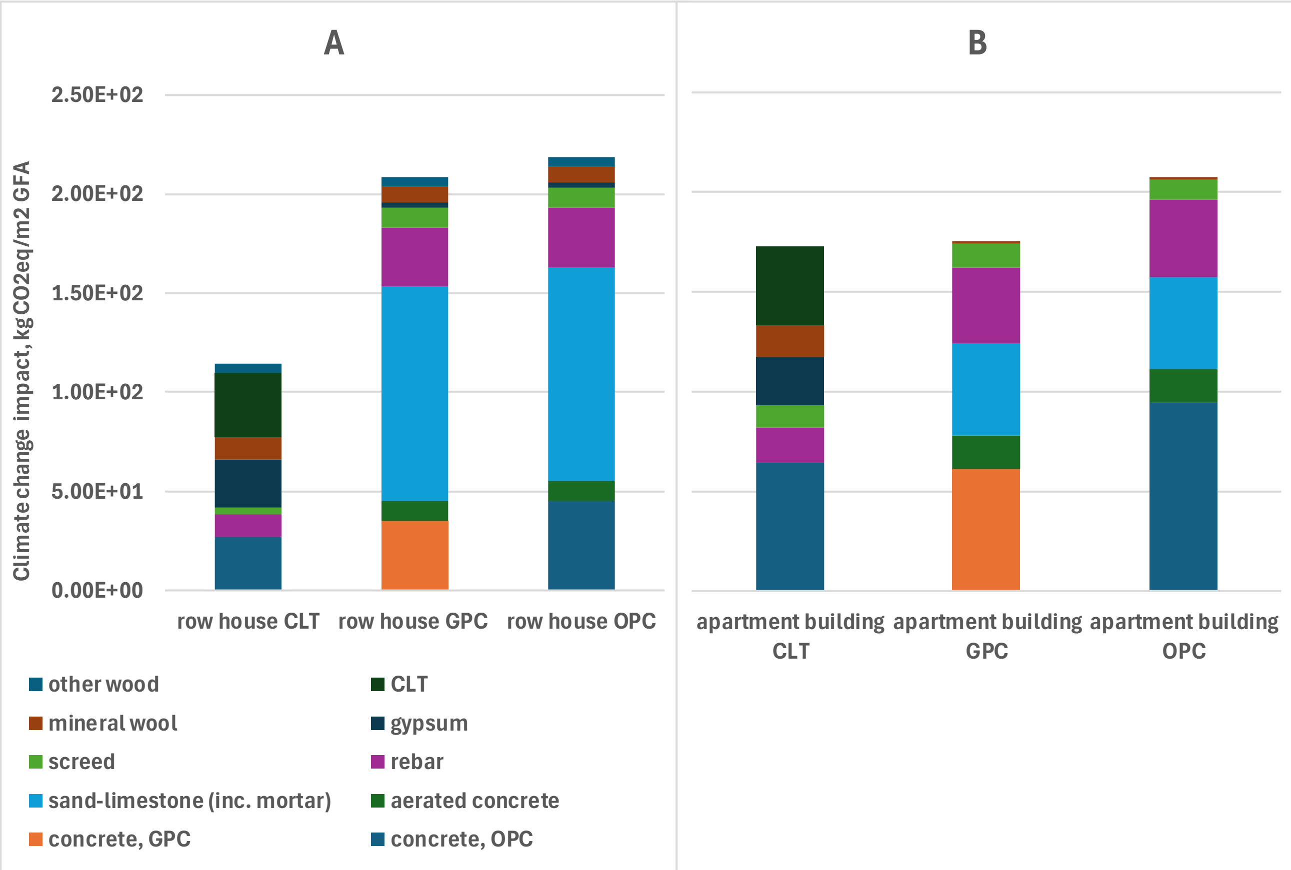


*Figure 9. Breakdown of climate change impacts per building material for the row houses (**A**) and the apartment buildings (**B**).*

4.2.4. Sensitivity Analysis

The change in environmental impacts per scenario relative to baseline is visualized in Figure10. To focus on the material-related impacts, the use stage is excluded from the analysis, as this stage may overshadow the results and is already addressed under the renewable energy scenario, see section 4.2.2.

Figure 10. Change in life cycle impacts under different scenarios for the case study row houses and apartment buildings, compared to their baseline performance. The use stage is excluded.

- SC OPT: material optimization scenario in which 20% less concrete, rebar, sand-lime stone, sand-lime stone mortar, and CLT are used for the load-bearing structure.
- SC EoL: alternative EoL scenario in which concrete is fully recycled into secondary aggregates and CLT panels are reused. The environmental benefit of these alternative

EoL pathways are considered as avoided production within the study's system boundaries.
- SC SUS GPC: More sustainable GPC production, using the waste stream silica fume instead of the energy-intensive sodium silicate as polymerization activator.

Figure 10 suggests that all three scenarios cause a reduction in environmental impacts relative to baseline across impact categories, except for ozone depletion under SC EoL – row house GPC; this category increases by approximately 13% relative to baseline.

For the concrete (OPC and GPC) row houses and apartment buildings, the optimization scenario seems to induce the highest overall reduction of impacts, displaying an approximate impact reduction range of 10-20%. The CLT buildings on the contrary showcase highest sensitivity of impacts for the reuse scenario, with a more spread-out range of 0% to -35%.

For the sustainable GPC scenario, the reduction per impact category seems to be higher for the GPC apartment building than for the GPC row house, which may be explained by the apartment building's higher GPC material intensity compared to the row house. The reduction in impacts for the GPC row house generally ranges between 2-10% and for the GPC apartment building between 5-17%.

4.3. Cost Assessment

Figure 11 presents the material cost per m2 GFA for each case study building, broken down by the major materials. It shows that sand-lime stone and CLT are the major material cost drivers for concrete (GPC and OPC) and CLT buildings respectively. Within both building typologies, OPC has the lowest material costs per m2 GFA, followed by GPC and CLT.

GPC and OPC apartment buildings both have around 30% lower material costs per m2 GFA than their equivalent row houses, largely due to the decrease in use of sand-lime stone. For the CLT buildings, this pattern is reversed as the CLT apartment building has 18% higher material costs than the CLT row house. This difference is caused by the CLT apartment building's higher concrete and CLT costs, while costs of other materials remain approximately the same. These observations align with the trend in climate change impacts when comparing row houses to their apartment building counterparts.

The CLT row house's material costs are only around 7% higher than the OPC row house's costs, while the CLT apartment building has approximately 90% higher material costs than its OPC counterpart. Within each building typology the OPC buildings are cheapest from a material costs perspective. However, note that rising CO_2 emissions prices in the EU, along with scarce supply of aggregates and high energy use cause rising concrete prices (Bisschop & de Waal, 2023). This could reduce the difference in material costs between the CLT buildings and their concrete counterparts.

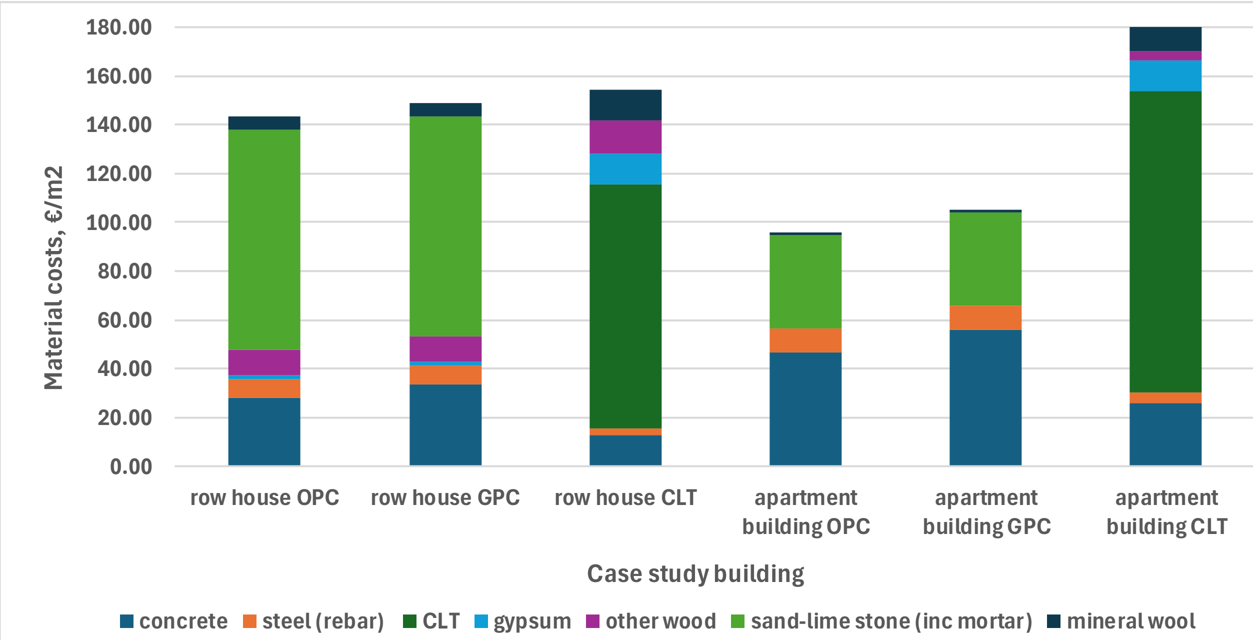


Figure 11. Material costs broken down per major building material per case study building.

Although material costs represent an important driver of a building's costs, construction and labour costs are relevant as well to consider. CLT is delivered to the building site as prefabricated elements, enabling rapid construction compared to concrete buildings. Jones et al. (2016) argued that the faster construction with CLT can reduce labour and construction costs to an extent that it offsets the initially higher material costs relative to traditional concrete alternatives. Ahmed & Arocho (2021) however reported 6.43% higher construction costs for a CLT building in England compared a traditional concrete building, including the benefits of faster construction CLT (Ahmed & Arocho, 2021).

5. Discussion

Operational energy drives environmental impacts

The study's results reveal that operational energy—the energy consumed during the building's use stage—dominates the life cycle impacts across all six case study buildings. This is in line with previous studies (Andersen et al., 2022; Y. Dong et al., 2020), although Ryberg et al. (2021) reported significantly higher contributions of materials and lower contributions of the use stage. This likely reflects their assumed building service life of 30 years, compared to the 75 years considered in this study. A shorter modelled service life increases the relative impact of materials compared to operational energy.

Even though use stage impacts are reduced by an average of 63% under a renewable energy scenario, they remain a substantial driver of environmental burden. Note that the renewable energy scenario fulfils the BENG requirements–norms that limit thermal energy use of new buildings in the Netherlands (Besluit Bouwwerken Leefomgeving, 2025). However, even under these standards, operational energy continues to generate high environmental impacts. These findings identify the building use stage as environmental hotspots, even under a renewable energy scenario and complying with the most recent Dutch standards. This suggests that addressing use stage impacts should take precedence over transitioning towards lower-impacts materials.

There are two main strategies to further reduce the environmental impacts of operational energy of buildings: (1) reducing energy consumption and (2) lowering the environmental impact per unit of energy used. Building design is especially relevant to the first strategy. For example, solar-oriented layouts, optimized insulation, and triple glazing can reduce heating demand (Sakshi et al., 2024; Y. Zhang et al., 2022), while incorporating energy-efficient appliances can lower electricity use (IEA, 2024). For some cases, such choices may conflict with material-related environmental impacts. Such trade-offs should be analysed in the context of the whole building life cycle. For instance, an increase in environmental impacts and economic costs for materials—such as for better-performing insulation materials and more efficient appliances—may be justified if it reduces overall life cycle impacts by decreasing operational energy use. The second strategy depends on low-impact energy production and distribution infrastructure, such as reducing the impacts of transmission networks and renewable energy technologies. However, this lies largely outside the scope of building design.

The identified importance of reducing operational energy impacts contrasts with current practices in the Dutch housing sector. Interviews with Dutch building policy agents highlighted that municipalities and construction companies focus on the cradle-to-gate impacts in housing construction and policy, potentially overemphasizing the importance of building materials (Personal communication, 2025). This is likely because new housing plans must comply with Dutch environmental standards for building materials, known as the Milieuprestatie Gebouwen (MPG), while regulations that account for environmental impacts across the full building life cycle are currently lacking (RVO, 2017).

To optimize the environmental performance of housing, it is therefore crucial to adopt a whole life cycle perspective in housing policy and construction practices. Current legislation however does not promote such choices, as construction companies have no strong incentive to consider use stage impacts. Therefore, it is recommended that current MPG policy is expanded to also include environmental impacts of the use phase. To support compliance with such regulations, LCA-based tools should be developed that allow construction companies to assess the environmental impact of a building during the design phase, accounting for both materials and simulated operational energy use.

OPC outperforms GPC economically and environmentally

Although GPC is often presented as a promising low-carbon alternative to OPC (Talaat et al., 2023; Zannerni et al., 2020), the study's results show that GPC outperforms OPC only in the climate change impact category. In most other environmental impact categories—including acidification, eutrophication, and human toxicity—GPC performs worse than OPC. This indicates that a focus on climate change can lead to environmental burden shifting, a concern identified as well by Sona & Sangeetha (2025), who also attribute these higher impacts to the use of alkaline activators. Compared to their CLT equivalents, the GPC row house performs worse in 15 out of 16 environmental impact categories and the GPC apartment building in 12 out of 16, including climate change in both cases. This suggests that a CLT-based structure is environmentally favourable over a GPC design for both low and mid-rise housing, also when optimizing for minimal climate change impacts.

Sensitivity analysis revealed that replacing sodium silicate with silica fume in GPC mixtures reduced environmental impacts (excluding the use stage) by 10% for row houses and 14% for apartment buildings—driven by the higher GPC intensity in the latter. This substitution caused only a ~2% increase in material costs for GPC. Further reductions of environmental impacts could be achieved by substituting NaOH, another alkaline activator used in this study's GPC mix. The findings suggest that due to conventional alkali activators use, current GPC mixes do not provide an environmentally sounder alternative for OPC.

However, green activators—which are available at a reasonable price compared to conventional activators—are a promising way to mitigate the impacts of current GPC mixes. Moreover, optimization of GPC mixes to reduce the need for activators represents a second strategy to mitigate GPC's impacts, while potentially lowering material costs related to activators. Additional research into the mechanical performance of such GPC mixes is required. Moreover, funding for scale-up is needed to enable application of alternative GPC mixes in construction. Semi-governmental organizations such as Rijkswaterstaat—the executive agency of the Ministry of Infrastructure and Water Management in the Netherlands—are ideally positioned to create a protected space from market influences, for instance by providing funding and applying GPC in their infrastructure projects.

Additionally, while GPC has circularity advantages—replacing cement with industrial by-products—results show that such substitution of primary product by a recyclate does not necessarily lead to improved environmental. This conflicts with circularity and waste management frameworks, such as the Waste Framework Directive proposed by the EU, which prioritize recycling over disposal (European Commission, n.d.). This study shows that such waste management hierarchies should be used carefully and that environmental performance of circular alternatives should always be assessed and compared quantitatively to the product they substitute.

Sand-lime stone: hidden relevance

The results reveal that the sand-lime stone bricks used for the OPC and GPC buildings significantly drive buildings' environmental impacts and material costs. For instance, sand-lime stone contributes on average 52% to the climate change material impacts of the GPC and OPC row houses; and 24% for the GPC and OPC apartment buildings. This seems to be in line with their material intensities—approximately 538 and 229 kg/m2 GFA for the row houses and apartment buildings respectively, presenting ca 52% and 22% of the material intensities. Regarding economics, sand-lime stone represents an even higher driver, accounting for an average 62% of the material costs of the GPC and OPC row houses and an average 38% of the material costs for the GPC and OPC apartment buildings.

Despite its clear relevance, the environmental impact of sand-lime stone is underexplored in literature, which typically emphasizes reinforced concrete (Abed et al., 2022; Tran et al., 2025). This focus likely reflects the global use of concrete in structural applications, whereas sand-lime stone is primarily used in the Dutch construction context and a few other Northern European countries (BouwTotaal, 2025; Esposito et al., 2018). Notably, no scientific studies were found assessing the environmental performance of sand-lime stone in load-bearing structures, indicating a significant knowledge gap. While Dutch producers market sand-lime stone as a sustainable and fully circular solution, based on proprietary LCAs, these claims lack independent scientific evaluation. Given its substantial environmental and economic contribution, sand-lime stone should be a key focus in future sustainability assessments of Dutch construction practices.

In the case study buildings, sand-lime stone is used for the load-bearing walls in both the GPC and OPC designs. To reduce environmental impacts, this material can be substituted with CLT panels. Such a replacement would result in a hybrid structural system, combining CLT load-bearing walls with reinforced concrete floors. This approach targets the most environmentally impactful material in the conventional design, while retaining the cost-effectiveness and structural benefits of reinforced concrete for the floor slabs.

CLT construction shows mixed results

From an environmental perspective and only considering cradle-to-gate impacts, the CLT row house performs better in 11 out of 16 impact categories than its GPC and OPC equivalents, while only having around 7% higher material costs. Previous studies report similar environmental performance of CLT buildings compared to reinforced concrete counterparts (Andersen et al., 2022; Robertson et al., 2012; Ryberg et al., 2021).

In contrast, the CLT apartment building has the worst environmental performance in 10 out of 16 impact categories and approximately 90% higher material costs than its GPC and OPC equivalents. This difference between the two building typologies seems have multiple causes: (1) the concrete apartment buildings have lower environmental impacts and economic costs since than their row house counterparts as they have a similar overall material intensity, but substitute sand-lime stone (high environmental burden and costs) by cheaper and better environmentally performing reinforced concrete; (2) The impacts and costs of the CLT apartment building are higher than the CLT row house—primarily due to higher concrete use—for instance climate change impacts of the materials, including transport to building site, are 114 kg CO2eq/m2 for the CLT row house and 173 kg CO2eq/m2 for the CLT apartment building. This overall trend is similar across all impact categories. Material costs increase from €143.51/m2 (CLT row house) to €181.63/m2 (CLT apartment building).

Besides CLT and reinforced concrete, gypsum is a high driver of environmental impacts as well for the CLT buildings. Gypsum has a high material intensity—63 kg/m2 GFA and 63.8 kg/m2 GFA for the CLT row house and apartment building respectively—related to its use as fire-protection agent in timber buildings (Allan & Phillips, 2021; Duan et al., 2022). Its environmental impacts can be as high as impacts of a buildings CLT itself (Duan et al., 2022). Identifying alternative fire-proofing methods is therefore essential. Pierobon et al. (2019) found that adding an additional layer of CLT can replace gypsum wallboard as fire-proofing agent and overall reduce environmental impacts. However, as CLT is expensive this strategy may drive up material costs (Ahmed & Arocho, 2021). It is therefore important to explore and develop alternative fire-protection materials that are economically feasible and have a low environmental burden.

The scenarios optimization and EoL showed that lighter structural design and reuse of concrete and CLT at the building's demolition are both effective ways to reduce the life cycle impacts of

CLT buildings. Although such strategies to reduce CLT's environmental impact are useful, CLT use requires a high material mass per unit area, as CLT panels are made of massive wood. Although this gives the material excellent strength, it also raises environmental impacts and economic costs. When the high strength of CLT is not required, lighter timber elements such as HSB may be more suited to both reduce environmental impacts and material costs.

In the context of Dutch housing policy, the higher material cost of CLT construction remains a barrier to large-scale adoption, particularly in a competitive and cost-sensitive construction market. While subsidies for timber construction could stimulate demand, they risk favouring one material—CLT—over potentially more suitable or innovative alternatives.

A more balanced and effective policy approach could be the implementation of a differentiated environmental tax on building materials, based on their life cycle impacts. This would internalise the environmental costs of conventional materials like concrete, steel, and sand-lime stone, thereby levelling the playing field for potentially lower-impact alternatives such as timber products. Given the construction sector's traditionally slow adaptation to innovation (Jones et al., 2016), the government could also take a facilitating role by supporting knowledge-sharing platforms that highlight best practices and practical guidance on construction with alternative materials that have a low environmental impact.

Temporary biogenic carbon storage

The study did not include temporary storage of carbon in timber products in the LCA's impact assessment phase, as the baseline scenario assumes timber components are incinerated at EoL, releasing stored biogenic carbon back into the atmosphere. However, there is ongoing debate on how biogenic carbon should be accounted for in LCA, particularly given uncertainties around the EoL treatment of biobased materials (Andersen et al., 2022; Hoxha et al., 2020; Younis & Dodoo, 2022). In future scenarios, incineration may be combined with carbon capture and storage, or higher rates of reuse and recycling may prolong biogenic carbon sequestration, thus strengthening the argument that biogenic carbon storage may help reduce climate change impacts of the built environment (Andersen et al., 2022).

Under the EoL scenario, the reuse of CLT panels results in continued storage of the biogenic carbon contained in these panels after building demolition. The potential climate change impact when fully including this temporary carbon storage in impact assessment is estimated here. As detailed in Section 3.3.2, 73% of the CLT panels at end-of-life are assumed to be reused and enter a subsequent life cycle. The CLT loss fraction is assumed to be incinerated. The average biogenic carbon content of CLT is 643.6 kg $CO_2eq/m3$ (Younis & Dodoo, 2022). Based on material intensities of 88.7 kg/m2 GFA and 109.3 kg/m2 GFA, this equates to biogenic carbon storage of 94.1 and 115.9 kg $CO_2eq/m2$ for the CLT row house and apartment building, respectively. When distributed over a 75-year service life, this corresponds to 1.3 and 1.5 kg $CO_2eq/m2/year$—potentially reducing baseline cradle-to-grave life cycle climate impacts of the CLT row house and CLT apartment building by 7% and 8%, respectively, representing a significant reduction.

However, it should be noted that although reuse extends the period during which carbon remains stored, this carbon will likely re-enter the atmosphere eventually through biological degradation or incineration (Younis & Dodoo, 2022). It may therefore be more logical to analyse temporary carbon storage in timber products at the regional or national building stock level rather than for individual buildings, as also proposed by Hart et al. (2021). This means that an increase in total carbon stored in timber building materials can reduce climate impacts, provided that carbon stocks in timber forestry are maintained. To evaluate this, a stock-and-flow model should be developed to estimate the total mass of timber — and the carbon it stores

— in Dutch buildings over time. Such a model should also account for growth rates and carbon sequestration in forestry.

Limitations

This study is subject to several limitations. First, while the case study buildings are published as representative of construction practices in the Netherlands, they may not fully capture the diversity of construction practices across locations, limiting generalizability.

Second, limitations inherent to the LCA methodology apply. These include methodological cut-offs (e.g., exclusion of operational water use and repair/maintenance), assumptions related to material intensity and timber construction, and the adoption of a 75-year service life—longer than the commonly used 50-year timeframe—despite uncertainties surrounding actual building lifespans. The chosen service life strongly affects LCA outcomes, as longer included service life periods increase the contribution of the use stage impacts while decreasing the impact of material production.

The omission of maintenance and repair represents a limitation of this study, particularly given the relatively long service life assumed for the case study buildings, which would likely require periodic replacements. Although maintenance and repair can significantly influence environmental performance, they are often simplified or excluded in building LCAs (Grant et al., 2014). An underlying reason is the lack in service life data for building materials—especially for relatively new materials such as CLT. Where data exists, it tends to vary widely, with notable discrepancies between manufacturer-reported and third-party values (Aktas & Bilec, 2012). It is therefore recommended that LCI data on maintenance and repair activities are developed, preferably tailored to specific climate conditions, as degradation of building materials may depend strongly on its environment (Aktas & Bilec, 2012). This would support more complete and consistent building LCA outcomes.

In addition, the assumed lower operational energy use of CLT buildings compared to their concrete counterparts was based on research by Andersen et al. (2022), whose case studies were located in Norway. It was further assumed that the relative difference in operational energy demand identified by Andersen et al. (2022) could be extrapolated to the case study buildings used in this research. However, due to differences in climate conditions and construction techniques between Norway and the Netherlands, the representativeness of this assumption is uncertain. Further research into the thermal performance of CLT buildings under Dutch climatic and construction conditions is therefore needed.

Data representativeness is also limited by the use of generic Ecoinvent processes, which may not accurately reflect supplier- or region-specific environmental impacts. Moreover, the baseline model does not credit the system for secondary products produced from EoL material, while the SC EoL credits the system for avoided production of CLT and gravel. This may cause an overestimation of environmental impact reduction achieved by the SC EoL compared to the baseline model.

Finally, in the cost assessment, only material costs were considered quantitatively. However, CLT buildings are typically constructed more quickly than their concrete equivalents, potentially leading to lower labour and construction costs (Ahmed & Arocho, 2021). These time- and cost-saving benefits were not fully captured. In addition, variation in maintenance costs across structural systems was not accounted for. A more comprehensive economic analysis would be necessary to reflect the full range of cost implications.

6. Conclusion

The Netherlands faces a pressing dual challenge: providing enough new housing while reducing the high environmental burden of construction. This thesis addresses this challenge through a comparative LCA and cost assessment of OPC, GPC, and CLT as structural materials for typical Dutch low- and mid-rise housing.

Over the full life cycle, the CLT row house and apartment building performed best in 12 and 13 out of 16 impact categories respectively, partly due to lower operational energy demand. A separate cradle-to-construction site analysis confirmed that the CLT row house achieved a 33% lower climate change impact than the OPC variant, while the CLT apartment building achieved a modest 17% reduction but had the highest impacts in 10 other categories. GPC buildings performed worse than OPC in all categories except climate change, mainly due to the high impacts of alkaline activators. Sand-lime stone emerged as a major hotspot in the concrete designs.

The results show that although ongoing decarbonization of the Dutch energy grid will reduce the relative importance of operational energy, it remains a dominant contributor to life cycle impacts. This highlights the need for integrated strategies that address both material-related and operational energy impacts over a building's lifetime. No single material–typology combination proved superior in both environmental and economic terms; however, the CLT row house combined significant environmental benefits with only ~7% higher material costs than OPC, making it a promising option for low-rise sustainable housing development in the Netherlands.

Future research should explore greener GPC activators and assess the full life cycle impacts of sand-lime stone. Policy should internalize the environmental costs of building materials through taxation, incentivize the use of lower-impact alternatives, and expand current norms to address the life cycle impacts of entire buildings rather than just individual materials. By providing an integrated environmental and economic assessment of structural material choices, this thesis offers practical insights for designers, builders, and policymakers seeking to address the Netherlands' dual housing and sustainability challenge.

7. References

Abed, J., Rayburg, S., Rodwell, J., & Neave, M. (2022). A Review of the Performance and Benefits of Mass Timber as an Alternative to Concrete and Steel for Improving the Sustainability of Structures. *Sustainability*, *14*(9), 5570. https://doi.org/10.3390/su14095570

Afzal, M., Liu, Y., Cheng, J. C. P., & Gan, V. J. L. (2020). Reinforced concrete structural design optimization: A critical review. *Journal of Cleaner Production*, *260*, 120623. https://doi.org/10.1016/j.jclepro.2020.120623

Ahmed, S., & Arocho, I. (2021). Analysis of cost comparison and effects of change orders during construction: Study of a mass timber and a concrete building project. *Journal of Building Engineering*, *33*, 101856. https://doi.org/10.1016/j.jobe.2020.101856

Aktas, C. B., & Bilec, M. M. (2012). Service life prediction of residential interior finishes for life cycle assessment. *The International Journal of Life Cycle Assessment*, *17*(3), 362–371. https://doi.org/10.1007/s11367-011-0367-6

Allan, K., & Phillips, A. R. (2021). Comparative Cradle-to-Grave Life Cycle Assessment of Low and Mid-Rise Mass Timber Buildings with Equivalent Structural Steel Alternatives. *Sustainability*, *13*(6), 3401. https://doi.org/10.3390/su13063401

Almutairi, A. L., Tayeh, B. A., Adesina, A., Isleem, H. F., & Zeyad, A. M. (2021). Potential applications of geopolymer concrete in construction: A review. *Case Studies in Construction Materials*, *15*, e00733. https://doi.org/10.1016/j.cscm.2021.e00733

Al-Shathr, B., Shamsa, M., & al-Attar, T. (2018). Relationship between amorphous silica in source materials and compressive strength of geopolymer concrete. *MATEC Web of Conferences*, *162*, 02019. https://doi.org/10.1051/matecconf/201816202019

Amran, Y. H. M., Alyousef, R., Alabduljabbar, H., & El-Zeadani, M. (2020). Clean production and properties of geopolymer concrete; A review. *Journal of Cleaner Production*, *251*, 119679. https://doi.org/10.1016/j.jclepro.2019.119679

Andersen, J. H., Rasmussen, N. L., & Ryberg, M. W. (2022). Comparative life cycle assessment of cross laminated timber building and concrete building with special focus on biogenic carbon. *Energy and Buildings*, *254*, 111604. https://doi.org/10.1016/j.enbuild.2021.111604

Appolloni, L., & D'Alessandro, D. (2021). Housing Spaces in Nine European Countries: A Comparison of Dimensional Requirements. *International Journal of Environmental Research and Public Health*, *18*(8), 4278. https://doi.org/10.3390/ijerph18084278

Assi, L., Carter, K., Deaver, E. (Eddie), Anay, R., & Ziehl, P. (2018). Sustainable concrete: Building a greener future. *Journal of Cleaner Production*, *198*, 1641–1651. https://doi.org/10.1016/j.jclepro.2018.07.123

Balasbaneh, A. T., & Sher, W. (2024). A systematic literature review of life cycle sustainability assessment of mass timber in the construction industry toward circular economy. *Environment, Development and Sustainability*. https://doi.org/10.1007/s10668-024-05377-9

Bamshad, O., & Ramezanianpour, A. M. (2024). Optimizing concrete for circularity: a comparative life cycle assessment of geopolymer and ordinary concrete. *Environmental Science and Pollution Research*. https://doi.org/10.1007/s11356-024-34863-w

BCI Gebouw. (2025, February 10). *Referentiegebouwen [data set]*.

Besluit Bouwwerken Leefomgeving (2025). https://wetten.overheid.nl/BWBR0041297/2025-01-01/0/Hoofdstuk4/Afdeling4.4/Paragraaf4.4.1/Artikel4.148/informatie

Bisschop, P., & de Waal, L. (2023). *Stand van de Bouw: de bouwsector in economisch perspectief*.

BouwTotaal. (2025, May 16). *Waarom is Nederland een kalkzandsteenland?* Https://Www.Bouwtotaal.Nl/2023/05/Waarom-Is-Nederland-Een-Kalkzandsteenland/.

Bruinsma, M., Bachaus, A., & Nusselder, S. (2021). *Circulair beton bij Rijkswaterstaat*.

CBS. (2024, December 23). *Verbrandingswaarden motorbrandstoffen; energiedrager*.

CBS. (2025, March 13). *Energieverbruik particuliere woningen; woningtype en regio's*.

Chen, C. X., Pierobon, F., & Ganguly, I. (2019). Life Cycle Assessment (LCA) of Cross-Laminated Timber (CLT) Produced in Western Washington: The Role of Logistics and Wood Species Mix. *Sustainability*, *11*(5), 1278. https://doi.org/10.3390/su11051278

Circle Economy. (2025, February 9). *Construction in a changing climate*.

Collivignarelli, M. C., Cillari, G., Ricciardi, P., Miino, M. C., Torretta, V., Rada, E. C., & Abbà, A. (2020). The Production of Sustainable Concrete with the Use of Alternative Aggregates: A Review. *Sustainability*, *12*(19), 7903. https://doi.org/10.3390/su12197903

D'Amico, B., Pomponi, F., & Hart, J. (2021). Global potential for material substitution in building construction: The case of cross laminated timber. *Journal of Cleaner Production*, *279*, 123487. https://doi.org/10.1016/j.jclepro.2020.123487

Darby, H., Elmualim, A. A., & Kelly, F. (2013, April 23). A case study to investigate the life cycle carbon emissions and carbon storage capacity of a cross laminated timber, multi-storey residential building. *Sustainable Building Conference*.

De Herde, A., & Evrard, A. (2005). *Beton en Rationeel Energiegebruik*.

Dong, W., Wang, Z., Zhou, J., & Gong, M. (2021). Experimental study on bending properties of cross-laminated timber-bamboo composites. *Construction and Building Materials*, *300*, 124313. https://doi.org/10.1016/j.conbuildmat.2021.124313

Dong, Y., Qin, T., Zhou, S., Huang, L., Bo, R., Guo, H., & Yin, X. (2020). Comparative Whole Building Life Cycle Assessment of Energy Saving and Carbon Reduction Performance of Reinforced Concrete and Timber Stadiums—A Case Study in China. *Sustainability*, *12*(4), 1566. https://doi.org/10.3390/su12041566

Duan, Z., Sun, Q., Zhang, Q., & Huang, Q. (2022). Comparative life cycle assessment of a reinforced concrete residential building with equivalent cross laminated timber alternatives in China. *Journal of Building Engineering*, *62*, 105357. https://doi.org/10.1016/j.jobe.2022.105357

Elkabany, S. N., Elkordy, A. M., & Sobh, H. A. (2020). Optimization of Load-Bearing concrete Wall Using Genetic Algorithm To achieve Mechanically Integrated Behavior. *IOP Conference Series: Materials Science and Engineering*, *974*(1), 012011. https://doi.org/10.1088/1757-899X/974/1/012011

Esposito, R., Jafari, S., Ravenshorst, G. J. P., Schipper, H. R., & Rots, J. G. (2018). Influence of the behaviour of calcium silicate brick and element masonry on the lateral capacity of structures. *10th Australasian Masonry Conference*.

European Commission. (n.d.). *Waste Framework Directive*. Retrieved June 5, 2025, from https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en#targets

European Commission. (2010). *International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance* (1st ed.). Publications Office of the European Union.

Fishman, T., Mastrucci, A., Peled, Y., Saxe, S., & van Ruijven, B. (2024). RASMI: Global ranges of building material intensities differentiated by region, structure, and function. *Scientific Data*, *11*(1), 418. https://doi.org/10.1038/s41597-024-03190-7

Grant, A., Ries, R., & Kibert, C. (2014). Life Cycle Assessment and Service Life Prediction. *Journal of Industrial Ecology*, *18*(2), 187–200. https://doi.org/10.1111/jiec.12089

Gu, H., Liang, S., Pierobon, F., Puettmann, M., Ganguly, I., Chen, C., Pasternack, R., Wishnie, M., Jones, S., & Maples, I. (2021). Mass Timber Building Life Cycle Assessment Methodology for the U.S. Regional Case Studies. *Sustainability*, *13*(24), 14034. https://doi.org/10.3390/su132414034

Guinee, J. B. (2002). *Handbook on Life Cycle Assessment* (H. de Bruijn, R. van Duin, M. A. J. Huijbregts, J. B. Guinee, M. Gorree, R. Heijungs, G. Huppes, R. Kleijn, A. de Koning, L. van Oers, A. Wegener Sleeswijk, S. Suh, & H. A. Udo de Haes, Eds.; Vol. 7). Springer Netherlands. https://doi.org/10.1007/0-306-48055-7

Habert, G., Miller, S. A., John, V. M., Provis, J. L., Favier, A., Horvath, A., & Scrivener, K. L. (2020). Environmental impacts and decarbonization strategies in the cement and concrete industries. *Nature Reviews Earth & Environment*, *1*(11), 559–573. https://doi.org/10.1038/s43017-020-0093-3

Hart, J., D'Amico, B., & Pomponi, F. (2021). Whole-life embodied carbon in multistory buildings: Steel, concrete and timber structures. *Journal of Industrial Ecology*, *25*(2), 403–418. https://doi.org/10.1111/jiec.13139

Hoogervorst, N. (2017). *Toekomstbeeld klimaatneutrale warmtenetten in Nederland*.

Hoxha, E., Passer, A., Saade, M. R. M., Trigaux, D., Shuttleworth, A., Pittau, F., Allacker, K., & Habert, G. (2020). Biogenic carbon in buildings: a critical overview of LCA methods. *Buildings and Cities*, *1*(1), 504–524. https://doi.org/10.5334/bc.46

IEA. (2024, April 4). *More efficient and flexible buildings are key to clean energy transitions*.

International Organization for Standardization. (2006). *ISO 14040:2006: Environmental Management - Life cycle assessment - principles and framework. ISO.* .

Jones, K., Stegemann, J., Sykes, J., & Winslow, P. (2016). Adoption of unconventional approaches in construction: The case of cross-laminated timber. *Construction and Building Materials*, *125*, 690–702. https://doi.org/10.1016/j.conbuildmat.2016.08.088

Ju, J., Feng, Y., Li, H., & Xu, C. (2023). Resource utilization of strongly acidic wastewater and red gypsum by a harmless self-treatment process. *Process Safety and Environmental Protection*, *172*, 594–603. https://doi.org/10.1016/j.psep.2023.02.067

Liang, S., Gu, H., Bergman, R., & Kelley, S. S. (2020). Comparative life-cycle assessment of a mass timber building and concrete alternative. *Wood and Fiber Science*, *52*(2), 217–229. https://doi.org/10.22382/wfs-2020-019

Liu, Y., Guo, H., Sun, C., & Chang, W.-S. (2016). Assessing Cross Laminated Timber (CLT) as an Alternative Material for Mid-Rise Residential Buildings in Cold Regions in China—A Life-Cycle Assessment Approach. *Sustainability*, *8*(10), 1047. https://doi.org/10.3390/su8101047

Mayencourt, P., & Mueller, C. (2019). Structural Optimization of Cross-laminated Timber Panels in One-way Bending. *Structures*, *18*, 48–59. https://doi.org/10.1016/j.istruc.2018.12.009

Mendes, B. C., Pedroti, L. G., Vieira, C. M. F., Marvila, M., Azevedo, A. R. G., Franco de Carvalho, J. M., & Ribeiro, J. C. L. (2021). Application of eco-friendly alternative activators in alkali-activated materials: A review. *Journal of Building Engineering*, *35*, 102010. https://doi.org/10.1016/j.jobe.2020.102010

Migoni Alejandre, E., Koskamp, G., van de Leur, M., Wandl, A., & van Timmeren, A. (2024). Quantifying the life cycle emissions of hybrid structures with advanced bio- and conventional materialization for low-embodied carbon urban densification of the Amsterdam Metropolitan Area. *Journal of Cleaner Production*, *483*, 144273. https://doi.org/10.1016/j.jclepro.2024.144273

Mohapatra, S. S., Mishra, J., Nanda, B., & Patro, S. K. (2022). A review on waste-derived alkali activators for preparation of geopolymer composite. *Materials Today: Proceedings*, *56*, 440–446. https://doi.org/10.1016/j.matpr.2022.01.400

Monteiro, P. J. M., Miller, S. A., & Horvath, A. (2017). Towards sustainable concrete. *Nature Materials*, *16*(7), 698–699. https://doi.org/10.1038/nmat4930

Muehleisen, N. (2021). *Ontwikkelingen betreffende hoofdbestanddelen voor klinkergebaseerde cementen en geopolymeren*.

Munir, Q., Abdulkareem, M., Horttanainen, M., & Kärki, T. (2023). A comparative cradle-to-gate life cycle assessment of geopolymer concrete produced from industrial side streams in comparison with traditional concrete. *Science of The Total Environment*, *865*, 161230. https://doi.org/10.1016/j.scitotenv.2022.161230

Nguyen, D. L., Luedtke, J., Nopens, M., & Krause, A. (2023). Production of wood-based panel from recycled wood resource: a literature review. *European Journal of Wood and Wood Products*, *81*(3), 557–570. https://doi.org/10.1007/s00107-023-01937-4

Pant, R., Castellani, V., Sala, S., Benini, L., De Laurentiis, V., & Vidal-Legaz, B. (2019). *Suggestions for the update of the Environmental Footprint Life Cycle Impact Assessment – Impacts due to resource use, water use, land use, and particulate matter*. Publications Office. https://doi.org/doi/10.2760/78072

Passarelli, R. (2018, May). *The Environmental Impact of Reused CLT Panels: Study of a Single-Storey Commercial Building In Japan*.

Pierobon, F., Huang, M., Simonen, K., & Ganguly, I. (2019). Environmental benefits of using hybrid CLT structure in midrise non-residential construction: An LCA based comparative case study in the U.S. Pacific Northwest. *Journal of Building Engineering*, *26*, 100862. https://doi.org/10.1016/j.jobe.2019.100862

Rijksoverheid. (n.d.). *Programma Woningbouw, Doel: 100.000 woningen per jaar gemiddeld*. Retrieved May 28, 2025, from https://mn.datawonen.nl/mosaic/programma-woningbouw/doel--100-000-woningen-per-jaar-gemiddeld#:~:text=Met%20programma%20woningbouw%20is%20in,2022%20tot%20en%20met%202030.

Rijksoverheid. (2025). *Besluit bouwwerken leefomgeving*. https://wetten.overheid.nl/BWBR0041297/2025-01-01#Hoofdstuk4.

Robertson, A. B., Lam, F. C. F., & Cole, R. J. (2012). A Comparative Cradle-to-Gate Life Cycle Assessment of Mid-Rise Office Building Construction Alternatives: Laminated Timber or Reinforced Concrete. *Buildings*, *2*(3), 245–270. https://doi.org/10.3390/buildings2030245

RVO. (2017, June 1). *MilieuPrestatie Gebouwen - MPG*. https://www.rvo.nl/onderwerpen/wetten-en-regels-gebouwen/milieuprestatie-gebouwen-mpg

RVO. (2022). *Aardgasvrije gebouwde omgeving: de realisatie en beïnvloedende factoren*.

RVO. (2024, February 16). *Energieprestatie - BENG*.

Ryberg, M. W., Ohms, P. K., Møller, E., & Lading, T. (2021). Comparative life cycle assessment of four buildings in Greenland. *Building and Environment*, *204*, 108130. https://doi.org/10.1016/j.buildenv.2021.108130

Sakshi, Anushka Jain, & Sunakshi Shokeen. (2024). Solar-Optimized Building Design. *International Research Journal on Advanced Engineering and Management (IRJAEM)*, *2*(09), 2956–2963. https://doi.org/10.47392/IRJAEM.2024.0437

Sandanayake, M., Zhang, G., & Setunge, S. (2019). Estimation of environmental emissions and impacts of building construction – A decision making tool for contractors. *Journal of Building Engineering*, *21*, 173–185. https://doi.org/10.1016/j.jobe.2018.10.023

Sijm, J. (2024). *Verkenning van toekomstige ontwikkelingen en uitdagingen voor een klimaatneutraal elektriciteitssysteem in Nederland, 2030-2050*.

Sona, S., & Sangeetha, S. P. (2025). Eco-friendly alternative activators derived from industrial wastes for the sustainable production of two-part geopolymer concrete at low cost. *Construction and Building Materials*, *467*, 140374. https://doi.org/10.1016/j.conbuildmat.2025.140374

Talaat, A., Emad, A., & Kohail, M. (2023). Environmental Impact Assessment for Performance-Oriented Geopolymer Concrete Research. *Journal of Materials in Civil Engineering*, *35*(1). https://doi.org/10.1061/(ASCE)MT.1943-5533.0004526

Todinov, M. (2024). Lightweight Designs and Improving the Load-Bearing Capacity of Structures by the Method of Aggregation. *Mathematics*, *12*(10), 1522. https://doi.org/10.3390/math12101522

Tokede, O. O., Rodgers, G., Waschl, B., Salter, J., & Ashraf, M. (2022). Harmonising life cycle sustainability thinking in material substitution for buildings. *Resources, Conservation and Recycling*, *185*, 106468. https://doi.org/10.1016/j.resconrec.2022.106468

Tran, C. N. N., Illankoon, I. M. C. S., & Tam, V. W. Y. (2025). Decoding Concrete's Environmental Impact: A Path Toward Sustainable Construction. *Buildings*, *15*(3), 442. https://doi.org/10.3390/buildings15030442

Tupenaite, L., Kanapeckiene, L., Naimaviciene, J., Kaklauskas, A., & Gecys, T. (2023). Timber Construction as a Solution to Climate Change: A Systematic Literature Review. *Buildings*, *13*(4), 976. https://doi.org/10.3390/buildings13040976

Verma, M., Dev, N., Rahman, I., Nigam, M., Ahmed, Mohd., & Mallick, J. (2022). Geopolymer Concrete: A Material for Sustainable Development in Indian Construction Industries. *Crystals*, *12*(4), 514. https://doi.org/10.3390/cryst12040514

Wang, B., Yan, L., Fu, Q., & Kasal, B. (2021). A Comprehensive Review on Recycled Aggregate and Recycled Aggregate Concrete. *Resources, Conservation and Recycling*, *171*, 105565. https://doi.org/10.1016/j.resconrec.2021.105565

Ycharts. (2025, April). *20-Year Breakeven Inflation Rate*. https://ycharts.com/indicators/20year_breakeven_inflation_rate#:~:text=Basic%20Info,long%20term%20average%20of%202.24%25.

Younis, A., & Dodoo, A. (2022). Cross-laminated timber for building construction: A life-cycle-assessment overview. *Journal of Building Engineering*, *52*, 104482. https://doi.org/10.1016/j.jobe.2022.104482

Zannerni, G. M., Fattah, K. P., & Al-Tamimi, A. K. (2020). Ambient-cured geopolymer concrete with single alkali activator. *Sustainable Materials and Technologies*, *23*, e00131. https://doi.org/10.1016/j.susmat.2019.e00131

Zayed, T. M., Halpin, D. W., & Basha, I. M. (2005). Productivity and delays assessment for concrete batch plant-truck mixer operations. *Construction Management and Economics*, *23*(8), 839–850. https://doi.org/10.1080/01446190500184451

Zhang, C., Hu, M., Yang, X., Miranda-Xicotencatl, B., Sprecher, B., Di Maio, F., Zhong, X., & Tukker, A. (2020). Upgrading construction and demolition waste management from downcycling to recycling in the Netherlands. *Journal of Cleaner Production*, *266*, 121718. https://doi.org/10.1016/j.jclepro.2020.121718

Zhang, Y., Jie, P., Liu, C., & Li, J. (2022). Optimizing environmental insulation thickness of buildings with CHP-based district heating system based on amount of energy and energy grade. *Frontiers in Energy*, *16*(4), 613–628. https://doi.org/10.1007/s11708-020-0700-5

Supplementary Material 1

Supplementary material 1 details calculations and data sources for the LCA and cost assessment. It also presents material intensity and cost assessment visualizations.

Supplementary Material 2

Supplementary material 2 presents the analyses of output from openLCA and the visualizations of LCA results.