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Parametrization of variables affecting the whole life carbon performance of nearly zero energy residential building renovation

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ABSTRACT

This research investigates the integration of life cycle impact assessment (LCIA) and building performance simulation (BPS) to evaluate the whole-life carbon performance of residential building renovations. A representative post-World War II single-family house in Belgium is used to analyze six renovation scenarios that combine petrochemical and bio-based materials. By coupling LCIA with BPS, the study captures both embodied and operational greenhouse gas (GHG) emissions across the building lifecycle, emphasizing the tradeoffs inherent in materials selection and renovation design. The adoption of a dynamic building performance simulation approach enables the accounting of variations in the electricity mix and future energy demand patterns. Results demonstrate that ultra-low energy renovations can reduce total emissions (embodied and operational) by 70 % compared to the base case non-renovated building, reaching a value of 11.7 $kgCO_2e/(m^2{\cdot}y)$. However, even this scenario does not meet the Danish total GHG emissions threshold of 8.2 $kgCO_2e/(m^2{\cdot}y)$. Sensitivity analyses highlight the influence of parameters like heat pump efficiency, airtightness, and photovoltaic system performance. Scenarios using bio-based insulation achieve up to a 7 % reduction in embodied emissions compared to those using petrochemical materials. This innovative approach provides a comprehensive framework to balance operational and embodied emissions, offering actionable insights for designers and policymakers to align with European zero-carbon targets while addressing the complexities of renovating existing building stocks.

Abbreviations

AHU	Air Handling Unit
BC	Base Case
BES	Building Energy Simulation
BPS	Building Performance Simulation
CDD	Cooling Degree Days
CLT	Cross-Laminated Timber
COP	Coefficient of Performance
DHW	Domestic Hot Water
EE	Elementary Effect
EER	Energy Efficiency Ratio
EF	Emission Factor
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate
EPDs	Environmental Product Declarations
ETICS	External Thermal Insulation Composite System
FAST	Fourier amplitude sensitivity test variance
GFA	Gross Floor Area
GHG	Greenhouse gas
GWP	Global Warming Potential
HDD	Heating Degree Days
HRUs	Heat Recovery Units
LCA	Lifecycle Assessment
LCIA	Life Cycle Impact Assessment
NZEB	Net-Zero Energy Building

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PE	Primary Energy
PEF	Product Environmental Footprint
PV	Photovoltaic
RCP	Representative Concentration Pathway
WWR	Window-to-Wall Ratio

1. Introduction

1.1. Study background

In 2024, global temperatures surpassed the +1.5 °C threshold relative to pre-industrial averages, marking the hottest year on record [19]. Despite a reduction in energy intensity since 2015, building emissions (including direct, indirect and embodied emissions) have increased by an average of 0.7 % annually [44]. In response, governments must strengthen commitments to near-zero emissions buildings [44], aiming for a 55 % reduction in net greenhouse gas (GHG) emissions by 2030 (relative to 1990 levels) and climate neutrality by 2050 [32]. Efforts should not only focus on renovating poorly performing buildings, but also consider actual zero-energy buildings, which will face overheating risk by 2050 due to climate change [11].

According to EN 15978 [29], a building's lifecycle includes product (A1-A3), construction (A4-A5), use (B1-B7), end of life (C1-C4), and beyond the building life cycle (D) stages. Embodied carbon refers to GHG emissions associated with the life cycle of the materials used in construction. This includes direct emissions from processes, such as material extraction and manufacturing, and indirect emissions from energy use and transportation during the product, construction, in-use and end-of-life lifecycle stages (A1-A5, B1-B5, C1-C4) [29]. These emissions mainly occur prior to the building operation stage, where emissions are referred to as operational emissions. The latter arise from energy and water consumption during building use (stages B6 and B7). Though no universal formula describes the relationship between embodied and operational emissions, improved building energy efficiency often results in embodied emissions outweighing operational emissions over the building lifecycle [63]. Complying with energy regulations usually requires more materials (e.g., thicker insulation, triple-glazed windows) and technologies not always locally manufactured (e.g., PV panels and battery components), which in turn demand additional energy for manufacturing, transportation and installation. As a result, the contribution of embodied emissions cannot be overlooked and should be assessed alongside operational emissions when achieving building emission targets [63].

Recent revisions to the Energy Performance of Buildings Directive (EPBD) mandate the inclusion of lifecycle Global Warming Potential (GWP) in the Energy Performance Certificate (EPC) for all new buildings by 2030 [33]. Nordic countries, particularly Denmark, are leading this effort, having already implemented regulations and established GHG emissions limit values for a wide range of building types [56].

1.2. Literature review

The existing literature highlights a gap in studies adopting a holistic approach to building energy simulation (BES) and lifecycle assessment (LCA), with most research addressing these areas separately [78]. Cellura et al. [17] were pioneers in integrating BES and LCA, demonstrating a trade-off between material use and energy consumption. Their findings, along with those of Yeung et al. [78] and Shadram & Mukkavaara [68], show that additional envelope layers enhance energy performance but increase embodied emissions, underscoring the need to balance both aspects to optimize the overall building performance.

Kiss & Szalay [49] and Abbasi & Noorzai [1] further support these findings, highlighting that multi-objective optimization is essential to balance operational energy reductions with embodied energy increases from renewable energy systems and additional materials. This is especially relevant when using higher quality and longer-lasting materials, which extend the building's use span, reduce operational energy, and enable recycling or reuse at the end-of-life stage. These findings emphasize the importance of a holistic whole-life cycle perspective, particularly in the early design stages [69].

At the European level, a Whole Life Carbon Roadmap targets reductions in both operational and embodied building emissions by 2050. Some countries have introduced mandatory declarations and limit values for new buildings, but not yet for renovations. For example, the Netherlands established a limit value in 2018 for the "Building environmental performance", that results from a conversion of the results of eleven impact categories into €/(m^2·y). France's RE2020 requires mandatory reporting on operational energy, materials emissions, and on-site activities, incorporating dynamic emission factors (EFs), and with limits based on building type, area, and location [15].

Nordic countries have adopted a limited number of life cycle modules, balancing industry and investors readiness for decarbonization with agreeable and manageable method at affordable cost. Sweden will cover stages A1-A5 by 2025, as they are well-documented in literature [34] and can be confirmed with real values [15]. Denmark's limit values include stages A1-A5, B4, B6, C3-C4, with values differentiated by building use. Finland is considering also stages C1 and C2, but debates whether differentiate limit values by building type, similar to Norway, which found no significant difference in impact across types.

Varying system boundaries hinder comparability across countries. The most significant discrepancy is the inclusion or exclusion of operational emissions. Sweden excludes operational emissions to prioritize reducing emissions today, while Norway omits them having already forbidden fossil fuel heating. These countries also exclude building services from their assessment scope, despite evidence that technical services significantly contribute to embodied emissions [64].

However, in regions with a clean electricity mix and mild climate, embodied emissions dominate over operational emissions, and high embodied emissions remain unrecouped [49,51]. Rodrigues et al. [65] observed that the use-phase impacts will rise by 12 % under future climate scenarios and retrofit benefits will decrease as the electricity grid decarbonizes. Therefore, a comprehensive methodology considering climate conditions and electricity grid evolution appears necessary.

Given that buildings generally have a service life exceeding 100 years, it is essential to consider the evolving climate and electricity mix to assess the robustness of renovation and new construction designs [48] and adequately quantify the environmental performance of buildings [70]. Dynamic LCA introduces a temporal dimension, acknowledging that the buildings' environmental performance evolves with technological advancements, construction processes, user behavior, and environmental conditions [42]. However, few studies apply dynamic LCA to retrofits. Van de moortel et al. [75] showed that including changes in indoor temperature, airtightness, envelope performance, heating system type and efficiency, materials production and electricity mix improves environmental assessment. Compared to a static LCA, dynamic LCA highlighted how changes in user behavior could offset renovation benefits and emphasized the need to include efficiency growth rate for heating systems and dynamic electricity mix parameters, especially for electricity-based heating.

Yeung et al. [78] introduced a dynamic lifecycle inventory via building information modelling (BIM), co-simulating BPS and LCA. This integration enabled dynamic foreground inventory for electricity, heating, and water, and allowed for material data extraction directly from BIM for LCA calculations. However, while innovative, it does not account for grid and climate variations, overlooking operational emissions changes over the building's lifecycle. Méndez Echenagucia et al. [51] considered grid carbon intensity changes over 50 years. They observed that interventions such as triple glazing reduce GHG emissions in a static scenario where operational emissions dominate, but offer limited benefits in decarbonization scenario, showing the need for designs that factor in the grid decarbonization timeline is clear. However, like most studies, their analysis focused solely on the building envelope.

Satola et al. [66] adopted a broader approach, considering envelope, geometry, systems and on-site renewables. They demonstrated that integrating structural, envelope, and system interventions yields the best environmental outcomes [14]. Also, unlike most studies, Satola et al. [66] conducted sensitivity analyses before GHG emissions optimization, identifying the most influential design parameters on lifecycle GHG emissions to be included in the retrofit optimization. They also considered the insulation material in the sensitivity analysis, but did not quantify the impact of using bio-based instead of traditional materials. Azzouz et al. [14] compared concrete, steel and cross-laminated timber (CLT) structures, as well as recycled materials, earth constructed and traditional walls. They concluded that CLT reduced lifecycle carbon by 3.1 % compared to concrete, while using recycled materials and earth constructed walls reduced emissions by 5.2 % and 2.0 %, respectively.

In conclusion, the literature review highlights gaps in integrating embodied and operational emissions dynamically, particularly in renovation. Few studies apply sensitivity analyses before optimization, and most focus on the building envelope, neglecting the environmental performance of materials, systems and on-site renewables. This impedes the adoption of integrated retrofit strategies.

1.3. Study relevance and research objectives

This study addresses the aforementioned gaps by identifying key parameters influencing building decarbonization through renovation, considering embodied and operational emissions, climate change predictions, and electricity mix variations. Six renovation alternatives for a post-World War II single-family dwelling in Belgium are analyzed to answer the following research questions:

- How can embodied and operational emissions be dynamically coupled in building retrofits?
- What variables affect the lifecycle environmental performance of building renovation? How can these variables be ranked and grouped? What are their interlinkages?
- Is there a trade-off between embodied and operational emissions, and what is it?
- How do climate change and electricity mix influence the transition from Zero Energy to Zero Carbon buildings?

The paper's novelty and added value lie in the integration of embodied and operational emissions, focusing on stages A1-A5, B4, B6 and C3-C4 per Danish regulations. Additionally, a life cycle perspective over a 50-year timespan is adopted, incorporating climatic and electricity mix dynamicity. Special emphasis is placed on the time resolution of EFs and its impact on operational emissions. Lastly, the research a wider research scope encompassing envelope, systems and on-site renewable energy generation. Also, it evaluates renovation strategies relying on both bio-based and synthetic materials, quantifying their impact on the total GHG emissions.

This study has implications for various stakeholders. By providing a comprehensive list of influential parameters on building emissions, this research aims to support designers in adopting lower carbon-intensive renovation alternatives in the early design. This paper aims to support policymakers in developing building renovation policies and guiding houseowners who will need to renovate their class G dwelling by 2030 [27]. Furthermore, this research contributes to a wider academic research effort on achieving net-zero whole-life carbon buildings [45] and developing a Belgian building renovation framework [13].

The paper is structured as follows: Section 1 introduces the research context, reviews literature on embodied and operational emissions integration and identifies knowledge gaps. Section 2 presents the case study and renovation strategies; describes the energy model and the Life Cycle Impact Assessment (LCIA) methodology; details the coupling of embodied and operational emissions; and concludes with the methodology employed for sensitivity and uncertainty analyses. Section 3 presents embodied, operational, and total emissions for each renovation scenario, highlights the most influential parameters on embodied and operational emissions, and the implications of electricity mix and climate variations on operational emissions. Section 4 summarizes findings, offers recommendations, discusses the strengths and limitations of the study, and suggests future research directions. Section 5 concludes the paper (Fig. 1).

2. Methodology

Fig. 2 illustrates the methodology of this study, beginning with an analysis of the building's location, climatic conditions, and the country's electricity mix. The focus then narrowed to the building scale. The single-family house archetype was characterized by its geometry, materials, envelope performance, systems, on-site renewable energy sources, and overall energy and environmental performance. This archetype served as the base case for two renovation scenarios: the "Low-Energy renovation scenario", aimed at achieving an Energy Class rating C/D, and the "Ultra-Low-Energy renovation scenario", targeting an Energy Class A/B. Each scenario included two material options: petrochemical and biobased. In the Low-Energy scenario, two mechanical ventilation systems (C and D) were tested, resulting in a total of six renovation scenarios. These scenarios were evaluated based on total annual and cumulative GHG emissions, which sum embodied and operational emissions. Embodied emissions were calculated over 50 years following EN 15804+A2:2019 [31] and EN 15978 [29] standards. The TOTEM tool [74], integrating Ecoinvent [77], provided material-specific impact data, while Revit and AutoCAD were used for materials inventory. The energy models of the renovation scenarios were developed in DesignBuilder [21]. The resulting .idf file served as an input for jE+ EA [79] to calculate the operational energy and emissions, alongside sensitivity analyses. Embodied and operational emissions were then combined to determine the total emissions.

Boundary conditions for the study were fixed. The research assumed a one-stage renovation process for the post-WWII house, with ownership transitioning between 2020 and 2035 from the current 70- and 80-year-old owners to new occupants (likely heirs). Secondly, renovation solutions were based on market feasibility and future optimal solutions, combining conventional options (e.g., radiators instead of floor heating) and advanced solutions [16]. Thirdly, wall renovations were implemented regardless of façade orientation or window-to-wall ratio (WWR), which ranges from 4 % (North-East façade) to 13 % (North-West and South-East façades), with opaque surfaces dominating all orientations. Gas boilers were excluded in favor of electric systems, in line with policies phasing out gas heating [26]. Finally, while dynamic factors such as climate and electricity mix were introduced, the performance degradation of materials still needs to be considered.

2.1. Building location

The study focuses on Belgium, chosen due to the relevance of existing case studies [12] and the opportunity to analyze the impact of future changes in the electricity mix, particularly due to the temporary phase-out of nuclear power. This analysis is further supported by recent literature on Belgium's future electricity mix and its environmental impact [60].

2.1.1. Weather file

The building under analysis is located in Brussels, Belgium, within the mixed-humid Climate Zone 4A [7]. This climate is representative of the region adjacent to the English Channel, legitimizing the extension of the study to North-Western Europe [6]. Even under the worst-case Representative Concentration Pathway (RCP) 8.5, the region is expected to remain heating-dominated until 2050. However, projections indicate a decrease in Heating Degree Days (HDD) and an increase in

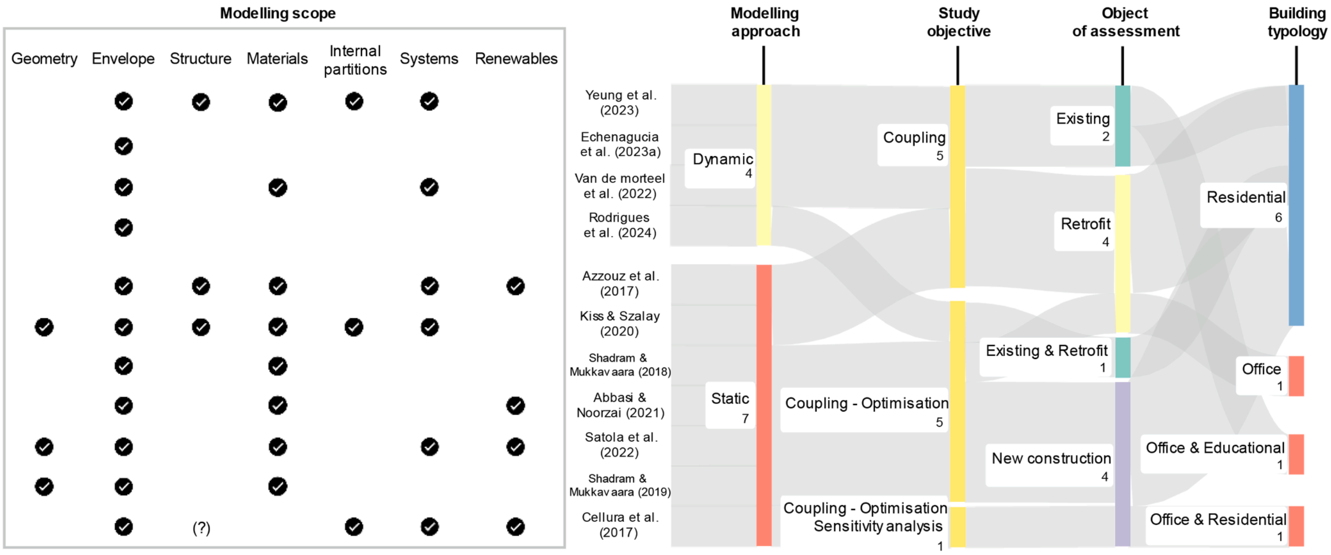

Fig. 1. Overview of the literature coupling embodied and operational emissions.

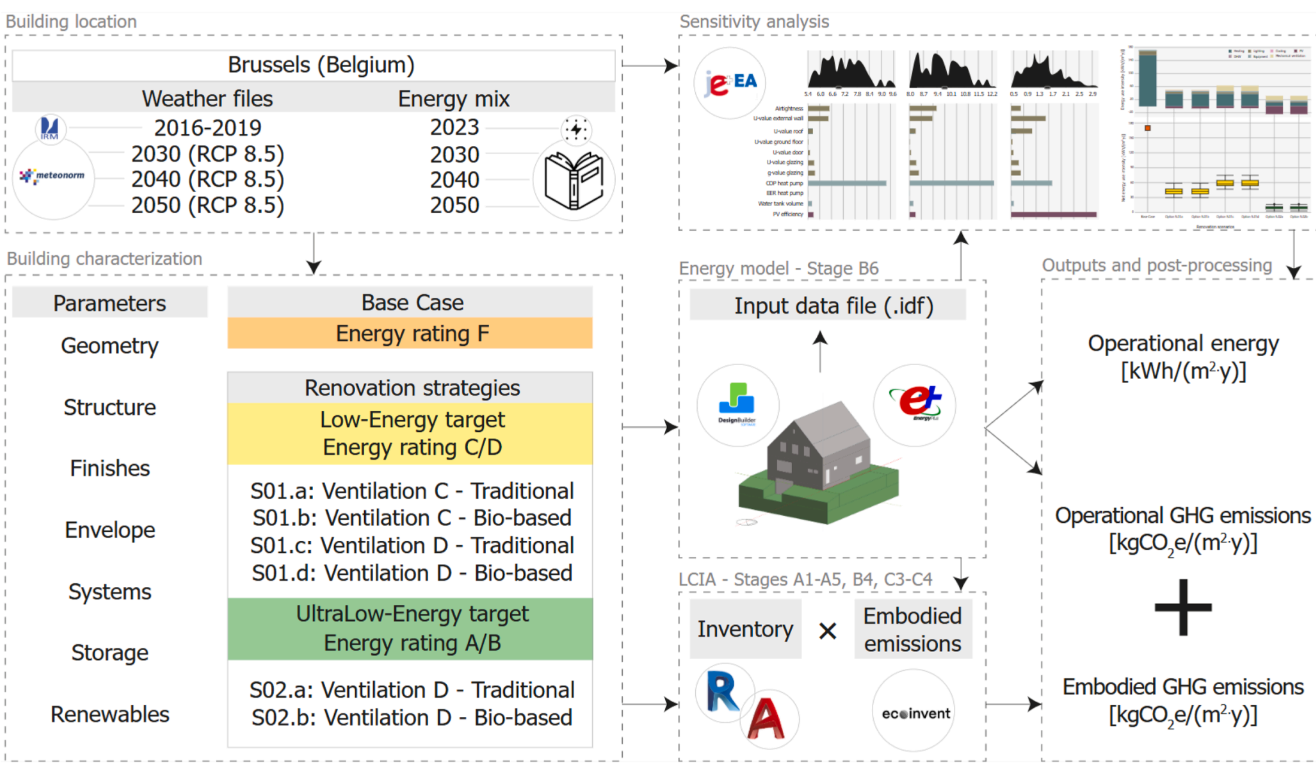

Fig. 2. Study conceptual framework indicating the key methodological milestones of the research methodology.

Cooling Degree Days (CDD), reducing the heating energy use but increasing cooling demand and overheating risk [4,59].

To address these changes, weather files for 2030, 2040 and 2050 were considered alongside the current weather data (2016–2019) used for model calibration. Current weather data were sourced from the Belgian Royal Meteorological Institute [46], while future weather data for Brussels – Zaventem airport were obtained from Meteonorm 8.0 [52]. RCP 8.5 was selected, as it reflects the current GHG emissions trajectory and aligns with mid-century projections [55,67].

2.1.2. Electricity mix

The Belgian electricity mix is currently dominated by nuclear power, followed by natural gas, wind and solar energy. The country imports electricity primarily from France and the UK, with smaller contributions from Germany and the Netherlands [24] (Fig. 3). The carbon intensity of the electricity mix, i.e., the GHG footprint of each kWh of electricity consumed, varies annually and daily due to the fluctuations in electricity generation sources (Fig. 4). In 2023, the peak EF occurred in February, due to higher natural gas use, while the lowest EF was registered in July, when solar energy production peaked. In Autumn wind power further reduced natural gas demand, maintaining low EF. On a daily scale, the highest carbon intensity generally occurred between 5 and 11 pm, coinciding with increased natural gas consumption, while the lowest occurred midday due to higher solar generation.

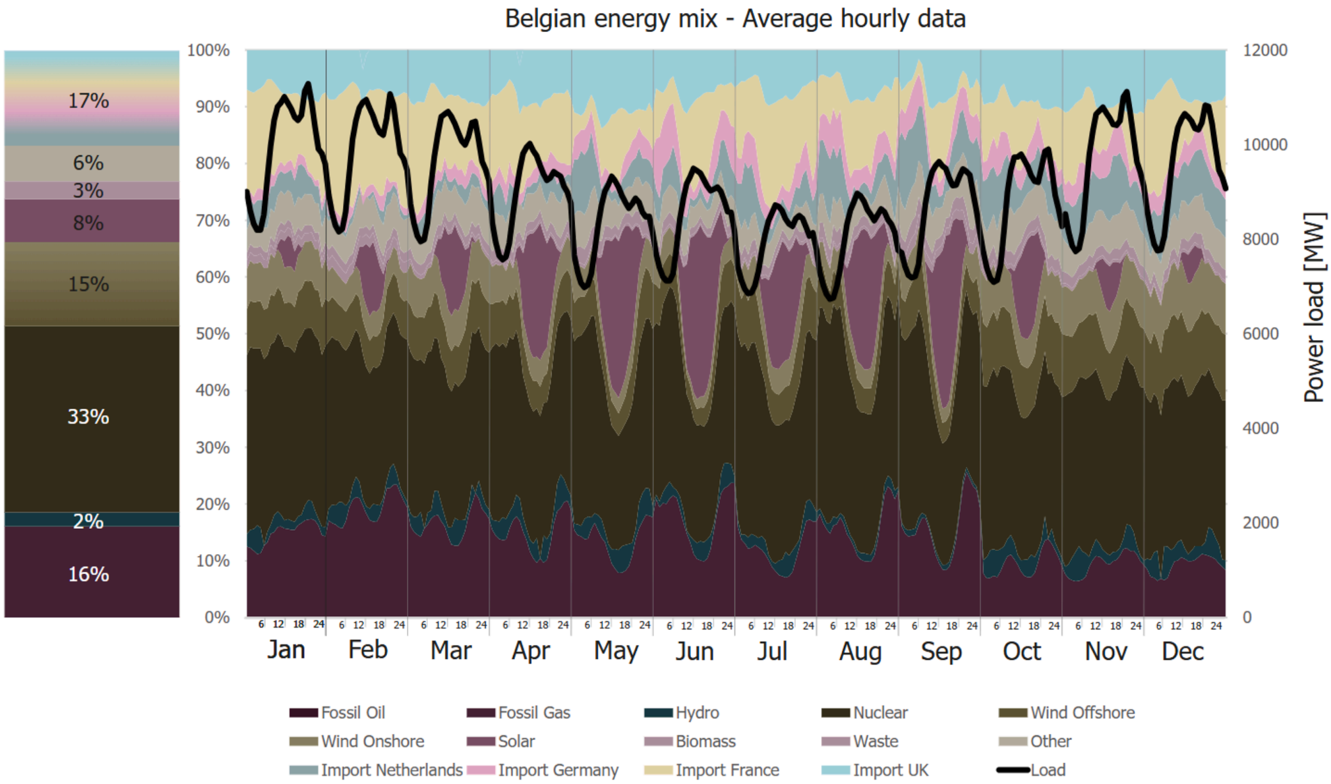

Fig. 3. Belgian electricity mix: the annual average percentage (left) and the average hourly data (right) by power generation source.

To assess the impact of the electricity mix's variability on building operational emissions, the study considered yearly, monthly, and hourly EF (Table A.1, Fig. 4). Data for 2023 were sourced from Electricity Maps [23]. Future electricity mixes for 2030, 2040, and 2050 were also included, to reflect the impact of the nuclear plant shutdown under RCP 8.5 projections. Data on future electricity mix composition were acquired from Ramon & Allacker [60]. Yearly EFs were calculated by multiplying each electricity source by its respective EF, assuming constant global electricity production and importation [22]. Table A. 1 summarizes the evolution of the electricity mix composition and the corresponding yearly EF.

2.2. Building characterization

The case study is an archetype of a detached single-family house built in Belgium between 1945 and 1969. The benchmark model was developed by Attia et al. [12] based on post-occupancy measurements and audits conducted between 2016 and 2019. This archetype is highly representative of the Belgian building stock, as post-WWII suburbanization led to the widespread construction of single-family detached houses, which now comprise 48 % of the country's housing stock [12]. The archetype was selected due to its poor EPC rating (class F) and high renovation potential, absence of aesthetic restrictions, and owner-occupied status, which simplifies renovation decisions. Finally, working with an archetype allows for standardizing renovation strategies, making them more widely applicable [12].

2.2.1. Base case description

The house is structured on four levels: −1 (garage), 0 (living area), +1 (sleeping area), and +2 (unoccupied attic), with a total net floor area of 259 m^2. Elevations and plans illustrating the internal distribution of spaces are provided in Annex (Fig. A.1).

The house has a load-bearing wall structure. The perimeter walls are made of concrete blocks and red bricks, the same bricks that also serve as internal partitions. The garage floor is cast concrete, while the remaining floors use *hourdi* concrete blocks. The ground floor is finished with clay tiles, while timber flooring is on the first floor and attic. The roof has a timber structure finished with fired clay tiles.

Partial renovations were conducted before 2000, including the installation of double-glazed windows (U-value of 2.9 W/(m^{2}K)), external shading, ground floor slab insulation (U-value of 0.5 W/(m^{2}K)), attic slab insulation (U-value of 1.1 W/(m^{2}K)), and roof insulation (U-value of 1.3 W/(m^{2}K)). The external walls remained uninsulated, maintaining a U-value of 1.7 W/(m^{2}K).

The house is heated by a gas boiler supplying hot water to radiators and Domestic Hot Water (DHW) [3]. The building lacks cooling and mechanical ventilation, relying on natural ventilation year-round. Fluorescent lamps provide a power density of 12 W/m^2 in the living room, kitchen and office, and 8 W/m^2 elsewhere. The equipment load is 9 W/m^2, reflecting typical appliances in post-WWII detached houses in Belgium [12].

Despite renovations, the house's airtightness remains inadequate (n50 = 14.5 ach), and the thermal transmittance of the envelope fails to meet current standards. Heat gains are low due to a small WWR, external shutters, and low occupancy density. Consequently, the building's annual heating use intensity is 148.7 kWh/(m^2·y), and its annual electricity use intensity is 17.7 kWh/(m^2·y). The total annual energy use intensity is 166 kWh/(m^2·y), corresponding to an energy efficiency class F and an annual GHG emission intensity of 32 kgCO_2e/(m^2·y).

2.2.2. Renovation strategies design

To explore the trade-off between embodied and operational emissions, and consider the market realities, two renovation scenarios were conceptualized: S.01 (Low-Energy scenario) and S.02 (UltraLow-Energy scenario). S.01 aims for energy class C/D with affordable, lower-performing systems, while S.02 targets energy class A/B with high-quality materials and technologies. Renovation focuses on three key components: the building envelope (materials and thermal transmittance), technical systems, and on-site renewable energy production.

In S.01, two mechanical ventilation systems are compared: System C

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00:00	0.196	0.236	0.217	0.213	0.163	0.173	0.122	0.133	0.155	0.131	0.136	0.143
01:00	0.193	0.235	0.213	0.203	0.155	0.168	0.117	0.128	0.151	0.126	0.132	0.139
02:00	0.188	0.233	0.208	0.199	0.150	0.169	0.116	0.128	0.149	0.125	0.128	0.134
03:00	0.186	0.229	0.205	0.205	0.155	0.172	0.119	0.131	0.155	0.133	0.127	0.130
04:00	0.189	0.233	0.207	0.211	0.163	0.172	0.120	0.136	0.168	0.149	0.131	0.134
05:00	0.191	0.238	0.213	0.214	0.166	0.172	0.122	0.139	0.184	0.169	0.147	0.144
06:00	0.200	0.244	0.213	0.214	0.169	0.169	0.120	0.133	0.183	0.178	0.159	0.153
07:00	0.202	0.246	0.203	0.202	0.169	0.165	0.118	0.132	0.178	0.171	0.162	0.160
08:00	0.202	0.235	0.190	0.187	0.163	0.154	0.114	0.130	0.159	0.158	0.155	0.158
09:00	0.194	0.218	0.177	0.173	0.154	0.140	0.110	0.120	0.146	0.145	0.144	0.148
10:00	0.190	0.206	0.169	0.168	0.151	0.135	0.105	0.114	0.140	0.138	0.137	0.140
11:00	0.185	0.200	0.164	0.161	0.143	0.130	0.101	0.110	0.134	0.129	0.135	0.137
12:00	0.182	0.196	0.162	0.158	0.137	0.131	0.100	0.108	0.135	0.127	0.134	0.136
13:00	0.185	0.199	0.165	0.156	0.132	0.131	0.101	0.106	0.138	0.127	0.133	0.141
14:00	0.188	0.207	0.172	0.154	0.132	0.140	0.102	0.108	0.146	0.134	0.138	0.145
15:00	0.194	0.218	0.183	0.165	0.137	0.156	0.109	0.119	0.166	0.149	0.150	0.150
16:00	0.206	0.231	0.200	0.189	0.150	0.172	0.124	0.143	0.195	0.173	0.164	0.164
17:00	0.217	0.245	0.219	0.213	0.162	0.189	0.142	0.166	0.218	0.193	0.179	0.174
18:00	0.218	0.256	0.229	0.228	0.173	0.197	0.157	0.180	0.224	0.195	0.183	0.176
19:00	0.218	0.259	0.232	0.239	0.181	0.204	0.163	0.186	0.220	0.182	0.176	0.167
20:00	0.212	0.257	0.231	0.241	0.191	0.207	0.167	0.198	0.213	0.173	0.166	0.158
21:00	0.209	0.255	0.227	0.243	0.193	0.208	0.170	0.196	0.204	0.165	0.161	0.155
22:00	0.206	0.252	0.220	0.230	0.177	0.189	0.139	0.154	0.175	0.146	0.159	0.149
23:00	0.198	0.244	0.212	0.220	0.165	0.177	0.126	0.135	0.160	0.133	0.148	0.140
Avg	**0.198**	**0.232**	**0.201**	**0.199**	**0.160**	**0.168**	**0.124**	**0.139**	**0.171**	**0.152**	**0.149**	**0.149**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00:00	0.196	0.236	0.217	0.213	0.163	0.173	0.122	0.133	0.155	0.131	0.136	0.143
01:00	0.193	0.235	0.213	0.203	0.155	0.168	0.117	0.128	0.151	0.126	0.132	0.139
02:00	0.188	0.233	0.208	0.199	0.150	0.169	0.116	0.128	0.149	0.125	0.128	0.134
03:00	0.186	0.229	0.205	0.205	0.155	0.172	0.119	0.131	0.155	0.133	0.127	0.130
04:00	0.189	0.233	0.207	0.211	0.163	0.172	0.120	0.136	0.168	0.149	0.131	0.134
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06:00	0.200	0.244	0.213	0.214	0.169	0.169	0.120	0.133	0.183	0.178	0.159	0.153
07:00	0.202	0.246	0.203	0.202	0.169	0.165	0.118	0.132	0.178	0.171	0.162	0.160
08:00	0.202	0.235	0.190	0.187	0.163	0.154	0.114	0.130	0.159	0.158	0.155	0.158
09:00	0.194	0.218	0.177	0.173	0.154	0.140	0.110	0.120	0.146	0.145	0.144	0.148
10:00	0.190	0.206	0.169	0.168	0.151	0.135	0.105	0.114	0.140	0.138	0.137	0.140
11:00	0.185	0.200	0.164	0.161	0.143	0.130	0.101	0.110	0.134	0.129	0.135	0.137
12:00	0.182	0.196	0.162	0.158	0.137	0.131	0.100	0.108	0.135	0.127	0.134	0.136
13:00	0.185	0.199	0.165	0.156	0.132	0.131	0.101	0.106	0.138	0.127	0.133	0.141
14:00	0.188	0.207	0.172	0.154	0.132	0.140	0.102	0.108	0.146	0.134	0.138	0.145
15:00	0.194	0.218	0.183	0.165	0.137	0.156	0.109	0.119	0.166	0.149	0.150	0.150
16:00	0.206	0.231	0.200	0.189	0.150	0.172	0.124	0.143	0.195	0.173	0.164	0.164
17:00	0.217	0.245	0.219	0.213	0.162	0.189	0.142	0.166	0.218	0.193	0.179	0.174
18:00	0.218	0.256	0.229	0.228	0.173	0.197	0.157	0.180	0.224	0.195	0.183	0.176
19:00	0.218	0.259	0.232	0.239	0.181	0.204	0.163	0.186	0.220	0.182	0.176	0.167
20:00	0.212	0.257	0.231	0.241	0.191	0.207	0.167	0.198	0.213	0.173	0.166	0.158
21:00	0.209	0.255	0.227	0.243	0.193	0.208	0.170	0.196	0.204	0.165	0.161	0.155
22:00	0.206	0.252	0.220	0.230	0.177	0.189	0.139	0.154	0.175	0.146	0.159	0.149
23:00	0.198	0.244	0.212	0.220	0.165	0.177	0.126	0.135	0.160	0.133	0.148	0.140
Avg	**0.198**	**0.232**	**0.201**	**0.199**	**0.160**	**0.168**	**0.124**	**0.139**	**0.171**	**0.152**	**0.149**	**0.149**

Fig. 4. Emission factor of the Belgian electricity mix with a yearly color scale (top), highlighting the most carbon intensive months, and monthly color scale (bottom), highlighting the most carbon intensive hours.

(S.01a), a cost-effective option with simple installation, and System D (S.01c), an optimal solution for indoor air quality, requiring precise design and higher costs. In S.02, only System D is implemented (S.02a), as it adopts top-performance materials and systems. The study compares petrochemical and biobased materials in all scenarios, adding the alternatives S.01b, S.01d and S.02b to the analysis (Fig. 5). This comparison quantifies the impact of materials on embodied and total GHG emissions.

The building envelope is renovated by improving insulation in external walls and roof, and replacing windows and doors to enhance airtightness. Since the house faces no architectural restrictions, insulation is applied externally to minimize thermal bridges and avoid reducing net floor area. No intervention is planned for the ground floor, as its U-value of 0.5 $W/(m^2K)$ is adequate [40]. For petrochemical insulation of walls, Kingspan External Thermal Insulation Composite System (ETICS) with extruded polystyrene (XPS) and polyurethane

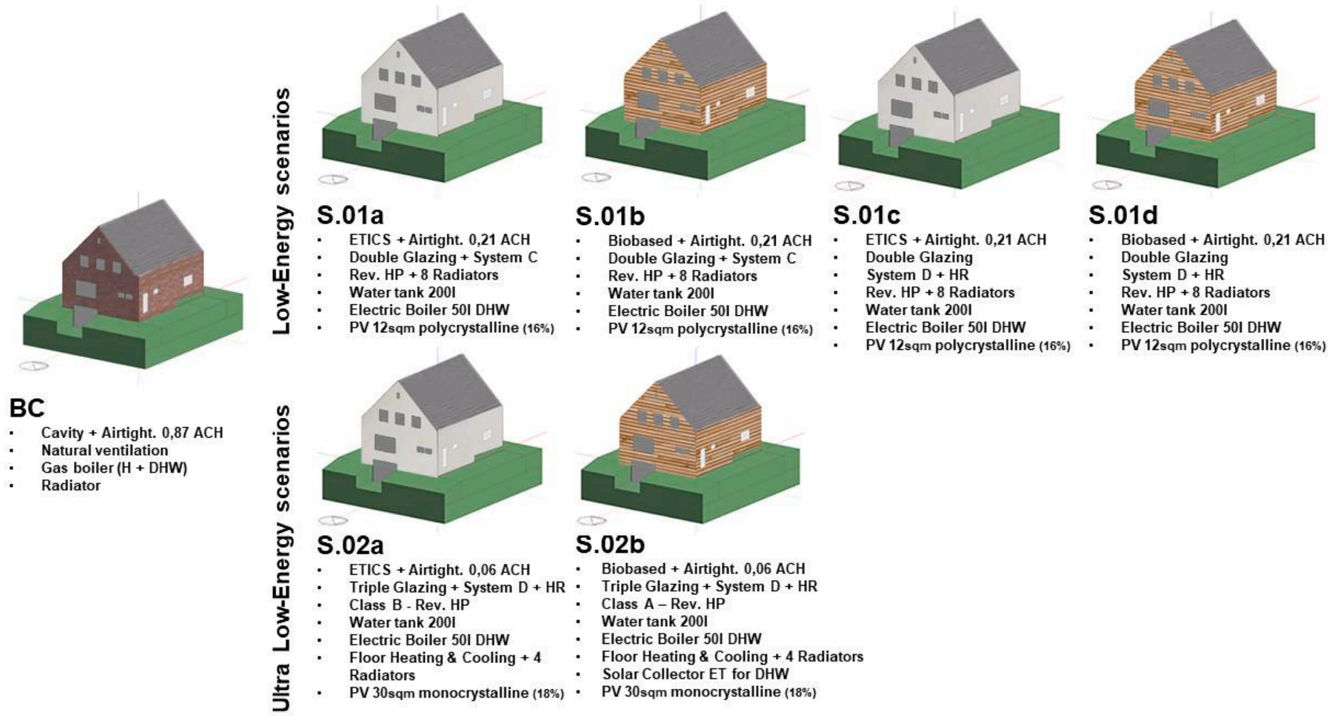
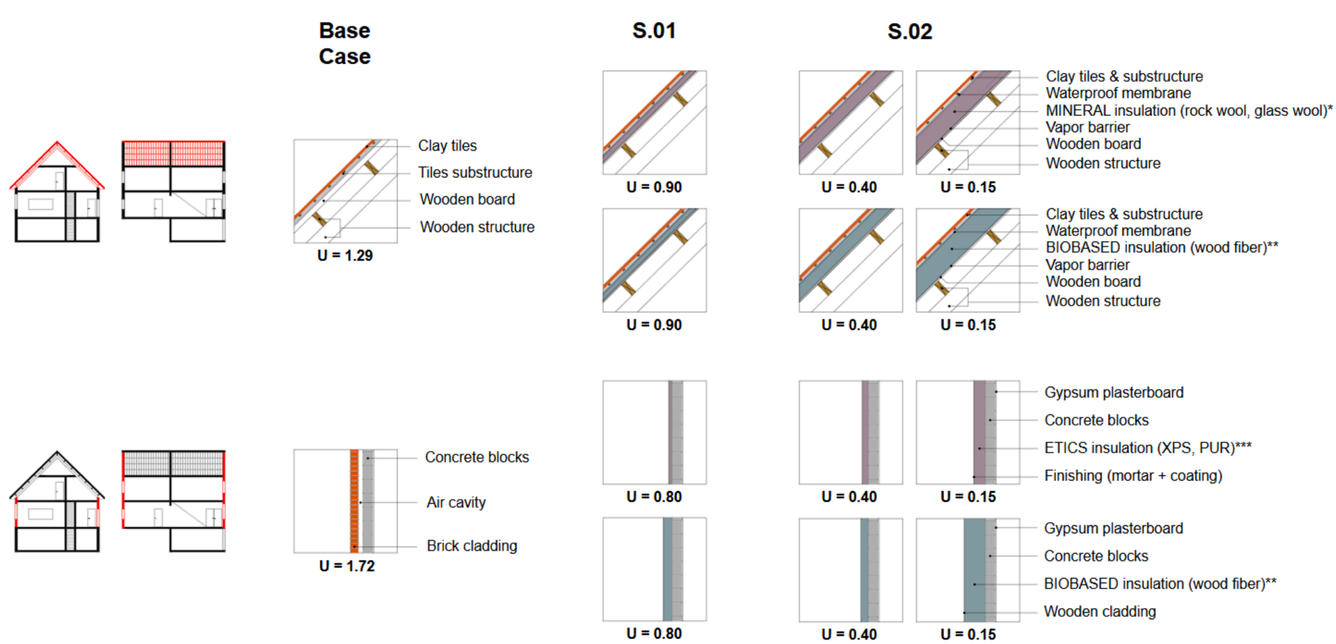


Fig. 5. Designed renovation scenarios.

(PUR) is considered, while for bio-based insulation, Steico wood fiber insulation is selected. Roof insulation options include Isover glass wool and Rockwool rock wool for the traditional renovation scenarios, and Steico wood fiber insulation for the bio-based scenarios (Fig. 6).

The primary distinction between S.01 and S.02 lies in the required U-values. S.02 targets Passive House standard's U-values and airtightness



*MINERAL INSULATION
Rock wool (Rockwool): density 100-150 kg/m³, thermal conductivity 0.035 W/(m K), heat capacity 840 J/(kg K), thermal effusivity 110 Ws$^{0.5}$/(m^2 K)
Glass wool (Isover): density 10-30 kg/m³, thermal conductivity 0.032 W/(m K), heat capacity 1030 J/(kg K), thermal effusivity 90 Ws$^{0.5}$/(m^2 K)

**BIOBASED INSULATION
Wood fiber (Steico): density 110-160 kg/m³, thermal conductivity 0.038 W/(m K), heat capacity 2100 J/(kg K), thermal effusivity 180 Ws$^{0.5}$/(m^2 K)

***ETICS
XPS (Kingspan): density 30-45 kg/m³, thermal conductivity 0.028 W/(m K), heat capacity 1450 J/(kg K), thermal effusivity 82 Ws$^{0.5}$/(m^2 K)
PUR(Kingspan): density 30-40 kg/m³, thermal conductivity 0.023 W/(m K), heat capacity 1470 J/(kg K), thermal effusivity 75 Ws$^{0.5}$/(m^2 K)

Fig. 6. Stratigraphy and thermal properties of the envelope elements for each renovation scenario.

[57], whereas S.01 targets U-values between the Base Case (BC) and S.02 objectives (Table 1). These targets influence the insulation thickness and glazing technology (Fig. 6).

For heating and cooling, all scenarios use a reversible air-to-water heat pump with integrated water storage. In S.01, existing radiators are retained, with the heat pump supplying water at 55 °C. In S.02, floor heating and cooling are installed on the ground floor, and low-temperature radiators on the first floor, with a heat pump supply temperature of 35 °C that improves its Coefficient of Performance (COP). The COPs are taken from producers. A stand-alone instantaneous electric boiler provides DHW in both scenarios.

Mechanical ventilation is introduced in all scenarios. System C entails the installation of extractors in humid rooms (i.e., toilet, bathroom, and kitchen) and air supply grids in dry spaces (i.e., living room, bedrooms and office). System D requires the installation of an Air Handling Unit (AHU) to regulate air volumes and ducts to supply or extract air from the rooms.

Both scenarios replace fluorescent lamps with LED lighting to reduce

Table 1
Input variables for each renovation scenario.

	BC	S.01a	S.01b	S.01c	S.01d	S.02a	S.02b
Geometry							
Total floor area [m^2]	259						
Occupation density [m^2/p]	129.5						
WWR [-]	10 %						
Orientation [°]	135						
Structure							
Structural type [-]	Load-bearing walls + Reinforced concrete beams + Timber roof beams						
Envelope							
Infiltration rate [ach]	0.87	Min: 0.12, Int: 0.03 Max: 0.30		Min: 0.12, Int: 0.03 Max: 0.30		Min: 0.04, Int: 0.01 Max: 0.09	
External Wall U-value [W/(m^2K)]	1.7	Min: 0.80 Int: 0.04 Max: 1.00		Min: 0.80 Int: 0.04 Max: 1.00		Min: 0.15 Int: 0.05 Max: 0.40	
Ground floor U-value [W/(m^2K)]	0.5						
Attic floor U-value [W/(m^2K)]	1.1						
Roof U-value [W/(m^2K)]	1.3	Min: 0.80 Int: 0.04 Max: 1.00		Min: 0.80 Int: 0.04 Max: 1.00		Min: 0.15 Int: 0.05 Max: 0.40	
Door U-value [W/(m^2K)]	2.8	Min: 1.40 Int: 0.10 Max: 2.00		Min: 1.40 Int: 0.10 Max: 2.00		Min: 0.80 Int: 0.10 Max: 1.20	
Glazing U-value [W/(m^2K)]	2.9	Min: 1.30 Int: 0.10 Max: 1.80		Min: 1.30 Int: 0.10 Max: 1.80		Min: 0.80 Int: 0.10 Max: 1.20	
Glazing g-value [-]	0.74	Min: 0.40 Int: 0.04 Max: 0.60		Min: 0.40 Int: 0.04 Max: 0.60		Min: 0.20 Int: 0.02 Max: 0.30	
Solar shading [-]	External shade rolls						
Systems							
Heating generation [-]	Gas boiler	Reversible heat pump		Reversible heat pump		Reversible heat pump	
Heating generation COP [-]	0.76	Min: 2.50 Int: 0.25 Max: 3.75		Min: 2.50 Int: 0.25 Max: 3.75		Min: 4.00 Int: 0.25 Max: 5.50	
Delivered hot water temperature [°C]	60	55		55		35	
Heating setpoint [°C]	16 (short-presence) - 18 (sleeping) - 22 (office) - 23 (living)						
Cooling generation [-]	–	Reversible heat pump		Reversible heat pump		Reversible heat pump	
Cooling generation EER [-]	–	Min: 3.00 Int: 0.25 Max: 4.25		Min: 3.00 Int: 0.25 Max: 4.25		Min: 4.50 Int: 0.25 Max: 6.00	
Chilled water temperature [°C]	–	18		18		18	
Cooling setpoint [°C]	–	26		26		26	
DHW generation [-]	Gas boiler	Electric boiler		Electric boiler		Electric boiler	
Ventilation							
Ventilation system [-]	Natural	Hybrid (System C)		Hybrid (System D)		Hybrid (System D)	
Natural ventilation flow rate [ach]	5	5		5		5	
Mechanical ventilation flow rate [l/s/person]	–	10		10		10	
Mech. Vent. air supply temperature [°C]	–	–		18/26		18/26	
Heat recovery [-]	–	–		75 %		75 %	
Lighting power density [W/m^2]	8 - 12	3		3		1.5	
Lamp type [-]	Fluorescent	LED		LED		LED	
Equipment power density [W/m^2]	9						
PV surface [m^2]	–	12		12		32	
PV efficiency [-]	–	Min: 0.13 Int: 0.01 Max: 0.16		Min: 0.13 Int: 0.01 Max: 0.16		Min: 0.15 Int: 0.01 Max: 0.20	
Solar thermal surface [m^2]	–	–		–		5	
Storage							
Water tank volume [m^3]	–	Min: 0.15 Int: 0.05 Max: 0.30		Min: 0.15 Int: 0.05 Max: 0.30		Min: 0.15 Int: 0.05 Max: 0.30	

energy use.

For on-site renewable energy generation, both scenarios install photovoltaic (PV) panels on the South-West roof pitch. S.01 uses 12 m^2 of polycrystalline PV panels, which offer a cost-effective and environmentally efficient solution despite their lower efficiency. S.02 employs 32 m^2 of more efficient monocrystalline panels [76]. In S.02, the remaining 5 m^2 of the pitch is used for solar thermal panels integrated with the heat pump to reduce its electricity consumption further.

2.3. Energy model

The energy models for the renovation scenarios were developed using the calibrated BC model from Attia et al. [10] in DesignBuilder 7.3.0 [21], operating on the EnergyPlus 9.4.0 simulation engine.

Spaces are categorized into living areas (dining room, living room and kitchen), sleeping areas (bedrooms and office), and short presence spaces (halls and bathrooms). Specific schedules for heating, ventilation, lighting, and occupancy are assigned to each group. As the residents are senior couples or single females, weekdays and weekends follow the same schedules.

Heating operates from October to April, while cooling from May to September. Heating setpoints follow the BC (i.e., 23 °C in living areas, 22 °C in the office, 18 °C in sleeping areas and 16 °C in short-presence spaces). Cooling operates 24/7 at 26 °C in all spaces.

The reversible heat pump is modeled via two separate loops: the chilled water loop and the hot water loop. The chiller water loop supplies cold water at 18 °C. The hot water loop provides water at 55 °C in S.01 and 35 °C in S.02.

For ventilation, system C model includes exhaust fans in humid rooms (kitchen, toilet and bathroom) operating 24/7. System D consists of an AHU with electric heating and cooling coils, supply and extract fans. A heat recovery system with an effectiveness of 75 % is included. Automatic sizing of AHU components allows for meeting the ventilation requirements. The AHU operates 24/7, providing a constant airflow rate of 10 l/s per person, in line with Category I of EN 16798-2 [30]. Air is supplied at 18 °C in Winter and 26 °C in Summer.

In scenarios using System D, mixed-mode ventilation is modeled, allowing natural ventilation when cooling is not required (i.e., indoor temperature is below 25.5 °C and outdoor temperatures range between 15 °C and 25.5 °C).

Lighting is switched from fluorescent to LED lamps, reducing the power density to 3 W/m^2 in S.01 and 1.5 $W/m^{2,}$ in S.02. The equipment load remains at 9 W/m^2, as in the BC.

PV panels and solar collectors are installed on the southwest roof pitch, maintaining the same tilt. PV efficiency is constant, excluding temperature effects and performance degradation over time. No storage battery is included, meaning excess energy from the PV system is exported to the grid.

Solar collectors are integrated into a solar plant loop providing hot water to the heat pump's water heater. Their efficiency is modeled using the ACR Solar international solar collector template coefficients.

Table 1 summarizes the most relevant model inputs.

2.4. Life cycle impact assessment (LCIA)

This study employs a consequential LCIA approach, following EN 15804+A2:2019 [30] and EN 15978 [29] standards. A 50-year reference period was selected to reflect the typical functional lifespan of buildings.

The LCIA methodology integrates multiple databases, software tools, and analytical frameworks for a comprehensive environmental evaluation (Fig. 7). The process begins with data collection from environmental impact datasets such as TOTEM [74], Ecoinvent [77], and B-EPD [41], which provide embodied emissions values and other impact factors for construction materials:

- TOTEM is a Belgian-based LCA tool used to assess the environmental impact of material selection and building life cycle stages. It evaluates the environmental impact of entire building assemblies and supports LCA-based decision making for optimizing materials at the building level. Compared to more complex LCA tools suitable for detailed, accurate and comprehensive assessments (e.g., SimaPro, GaBi, OpenLCA), TOTEM was selected since it is designed for early-stage design decisions and focuses primarily on embodied emissions, making it user-friendly for architects, engineers, and designers, even beginners.

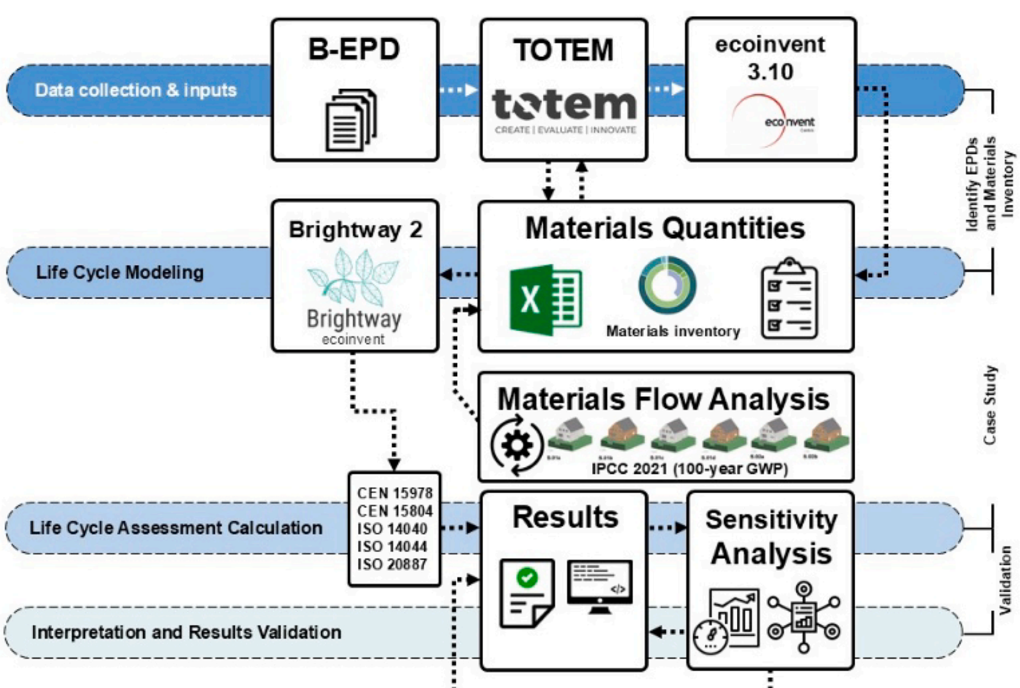


Fig. 7. Life Cycle Impact Assessment Methodology and Tool Interactions.

- B-EPD provides environmental impact data for specific construction products, following ISO 14025 and EN 15804+A2 standards. B-EPD is intended for use by manufacturers, policymakers, and LCIA practitioners.
- Ecoinvent is a Life Cycle Inventory (LCI) database offering standardized impact factors for materials and energy use, integrated into LCA software and widely utilized by LCA practitioners, researchers, and industry professionals.

In this study, TOTEM, integrating Ecoinvent [77], provided product and component-specific impact data. Verified Environmental Product Declarations (EPDs) were prioritized, with secondary data from Ecoinvent used when necessary. The functional unit was defined as kilograms (kg) for material-specific assessments and square meters (m^2) of gross floor area (GFA) for building-level evaluations. This approach aligns with the ILCD Handbook recommendations for LCIA in Europe [28].

During the LCI modeling phase, collected data was processed in TOTEM, where materials and construction scenarios were modeled. Material Flow Analysis (MFA) was applied to track material and energy flows, ensuring balance of mass and energy while identifying inflows, stocks, and outflows across different life cycle stages. A hybrid approach was employed in creating the materials inventory. Revit was used to extract data from 3D BIM models for structural, architectural, and envelope components, while mechanical systems like ventilation ducts and connections were modeled in AutoCAD. Systems material quantities were manually quantified based on technical sheets, CIBSE TM65 guidelines [18], and EPDs for critical components like steel, aluminum, and plastics. This ensured precise quantification reflecting both as-designed and as-built conditions. Material quantities, expressed in kilograms (kg), were cross-validated against project documentation and benchmarks to ensure traceability and reliability for LCIA calculations. The inclusion of such digital tools supports enhanced transparency and reproducibility of the inventory, as highlighted in studies by Monteiro & Freire [53]. Table 3 presents the full inventory of building materials and construction products.

Calculations were conducted for Modules A1–A3, A4–A5, B4 and C3–C4, following EN 15804+A2 guidelines [30] (Fig. 8). Processes for manufacturing, transport, use, and disposal of concrete, reinforced steel, cement blocks, bricks, and timber were selected from Ecoinvent [77]. Input-output relationships were mapped to incorporate energy and emissions, while connections were modeled as networks representing the entire product lifecycle. The analysis was regionalized using Belgium-specific data. The [47] characterization method [47] was used to calculate the GWP [25] (Table 2), ensuring compliance with ILCD Handbook recommendations [28] and alignment with European best practices.

Brightway2, an open-source LCA framework, was used for advanced customizable LCA modeling in Python, allowing flexibility in defining system boundaries and impact assessment methods. The LCIA of building services, including heat pumps, PV panels, ventilation ducts, AHUs, and heat recovery units (HRUs), was conducted using the Building Carbon Modeling Framework [13]. This approach integrated embodied, operational, and end-of-life emissions calculations across all life cycle stages. Upstream emissions from material extraction, manufacturing, and transport were calculated, alongside emissions from equipment operation and maintenance. End-of-life impacts included emissions from material recovery, solid waste transport, and unrecovered refrigerant [2].

Validation was conducted using a multi-step approach to ensure the robustness and reliability of results. Material data from Revit and AutoCAD models were cross-referenced with project specifications and

Table 2
Global Warming Potential (GWP) Assumptions.

Material	GWP ($kgCO_2e$/kg)	Source[a]	Lifecycle Modules
Kingspan XPS	3.50	TOTEM Database B-EPD	A1-A3, C
Kingspan PUR	3.90	Ecoinvent 3.10	A1-A3, C
Steico Wood Fiber	0.45	EPD Manufacturer Data B-EPD	A1-A3, C, D
Rockwool (Rockwool)	1.10	Ecoinvent 3.10 B-EPD	A1-A3, C
Glass Wool (Isover)	1.00	TOTEM Database B-EPD	A1-A3, B, C

[a] For all products with more than one source the GWP values were cross checked.

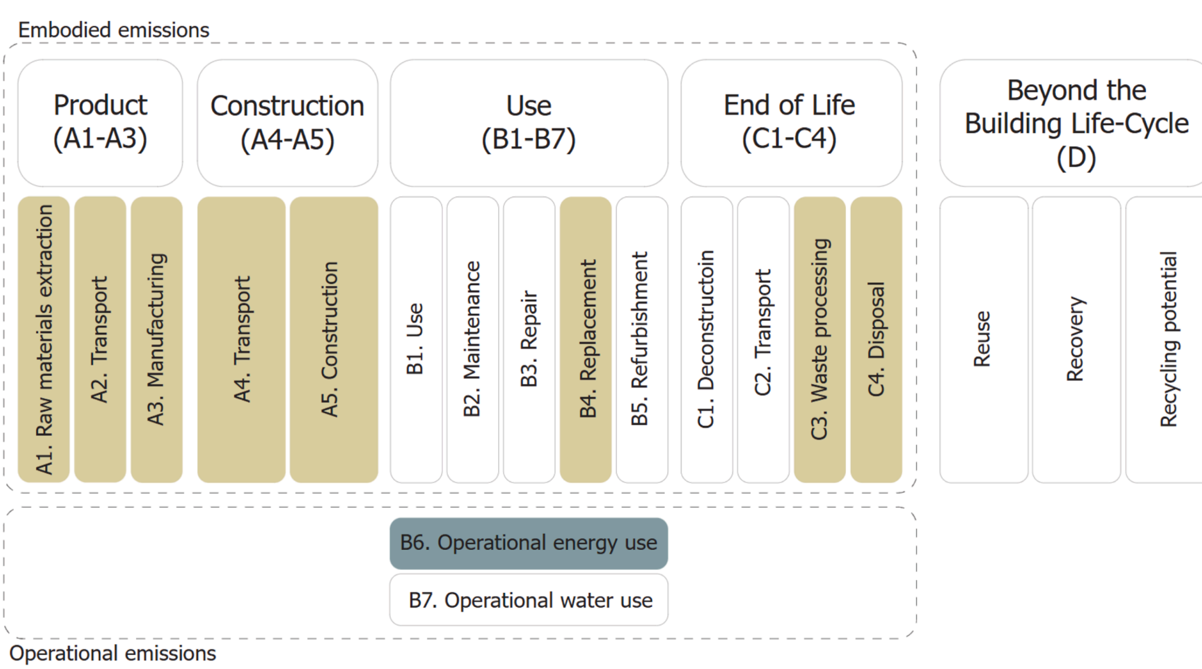


Fig. 8. Lifecycle stages, embodied and operational emissions definition according to EN 15978. Highlighted are the stages included in the Danish GHG emissions calculation approach and the current study.

Table 3
Life cycle inventory for modules A1 to A3.

Component (Modules A1-A3)	Embodied Carbon ($kgCO_2e$)	Range ($kgCO_2e$)	Life Service (years)	Functional Unit
Biobased Wall (U-Value 0.4)	30	20–40	30	Per m^2
Biobased Wall (U-Value 0.2)	50	40–60	30	Per m^2
ETICS (U-Value 0.4)	48	40–60	30	Per m^2
ETICS (U-Value 0.2)	68	60–80	30	Per m^2
Double Glass Windows (low-e, PVC: 25 kg/m^2)	60	50–80	25	Per m^2
Triple Glass Windows (low-e, PVC: 30 kg/m^2)	120	110–140	30	Per m^2
External Automated Shading System	320	220–350	25	Per m^2
Cavity Wall (U-Value 1.7, Brick and Cinder Block, 1960s)	49	40–60	50	Per m^2
Internal Wall of Cinder Brick with Mortar (1960)	12.25 $kgCO_2e/m^2$ 0.98 $kgCO_2e$ per block	11–14 $kgCO_2e/m^2$ 0.8–1.0 $kgCO_2e$ per block	50	Per m^2
Roof (Terracotta, Non-Insulated)	35	30–50	50	Per m^2
Roof 2 Insulated (U-Value 0.4)	50	40–60	30	Per m^2
Roof 3 Insulated (U-Value 0.2)	70	60–80	30	Per m^2
Ground Floor Insulated (Ceramic Tiles, Mortar, Reinforced Concrete, Low-Density Insulation)	90	80–110	50	Per m^2
Internal Paint (230 m^2, Acrylic)	60	50–70	10	All
Heat Pump R Class B	480	400–550	20	Per unit
Heat Pump R Class A	600	500–700	20	Per unit
Gas Boiler	500	450–550	15	Per unit
Radiators (4 units)	300	250–350	30	All
Radiators (8 units)	600	500–700	30	All
System D with heat recovery (350 m^3/h)	500	450–550	20	Per unit
System C with heat recovery (350 m^3/h)	300	250–350	20	Per unit
Ventilation Ductworks	100	85–135	20	All
Plumbing (Ground Heating + Radiators)	400	300–500	30	All
Lighting (Mainly LED Lamps)	100	80–120	15	All
PV System (Monocrystalline, 18 %)	800	750–850	25	Per m^2
PV System (Polycrystalline, 16 %)	700	650–750	25	Per m^2
Inverters	250	200–300	15	Per unit

benchmarks. For building service calculations, the validation was enhanced using OneClick LCA MEP Carbon Tool and methodologies from Francis et al. [35] and García-Sanz-Calcedo et al. [38]. Environmental indicators, such as GWP, were benchmarked against European standards and regional studies to validate contextual relevance [36]. GWP values were primarily derived from TOTEM, B-EPD and supplemented with Ecoinvent 3.10 data. The timeframe (100-year GWP) and [47] characterization method was used to ensure consistency with standard LCIA methodologies. Plausibility checks ensured consistency across lifecycle stages, identifying any outliers or anomalies. Independent peer reviews by LCA experts refined assumptions and methodologies, and dynamic validation within TOTEM ensured consistency across all inputs and outputs. This comprehensive process ensured scientifically robust results suitable for decision-making in sustainable building design.

Finally, in the interpretation and decision support phase, LCIA results were analyzed to determine optimal renovation strategies in terms of carbon performance. Correlation analysis and sensitivity tests were conducted to evaluate how input variability (e.g., energy mix, material emissions, material quantities) affects LCIA results, identifying key variables contributing to uncertainty. Sensitivity analysis helped refine conclusions, ensuring a more reliable and robust environmental assessment.

2.5. GHG emissions calculation and coupling

Operational emissions refer to the lifecycle stage B6. They are expressed in $kgCO_2e/(m^2 \cdot y)$ and are obtained by multiplying the building energy use (in $kWh/(m^2 \cdot y)$) from the energy simulations by the EF of the electricity mix (in $kgCO_2e/kWh$). Operational emissions also include the impact of heat pump refrigerant leakage. The yearly GHG emissions intensity from refrigerant leakage is calculated using the following formula [13]:

$$GHG_{ref} = G \cdot \omega \cdot \alpha$$

where G is the charge of refrigerant [kg], ω is the GWP of the refrigerant [$kgCO_2e$/kg], and α is the annual leakage of the refrigerant [-]. G and the type of refrigerant are provided by producers' datasheets. For this study, it is assumed a charge of 3.25 kg of R-32, which has a GWP of 675 $kgCO_2e$ per kg of refrigerant. The annual leakage is assumed at 5 % [13]. Thus, the yearly GHG emissions intensity from refrigerant leakage is 0.55 $kgCO_2e/(m^2 \cdot y)$.

The resulting annual operational emissions are first used as a metric for the sensitivity analysis (Section 2.6). Afterwards, they are combined with the embodied emissions from the LCIA (Section 2.5), averaged over 50 years to obtain an annual value expressed in $kgCO_2e/(m^2 \cdot y)$. This coupling is done a posteriori, meaning that operational and embodied emissions are calculated separately, then summed to obtain the total annual GHG emissions (expressed in $kgCO_2e/(m^2 \cdot y)$) and the cumulative GHG emissions intensity ($kgCO_2e/m^2$) for the dwelling. These metrics are used to compare the environmental performance of the renovation scenarios.

2.6. Sensitivity and uncertainty analysis

Global sensitivity analysis was conducted to identify the most influential parameters on operational emission, with all input parameters varying simultaneously. The Morris method [54] was adopted, being the most suitable when the variation of input parameters is uniformly distributed between chosen boundaries [50]. This method provides the same identification and ranking as Sobol's method [71], but with a lower computational cost.

The following steps were applied to conduct the analysis [58]:

- Definition of input parameters: parameters for the envelope, systems, and on-site renewable energy generation parameters were varied simultaneously (Table 1), adopting a cross-staged approach.
- Definition of the sample size: Morris recommends using $k+1$ input parameters in a space with r trajectories. Based on suggestions from Deng et al. [20] and Pianosi et al. [58], 25 trajectories were used, being them sufficient to fix the parameters ranking. This choice resulted in a sample size of 300.
- Definition of the output function: operational emissions ($kgCO_2e/(m^2 \cdot y)$) and annual net primary energy ($kWh/(m^2 \cdot y)$) were used as output functions.
- Simulation of the output function: simulations were performed using jE+ EA [79], with input data from the DesignBuilder models exported as .idf files.

- Analysis of the sensitivity indices: jE+ EA calculated the standard deviation (σ) and the absolute mean (μ*) of the elementary effect (EE), ranking parameters by importance and identifying potential correlations among them.

For LCIA, an uncertainty analysis was performed with Montecarlo simulations [43], focusing on material quantities and EFs for the most influential materials. Material quantities were varied by ±10 % to account for discrepancies in project specifications or construction tolerances. Sensitivity analyses also considered variations in transport distances and energy use. For EFs, data from at least three EPDs per material, representing different manufacturers or regional production contexts, were incorporated for concrete, reinforced steel, and timber. Montecarlo simulations were conducted by running the LCA model 230 times with varied input parameters, generating probabilistic distributions and confidence intervals for the results. This approach systematically addressed uncertainties in material data and emissions, enhancing the reliability and transparency of the LCIA outcomes.

3. Results

3.1. Variables affecting operational emissions in building renovation

Starting with an annual net energy use intensity of 166 kWh/(m^2·y) in the BC, the energy use intensity is reduced to an average of 42 kWh/(m^2·y) in the renovation scenarios S.01a and S.01b, 57 kWh/(m^2·y) in scenarios S.01c and S.01d, and 9 kWh/(m^2·y) in the scenarios S.02a and S.02b (Fig. 9). When translating these results into primary energy (PE) and energy labeling, the dwelling shifts from class F (PE of 415 kWh/(m^2·y)) to class C in all Low-Energy cases (PE of 105 and 142 kWh/(m^2·y)), and to class A in the UltraLow-Energy scenarios (PE of 23 kWh/(m^2·y)).

The most significant effect of the building renovation is the reduction in heating energy use, which decreases from 148 kWh/(m^2·y), representing 90.4 % of total energy use, to 38 kWh/(m^2·y) (58.7–76.8 %) in the Low-Energy scenarios and 11 kWh/(m^2·y) (35.7 %) in the UltraLow-Energy scenarios. Conversely, cooling is negligible in all scenarios,

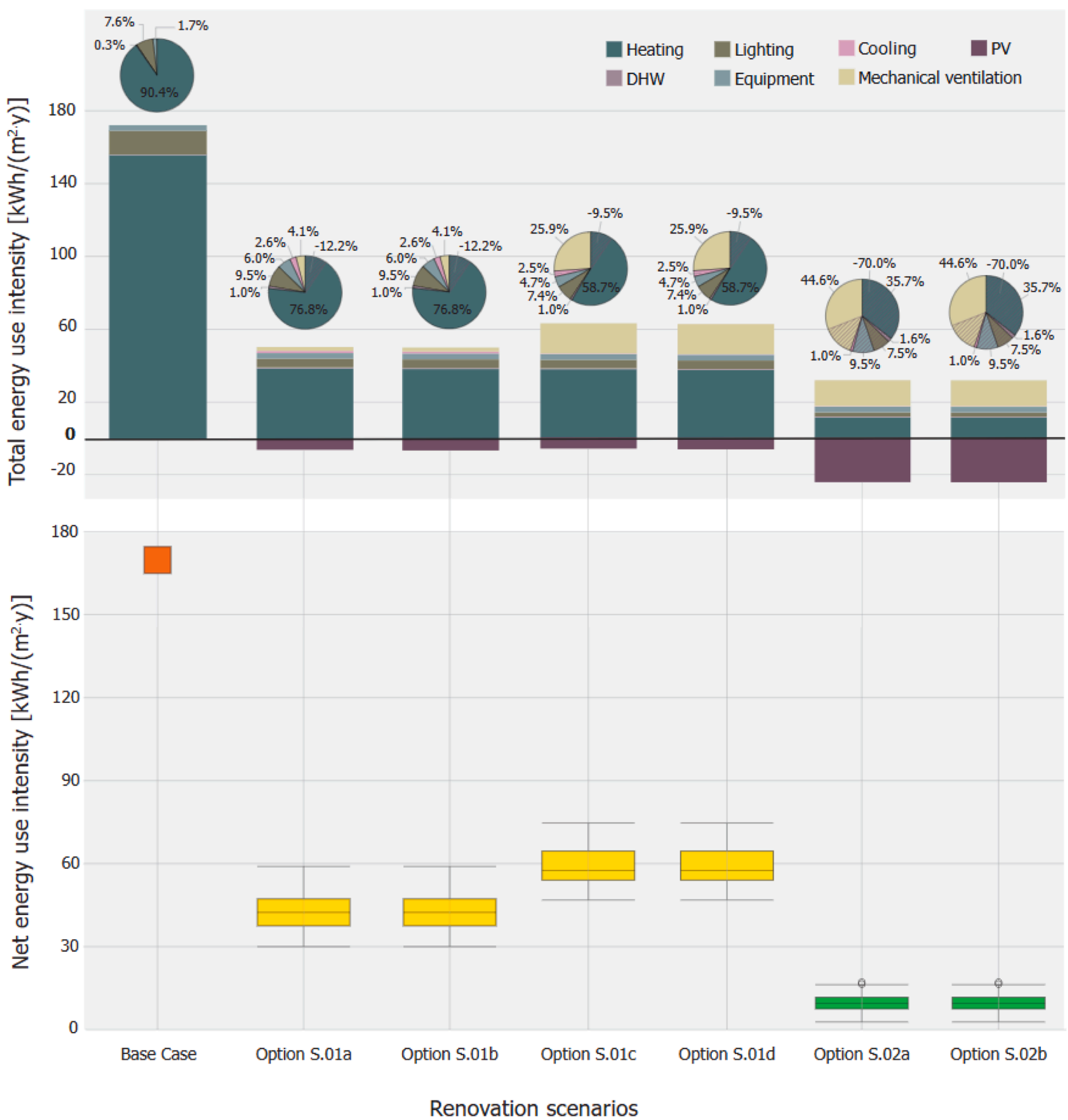


Fig. 9. Effect of building renovation scenarios on building net energy use intensity: the impact by energy use category (top) and the total net energy use intensity (bottom) per renovation scenario.

contributing only 1.6–2.6 % of total energy use. The building is thus clearly heating-dominated. Scenarios S.01c and S.01d exhibit higher energy use intensity than S.01a and S.01b because the installation of the mechanical ventilation System D consumes more electricity than System C, contributing with 16.64 kWh/(m^{2}·y) and 2.04 kWh/(m^{2}·y) to the total energy use, respectively. In the UltraLow-Energy scenarios (S.02a and S.02b), electricity consumption for mechanical ventilation becomes the dominant factor in the overall energy use intensity, reaching a share of 44.6 % of total energy use. However, thanks to additional improvements in the building envelope and systems performance, as well as the installation of a larger surface of PV panels (which reduces the dwelling's energy use by 70 %, compared to just 9–12.2 % in the Low-Energy scenarios), the electricity consumption in S.02a and S.02b is the lowest when compared to the other scenarios.

Operational emissions range from an average of 7.3 kgCO_2e/(m^{2}·y) in the Low-Energy scenarios S.01a and S.01b, to 9.9 kgCO_2e/(m^{2}·y) in S.01c and S.01d, and 6 kgCO_2e/(m^{2}·y) in the UltraLow-Energy scenarios S.02a and S.02b (Fig. 10).

The ranking of design parameters is based on the absolute mean of the Elementary Effect (μ*). The Low-Energy scenarios show similar rankings, with the most influential parameters being the COP of the heat pump, followed by the airtightness and the U-value of the external walls. Other relevant parameters, in order, include the g-value and U-value of the glazing, PV efficiency, and the U-value of the roof.

In the UltraLow-Energy scenarios S.02a and S.02b, the most influential parameter shifts to PV efficiency, followed by the COP of the heat pump and the U-values of the walls and roof. Airtightness ranks after the roof U-value, followed by the g-value and U-value of glazing. The water tank volume, U-value of the door, U-value of the ground floor, and Energy Efficiency Ratio (EER) of the heat pump have a negligible impact in all cases.

The parameter rankings are explained by the heating dominance of the dwelling. The most influential parameters improve heating system performance and reduce the heating load. In contrast, the negligible cooling demand diminishes the importance of the heat pump's EER. Regarding U-values, the most influential parameters combine significant performance improvements over the BC and larger envelope surface areas. As a result, the placement of PV panels is particularly relevant in

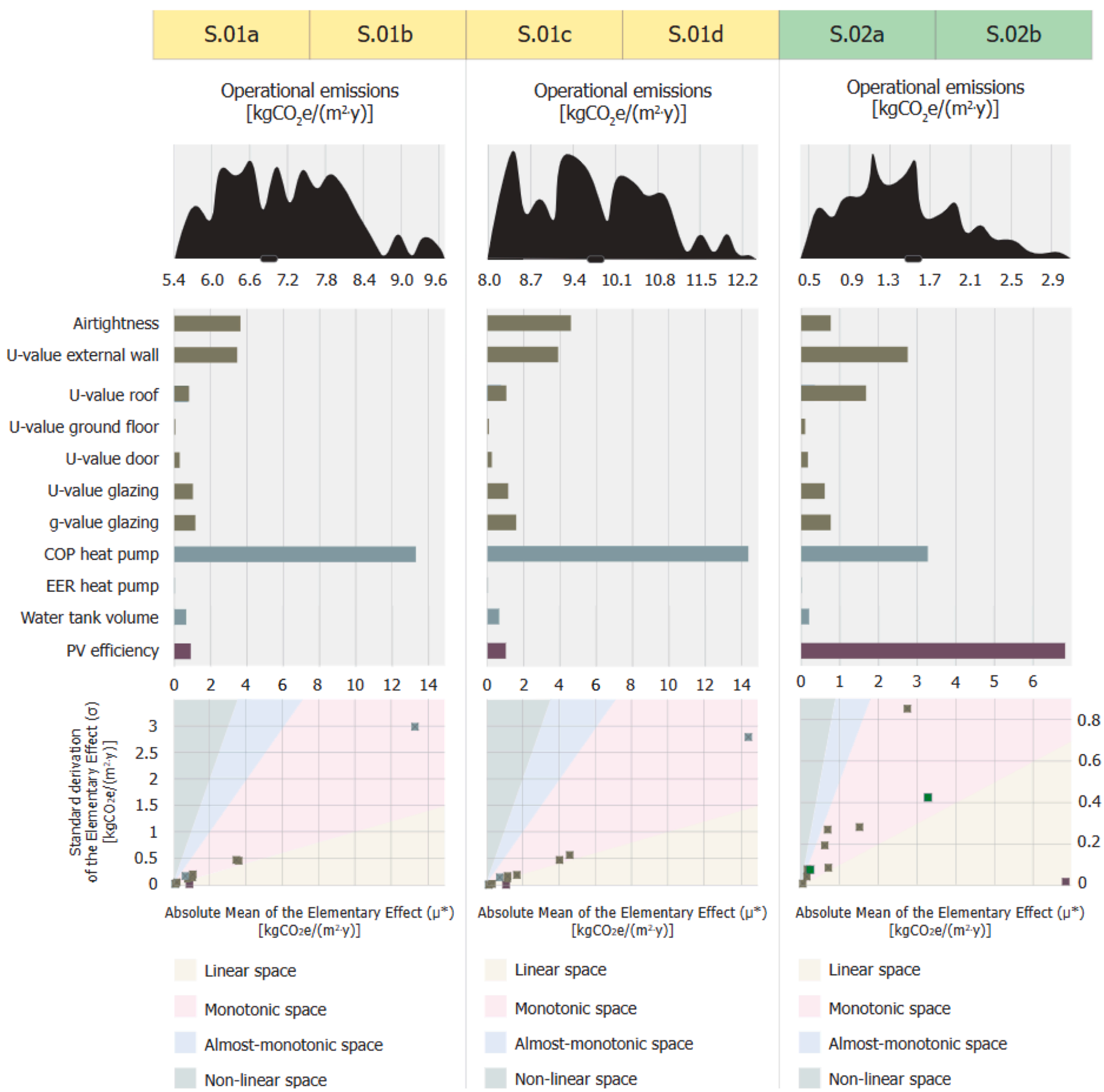


Fig. 10. Sensitivity analysis results for operational emissions: the distribution of the operational emissions (top), and parameters ranking according to the Morris absolute mean of the elementary effect (μ*) (middle), correlations among parameters according to the Morris indices (bottom).

the S.02 scenarios, while the intervention on external walls has a larger impact than on the roof, since the BC's roof performance was superior to that of the external walls. Lastly, external walls are prioritized due to their larger surface area, while window renovations have lower importance due to a low WWR.

Regarding parameter interactions, the Morris standard deviation of the Elementary Effect (σ) shows no correlation among parameters in any of the renovation scenarios. All parameters are monotonic, except for the PV efficiency, which is linear. The only exception is the EER of the heat pump, which is almost monotonic in the Low-Energy scenarios and nonlinear in the UltraLow-Energy scenarios. In fact, the EER is linked to the COP of the heat pump: higher COP values result in a higher EER.

3.2. Variables affecting embodied emissions in building renovation

Starting from 8.5 $kgCO_2e/(m^{2}\cdot y)$ in the BC, the embodied emissions are reduced to an average of 7.2 $kgCO_2e/(m^{2}\cdot y)$ in the renovation scenario S.01a, 6.7 $kgCO_2e/(m^{2}\cdot y)$ in S.01b, 7.3 $kgCO_2e/(m^{2}\cdot y)$ in S.01c, and 6.7 $kgCO_2e/(m^{2}\cdot y)$ in S.01d Embodied emissions increase to an average of 10.0 $kgCO_2e/(m^{2}\cdot y)$ in S.02a and 9.6 $kgCO_2e/(m^{2}\cdot y)$ in S.02b (Fig. 11). The BC reveals higher embodied emissions than the Low-Energy scenarios, primarily due to ground and internal floors, which were not renovated.

Renovation scenarios adopting bio-based materials consistently result in lower GHG emissions compared to the petrochemical-based scenarios (−7.6 % in Low-Energy and −3.9 % in UltraLow-Energy scenarios).

In all scenarios, the most impacting element is the PV panel. It has a lower environmental impact in the Low-Energy due to the use of polycrystalline panels (which are less carbon-intensive than monocrystalline panels) and a smaller panel surface area (12m^2 vs 32m^2 in the UltraLow-Energy scenarios). Except for S.01b and S.01d, PV panels are followed by external wall renovation, shading installation, roof renovation, and windows replacement. In the bio-based Low-Energy scenarios, shading emissions are more significant than those from external wall renovation, followed by roof renovation and window replacement, as in other cases. For building systems, the heat pump installation contributes most to embodied emissions in scenarios with ventilation system C (i.e., S.01a and S.01b), while mechanical ventilation system D contributes most in all other scenarios.

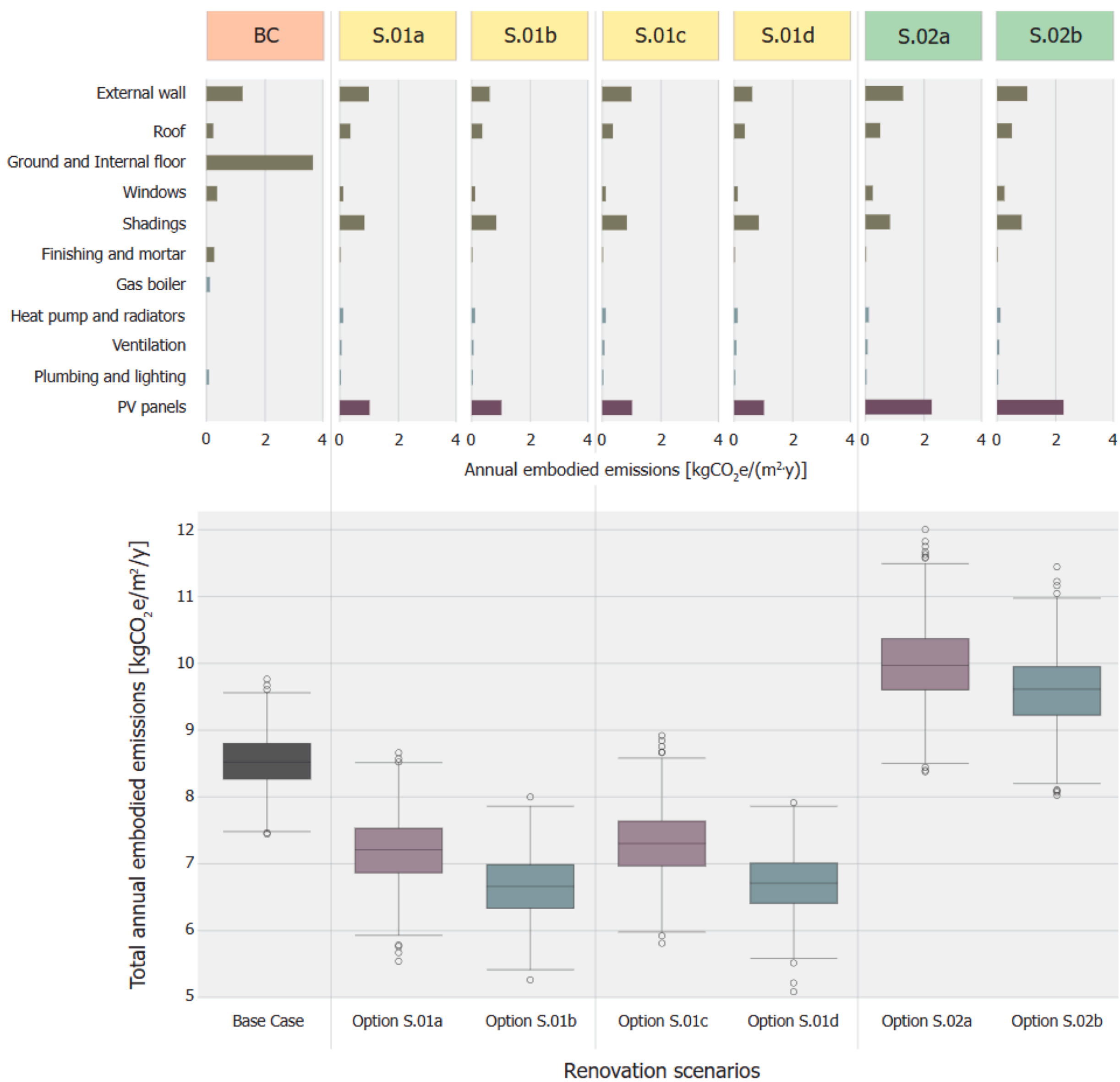


Fig. 11. Effect of renovation scenarios on annual embodied emissions: the impact by material (top) and the total annual embodied emissions (bottom) per renovation scenario.

3.3. Embodied and operational emissions trade-off

There is a tradeoff between embodied and operational emissions. In the BC, where operational energy use intensity and emissions are high, embodied emissions account for 20 % of total GHG emissions (Fig. 12). This share increases in the Low-Energy scenarios (Options S.01a to S.01d), where embodied emissions make up 39–48 % of total emissions, and rises further in the UltraLow-Energy scenarios (S02a, S02b), where they represent 82–83 % of total emissions. Thus, the greater the improvement in energy performance, the higher the material demand and, consequently, the embodied emissions associated with the renovation scenario.

Table 4 summarizes the results. Building renovation reduces the dwelling's net energy use intensity in all scenarios. S.01c and S.01d exhibit the highest environmental performance, followed by S.01a and S.01b, which are closer to the UltraLow-Energy scenarios S.02a and S.02b Despite the significant increase in the embodied emissions due to improved energy performance, the S.02b scenario remains the least GHG-intensive. However, even this scenario fails to meet the Danish threshold of 8.2 $kgCO_2e/(m^2 \cdot y)$.

3.4. Impact of climate change and electricity mix on emissions

Annual and daily variations in the electricity mix have the least impact on the operational emissions in scenarios with the highest energy use intensity (Table 5). For the BC, variations in operational emissions due to finer EF are negligible (+0.05 % with monthly EF and +0.13 % with hourly EF). This is because heating energy use dominates, but it is gas-powered.

The percentage difference in operational emissions increases as the energy use intensity decreases, reaching 16 % and 54 % with monthly and hourly EF, respectively, in the S.02a and S.02b scenarios. Comparing the house's electricity load profiles (Fig. A.2) and EF evolution (Fig. 4), this difference can be attributed to the highest electricity load occurring during winter, when the EF peaks, and during the most carbon-intensive hours of the day.

When combining climate and electricity mix variations for a 2050 horizon, a different trend emerges. The greatest difference between static (i.e., fixed climatic conditions and electricity mix) and dynamic approaches (i.e., incorporating climate and electricity mix projections) occurs in scenarios S.01c and S.01d, with differences of 19 % and 20 %, respectively (Fig. 13). This difference decreases to 3 % in scenarios S.02a and S.02b

This trend is due to two factors: the reduction in energy use intensity (Fig. 13) and the increase in the EF of the electricity mix (Table A.1). The reduction in energy use intensity is attributed to lower heating and mechanical ventilation energy use, which is not offset by a significant

Table 4
Net energy use intensity, embodied, operational and total annual GHG emissions for each renovation scenario.

Average	Base Case	Low-Energy				UltraLow-Energy	
		S.01a	S.01b	S01c	S01d	S02a	S02b
Annual net energy use intensity [$kWh/(m^2 \cdot y)$]	166	42	42	57	57	9	9
Renewables production [%]	/	19	19	13	13	70	70
Annual net source energy [$kWh/(m^2 \cdot y)$]	415	105	105	142	142	23	23
Energy efficiency rating							
Annual operational emissions (energy) [$kgCO_2e/(m^2 \cdot y)$]	32	7.3	7.3	9.9	9.9	1.6	1.6
Annual operational emissions (refrigerant) [$kgCO_2e/(m^2 \cdot y)$]	0	0.5	0.5	0.5	0.5	0.5	0.5
Annual embodied emissions [$kgCO_2e/(m^2 \cdot y)$]	8.5	7.2	6.7	7.3	6.7	9.9	9.6
Total annual GHG emissions [$kgCO_2e/(m^2 \cdot y)$]	40.5	15.0	14.5	17.7	17.1	12.0	11.7

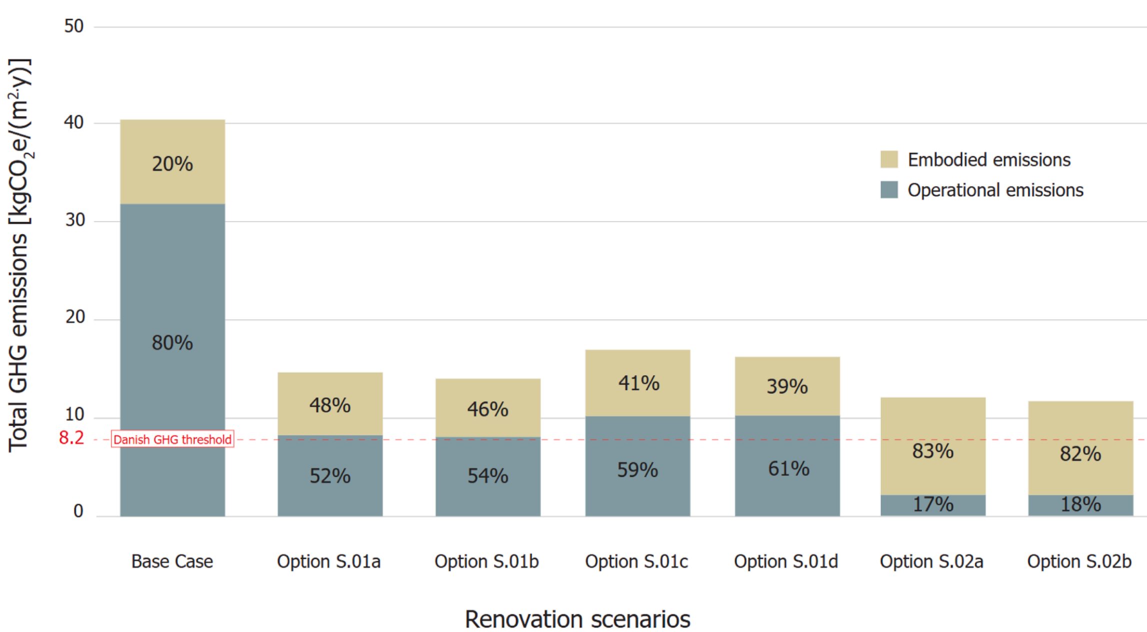


Fig. 12. Total annual GHG emissions (embodied + operational) in comparison with the Danish GHG threshold, and share between embodied and operational emissions for each renovation scenario.

Table 5
Variation of the annual operational emissions according to the emission factor used (annual average, monthly average, hourly) per renovation scenario.

Renovation scenario	Operational emissions [kgCO2e/(m^2·y)]				
	Annual EF [kgCO2e/(m^2·y)]	Monthly EF [kgCO2e/(m^2·y)]	Δ [%]	Hourly EF [kgCO2e/(m^2·y)]	Δ [%]
BC	32.41	32.43	+0.05 %	32.45	+0.13 %
S.01a	7.36	7.90	+7 %	8.04	+9 %
S.01b	7.36	7.90	+7 %	8.04	+9 %
S.01c	9.89	10.40	+5 %	10.60	+7 %
S.01d	9.89	10.40	+5 %	10.60	+7 %
S.02a	1.61	1.88	+16 %	2.48	+54 %
S.02b	1.61	1.88	+16 %	2.48	+54 %

rise in cooling energy use. However, the reduction in energy use intensity is insufficient to cover the doubling of the EF, especially in the scenarios with initially high energy use intensity, leading to higher operational emissions in dynamic scenarios. An exception is the S.02a and S.02b scenarios, where, by 2050, the dwelling becomes energy-negative. In these cases, the static approach results in higher operational emissions in the long term compared to the dynamic approach.

From a lifecycle perspective, despite the GHG emissions spike from building renovation, the BC has the highest emissions over 50 years, followed by scenarios S.01c, S.01d, S.01a, S.01b, S.02a, and S.02b (Fig. 13). Cumulative emissions decrease as embodied emissions increasingly dominate operational emissions over the lifecycle. Specifically, in S.01c and S.01d, embodied emissions account for 39–37 % of the total emissions. This share increases to 46–44 % in S.01a and S.01b and rises to 86–85 % in S.02a and S.02b

Cumulative emissions of the BC overcome retrofit emissions in nine years for S.01b (both static and dynamic). It is followed by S.01a, which recoups emissions in ten years, then S.01c dynamic, S.01d dynamic, and S.02b (static and dynamic) in twelve years. Finally S.01c static, S.01d static, and S.02a (both static and dynamic) recoup emissions in thirteen years.

4. Discussion

4.1. Findings and recommendations

The application of the six renovation scenarios indicates that, for a heating-dominated dwelling, the most impactful interventions to reduce operational emissions are replacing the heating system ($\mu^* = 13.38$–14.40 for S.01a,b and S.01c,d), improving airtightness ($\mu^* = 3.65$–4.54 for S.01a,b and S.01c,d), and insulating external walls ($\mu^* = 3.52$–3.95 for S.01a,b and S.01c,d) in the Low-Energy scenarios. In the UltraLow-Energy scenarios, the most influential interventions are improving PV panel efficiency ($\mu^* = 6.83$), installing high-performance heat pumps ($\mu^* = 3.29$), and insulating walls ($\mu^* = 2.76$) and roof ($\mu^* = 1.66$) (Fig. 10).

However, reducing operational emissions results in an increase in embodied emissions, as the most impactful element is the PV panel, followed by external wall renovation, shading installation, roof renovation, and windows replacement. The significant impact of PV panels was also highlighted by Rasmussen et al. [62], who found that PV panels contribute 55–65 % of lifecycle GHG emissions, potentially increasing Net-zero energy buildings (NZEBs) lifecycle GHG emissions by 1.5–2.5 times compared to BC designs.

NZEBs are crucial for reducing building energy consumption and GHG emissions, but their design, optimization, and modeling present challenges [9]. As operational energy use decreases, embodied emissions rise, reaching 21–79 % in option S.02a for the yearly average (Fig. 12) and 14–86 % for cumulative emissions over 50 years (Fig. 13). This trend, also noted by Röck et al. [63], underscores the growing dominance of embodied emissions over operational emissions.

Despite the increase in embodied emissions, the UltraLow-Energy scenarios remain the least carbon-intensive renovation options from both a yearly average and whole lifecycle perspective. The use of bio-based materials offers greater potential for recycling or composting at the end of their life, further reducing embodied emissions by 4 % compared to petrochemical materials (Table 4). Therefore, to achieve the zero-carbon target for Post-WWII dwellings, adopting the UltraLow-energy renovation standard alongside bio-based materials is essential, as also observed by Galimshina et al. [37]. However, cost implications should be considered, as bio-based materials and certain interventions for UltraLow-Energy scenarios, such as monocrystalline PV panels and mechanical ventilation d-systems, are more expensive than traditional materials and low-energy interventions like those in the C-class scenario S.01b These higher costs may challenge their widespread adoption, especially for building owners within tight budgets.

Renovation design and simulation must consider yearly and daily variations in the electricity mix and future climatic conditions. Adopting hourly EF instead of annual averages increases operational emissions by 5–54 %, particularly in the UltraLow-Energy scenarios (Table 5). The significant difference in results emphasizes that adopting hourly EF helps identify additional opportunities to reduce building emissions [72].

Considering long-term variation in the Belgian electricity mix and climate, operational energy use decreases. However, with a rise in EF after 2030, operational emissions increase by 16–20 % by 2060 compared to a static approach (Fig. 13). Similar findings were reported by Ramon et al. [61] and Su et al. [73], underscoring the need for a dynamic approach.

Based on these findings, the following recommendations are made:

1. Prioritize heat pump and PV panel installation alongside external walls and roof insulation.
2. Use biobased materials over petrochemical ones to mitigate the GHG emissions spike from embodied emissions.
3. Adopt a dynamic approach to accurately estimate annual and long-term building GHG emissions.

4.2. Strengths, limitations and future work

The main strength of this study lies in its integrationg of operational and embodied emissions, using a whole-life carbon approach that includes lifecycle stages A1-A5, B4, B6, and C3-C4 as per Danish regulations [56]. As demonstrated by the results, focusing solely on operational or embodied emissions can lead to misleading conclusions and poor renovation choices. Secondly, by following best practices outlined in IEA Annex 89 [45] and using the Danish GHG emissions calculation approach, the methodology used can be applied to other studies. However, the case study analyzed is specific to a single climatic zone and location, and the building's life cycle is influenced by a variety of factors such as temperature, soil characteristics, and local building practices. Therefore, applying these findings to other regions or countries requires careful consideration ([5,52]). Additionally, results could differ for other building typologies, as factors like external wall, roof, and glazed surfaces, occupancy patterns, and schedules can influence parameters ranking. Thus, the scalability of these findings to other building types needs to be evaluated carefully.

Another strength of this study is the adoption of a dynamic modeling approach, incorporating hourly EF and future projections of the Belgian electricity mix and climatic conditions. This long-term approach provides a more comprehensive analysis of building renovation effectiveness. This research is also one of the few to combine dynamic modeling with a simultaneous evaluation of embodied and operational emissions in building retrofits, while conducting a prior sensitivity analysis (Section 1.2). Finally, this research analyzes a calibrated building

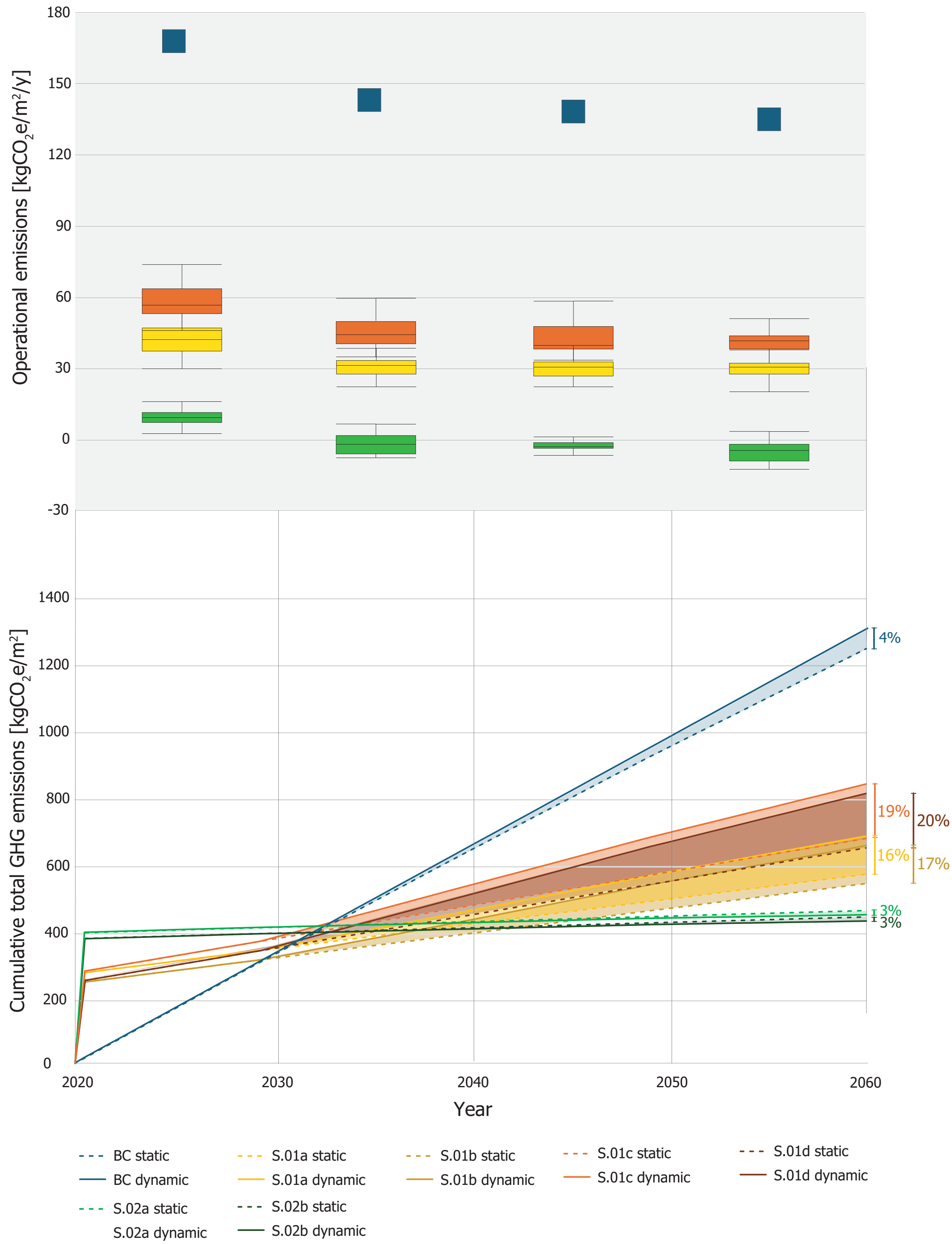


Fig. 13. Annual operational (top) and cumulative GHG emissions (bottom) considering climate change effects and electricity mix variations.

archetype representing Belgian single-family houses built post-WWII, which can support broader application of the same renovation strategies.

A major limitation of this study is the exclusion of cost analysis, which significantly impacts renovation decisions [39]. This becomes particularly evident in Fig. 12, where S.01a and S.01b scenarios, despite using less efficient technologies (e.g., mechanical ventilation type C), show environmental performance similar to S.02a and S.02b

Furthermore, uncertainty analysis was only performed for the LCIA, with BPS and LCIA still treated separately. BPS has lower uncertainty due to the installation of smart meters, whereas LCIA involves higher uncertainty in material quantities estimation, particularly with older materials, and often relies on secondary databases for emissions quantification.

It is also important to recognize that sensitivity analysis results may vary depending on the calculation method. In this study, the Morris method was used to rank parameter, but Satola et al. [66] observed that different methods (e.g., Fourier amplitude sensitivity test variance (FAST)) can yield different rankings. Therefore, to further strengthen the findings, comparisons between Morris and other sensitivity analysis methods would be valuable.

Lastly, while dynamic aspects were considered, the study still needs to account for future variations and long-term impacts of the electricity mix on construction materials production and potential technological advancements in renewable energy sources. Technological progress, resulting in more efficient and cheaper PV panels, energy storage, and wind turbines, could increase the renewable energy share in the electricity mix and reduce the carbon intensity of construction products. These factors should be integrated into future studies to provide a more comprehensive carbon assessment.

Future research should address these limitations to improve the consistency of whole life carbon assessments. Key areas for further investigation include integrating cost analysis (considering both investment and operational costs, including country-specific energy taxes) and applying this methodology to different locations and building typologies worldwide. Additionally, despite efforts in building decarbonization, a standardized framework is needed to ensure buildings meet net-zero carbon targets [8]. This should include validating environmental performance with real-time data collected during the building's in-use phase. Parameters, scenarios, and model uncertainty, particularly regarding user behavior and maintenance/replacement needs, poses a challenge in lifecycle assessment (LCA) [42]. Collecting real-world data on these factors will help refine embodied emissions estimates and quantify discrepancies between modeled and actual emissions.

5. Conclusion

The enhancement of energy efficiency in buildings results in a decrease in operational emissions but also leads to an increase in embodied emissions. Consequently, as emphasized by the EPBD revision, it is crucial to evaluate operational and embodied emissions concurrently to reduce the total GHG emissions of buildings. However, existing literature primarily examines these aspects separately, often lacking a whole lifecycle perspective and dynamic modeling methodology in building retrofit.

This paper aims to fill these gaps. Six renovation scenarios for a single-family house in Belgium were designed, incorporating both conventional petrochemical and bio-based materials. A building energy model was developed for each renovation alternative to calculate operational energy use and emissions. Additionally, the materials used in each renovation scenario were quantified to compute the associated embodied emissions. The results from both models were then coupled a posteriori to calculate the total yearly average emissions and cumulative emissions over 50 years.

The sensitivity analysis findings revealed that, in a heating-dominated climate, the most impactful measures for reducing operational emissions include installing efficient PV panels, replacing the heating generation system, and improving the envelope performance through external walls and roof insulation and enhanced airtightness. However, PV panels also emerged as the most significant parameter in terms of embodied emissions, followed by external wall renovation, shading installation, roof renovation, and window replacement. Consequently, transitioning from the BC with an EPC rating F to the UltraLow renovation scenarios results in a shift in the proportion of embodied versus operational emissions.

Despite the GHG emissions spike associated with building renovation, the UltraLow renovation scenarios (particularly S.02b, which uses bio-based materials) remain the least carbon-intensive, both in terms of yearly average emissions and cumulative emissions over 50 years. The study also indicates that adopting a dynamic modelling approach rather than a static one significantly impacts operational and cumulative emissions. Specifically, using an hourly EF instead of an annual average can lead to a significant increase in operational emissions for UltraLow-Energy scenarios. On the other hand, introducing future climate and electricity mix projections primarily affects the Low-Energy scenarios.

In conclusion, the findings support the adoption of UltraLow-Energy renovation scenarios using bio-based materials to meet established emissions targets. The study also highlights the necessity of employing a lifecycle and dynamic modeling approach to enhance the robustness and effectiveness of building renovation strategies.

CRediT authorship contribution statement

Aurora Bertini: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Muheeb Al-Obaidy:** Software, Data curation. **Maxime Dasse:** Writing – review & editing, Visualization, Conceptualization. **Deepak Amaripadath:** Writing – review & editing, Resources, Formal analysis. **Emilie Gobbo:** Writing – review & editing, Resources, Methodology, Conceptualization. **Shady Attia:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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

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Annex

Fig. A.1. Plans and elevations of the single-family house archetype (from Attia et al., [12]).

Table A.1
Projection of the Belgian electricity mix composition in 2030, 2040, 2050 and corresponding yearly emission factors.

	2023	2030	2040	2050
Oil [TW]	0.0	1.0	0.5	0.5
Emission factor [kgCO$_2$e/kWh]	0.650	0.650	0.650	0.650
Natural gas [TW]	15.3	41.9	45.7	40.9
Emission factor [kgCO$_2$e/kWh]	0.514	0.514	0.514	0.514
Hydro [TW]	2.3	0.9	0.5	0.5
Emission factor [kgCO$_2$e/kWh]	0.024	0.024	0.024	0.024
Nuclear [TW]	31.3	0.0	0.0	0.0
Emission factor [kgCO$_2$e/kWh]	0.005	0.005	0.005	0.005
Wind [TW]	14.1	15.2	17.1	23.8
Emission factor [kgCO$_2$e/kWh]	0.013	0.013	0.013	0.013
Solar [TW]	7.2	3.8	3.8	4.8
Emission factor [kgCO$_2$e/kWh]	0.036	0.036	0.036	0.036
Biomass and Waste [TW]	3.0	7.6	8.6	7.6
Emission factor [kgCO$_2$e/kWh]	0.230	0.230	0.230	0.230
Other [TW]	6.0	0.0	0.0	0.0

(*continued on next page*)

Table A.1 (*continued*)

	2023	2030	2040	2050
Emission factor [$kgCO_2e/kWh$]	0.700	0.700	0.700	0.700
Yearly emission factor [$kgCO_2e/kWh$]	**0.174**	**0.325**	**0.345**	**0.312**

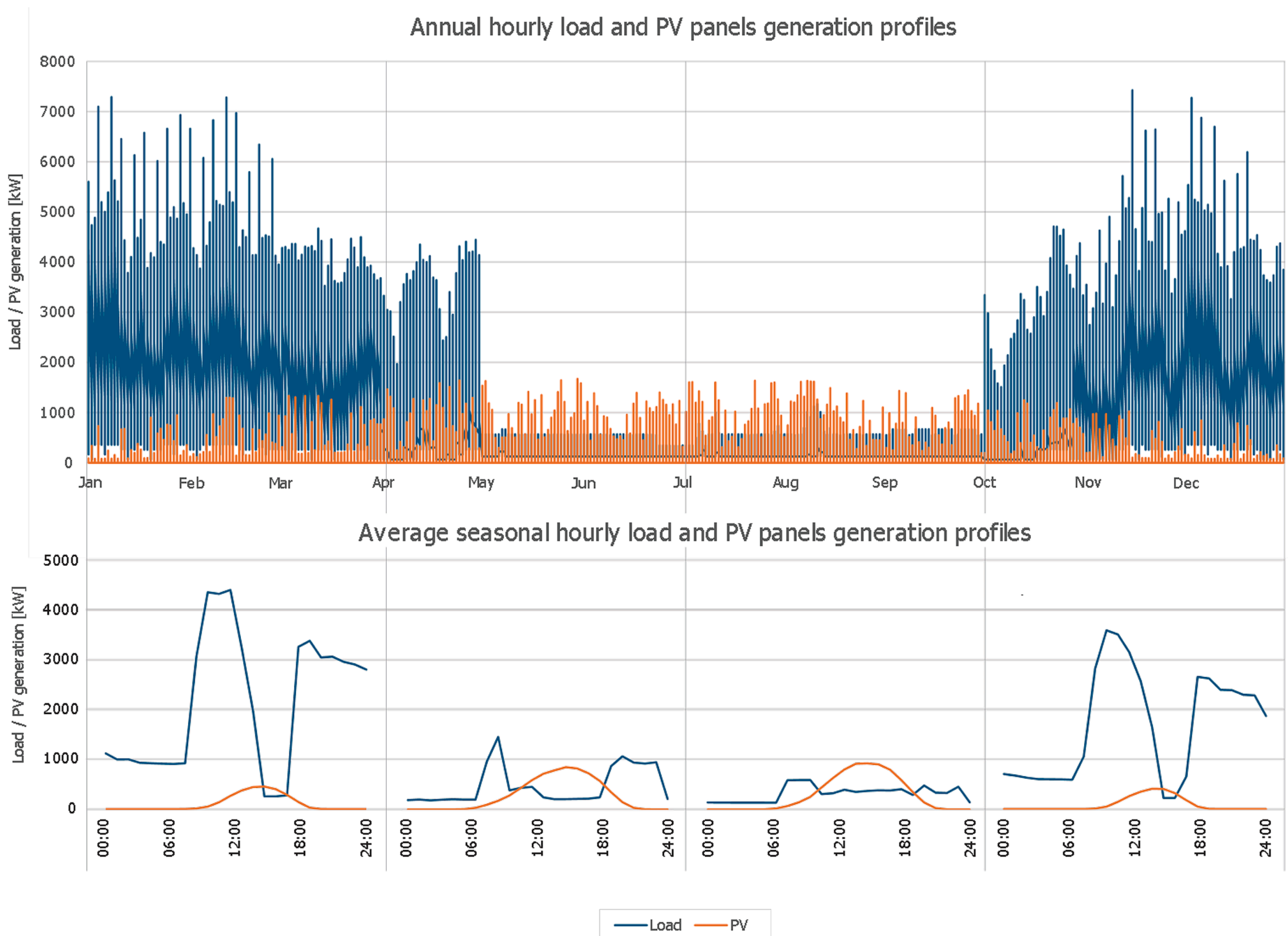

Fig. A.2. Annual hourly load and PV panels generation profiles (top) and Average seasonal hourly load and PV panels generation profile for the scenario S01a.

Data availability

Data will be made available on request.

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