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Decarbonization Assessment of External Wall Systems: Thermal Transmittance and Cradle-to-Gate Embodied Carbon Comparison of Conventional and Modular Configurations

Anita Terjék [1,2], Klára Tóthné Szita [3,*] and Viktoria Mannheim [4]

[1] Institute of Water Resources and Environmental Management, Faculty of Earth and Environmental Sciences and Engineering, University of Miskolc, 3515 Miskolc-Egyetemváros, Hungary; anita.terjek@uni-miskolc.hu
[2] Institute for Transport Sciences and Quality Control in Buildings, Than Károly Str. 3-5, 1119 Budapest, Hungary
[3] Institute of World and Regional Economics, Faculty of Economics, University of Miskolc, 3515 Miskolc-Egyetemváros, Hungary
[4] Department of Engineering Management, Faculty of Engineering, University of Debrecen, Ótemető Str. 2-4, 4028 Debrecen, Hungary; mannheim.viktoria@eng.unideb.hu
* Correspondence: regszita@uni-miskolc.hu

Abstract

Improving the environmental performance of ageing residential buildings requires design strategies that consider both thermal performance and material-related embodied impacts. This study provides early-stage, wall-level comparative evidence on the decarbonization potential of alternative external wall assemblies. A representative Hungarian "Kádár" Cube house is used as a reference to evaluate three configurations under identical geometric and climatic conditions: (i) the original uninsulated masonry wall, (ii) a masonry wall retrofitted with an External Thermal Insulation Composite System (ETICS), and (iii) a modular wall system based on Structural Insulated Panels (SIPs) applied in a morphology preserving reconstruction scenario. The analysis combines steady-state thermal transmittance (U-value) calculations with a cradle-to-gate (A1–A3) embodied-carbon assessment. Results show that both ETICS and SIP solutions substantially reduce heat loss compared to the baseline wall. The SIP configuration achieves the lowest U-value and cradle-to-gate embodied carbon due to its lightweight structure and reduced material mass. As the study focuses exclusively on wall-level A1–A3 impacts and steady-state thermal indicators, the findings support early design-stage decision-making rather than full building-level decarbonization modelling. The results highlight the importance of jointly considering thermal-transmittance performance and embodied impacts when comparing retrofit and modular reconstruction options for ageing residential buildings.

Keywords: building envelope; thermal performance; embodied carbon; structural insulated panel (SIP); external thermal insulation composite system (ETICS); residential retrofit; Kádár cube

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1. Introduction

1.1. Building Decarbonization and the Increasing Importance of Embodied Carbon

The building sector is one of the largest contributors to global energy consumption and greenhouse gas (GHG) emissions [1]. In the European Union, buildings account for approximately 40% of total energy use and 36% of energy-related carbon emissions [2–6].

Consequently, the decarbonization of the built environment has become a key objective of climate and energy policies [7,8].

While previous efforts primarily focused on reducing operational energy demand, the increasing adoption of nearly zero-energy buildings (nZEBs) has shifted attention toward the embodied environmental impacts of construction materials and building systems [9,10]. As operational emissions decrease, embodied carbon represents an increasingly significant share of total lifecycle emissions [11]. Therefore, effective decarbonization strategies require integrated approaches that consider both operational and embodied impacts.

In Central and Eastern Europe, a substantial share of the residential building stock consists of standardised detached houses constructed between the 1960s and 1980s [12]. In Hungary, the so-called "Kádár" Cube houses are among the most common residential typologies [13]. These buildings are typically characterised by poor thermal performance, outdated envelope systems, and high operational energy demand, making them prime targets for deep energy renovation strategies. To address these challenges, there is a need for comparative analyses of alternative wall structures that integrate thermal performance evaluation with life cycle assessment (LCA) [14].

Previous research has identified several effective design strategies for reducing embodied energy and GHG emissions in both new-build and refurbishment projects, including optimised structural systems, material reduction, and improved envelope solutions [15]. Historically, decarbonization efforts have primarily focused on reducing operational energy demand through improved thermal performance, energy-efficient building systems, and the integration of renewable energy sources [16]. However, as energy efficiency standards have advanced and the implementation of nZEBs has increased, the relative contribution of embodied carbon emissions (ECEs) has gained growing attention [17].

Recent research highlights that emissions associated with material production, construction, maintenance, and end-of-life processes can account for a substantial share of total life-cycle impacts, particularly in highly energy-efficient buildings [18–20], thus shifting the focus towards a whole-life perspective in building assessment [19,21]. Measures aimed at reducing operational energy demand (e.g., high-performance insulation systems, advanced façade technologies, and additional structural layers) may increase material use and associated embodied impacts [22]. Therefore, excessive optimisation of operational performance without considering material-related impacts may lead to an overall suboptimal environmental outcome [23,24].

The operational-embodied carbon trade-off is particularly important for ageing residential buildings, where renovation measures strongly shape long-term environmental performance. Refurbishment strategies can significantly extend building lifespans and reduce resource consumption; however, their environmental effectiveness depends on a balanced assessment of circularity and embodied-carbon impacts [25]. Building envelope performance has been identified as a key factor influencing both operational energy demand and life-cycle environmental performance. Poor thermal performance in existing buildings is a major driver of energy consumption, particularly in Europe [26]. At the same time, material selection and construction design decisions significantly affect embodied emissions, highlighting the need for integrated optimisation approaches [27].

As a result, there is a growing emphasis on whole-life carbon (WLC) assessment frameworks that account for both operational and embodied emissions across the entire building lifecycle. Policy developments and methodological frameworks increasingly promote the adoption of lifecycle-based approaches to support decarbonization in the building sector [28]. Despite these advancements, the lack of standardised, comprehensive environmental datasets for construction materials introduces uncertainty into LCA studies and may affect decision-making [29].

To avoid overstating the methodological scope, the present study does not aim to quantify whole-building operational energy demand or to provide a complete decarbonization pathway. Instead, it offers early-stage, wall-level comparative evidence based on two intuitive indicators—steady-state thermal transmittance and cradle-to-gate embodied carbon—supporting the preliminary evaluation of envelope design options for ageing residential buildings.

1.2. Circular Retrofit Strategies and SIP-Based Modular Systems

The transition toward low-carbon buildings is increasingly associated with circular economy (CE) principles aiming to reduce resource consumption, minimise waste generation, and extend building service life [30]. In this study, low-carbon buildings are defined as those designed, renovated, or operated to minimise GHG emissions throughout their life cycle, accounting for both operational and embodied carbon impacts. In the construction sector, circular strategies increasingly focus on refurbishment, retrofitting, reuse, and industrialised construction methods that can reduce both operational and embodied environmental impacts [20].

Boskovic and Cullen [31] highlighted that approximately 80% of the anticipated 2050 building stock in the United Kingdom has already been constructed, making renovation of existing buildings a critical climate mitigation pathway. Similar conditions characterise many Central and Eastern European countries, where ageing detached residential buildings with poor thermal performance continue to dominate the housing stock.

At the same time, large-scale retrofit activities may themselves generate significant embodied carbon burdens. According to Bienert et al. [32], energy-efficiency retrofits could consume approximately 8.5% of the remaining global GHG emissions budget under a 1.5 °C climate scenario if circular strategies are not integrated into renovation practices.

This challenge has intensified interest in modular and off-site approaches that can improve thermal performance while reducing lifecycle impacts. Modular systems further support circular economy objectives through dry assembly techniques, greater adaptability, and the potential for partial disassembly.

Among modular envelope technologies, Structural Insulated Panels (SIPs) have attracted growing attention for their ability to integrate structural and thermal functions within a single lightweight prefabricated element [33,34]. SIP systems are increasingly investigated from a lifecycle perspective. Previous studies have shown that SIP-based envelopes may have a lower global warming potential (GWP) than conventional wall systems, depending on the selection of the insulation core and material composition [9].

Furthermore, lightweight SIP envelope systems may reduce additional structural loads and improve the applicability of modular reconstruction approaches in ageing residential housing stock [35].

Despite growing interest in modular systems, relatively few studies examine the combined thermal and embodied carbon performance. In particular, few studies assess conventional External Thermal Insulation Composite System (ETICS) retrofits and SIP-based reconstruction approaches [36,37]. Building performance evaluation frameworks increasingly support retrofit decision-making by integrating technical, environmental and economic considerations.

Previous studies [38,39] comparing refurbishment and replacement strategies have demonstrated the importance of assessing life cycle carbon impacts alongside building performance indicators when evaluating long-term decarbonization pathways.

1.3. Life Cycle Assessment and Whole-Life Carbon Trade-Offs

LCA has become one of the most widely used methodologies for evaluating the environmental impacts of buildings and construction materials throughout their life cycle. Standardised under ISO 14040 [40] and ISO 14044 [41], LCA enables the systematic assessment associated with raw material extraction, manufacturing, transportation, construction, operation, maintenance, and end-of-life stages. Within the building sector, EN 15978 [42] and EN 15804 [43] provide additional frameworks for building-level environmental assessment and the development of Environmental Product Declarations (EPDs).

The increasing adoption of highly insulated, low-energy buildings has intensified the need to evaluate both operational performance and ECEs simultaneously. Consequently, integrated whole-life carbon approaches are increasingly recommended for evaluating retrofit and reconstruction strategies. EPDs have therefore become important data sources for building-level embodied-carbon assessment by providing standardised, independently verified environmental information on construction products [44,45]. However, previous studies have also identified uncertainties in EPD-based calculations, including regional variability, inconsistent system boundaries, and database interoperability issues [46,47]. These methodological uncertainties may substantially influence comparative LCA results.

Recent research further emphasises the importance of integrating LCA into early-stage retrofit decision-making and into building envelope optimisation processes [48,49]. Nevertheless, relatively few studies simultaneously investigate thermal performance improvements and embodied carbon trade-offs in modular SIP-based reconstruction systems applied to ageing detached residential buildings under identical geometric and climatic conditions [50].

This study examines the role of alternative wall structures in decarbonization through a life-cycle-based methodology. Three configurations are analysed: the original uninsulated masonry wall, a conventional wall retrofitted with external thermal insulation, and a form-preserving reconstruction of a new building with identical geometry and external appearance. The evaluation incorporates steady-state thermal performance, quantified by thermal transmittance values, within a life cycle assessment framework that emphasises material-related impacts and processes.

By integrating envelope performance with life-cycle environmental impacts, this study seeks to provide a more comprehensive understanding of decarbonization pathways. The findings are intended to assist designers, researchers, and policymakers in identifying context-specific, low-carbon renovation strategies for existing residential buildings and to emphasise the significance of modular construction technologies in life-cycle-oriented decarbonization of energy systems.

The contribution of this study lies in providing wall-level, early-stage comparative evidence of retrofit and modular reconstruction strategies under identical morphological conditions, utilising a combined thermal and embodied-carbon assessment.

2. Materials and Methods

2.1. Research Design and Scenario Definition

This study applies an integrated assessment framework combining steady-state thermal performance evaluation and LCA to investigate the decarbonization potential of alternative building envelope strategies for ageing residential buildings.

An integrated assessment framework that combines steady-state thermal performance evaluation and life cycle assessment is applied to investigate the decarbonization potential of alternative building envelope strategies for ageing residential buildings.

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The methodological approach consists of a comparative case study analysis of three external wall configurations applied to a representative Hungarian "Kádár" Cube house typology. The analysed scenarios include the following:

- The original uninsulated masonry wall;
- A conventional retrofit solution based on External Thermal Insulation Composite Systems;
- A modular reconstruction solution utilising SIPs.

Figures 1 and 2 present the schematic structures of the investigated ETICS and SIP configurations.

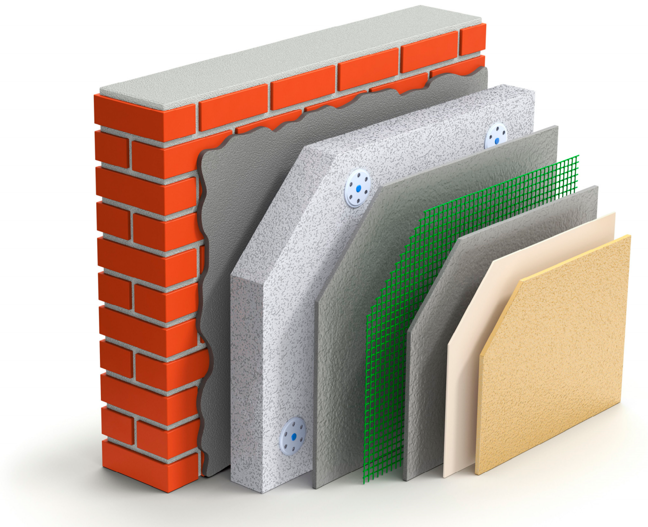

Figure 1. Schematic structure of an ETICS consisting of adhesive, thermal insulation board, mechanical fixing, base coat, reinforcement, and finishing layer [51].

Figure 2. Schematic structure of a SIP consisting of Oriented Strand Board (OSB) facings and an EPS insulation core [34].

All scenarios were evaluated under identical geometric, climatic, and operational boundary conditions to ensure strict comparability. The analyses focused exclusively on external wall systems, with roof structures, floor assemblies, building geometry, operational assumptions, and climatic conditions maintained consistently across all cases.

The system boundary is defined at the national level, with materials assumed to be sourced or processed within the European market context. Figure 3 illustrates the established system boundary for this cradle-to-gate assessment.

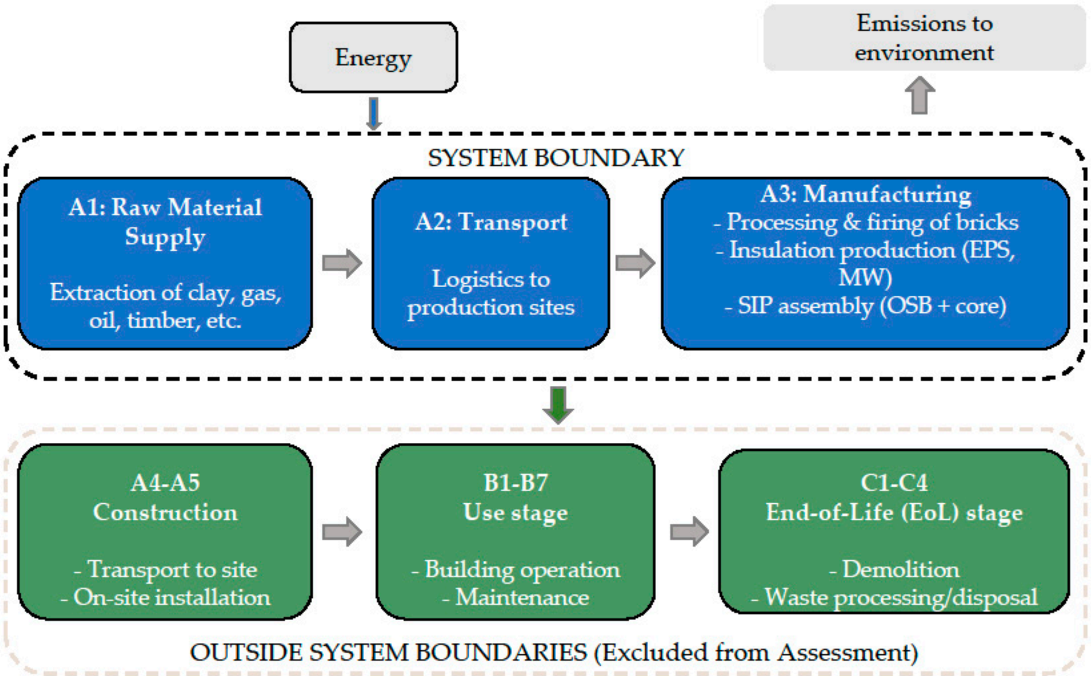

Figure 3. System boundaries of the assessment, defining the included cradle-to-gate product stages (A1–A3) and the excluded downstream life cycle stages for the evaluated wall configurations.

2.2. Thermal Performance Evaluation

Thermal performance assessment was conducted using steady-state U-value calculations in accordance with the EN ISO 6946 [52] methodology. The U-value of each wall assembly was determined based on the material layer composition, thermal conductivity values, and surface resistances. The comparative analysis focused on exploring the relationship between thermal performance indicators and embodied carbon impacts.

Figure 4 demonstrates the methodological framework of the integrated evaluation process, illustrating the parallel workflows of thermal transmittance calculations and cradle-to-gate LCA.

2.3. Life Cycle Assessment Framework

The environmental assessment was performed using a cradle-to-gate LCA approach focusing on construction material-related impacts. The assessment framework followed the principles of the ISO 14040 and ISO 14044 standards [40,41], utilising standardised embodied carbon datasets compliant with EN 15804 [43].

The functional unit of the study was defined as 1 m^2 of external wall assembly with a reference service life (RSL) of 50 years under Hungarian climatic conditions (heating degree days HDD ≈ 3200 Kd), in compliance with EN 15978:2011 [42].

The adopted reference service life of 50 years aligns with EN 15978 [42] and is widely used in building LCA studies. Properly protected OSB-based SIP assemblies have been reported to achieve service lives comparable to those of conventional envelope systems under normal exposure conditions [53].

The study does not provide a comprehensive whole-building LCA; rather, it specifically examines the contribution of alternative wall structures to building decarbonization. The LCA applies cradle-to-gate system boundaries (modules A1–A3), encompassing raw material extraction, material production, and manufacturing processes, focusing on the embodied environmental impacts of wall construction materials across various scenarios.

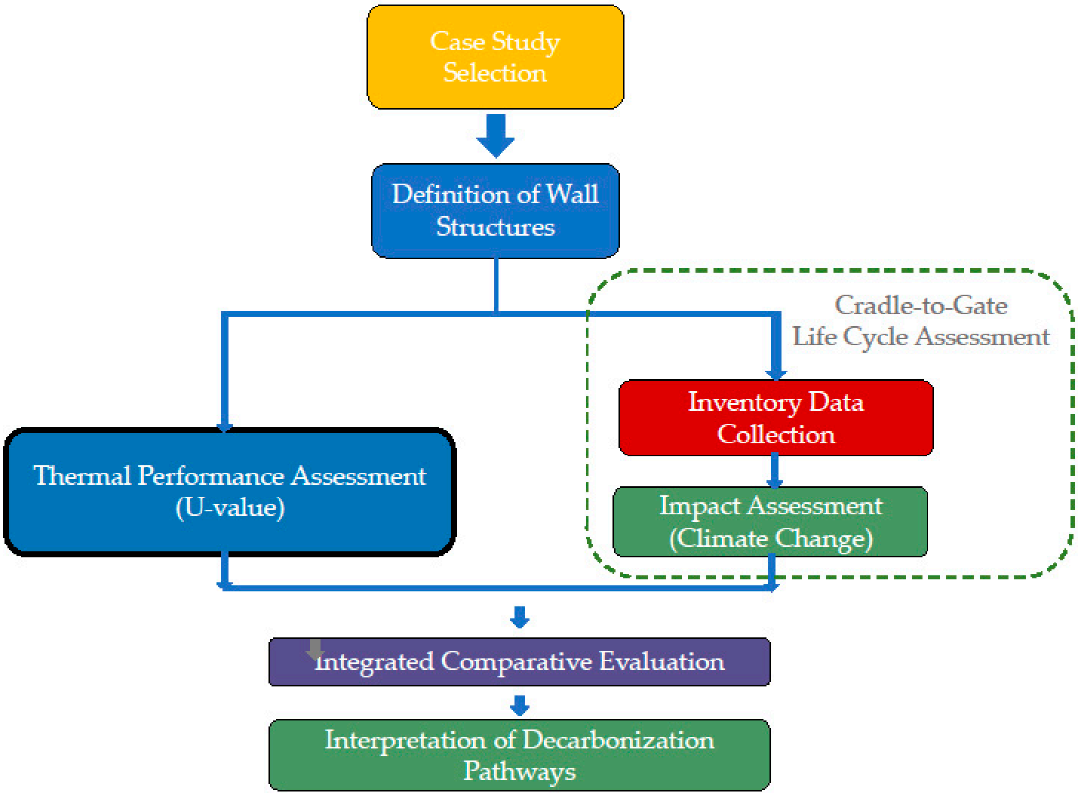

Figure 4. Methodological framework of the integrated evaluation process.

The chosen system boundary ensures the availability of standardised and reliable environmental data for these stages. In contrast, inclusion of modules A4–A5, B, and C would introduce significant methodological uncertainty due to project-specific variability in transport, installation, maintenance, and end-of-life processes.

The primary environmental indicator used in the assessment is Climate Change (CC), expressed as kg CO_2 equivalent (CO_2 eq.). This indicator quantifies the ECEs associated with material production and manufacturing processes. The assessment was modelled at the European level (RER datasets) using LCA for Experts software (v 10.9.6.1) [54], incorporating the GaBi Professional Database and MLC Database Premium Construction. The environmental life cycle impact assessment (LCIA) was determined using the EF 3.1 method's climate change (total) metric.

A key aspect of the methodology is the integration of thermal performance and life-cycle environmental assessment, so the evaluation allows the identification of

- Optimal balance between energy efficiency and embodied impacts;
- Effectiveness of modular vs. conventional retrofit solutions;
- Contribution of envelope design to overall decarbonization pathways.

To operationalise this integrated lifecycle framework, a representative building typology reflecting the typical constraints of the regional housing stock must be defined. The following section outlines the characteristics of the selected reference building.

2.4. Reference Building Typology and Market Context

This case study focuses on a representative Hungarian detached residential building, commonly known as a "Kádár" Cube house. This building typology was extensively constructed between the 1960s and 1980s and remains one of the dominant residential forms within the Hungarian housing stock. The KSH (Hungarian Central Statistical Office) micro-census in 2016 [13] recorded a total housing stock comprising 4,404,518 dwelling units, with approximately 750,000 to 770,000 units estimated to be of this typology, representing nearly one-fifth of all residential units in Hungary. The most distinctive characteristics of this typology are presented in Table 1.

Table 1. Key geometric and architectural parameters of the reference "Kádár" Cube house.

Parameter	Typical Value/Description
Plan shape	Square (regular quadrilateral)
Floor plan dimensions	9 × 9 m or 10 × 10 m
Net heated floor area	~64–80 m^2 (ground floor)
Storey height (clear)	~2.5–2.7 m
Building volume	~160–220 m^3

These houses are typically characterised by compact, square floor plans, masonry walls, pitched roofs, and poor thermal performance due to inadequate insulation and outdated envelope systems. Typical heating solutions during this period include individual stoves, mixed-fuel heating systems, and, in many cases, outdated, low-efficiency boilers. These systems are characterised by high energy consumption and poor efficiency. A previous study [12] indicates that transmission losses through envelope elements may account for approximately 35–45% of total heating demand in poorly insulated detached houses from this period.

Many authors have examined the "Kádár" Cube house from architectural [55,56], social economy [56,57], sociological [58], and energy perspectives, and have also analysed its renovation possibilities [51,59], while its visual typology has been documented by [60]. Figure 5 shows the "Kádár" Cube houses in Hungary.

Figure 5. "Kádár" Cube houses in Hungary (self-made photos).

These buildings represent highly relevant targets for deep energy retrofit and decarbonization strategies. Its homogeneous geometric form and well-documented thermal deficiencies make it an ideal reference object for comparing conventional, retrofitted, and modular wall assembly solutions within a harmonised LCA framework. For these houses, proposed renovation measures typically emphasise a combination of building insulation and window replacement, as well as installing heat pump systems and using renewable energy [60,61]. A typical "Kádár" Cube house, which accounts for a large share of the current Hungarian housing stock, has an estimated annual heating energy demand of 375 kWh/m^2/a [62].

2.5. Wall Structure Scenarios

The original external wall assembly of the analysed case-study building consists of uninsulated masonry with high thermal transmittance and significant operational heat losses. To investigate alternative decarbonization strategies, three wall system configurations were evaluated:

- Case A: original uninsulated masonry wall.
- Case B: conventional ETICS-based retrofit solution.
- Case C: SIP-based modular reconstruction system.

Table 2 provides an overview of the three wall assembly variants defined for LCA comparison.

Table 2. Overview of the three wall assembly variants defined for LCA comparison.

ID	Case Name	Description
Case A	Existing wall	Reference state; original construction, as-built baseline
Case B	Retrofitted wall	Original wall retrofitted by installing ETICS, thermal insulation can be EPS or rock wool
Case C	Modular SIP wall	Replacement of the existing building with a modular new-build structure maintaining identical geometry and streetscape characteristics

Case A refers to the unmodified original wall assembly of the Cube house as constructed. This configuration serves as the baseline for environmental and energy performance. No thermal insulation or vapour control layer is present; the wall relies entirely on the thermal mass and resistance of brick masonry. Table 3 describes the layer composition.

Table 3. Layer composition for Case A (from inside to outside).

Layers	Thickness [mm]	Total Thickness [mm]	Density [kg/m^3]
Interior lime plaster	15		1600
Hollow fired clay brick masonry (B30)	300	335	850
Exterior cement-lime plaster	20		1800

Case B represents the most common deep energy retrofit solution currently applied to the Cube house stock in Hungary: the application of an ETICS. This approach leaves the existing masonry wall intact. Two insulation material sub-variants are considered: Case B1, using expanded polystyrene (EPS), in Table 4, and Case B2, using mineral wool (MW), in Table 5.

Table 4. Layer composition for Case B1 (from inside to outside).

Layers	Thickness [mm]	Total Thickness [mm]	Density [kg/m^3]
Interior lime plaster	15		1600
Hollow fired clay brick masonry (B30)	300		850
Adhesive layer (cement-based adhesive mortar)	5		1900
EPS rigid foam boards	200	527	16.5
Fibreglass reinforcement mesh embedded in base coat	4		1900
Mineral render (exterior finish)	3		1800
Mechanical anchors from polypropylene (PP) (25 g/piece)	7 pcs/m^2		910

Table 5. Layer composition for Case B2 (from inside to outside).

Layers	Thickness [mm]	Total Thickness [mm]	Density [kg/m^3]
Interior lime plaster	15		1600
Hollow fired clay brick masonry (B30)	300		850
Adhesive layer (cement-based adhesive mortar)	5		1900
Mineral wool boards	200	527	100
Fibreglass reinforcement mesh embedded in base coat	4		1900
Mineral render (exterior finish)	3		1800
Mechanical anchors (PP) (25 g/piece)	7 pcs/m^2		910

Case C involves a form-preserving reconstruction scenario in which the original building is replaced by a newly constructed modular structure that replicates its geometry, spatial organisation, and external appearance. In this context, the SIP wall system does not serve as an upgrade to the existing wall; rather, it forms the envelope of a new building designed to meet local building regulations, including height restrictions and requirements for integration with the streetscape. The composition of the layers is detailed in Table 6.

Table 6. Layer composition for Case C (from inside to outside).

Layers	Thickness [mm]	Total Thickness [mm]	Density [kg/m^3]
Interior gypsum plaster	10		1200
Gypsum board cladding (2 × 12.5 mm)	25		800
Internal service cavity (50 mm timber lath)	50		500
Polyamide foil	0.2		950
OSB board	15		650
Adhesive polyurethane (PUR)	0.2		1200
EPS core	140	467.6	16.5
Adhesive PUR (0.5 kg/m^2)	0.2		1200
OSB board	15		650
Adhesive PU foam	5		27.5
Mineral wool boards	200		100
Fibreglass reinforcement mesh embedded in base coat	4		1900
Mineral render (exterior finish)	3		1800

2.6. Life Cycle Inventory

The Life Cycle Inventory (LCI) comprises the material and resource inputs for each wall assembly evaluated in this study. To ensure comparability, all quantities are calculated per 1 m^2 of wall area. The inventory data form the basis for the subsequent environmental Life Cycle Impact Assessment (LCIA) by specifying the material composition and resource requirements for each wall configuration. Tables 7–10 present the LCI data for cases A, B1, B2, and C.

Table 7. Life Cycle Inventory for Case A (from inside to outside).

Layers	Thickness [mm]	Volume (m^3/m^2)	Mass (kg/m^2)	Water (kg/m^2)	Waste/Loss (kg/m^2)
Interior lime plaster	15	0.0150	24.00	4.80	3.60
Hollow fired clay brick masonry (B30)	300	0.3000	255.00	-	12.75
Mortar joints	10	0.0185	21.00	3.24	1.80
Exterior cement-lime plaster	20	0.0200	36.00	6.48	5.40
Total (all layers)			336.00	14.52	21.75

Table 8. Life Cycle Inventory for Case B1 (from inside to outside).

Layers	Thickness [mm]	Volume (m^3/m^2)	Mass (kg/m^2)	Water (kg/m^2)	Waste/Loss (kg/m^2)
Interior lime plaster	15	0.0150	24.00	4.80	3.60
Hollow fired clay brick masonry (B30)	300	0.3000	255.00	-	-
Mortar joints	10	0.0185	21.00	3.24	1.80
Adhesive layer (cement-based adhesive mortar)	5	0.0050	9.50	2.09	0.95
EPS rigid foam boards	200	0.2000	3.30	-	0.17
Fibreglass mesh embedded in base coat	4	0.0040	7.60	1.67	0.76
Mineral render (exterior finish)	3	0.0030	5.40	0.54	0.54
Mechanical anchors (PP) 25 g/pcs	-	7 pcs	0.175	-	0.01
Total (all layers)			325.975	12.34	6.03

Table 9. Life Cycle Inventory for Case B2 (from inside to outside).

Layers	Thickness [mm]	Volume (m^3/m^2)	Mass (kg/m^2)	Water (kg/m^2)	Waste/Loss (kg/m^2)
Interior lime plaster	15	0.0150	24.00	4.80	3.60
Hollow fired clay brick masonry (B30)	300	0.3000	255.00	-	-
Mortar joints	10	0.0185	21.00	3.24	1.80
Adhesive layer (cement-based adhesive mortar)	5	0.0050	9.50	2.09	0.95
Mineral wool boards	200	0.2000	20.00	-	1.00
Fibreglass mesh embedded in base coat	4	0.0040	7.60	1.67	0.76
Mineral render (exterior finish)	3	0.0030	5.40	0.540	0.54
Mechanical anchors (PP) 25 g/pcs	-	7 pcs	0.175	-	0.01
Total (all layers)			342.675	12.34	6.86

Table 10. Life Cycle Inventory for Case C (from inside to outside).

Layers	Thickness [mm]	Volume (m^3/m^2)	Mass (kg/m^2)	Water (kg/m^2)	Waste/Loss (kg/m^2)
Interior gypsum plaster	10	0.0100	12.00	6.00	1.80
Gypsum board cladding (2 × 12.5 mm)	25	0.0250	20.00	-	1.60
Polyamide foil	0.2	0.0002	0.19	-	0.02
Internal service cavity (50 mm timber lath)	50	0.0500	5.00	-	2.50
OSB board	15	0.0150	9.75	-	0.78
Adhesive PUR (0.5 kg/m^2)	0.2	-	0.50	-	0.03
EPS core	140	0.1400	2.31	-	0.12
Adhesive PUR (0.5 kg/m^2)	0.2	-	0.50	-	0.03
OSB board (15 mm)	15	0.0150	9.75	-	0.78
Adhesive PU foam	5	0.0050	0.14	-	0.01
Mineral wool insulation	200	0.2000	20.00	-	1.00
Fibreglass mesh embedded in base coat	4	0.0040	7.60	1.672	0.76
Mineral render (exterior finish)	3	0.0030	5.40	0.540	0.54
Total (all layers)			93.14	8.212	9.95

The wall configurations are compared using a unified assessment framework based on the thermal performance indicators and the embodied carbon. The evaluation focuses on

- Relative improvement compared to the baseline case;
- Comparative performance between retrofit and modular solutions;
- Identification of performance trade-offs.

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The results are interpreted in the context of building energy system decarbonization, emphasising how envelope design decisions influence both operational and embodied environmental impacts.

2.7. Scenario-by-Module Accounting Matrix

Table 11 summarises the materials used in each scenario and details their allocation to A1 (raw material supply), A2 (transport to manufacturing), and A3 (manufacturing). For retrofit cases (B1 and B2), only materials associated with the intervention are included in the embodied-carbon calculations, while the existing masonry wall is treated as an unchanged background condition.

Table 11. Scenario-by-Module Accounting Matrix for A1–A3 Stages.

Case	Material/Component	Module A1	Module A2	Module A3	Notes
A—Existing masonry wall	Fired clay brick (B30)	✔	✔	✔	Baseline wall; no intervention materials
	Interior lime plaster	✔	✔	✔	Original construction
	Exterior cement-lime plaster	✔	✔	✔	Original construction
B1—ETICS with EPS	EPS insulation board (200 mm)	✔	✔	✔	Retrofit intervention only
	Adhesive mortar	✔	✔	✔	Applied on existing wall
	Base coat + fibreglass mesh	✔	✔	✔	Included as ETICS system
	Mineral render	✔	✔	✔	Exterior finish
	PP mechanical anchors	✔	✔	✔	7 pcs/m^2
	Existing masonry wall	-	-	-	Excluded (background condition)
B2—ETICS with MW	Mineral wool board (200 mm)	✔	✔	✔	Retrofit intervention only
	Adhesive mortar	✔	✔	✔	Same as B1
	Base coat + fibreglass mesh	✔	✔	✔	Same as B1
	Mineral render	✔	✔	✔	Same as B1
	PP mechanical anchors	✔	✔	✔	Same as B1
	Existing masonry wall	-	-	-	Excluded (background condition)
C—SIP modular wall	Gypsum plaster	✔	✔	✔	New-build reconstruction
	Gypsum board (2 × 12.5 mm)	✔	✔	✔	Interior cladding
	Timber service cavity (50 mm)	✔	✔	✔	Structural cavity
	Polyamide foil	✔	✔	✔	Vapour barrier
	OSB board	✔	✔	✔	SIP facing
	PUR adhesive	✔	✔	✔	SIP bonding
	EPS core (140 mm)	✔	✔	✔	SIP insulation
	Exterior render system	✔	✔	✔	Applied on SIP panel

Note: Modules A1: Raw Material Supply, A2: Transport to Manufacturing, and A3: Manufacturing/Processing; ✔ means: Technology modules taken into account for the given input current during the software analysis.

Retrofit cases (B1 and B2) include only intervention-related materials in A1–A3, with the existing masonry wall treated as an unchanged background condition. Case C represents a full reconstruction scenario; therefore, all wall layers are included in A1–A3.

2.8. Material-to-Dataset Mapping

To enhance transparency and reproducibility, Table 12 presents the dataset mapping used in the LCA model, including dataset name, geographical scope (RER), database version, unit assumptions, waste/loss factors, and treatment of biogenic carbon.

Table 12. Material-to-Dataset Mapping Used in the LCA Model.

Material/Component	Dataset Name (GaBi/MLC)	Geographical Scope	Database Version	Unit	Waste/Loss Assumption	Biogenic Carbon Treatment
Fired clay brick (B30)	Brick, fired, at plant	RER	GaBi 10.9.6.1	kg	2%	Not applicable
Lime plaster	Plaster, lime-based, at plant	RER	GaBi 10.9.6.1	kg	2%	Not applicable
Cement-lime plaster	Plaster, cement-lime, at plant	RER	GaBi 10.9.6.1	kg	2%	Not applicable
EPS insulation	EPS board, expanded polystyrene, at plant	RER	MLC Premium Construction	kg	3%	Fossil carbon only
Mineral wool	Mineral wool board, at plant	RER	MLC Premium Construction	kg	3%	Not applicable
Adhesive mortar	Mortar, cement-based, at plant	RER	GaBi 10.9.6.1	kg	2%	Not applicable
Fiberglass mesh	Glass fibre fabric, at plant	RER	GaBi 10.9.6.1	kg	1%	Not applicable
Mineral render	Render, mineral-based, at plant	RER	MLC Premium Construction	kg	2%	Not applicable
PP anchors	Polypropylene (PP), injection moulding	RER	GaBi 10.9.6.1	kg	0%	Fossil carbon only
Gypsum plaster	Gypsum plaster, at plant	RER	GaBi 10.9.6.1	kg	2%	Not applicable
Gypsum board	Gypsum plasterboard, at plant	RER	MLC Premium Construction	kg	2%	Not applicable
Timber lath	Sawn timber, kiln dried	RER	GaBi 10.9.6.1	kg	5%	Biogenic carbon included
Polyamide foil	Polyamide film, at plant	RER	GaBi 10.9.6.1	kg	0%	Fossil carbon only
OSB board	OSB board, at plant	RER	MLC Premium Construction	kg	5%	Biogenic carbon included
PUR adhesive	Polyurethane adhesive, at plant	RER	GaBi 10.9.6.1	kg	0%	Fossil carbon only
Exterior render (SIP)	Render, mineral-based, at plant	RER	MLC Premium Construction	kg	2%	Not applicable

Dataset selection followed EN 15804-compliant RER datasets [43]. Biogenic carbon was included only for timber-based components (OSB, timber lath), consistent with dataset documentation.

2.9. Limitations

This study focuses exclusively on external wall assemblies and evaluates cradle-to-gate (A1–A3) embodied carbon and steady-state thermal transmittance. Downstream lifecycle stages (A4–C4), operational energy use, façade orientation, and the effects of whole-building geometry are excluded. Embodied carbon results rely on European average datasets (RER), which introduce methodological uncertainty typically within ±10–20%. Therefore, the findings support early-stage comparative assessment rather than full lifecycle optimisation.

In addition, variations in data quality, EPD assumptions, database interoperability, and the representativeness of European-average datasets for local production conditions may affect both absolute embodied-carbon values and the relative differences observed across the analysed wall systems. Therefore, the results should be interpreted primarily as comparative indicators for early-stage decision-making.

3. Results

3.1. Thermal Performance of Wall Structures

The thermal performance of each wall structure is assessed using steady-state heat transfer analysis in accordance with EN ISO 6946 [52], expressed as U-values. The calculation includes the internal and external surface resistances, material-specific thermal conductivities and the layer thicknesses.

The U-value can be calculated using standard heat transfer principles:

$$U = 1/(\sum R_{tot}), \quad (1)$$

where

R_{tot} = total thermal resistance, in $m^2 \cdot K/W$.

$$R_{tot} = R_{si} + R_1 + R_2 + \ldots + R_n + R_{se}, \quad (2)$$

where

R_{si} = internal surface resistance, in $m^2 \cdot K/W$;

R_1, $R_2 \ldots R_n$ = design thermal resistances of each layer, in $m^2 \cdot K/W$;

R_{se} = external surface resistance, in $m^2 \cdot K/W$.

When calculating the thermal resistance of homogeneous components as layers of the wall structure, the design thermal values can be given by

$$R = d/\lambda, \quad (3)$$

where

d = thickness of the material layer, in m;

λ = design thermal conductivity of the material, expressed in W/mK.

Tables 13–16 present the input data for the thermal resistance calculation for the different cases.

Table 13. Input data of the wall structure in Case A (from inside to outside).

Layers	Thickness, d [m]	Thermal Conductivity, λ [W/mK]	Thermal Resistance, R [m^2K/W]
Interior lime plaster	0.015	0.80	0.019
Hollow fired clay brick masonry (B30)	0.300	0.57	0.526
Exterior cement-lime plaster	0.020	0.80	0.025

Table 14. Input data of wall structure in Case B1 (from inside to outside).

Layers	Thickness, d [m]	Thermal Conductivity, λ [W/mK]	Thermal Resistance, R [m^2K/W]
Interior lime plaster	0.015	0.80	0.019
Hollow fired clay brick masonry (B30)	0.300	0.57	0.526
Adhesive layer (cement-based adhesive mortar)	0.005	1.00	0.005
EPS rigid foam boards	0.200	0.036	5.556
Base coat + fibreglass reinforcement mesh	0.004	1.00	0.004
Mineral render (exterior finish)	0.003	0.87	0.003

Table 15. Input data of wall structure in Case B2 (from inside to outside).

Layers	Thickness, d [m]	Thermal Conductivity, λ [W/mK]	Thermal Resistance, R [m^2K/W]
Interior lime plaster	0.015	0.80	0.019
Hollow fired clay brick masonry (B30)	0.300	0.57	0.526
Adhesive layer (cement-based adhesive mortar)	0.005	1.00	0.005
Mineral wool boards	0.200	0.039	5.128
Base coat + fibreglass reinforcement mesh	0.004	1.00	0.004
Mineral render (exterior finish)	0.003	0.87	0.003

Table 16. Input data of wall structure in Case C (from inside to outside).

Layers	Thickness, d [m]	Thermal conductivity, λ [W/mK]	Thermal resistance, R [m^2K/W]
Interior gypsum plaster	0.010	0.40	0.025
Gypsum board cladding (2 × 12.5 mm)	0.025	0.21	0.119
Internal service cavity (50 mm timber lath)	0.050	0.03	0.180 *
Polyamide foil	0.0002	0.25	0.001
OSB board	0.015	0.13	0.115
Adhesive PUR	0.0002	0.25	0.001
EPS core	0.140	0.036	3.889
Adhesive PUR	0.0002	0.25	0.001
OSB board	0.015	0.13	0.115
Adhesive PU foam	0.005	0.03	0.167
Mineral wool boards	0.200	0.039	5.128
Base coat + fibreglass reinforcement mesh	0.004	1.00	0.004
Mineral render (exterior finish)	0.003	0.87	0.003

Note: Unventilated air layer (50 mm, horizontal heat-flow direction)—thermal resistance taken directly from EN ISO 6946:2017, Table 8 (6.9.2 “Unventilated air layer”): R = 0.18 m^2·K/W.

The U-values calculated according to standard heat transfer principles, based on Equation (1) for each case, are summarised in Table 17. In this study, U-values serve as steady-state indicators of thermal performance and transmission heat-loss potential. Operational energy consumption was not directly calculated.

Table 17. U-value, a steady-state thermal performance indicator, is calculated for different wall-structure cases.

Wall Structures	Design Thermal Resistance of the Layers, R_i [m^2K/W]	Total Thermal Resistance, R_{tot} [m^2K/W]	Thermal Transmittance, U [W/ m^2K]
Case A	0.570	0.740	1.35
Case B1	6.113	6.283	0.16
Case B2	5.686	5.856	0.17
Case C	9.748	9.918	0.10

Note: According to EN ISO 6946 [52], R_{si} = 0.13 m^2·K/W and R_{se} = 0.04 m^2·K/W for the horizontal direction of heat flow.

The baseline wall, representing the original uninsulated solid masonry structure, exhibits a high thermal transmittance, indicating substantial heat loss through the building envelope. This level of performance is typical of mid-20th-century residential buildings lacking thermal insulation and significantly exceeds current energy-efficiency standards.

The implementation of a conventional ETICS retrofit significantly enhances the wall’s thermal performance. Both retrofit approaches yield nearly a 90% improvement compared to the original wall. These findings confirm the effectiveness of externally applied insulation systems in reducing transmission losses while maintaining the integrity of the existing load-bearing masonry structure.

The modular wall configuration exhibits the lowest thermal transmittance, achieving approximately a 94% reduction compared to the baseline masonry wall. These results indicate that advanced modular envelope systems can exceed nZEB-level thermal performance requirements and demonstrate improved thermal efficiency. It should be noted that operational energy use was not directly assessed in this study.

Although these thermal transmittance metrics demonstrate substantial operational benefits, it is necessary to evaluate them alongside the material-related environmental impacts of each configuration, as discussed in the following section.

3.2. Embodied Carbon of Wall Structures

The LCA results reveal distinct differences in material-related impacts between the analysed wall systems, reflecting the influence of material composition, structural mass, and insulation strategy on environmental performance.

Table 18 summarises the embodied carbon results for the analysed wall structures as a complete wall assembly (Module A1–A3).

Table 18. Embodied carbon results for the analysed wall structures.

Wall Structures	Climate Change—Total [kg CO_2 eq./m^2]
Case A	92.35
Case B1	89.49
Case B2	104.40
Case C	55.27

The original masonry wall (Case A) exhibits relatively high embodied carbon due to the extensive use of high-mass materials, particularly fired clay masonry and cement-based rendering layers. Although the wall contains no dedicated insulation materials, the large quantity of dense mineral-based components significantly contributes to the overall GWP.

Both ETICS retrofit configurations moderately modify the embodied carbon profile of the original wall. The results indicate that the selection of insulation material strongly affects environmental impacts. Case B1, based on EPS insulation, achieves the lowest embodied carbon among the retrofit scenarios. The low density and relatively small material mass of EPS reduce the environmental burden associated with the insulation layer. In contrast, Case B2, utilising MW insulation, exhibits higher embodied carbon. This difference is primarily associated with the higher density and manufacturing-related impacts of MW production. Nevertheless, mineral wool offers additional functional advantages, including improved fire resistance, acoustic insulation, and vapour permeability, which may justify its use in certain renovation contexts.

The modular SIP-based wall system (Case C) demonstrates the lowest embodied carbon among all analysed solutions. Unlike the retrofit cases, the modular system replaces the conventional high-mass masonry structure with a lightweight prefabricated assembly consisting of engineered wood-based components, integrated insulation layers, and dry construction technologies. The reduction in material mass significantly decreases the embodied environmental burden of the wall system.

Figure 6 presents the contribution of main material groups to embodied carbon.

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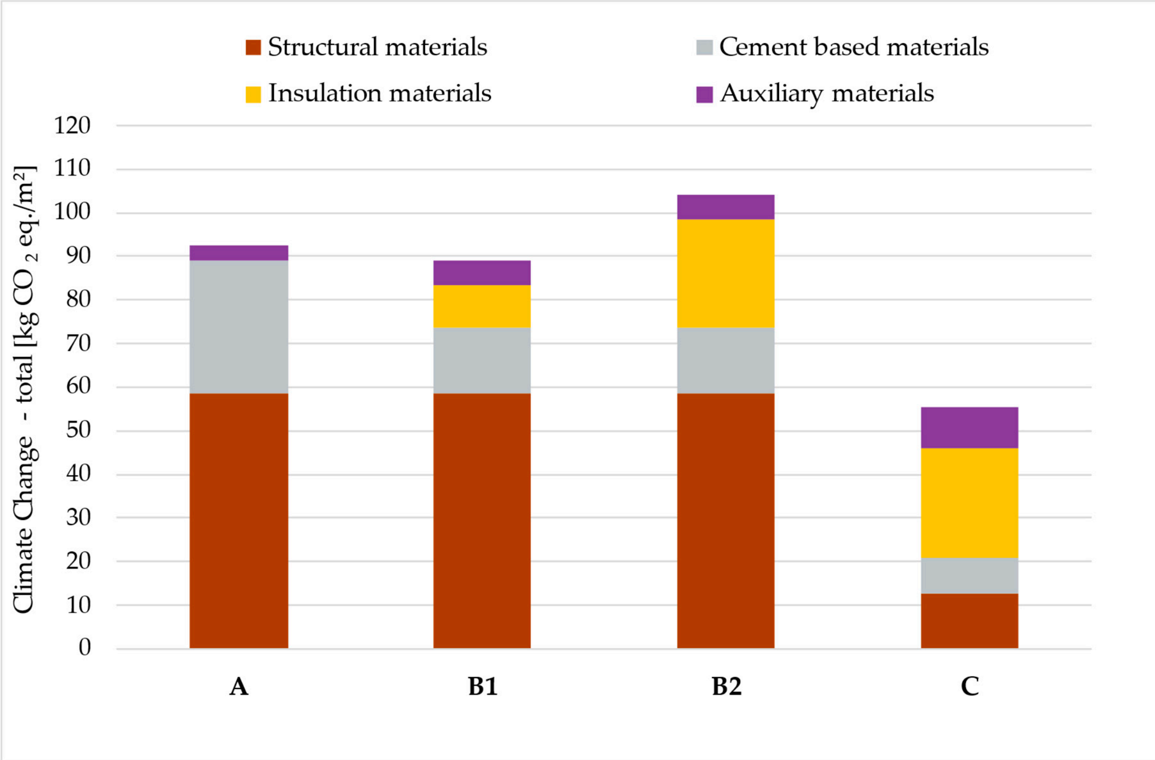

Figure 6. Contribution of main material groups to embodied carbon calculated on complete wall assembly (Module A1–A3).

At the material level, as shown in Figure 6, the results indicate that embodied carbon contributions differ substantially between conventional and modular construction approaches. In masonry-based systems, environmental impacts are dominated by brick and cement-based materials, whereas in modular walls, the primary contributors are insulation materials and engineered wood-based components such as OSB panels and polyurethane-based adhesives.

Based on the results in Figure 6, Case B1 and Case B2 differ only in the insulation material. The relatively low density and mass of EPS reduce its embodied carbon contribution compared with MW insulation, which is mainly associated with MW insulation's greater density and manufacturing-related impacts. Nevertheless, this material offers additional functional advantages, including improved fire resistance, acoustic performance, and vapour permeability, which may justify its application in specific renovation contexts.

Overall, the results demonstrate that embodied carbon performance is strongly influenced not only by insulation type, but also by the structural logic and material intensity of the wall system itself. The findings, therefore, underline the importance of an integrated assessment approach in which thermal efficiency and life-cycle environmental impacts are assessed simultaneously.

3.3. Comparative Evaluation of the Three Scenarios

From a lifecycle perspective, the results of this study highlight that improvements in thermal performance must be evaluated alongside material-related environmental impacts. For a better interpretation, we examined the data in 3 comparative groups. Calculated U-values are presented as steady-state indicators of thermal performance and heat-loss reduction potential, while embodied carbon values refer exclusively to the cradle-to-gate (A1–A3) life-cycle stages.

Figure 7 demonstrates the importance of selecting insulation materials in improving thermal performance and influencing material-related impacts.

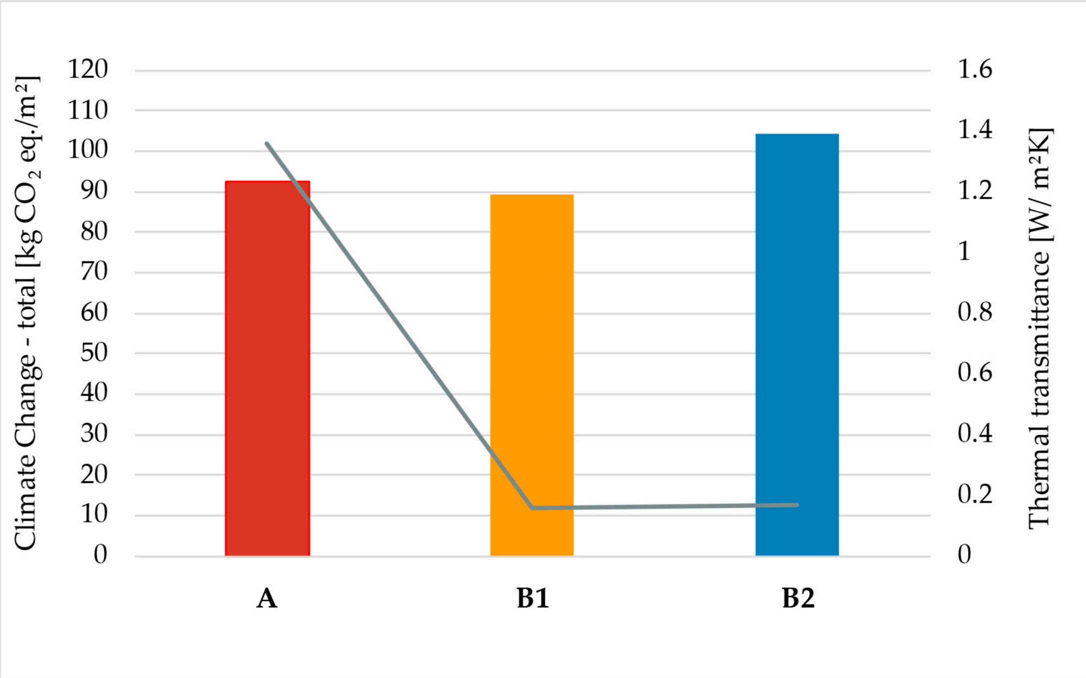

Figure 7. Comparative interpretation of Cases A, B1, and B2: Influence of insulation material selection; U-values are presented as steady-state thermal performance indicators, and embodied-carbon results cover complete wall assemblies within modules A1–A3.

The comparison highlights that the transition from the original masonry wall to insulated retrofit systems significantly reduces heat losses regardless of insulation type. At the same time, the choice of insulation material strongly affects the embodied environmental performance of the retrofit strategy. Consequently, insulation selection should be based not only on thermal performance but also on life-cycle environmental considerations and functional building requirements.

A comparison of the retrofit solutions with the modular SIP-based wall system is shown in Figure 8. It reveals important differences in both thermal performance and embodied carbon, particularly regarding the influence of insulation material selection.

Both retrofit scenarios deliver substantial thermal improvements over the original masonry wall; however, their environmental performance differs due to the properties of the applied insulation materials.

The modular SIP-based solution is a complete, lightweight reconstruction system rather than an additional insulation layer applied to an existing masonry wall. Despite incorporating both EPS and MW insulation, Case C's embodied carbon remains substantially lower than that of Cases B1 and B2. This result is mainly attributable to the elimination of high-mass masonry materials and the use of lightweight structural components.

Figure 9 compares the original masonry wall with the modular SIP-based wall system, illustrating substantial differences between conventional high-mass construction and lightweight modular envelope technologies in both thermal performance and embodied carbon.

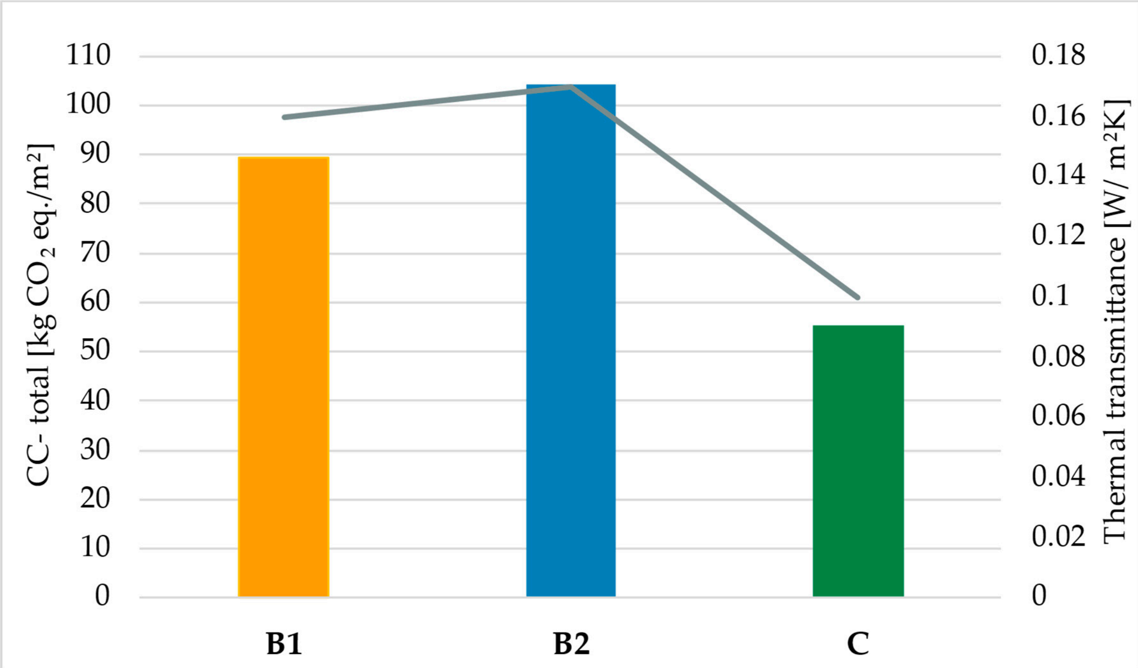

Figure 8. Comparative interpretation of Cases B1, B2, and C: U-values are presented as steady-state thermal performance indicators, and embodied-carbon results cover complete wall assemblies within modules A1–A3.

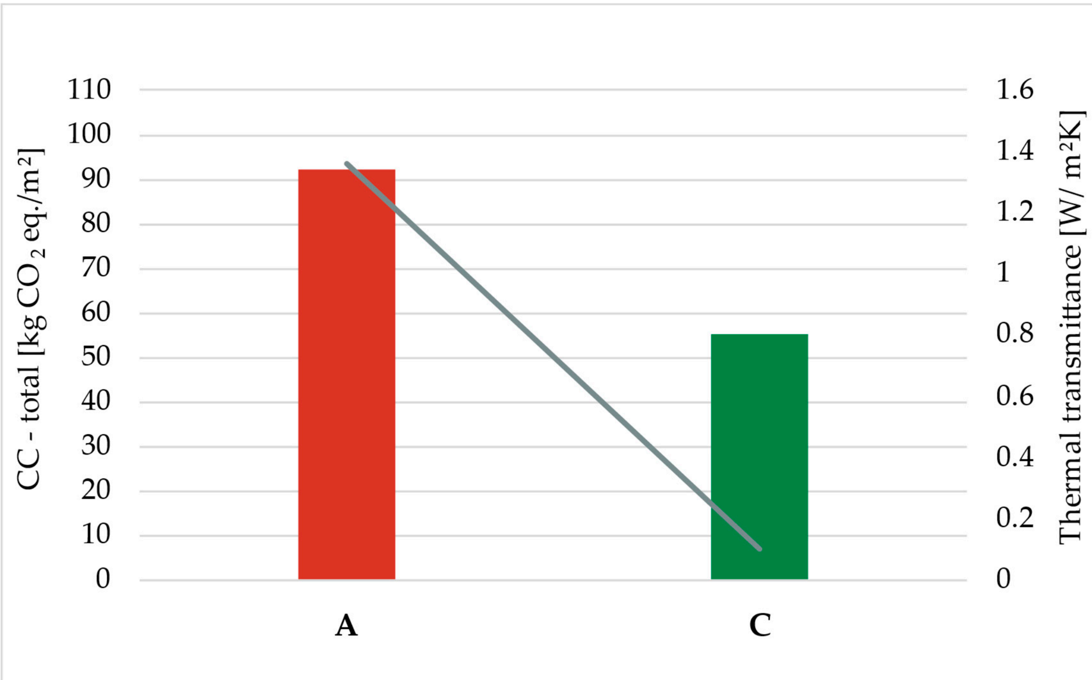

Figure 9. Comparative interpretation of Cases A and C: Conventional masonry versus modular SIP-based reconstruction; U-values are presented as steady-state thermal performance indicators, and embodied-carbon results represent complete wall assemblies within modules A1–A3.

Case A represents a typical uninsulated masonry wall. Its thermal performance is poor. The wall assembly has a relatively high embodied-carbon contribution due to its substantial material mass. In contrast, Case C, with a fundamentally different construction approach, achieves the lowest U-value, indicating a substantial reduction in heat transfer and a significant improvement in thermal efficiency. Despite the use of engineered materials such as OSB boards, PUR adhesives, and EPS insulation, the building's embodied carbon is considerably lower than that of the original masonry wall.

The overall comparison of the analysed wall structures can be summarised as follows:

- The baseline wall performs poorly in terms of energy efficiency and does not support decarbonization goals.
- The retrofit solution offers a significant improvement in thermal performance with moderate additional embodied impacts, making it a viable and widely applicable solution.
- The modular SIP-based solution provides the best performance under the assumption of reconstruction, highlighting its potential in scenarios where replacement of the existing building is feasible.

4. Discussion

The comparative evaluation of the three wall configurations offers early-stage, wall-level insights into how alternative envelope solutions may contribute to the decarbonization of ageing residential buildings. As highlighted in previous research, the building sector plays a central role in global energy consumption and GHG emissions [1–6], and the shift towards nearly zero-energy buildings has increased the relative importance of embodied carbon [10,11,17–21]. By combining steady-state thermal transmittance assessment with cradle-to-gate embodied carbon evaluation, this study addresses the growing need for integrated life-cycle perspectives in building performance analysis [19,21,28].

4.1. Thermal Performance Improvements and Their Implications

Both ETICS retrofit solutions and the SIP-based modular wall system substantially reduce the thermal transmittance of the original masonry wall, consistent with findings that envelope performance is a key determinant of operational energy demand [26].

However, as noted in the literature, the U value alone does not capture dynamic operational behaviour [48,49]. Therefore, the present study treats the U value strictly as a proxy for heat-loss reduction potential rather than as a direct measure of operational energy or operational carbon.

The broader implications for building-level performance would require calibrated energy modelling approaches, such as those discussed by Ozarisoy and Altan [38] and Schwartz et al. [39], which fall outside the scope of this assessment.

Actual building-level energy savings also depend on factors such as thermal bridges, airtightness, HVAC system efficiency, climatic conditions, occupancy patterns, and occupant behaviour. Therefore, the U-values reported in this study should be interpreted exclusively as indicators of heat-loss reduction potential.

4.2. Embodied Carbon Differences and Material Efficiency

The cradle-to-gate embodied carbon results reveal clear differences among the analysed wall systems. ETICS solutions (B1 and B2) add extra material layers to the existing masonry wall, leading to moderate increases in embodied carbon, consistent with previous findings that insulation-intensive retrofits may increase material-related impacts [22–24]. The SIP-based modular wall system (Case C) has the lowest A1–A3 embodied carbon per square metre, reflecting its lightweight structure and reduced material mass, in line with earlier studies on SIP systems [9,33–35].

However, as highlighted by several authors [29,46,47], LCA results are sensitive to dataset variability, system boundaries, and regional factors. Typical uncertainty ranges of ±10–20% indicate that the difference between EPS-based and mineral wool-based ETICS systems (B1 versus B2) falls within the expected methodological variability. Consequently, while the results suggest a general trend, they should not be interpreted as exact quantitative differences.

4.3. Retrofit vs. Reconstruction: Conceptual Asymmetry

The results should be interpreted in light of the fundamental difference between the retrofit scenarios (B1 and B2) and the SIP-based reconstruction scenario (C). ETICS solutions improve the thermal performance of the existing wall through targeted retrofit measures, whereas the SIP configuration represents a form-preserving reconstruction based on a newly built wall system. This distinction reflects the different intervention logics of retrofit and modular reconstruction approaches discussed in the literature [30,31,35]. The analysed intervention strategies differ not only in material characteristics but also in practical applicability, regulatory framework, and construction requirements. As highlighted by Schwartz et al. [39], retrofit and replacement options involve different lifecycle considerations and should not be treated as direct substitutes. Consequently, the comparison presented here is intended to evaluate the relative performance of these alternative approaches under identical geometric and climatic conditions rather than to imply one-to-one practical equivalence.

4.4. Synthesis of Thermal and Embodied Environmental Impacts

Considering both thermal transmittance and embodied carbon, the SIP configuration demonstrates the most advantageous combination within the A1-A3 boundary. This observation is consistent with previous research indicating that lightweight modular systems can enhance material efficiency and thermal performance [9,33–35]. However, as emphasised in the literature [20,25,29], downstream lifecycle stages—including transport, installation, maintenance, replacement cycles, and end-of-life processes—may significantly influence overall environmental performance. These stages were excluded from the present cradle-to-gate assessment, and their omission is particularly relevant for modular systems, where transport and assembly impacts may be non-negligible.

Similarly, ETICS retrofit solutions can provide benefits by preserving existing structures, minimising demolition waste, and facilitating staged renovation strategies, which align with circular economy principles [30,31]. Consequently, the integrated results should be regarded as early-stage comparative evidence rather than as definitive lifecycle rankings.

4.5. Broader Context and Limitations

The present study contributes to the growing body of literature advocating the integrated assessment of operational and embodied environmental impacts in building-envelope design [15,19,21,28]. Nevertheless, several limitations should be considered when interpreting the findings. The analysis was restricted to external wall assemblies and did not account for other building components, such as roofs, floors, or foundations, nor for whole-building interactions.

Furthermore, factors known to influence thermal performance, including façade orientation, thermal bridging, and dynamic climatic conditions, were beyond the scope of the assessment [26,48]. The embodied-carbon analysis was based on European average (RER) datasets, which may not fully capture regional variations in material production and supply chains [29,46]. While these constraints limit the broader applicability of the results, they do not affect the validity of the comparative assessment. Rather, they highlight the need for future studies to incorporate whole-building and whole-life carbon perspectives to provide a more comprehensive evaluation of decarbonization strategies.

5. Conclusions

This study presents an early-stage, wall-level comparative assessment of three external wall configurations—an existing uninsulated masonry wall, two ETICS retrofit solutions, and a SIP-based modular reconstruction system—applied to a representative Hungarian "Kádár" Cube house. By integrating steady-state thermal transmittance calculations with a cradle-to-gate (A1–A3) embodied carbon assessment, the analysis contributes to the growing body of research emphasising the need to consider operational and embodied impacts jointly in building envelope design.

The results show that both ETICS retrofit solutions and the SIP-based modular wall system substantially improve thermal transmittance relative to the original masonry wall, consistent with previous findings on the importance of envelope performance in reducing heat-loss potential. The lower U-value of the SIP wall system indicates greater potential to reduce heat transmission losses; however, operational energy use and carbon emissions were not directly assessed in this study.

At the same time, the embodied carbon results highlight meaningful differences among the configurations. ETICS systems introduce additional material layers and therefore entail moderate increases in embodied carbon, in line with earlier observations that insulation-intensive retrofits may elevate material-related impacts. Within the wall-level cradle-to-gate (A1–A3) assessment conducted in this study, the SIP wall system demonstrated the most favourable combination of thermal performance and embodied-carbon indicators.

These findings should be interpreted within clearly defined methodological boundaries. The assessment considers only A1–A3 product-stage impacts and steady-state U-values, excluding operational energy use, transport, installation, maintenance, replacement cycles, and end-of-life processes. According to the literature, LCA outcomes are highly sensitive to dataset variability and system-boundary delineation. The commonly reported ±10–20% uncertainty range indicates that the observed differences between ETICS variants (EPS versus mineral wool) are likely attributable to methodological variability rather than representing a robust distinction.

Furthermore, the comparison between ETICS retrofit and SIP reconstruction involves a conceptual asymmetry. SIP reconstruction represents a complete, morphology-preserving replacement of the wall system, whereas ETICS retrofit is an incremental intervention. This distinction aligns with the broader literature on the differing lifecycle implications of retrofit and replacement strategies.

Within these limitations, the study offers several key insights. First, the SIP-based modular wall system provides the most favourable balance of low thermal transmittance and low cradle-to-gate embodied carbon at the wall assembly level. Second, ETICS retrofit solutions remain effective for improving thermal performance while preserving existing structures, thereby supporting circular economy principles. Third, the results underscore the importance of evaluating operational and embodied impacts together, particularly for ageing residential building stock, where renovation decisions have long-term environmental implications.

Future research should expand the analysis to encompass whole-building and whole life cycle assessments, including dynamic energy simulation, transport and installation impacts, maintenance and replacement cycles, and end-of-life scenarios. This approach would align with emerging methodological frameworks and offer a more comprehensive foundation for evaluating retrofit and reconstruction strategies within the built environment.

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A.T.; supervision, K.T.S. and V.M. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

CC	Climate Change
CO_2 eq.	Carbon Dioxide Equivalent
ECE	Embodied Carbon Emission
EPS	Expanded Polystyrene
EPD	Environmental Product Declaration
ETICS	External Thermal Insulation Composite System
GHG	Greenhouse Gas
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MW	Mineral Wool
nZEB	Nearly Zero-Energy Building
OSB	Oriented Strand Board
PP	Polypropylene
PUR	Polyurethane
SIP	Structural Insulated Panel
U-value	Thermal Transmittance

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