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Toward Net-Zero Renovations: Integrating Building Simulation and LCA for Whole-Life Carbon Assessment

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Abstract. Enhancing the energy efficiency of buildings often necessitates additional materials and advanced technologies, many of which are not locally sourced. This can result in embodied greenhouse gas (GHG) emissions that may offset the savings from reduced operational emissions over the building's lifetime. Consequently, embodied emissions play a critical role in whole-life GHG emissions reduction and must be evaluated alongside operational emissions to meet emission reduction goals. This study explores the integration of life cycle impact assessment (LCIA) with building performance simulation (BPS) to assess the whole-life GHG emissions of residential renovation strategies. An archetype representing a post-World War II single-family dwelling in Belgium serves as a case study for evaluating six retrofit scenarios. These scenarios combine different envelope interventions and materials (petrochemical-based and bio-based options) with varied energy systems and storage technologies, aiming for low-energy and ultra-low energy performance levels. By coupling LCIA with BPS, the analysis captures both embodied and operational GHG emissions over the building's lifecycle and illustrates the trade-offs involved in material and design choices. The dynamic BPS approach also accounts for projected changes in the electricity mix and energy demand patterns. Findings show that deep energy retrofits can lower total GHG emissions by up to 70% compared to the unrenovated baseline, achieving a minimum of 11.7 $kgCO_2e/(m^2 \cdot y)$. Despite this improvement, none of the scenarios satisfy the Danish threshold of 8.2 $kgCO_2e/(m^2 \cdot y)$ for total GHG emissions. Sensitivity analysis reveals that factors such as heat pump efficiency, building airtightness, and photovoltaic panels efficiency significantly affect results. The use of bio-based insulation materials achieves up to 7% lower embodied emissions compared to synthetic alternatives. This research presents an integrated framework for balancing operational and embodied emissions, delivering practical guidance for practitioners and policymakers aiming to meet European decarbonization targets through sustainable renovation of the existing building stock.

1. Introduction

Improving building energy performance typically involves materials and technologies that are resource- and energy-intensive to produce, often sourced internationally. Consequently, embodied emissions now represent a substantial share of whole-life greenhouse gas (GHG) emissions and must be assessed alongside operational energy use to inform realistic decarbonization strategies (1).

The European Whole Life Carbon Roadmap addressed this by setting ambitious goals to reduce both operational and embodied carbon emissions from buildings by 2050. Denmark, among the Nordic frontrunners, has already enforced building regulations that include specific GHG emission limits based on EN 15978 (2) stages A1-A5 (product and construction), B4 (replacement), B6 (operational energy), and C3-C4 (end-of-life) (3).

Despite progress, integration of building energy simulation (BES) with life cycle assessment (LCA) remains limited and centred on the envelope. Early work by Cellura et al. (4), followed by Yeung et al. (5), Shadram & Mukkavaara (6), and others (7,8), identified a trade-off between material use and energy consumption. Satola et al. (9) provided a more holistic perspective, combining interventions in the envelope, geometry, systems, and renewables. These studies underline the value of whole-life cycle thinking, especially during the initial design stages (10).

Given buildings often last over a century, environmental assessments must consider future shifts in climate and energy systems (11). Dynamic LCA enables this by incorporating time-dependent variables such as technological advancements, occupant behavior, and changes in energy systems (12). Mendez Echenagucia et al. (13) showed that envelope upgrades have reduced effectiveness as the grid decarbonizes. Van de Moortel et al. (14) stressed the relevance of integrating dynamic electricity mix data and efficiency growth trajectories for electrical heating systems. However, the use of a dynamic approach remains rare in retrofit studies.

This study addresses these research gaps by examining six renovation alternatives for a post-World War II single-family dwelling in Belgium. It explores how embodied and operational emissions can be dynamically coupled in building retrofits, identifies critical variables affect the lifecycle environmental performance, evaluates potential trade-offs between embodied and operational emissions, and examines how climate change and evolving electricity mix affect progress toward Zero Carbon buildings.

Novel contributions include dynamic integration of embodied and operational emissions on a 50-year horizon, integrating time-varying emission factors and climatic conditions. The analysis spans envelope, systems, and on-site renewables, and pinpoints the most influential design variables via a sensitivity analysis. Finally, the study includes life cycle stages A1-A5, B4, B6, and C3-C4, in line with Danish regulation (3). Since Belgium lacks GHG thresholds and no retrofit-specific regulations are available, the Danish standard was adopted as a reference for its comprehensive LCA coverage and typology-specific thresholds. Nonetheless, this choice entails limitations due to differences in emission factor databases and projected energy mixes between Belgium and Denmark, as well as the scope of the standard, which targets new constructions rather than retrofits.

2. Methodology

2.1 Building location

The analyzed building is located in Brussels, within the mixed-humid Climate Zone 4A (15). Historical weather data (2016–2019) from the Royal Meteorological Institute (16) were used for model calibration. Future hourly weather files (2030, 2040, 2050) were generated using Meteonorm 8.0 (17) under Representative Concentration Pathway (RCP) 8.5, aligning with current global GHG emission trends (18).

Electricity mix dynamics were modeled with emission factors (EFs) at yearly resolution. Current data (2023) were sourced from Electricity Maps (19), while future projections (2030–2050) were based on Ramon & Allacker (20), who analyzed the changes in the electricity grid composition (including the temporary nuclear phase-out) under RCP 8.5.

2.2 Building characterization

The case study builds on work by Attia et al. (21), focusing on an archetype of a Belgian single-family home constructed between 1945 and 1969, a typology representing 48% of the national housing stock (21). The building includes four levels (garage, living, sleeping, and attic) with a net floor area of 259 m^2. It has a load-bearing wall structure, concrete block walls, red brick façade, and timber roofing. The building uses a gas boiler for space heating and DHW, with no mechanical ventilation or cooling.

Previous partial retrofits included double-glazed windows, ground floor, attic slab and roof insulation, and external shadings. Despite these, the current energy class is F, with an energy use intensity of 166 $kWh/m^2 \cdot y$ and operational GHG emissions of 32 $kgCO_2e/(m^2 \cdot y)$.

2.3 Renovation scenarios and energy model

Two renovation scenarios were designed: S.01 (Low-Energy scenario) targeting energy class C/D, and S.02 (UltraLow-Energy scenario) targeting energy class A/B. Renovation covered three main aspects: envelope, technical systems, and renewable energy systems.

As for the envelope, S.01 requires moderate U-values, while S.02 aligns with Passive House standards (22) (Table 1). Both scenarios test petrochemical and bio-based insulation materials. External insulation was chosen to preserve the floor area and minimize thermal bridges.

As for systems, S.01 includes System C (natural air supply and mechanical exhaust) and System D (mechanical air supply and exhaust with heat recovery). S.02 includes System D only as it adopts top-performance materials and systems. All scenarios use reversible air-to-water heat pumps for heating and cooling. S.01 retains the original radiators and operates at 55°C. S.02 introduces low-temperature emitters and underfloor heating, operating at 35°C. All scenarios replace existing lamps with LEDs, reducing the power density from 8-12 W/m^2 in the base case (BC) to 3 W/m^2 in S.01 and 1.5 W/m^2 in S.02.

On-site photovoltaic (PV) systems are installed on the southwest-facing roof, with 12 m^2 polycrystalline PV panels in S.01, and 32 m^2 of monocrystalline PV panels plus 5 m^2 of solar thermal collectors in S.02.

A total of six alternatives were therefore analysed: S.01a (Low-Energy - System C – Petrochemical), S.01b (Low-Energy - System C – Bio-based), S.01c (Low-Energy - System D – Petrochemical), S.01d (Low-Energy - System D - Bio-based), S.02a (UltraLow-Energy - System D - Petrochemical) and S.02b (UltraLow-Energy - System D - Bio-based). The energy models were created using DesignBuilder 7.3.0 and EnergyPlus 9.4.0, and were calibrated with measured data. More details can be found in Bertini et al. (23).

2.4 Life cycle impact assessment (LCIA)

The LCIA followed EN 15804+A2:2019 (24) and EN 15978 (2) standards, using a 50-year reference period. An attributional LCA with dynamic prospective modelling was adopted, including future electricity mixes, climate change scenarios, and replacement cycles to better reflect the consequences of renovation decisions over 50 years. Strict consequential LCA (requiring system expansion and marginal technologies) was not performed.

Materials and components emissions were sourced from TOTEM (25) (integrating Ecoinvent (26)) and B-EPD (27). Verified Environmental Product Declarations (EPDs) were prioritized. When EPDs were unavailable, secondary data from Ecoinvent was used, following ILCD Handbook recommendations (28).

Material and energy flows were tracked and balanced using Material Flow Analysis (MFA), identifying inflows, stocks, and outflows across life cycle stages. Material inventories were extracted from Revit (for envelope and structure) and AutoCAD (for technical systems). Quantities for systems were verified manually using datasheets, CIBSE TM65 guidelines (29), and product-specific EPDs.

The LCIA focused on modules A1–A3 (material production), A4–A5 (transport and construction), B4 (replacement), and C3–C4 (end-of-life) following EN 15804+A2 guidelines (24). Manufacturing, transport, use, and disposal of concrete, reinforced steel, cement blocks, bricks, and timber were sourced from Ecoinvent (26). Brightway2, a Python-based open-source LCA framework, allowed advanced modeling flexibility. The Building Carbon Modeling Framework (30) was used to model building services like PV panels, air handling units, heat recovery units, and heat pumps. Emissions from upstream processes, usage, maintenance, and end-of-life (including refrigerant loss, material recovery, solid waste transport) were calculated.

Table 1. Input variables for each renovation scenario

	BC	S.01a	S.01b	S.01c	S.01d	S.02a	S.02b
Infiltration rate [ach]	0.87	0.12:0.03:0.30		0.12:0.03:0.30		0.04:0.01:0.09	
External Wall U-value [W/(m^{2}K)]	1.7	0.80:0.04:1.00		0.80:0.04:1.00		0.15:0.05:0.40	
Roof U-value [W/(m^{2}K)]	1.3	0.80:0.04:1.00		0.80:0.04:1.00		0.15:0.05:0.40	
Door U-value [W/(m^{2}K)]	2.8	1.40:0.10:2.00		1.40:0.10:2.00		0.80:0.10:1.20	
Glazing U-value [W/(m^{2}K)]	2.9	1.30:0.10:1.80		1.30:0.10:1.80		0.80:0.10:1.20	
Glazing g-value [W/(m^{2}K)]	0.74	0.40:0.04:0.60		0.40:0.04:0.60		0.20:0.02:0.30	
Heating generator	Gas boiler	Heat pump (55°C)		Heat pump (55°C)		Heat pump (35°C)	
Heating COP [-]	0.76	2.50:0.25:3.75		2.50:0.25:3.75		4.00:0.25:5.50	
Cooling EER [-]	-	3.00:0.25:4.25		3.00:0.25:4.25		4.50:0.25:6.00	
Ventilation system	Natural	C		D		D	
Renewables	-	12 m^2 Poly PV		12 m^2 Poly PV		32 m^2 Mono PV + Solar collector	
PV panels efficiency [-]	-	0.13:0.01:0.16		0.13:0.01:0.16		0.15:0.01:0.20	
Water tank volume [m^3]	-	0.15:0.05:0.30		0.15:0.05:0.30		0.15:0.05:0.30	

2.5 GHG emissions calculation and coupling

Operational emissions (Stage B6) were calculated in $kgCO_2e/(m^2·y)$ by multiplying simulated energy use by the corresponding electricity emission factor (EF). Annual refrigerant leakage from the heat pump (30) (based on a charge of 3.25 kg of R-32 and an annual leakage rate of 5%) contributed an additional 0.55 $kgCO_2e/(m^2·y)$.

Embodied emissions were derived from the LCIA (Section 2.5) and averaged over 50 years. Total emissions were calculated by summing operational and embodied emissions, obtaining annual (in $kgCO_2e/(m^2·y)$) and cumulative GHG emission intensities (in $kgCO_2e/m^2$) metrics for scenario comparison.

2.6 Sensitivity and uncertainty analysis

To identify the key factors influencing operational emissions, a global sensitivity analysis was carried out in jE+EA (31) using the Morris method (32). Envelope properties, system specifications, and renewable generation inputs were varied concurrently (Table 1). 25 trajectories (resulting in a sample size of 300) were set to run the simulations.

For the LCIA, Montecarlo simulations (33) were performed to assess uncertainties related to material quantities and emission factors for the most influential materials. Quantities were varied by ±10%. For the emission factors, values from at least three EPDs per material were considered for concrete, steel, and timber. A total of 230 runs generated probabilistic distributions and confidence intervals for the resulting embodied emissions.

3. Results

3.1. Influential factors in operational emissions

Operational emissions range between 6.0 and 9.9 $kgCO_2e/(m^2·y)$. UltraLow-Energy scenarios (S.02a/b) yield the lowest emissions, followed by Low-Energy scenarios with System C ventilation (S.01a/b), and highest in Low-Energy with System D ventilation (S.01c/d) (Figure 1).

Sensitivity analysis shows that in Low-Energy cases, the heat pump's COP is the most influential factor, followed by airtightness and external wall U-values. In UltraLow-Energy scenarios, PV panels efficiency becomes most critical due to the larger system size, followed by COP and external walls and roof U-values. Factors like water tank size, door and ground floor U-values, and the heat pump's cooling performance (EER) contribute negligibly across all cases.

These rankings correlate with the building's heating-dominated profile, where emissions reductions stem from improved heating efficiency and thermal envelope upgrades. The roof's lower impact compared to walls is attributed to its relatively better baseline performance and smaller surface area. The impact of window replacement is also limited due to the low window-to-wall ratio.

3.2. Influential Factors in Embodied Emissions

Embodied emissions of retrofit scenarios range from 6.7 to 10.0 $kgCO_2e/(m^2·y)$ (Figure 2). UltraLow-Energy cases have higher emissions than Low-Energy scenarios due to more intensive upgrades and larger PV systems. Using bio-based alternatives reduces embodied emissions by 7.6% in Low-Energy and 3.9% in UltraLow-Energy scenarios compared to petrochemical options. PV systems are the largest contributors, especially in UltraLow-Energy cases with 32 m^2 monocrystalline panels. Secondary contributors include external wall insulation, shading devices, roof insulation, and windows. Among building systems, the heat pump dominates emissions in scenarios with mechanical ventilation type C, while mechanical ventilation units are the primary contributors in System D configurations.

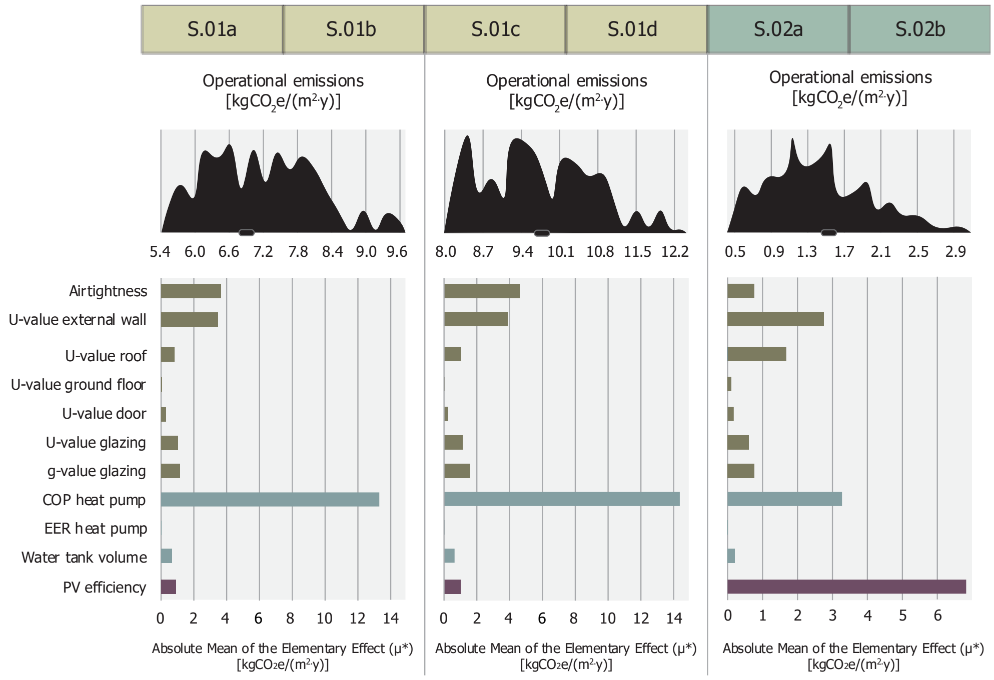

Figure 1. Sensitivity analysis results for operational emissions: the distribution of the operational emissions (top), and parameters ranking according to the Morris absolute mean of the elementary effect (μ*) (bottom).

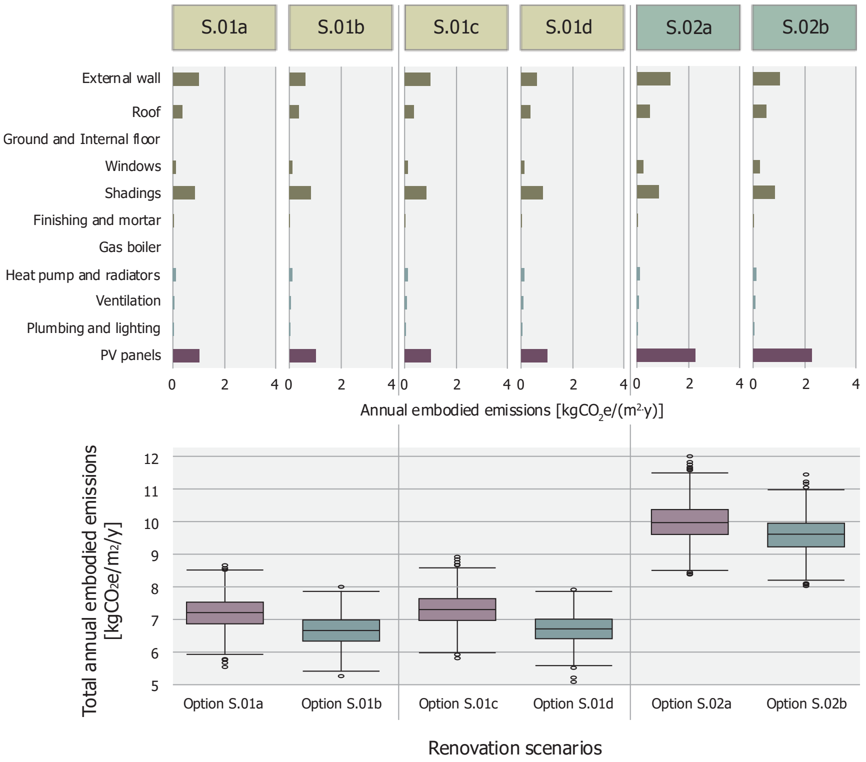

Figure 2. Impact by material on embodied emissions (top) and total annual embodied emissions (bottom) per renovation scenario.

3.3. Embodied and operational emissions trade-off

A trade-off emerges between operational and embodied emissions. In Low-Energy scenarios, where operational energy use is higher, embodied emissions account for 39–48% of total GHG emissions (Table 2). This proportion increases to 82–83% in UltraLow-Energy scenarios. While operational emissions decrease with performance upgrades, material demand (and thus embodied emissions) increase accordingly. Despite this, retrofit scenarios result in lower total annual emissions than in the BC.

Table 2. Embodied, operational and total annual GHG emissions for each renovation scenario

	BC	S.01a	S.01b	S.01c	S.01d	S.02a	S.02b
Annual embodied emissions [kgCO2e/(m^2·y)]	0	7.2 (48%)	6.7 (46%)	7.3 (41%)	6.7 (39%)	9.9 (83%)	9.6 (82%)
Annual operational emissions [kgCO2e/(m^2·y)]	32	7.8 (52%)	7.8 (54%)	10.4 (59%)	10.4 (61%)	2.1 (17%)	2.1 (18%)
Total annual GHG emissions [kgCO2e/(m^2·y)]	**32**	**15.0**	**14.5**	**17.7**	**17.1**	**12.0**	**11.7**

3.4. Static vs dynamic GHG emissions modeling

The application of a delayed stepped cumulative emissions approach over 2025–2055 provides a nuanced understanding of embodied GHG emissions distribution in renovation scenarios, capturing initial lower emissions in 2025 and gradual increases from component replacements.

Across all renovation scenarios, initial embodied emissions are 25–30% lower than in static models (which condense total embodied emissions at the moment of renovation). This more accurately represents the emissions from first-time installations. Replacement emissions are reintroduced in three steps: 2035-40 (internal paint and LED lighting), 2045-2050 (heat pumps and ventilation units, shading devices, glazing systems and PV systems), and 2055 (external walls and insulated roof assemblies).

Overall, 60–65% of total embodied emissions occur in the first 25 years, with the remainder post-2050, highlighting potential lifecycle carbon escalation, especially in S.02a and S.02b due to heavy insulation greater reliance on renewables.

Dynamic scenarios also include future changes in the Belgian electricity mix and in building energy use due to climate change, resulting in steeper emission curves after 2030. In fact, higher future EFs, except in S.02, do not fully offset energy-use reductions related to climate change.

Cumulative emissions in BC are surpassed by retrofits within 5–13 years, with dynamic scenarios (and especially S.01b) recovering the fastest and static scenarios (particularly S.02a) the slowest. These findings demonstrate that static LCA underestimate the true GHG emissions trajectory, and underscore the importance of dynamic modeling to capture the cumulative impact of scheduled replacements, climate change, and EF evolution.

4. Discussion

4.1. Findings and recommendations

For heating-dominated buildings, reducing operational emissions effectively involves upgrading heating systems, enhancing airtightness, and insulating external walls in Low-Energy

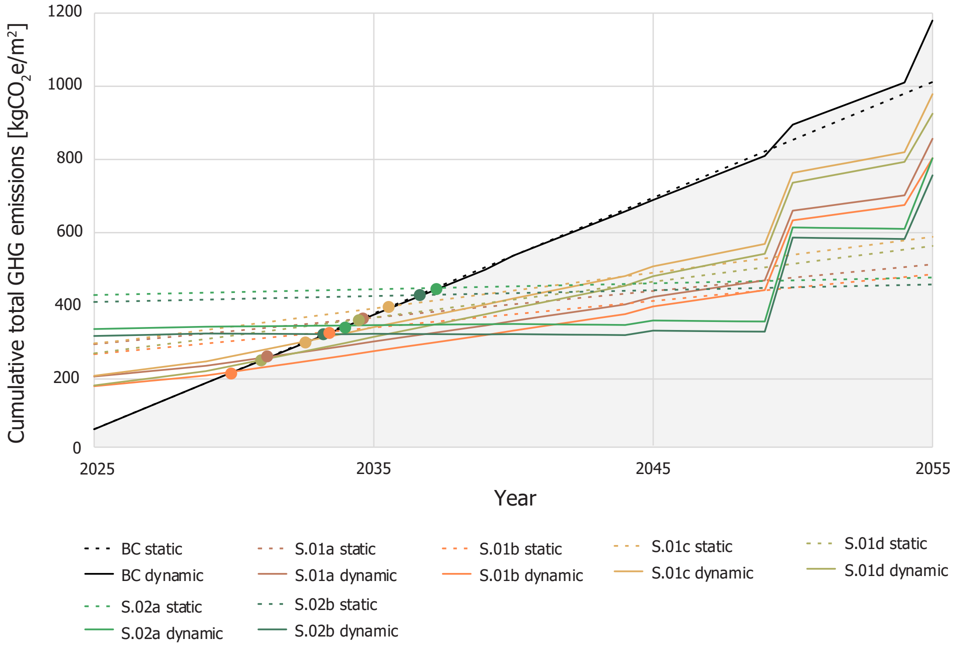

Figure 3. Comparison of static and dynamic modelling of cumulative GHG emissions (2025–2055)

renovations. In UltraLow-Energy strategies, PV panels efficiency and high-performing heating systems become key, alongside walls and roof insulation (Figure 1).

However, lower operational emissions often mean higher embodied emissions, largely due to extensive use of PV panels and material-intensive envelope renovation. Despite this, UltraLow-Energy retrofits still deliver the lowest life-cycle emissions, especially when bio-based materials are used, cutting embodied emissions by up to 4% (Figure 2). Using static emission factors, climatic conditions and averaged embodied emissions can misrepresent real-world GHG emissions trajectories (34) in retrofit scenarios (Figure 3). In contrast, dynamic modeling enables more accurate scheduling of carbon-intensive interventions, supports lifecycle-based carbon budgeting and policy planning, and informs strategic design decisions about material longevity and replacement frequency.

The results obtained show that, to reach zero-carbon targets for Post-WWII housing stock, the following steps are essential: 1. Integrate PV systems and heat pumps with envelope upgrades (walls and roof). 2. Use bio-based materials to minimize embodied GHG emissions spike. 3. Apply dynamic modeling approaches to improve the accuracy of GHG emissions over time.

4.2 Strengths and limitations

A core strength of this work is its integrated life-cycle approach, evaluating both operational and embodied emissions across stages A1–A5, B4, B6, and C3–C4, in line with Danish regulation (3) and IEA Annex 89 (35). Moreover, the combination of life-cycle approach with dynamic energy modeling and sensitivity analysis makes it one of the few retrofit studies to apply such a comprehensive framework (Section 1). The methodology is transferable to other case studies, yet results are context-specific, influenced by local climate, construction practices, building geometry and occupation patterns. Finally, the use of a building archetype allows for broader application of the same renovation strategies within the building stock.

Limitations include a lack of economic analysis, which is critical in real-world decision-making. Uncertainty assessment was restricted to embodied emissions, and future changes in material supply chains and technological improvements were not considered in emission calculations. For instance, technological progress could yield more efficient and cost-effective renewable energy and storage systems, thereby increasing their share in the electricity mix and reducing the carbon intensity of construction products.

These aspects should address in future research by integrating cost analysis in whole-life GHG emissions assessment and applying the methodology to broader case study application. Finally, a standardized framework (36) and real-time emissions monitoring during building operation would support net-zero carbon target achievement and validation of modeled outcomes.

5. Conclusion

The study evaluated six retrofit scenarios for a post-WWII single-family home in Belgium, using both petrochemical and bio-based materials. Operational and embodied emissions were calculated via dynamic simulation and life cycle modeling, then combined to assess total and long-term impacts over 50 years.

Results show that UltraLow-Energy renovations with bio-based materials offer the best path toward emission reduction targets. Findings also underscore the need for full life-cycle and dynamic modeling, considering electricity grid evolution and climate trends, to improve the robustness and effectiveness of retrofit strategies.

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References

1. Röck M, Saade MRM, Balouktsi M, Rasmussen FN, Birgisdottir H, Frischknecht R, et al. Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation. Appl Energy. 2020 Jan 15;258:114107.
2. CEN. EN 15978: Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method. European Committee for Standardization, Brussels, Belgium.; 2011.
3. Nordic Sustainable Construction. Danish Political Agreement Tightens the Limit Values for New Buildings and Extends the Impact [Internet]. 2024 [cited 2024 Dec 6]. Available from: https://www.nordicsustainableconstruction.com/news/2024/june/tillaegsaftale-paa-engelsk
4. Cellura M, Guarino F, Longo S, Mistretta M. Modeling the energy and environmental life cycle of buildings: A co-simulation approach. Renew Sustain Energy Rev. 2017 Dec 1;80:733–42.
5. Yeung J, J Hahn Menacho A, Marvuglia A, Navarrete Gutiérrez T, Beach T, Rezgui Y. An open building information modelling based co-simulation architecture to model building energy and environmental life cycle assessment: A case study on two buildings in the United Kingdom and Luxembourg. Renew Sustain Energy Rev. 2023 Sep 1;183:113419.
6. Shadram F, Mukkavaara J. An integrated BIM-based framework for the optimization of the trade-off between embodied and operational energy. Energy Build. 2018 Jan 1;158:1189–205.
7. Kiss B, Szalay Z. Modular approach to multi-objective environmental optimization of buildings. Autom Constr. 2020 Mar 1;111:103044.
8. Abbasi S, Noorzai E. The BIM-Based multi-optimization approach in order to determine the trade-off between embodied and operation energy focused on renewable energy use. J Clean Prod. 2021 Jan 25;281:125359.

9. Satola D, Houlihan-Wiberg A, Gustavsen A. Global sensitivity analysis and optimisation of design parameters for low GHG emission lifecycle of multifamily buildings in India. Energy Build. 2022 Dec 15;277:112596.
10. Shadram F, Mukkavaara J. Exploring the effects of several energy efficiency measures on the embodied/operational energy trade-off: A case study of swedish residential buildings. Energy Build. 2019 Jan 15;183:283–96.
11. Slavkovic K, Stephan A. Dynamic life cycle assessment of buildings and building stocks – A review. Renew Sustain Energy Rev. 2025 Apr 1;212:115262.
12. Hosamo H, Coelho GBA, Buvik E, Drissi S, Kraniotis D. Building sustainability through a novel exploration of dynamic LCA uncertainty: Overview and state of the art. Build Environ. 2024 Oct 1;264:111922.
13. Méndez Echenagucia T, Moroseos T, Meek C. On the tradeoffs between embodied and operational carbon in building envelope design: The impact of local climates and energy grids. Energy Build. 2023 Jan 1;278:112589.
14. Van De Moortel E, Allacker K, De Troyer F, Schoofs E, Stijnen L. Dynamic Versus Static Life Cycle Assessment of Energy Renovation for Residential Buildings. Sustainability. 2022 Jun 2;14(11):6838.
15. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). Energy Standard for Sites and Buildings Except Low-Rise Residential Buildings [Internet]. Georgia, US: ASHRAE, Atlanta, GA, USA.; 2022. Available from: https://www.ashrae.org/technical-resources/bookstore/standard-90-1
16. Institut royal météorologique (IRM). 2021 [cited 2024 Nov 14]. Available from: https://www.meteo.be/fr/belgique
17. Meteonorm. Meteonorm [Internet]. 2024. Available from: https://meteonorm.com/en/meteonorm-version-8
18. Schwalm CR, Glendon S, Duffy PB. RCP8.5 tracks cumulative CO2 emissions. Proc Natl Acad Sci. 2020 Aug 18;19656–7.
19. Electricity Maps. 2024 [cited 2024 Nov 12]. Available from: https://www.electricitymaps.com/
20. Ramon D, Allacker K. Integrating long term temporal changes in the Belgian electricity mix in environmental attributional life cycle assessment of buildings. J Clean Prod. 2021 May 15;297:126624.
21. Attia S, Mustafa A, Giry N, Popineau M, Cuchet M, Gulirmak N. Developing two benchmark models for post-world war II residential buildings. Energy Build. 2021 Aug 1;244:111052.
22. Passive House Institute. Criteria for Buildings. Passive House - EnerPHit - PHI Low Energy Building [Internet]. Darmstadt, Germany; 2023. Available from: https://passiv.de/downloads/03_building_criteria_en.pdf
23. Bertini A, Al-Obaidy M, Dasse M, Amaripadath D, Gobbo E, Attia S. Parametrization of variables affecting the whole life carbon performance of nearly zero energy residential building renovation. Build Environ. 2025 Jun 15;278:113013.
24. CEN. EN 15804+A2: Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products. European Committee for Standardization, Brussels, Belgium.; 2019.
25. TOTEM. TOTEM [Internet]. 2024. Available from: https://www.totem-building.be/
26. Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B. The ecoinvent database version 3 (part I): Overview and methodology. The International Journal of Life Cycle Assessment. 2016;The International Journal of Life Cycle Assessment, 21(9):1218–30.
27. Health Food Chain Safety Environment. FPS Public Health, Belgium. 2016 [cited 2025 Mar 7]. Database for environmental product declarations (EPD). Available from: https://www.health.belgium.be/en/database-environmental-product-declarations-epd
28. European Commission Joint Research Centre (EC JRC). International Reference Life Cycle Data System (ILCD) handbook: General guide for life cycle assessment- Detailed guidance. Publications Office of the European Union, Brussels, Belgium.; 2010.
29. Chartered Institution of Building Services Engineers (CIBSE). TM65 Embodied carbon in building services: A calculation methodology. London, UK; 2024.
30. Attia S, Petersen S, Hoxha E, Gobbo Emilie, Bertini A, Dasse M, et al. Framework to Model Building Carbon Emissions. (Version 5). 2024;Liege, Belgium: Sustainable Building Design Lab.
31. Zhang Y. jEplus+EA [Internet]. [cited 2024 Nov 15]. Available from: https://www.jeplus.org/wiki/doku.php?id=docs:jeplus_ea_v2
32. Morris MD. Factorial Sampling Plans for Preliminary Computational Experiments. Technometrics. 1991 May;33(2):161–74.
33. Huijbregts MAJ. Application of uncertainty and variability in LCA. Int J Life Cycle Assess 3. 1998;3(5):273–80.
34. Amaripadath D, Sailor DJ, Bertini A, Barker M, Attia S. Are net zero energy buildings necessarily also net zero emission buildings? Time-integrated analysis using dynamic grid emission factors. Build Environ. 2025 Sep 1;283:113367.
35. IEA EBC. Annex 89 - Ways to Implement Net-zero Whole Life Carbon Buildings [Internet]. 2023 [cited 2024 Dec 9]. Available from: https://annex89.iea-ebc.org/
36. Arnold W. Introducing the Net Zero Carbon Buildings Standard – a cross-industry approach to decarbonisation. 2024;The Structural Engineer, Volume 102, Issue 10, Pages 8-9.