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Quantifying the hidden embodied carbon gap in Turkish construction: A scenario-based assessment and policy roadmap

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Abstract

Despite the ambitious 2053 net-zero targets, the Turkish construction regulatory framework remains predominantly focused on operational energy efficiency, leaving a critical hidden carbon gap regarding embodied emissions. This study evaluates the misalignment between national codes (BEP-TR) and international whole-life carbon principles by analyzing the material-related carbon gap of a typical residential building in Zonguldak. Using verified Bill of Quantities (BoQ) data, a scenario-based embodied carbon assessment was conducted across three trajectories: Pessimistic (Business-as-Usual), Baseline (Standard Practice), and Optimistic (Low-Carbon Transformation). The results reveal that current regulations ignore 249.0 kgCO$_2$e/m^2 of upfront embodied carbon in a standard code-compliant building, increasing to 256.0 kgCO$_2$e/m^2 when scenario-based end-of-life emissions (C1–C4) are included. The structural system alone accounts for 71.4% of these unregulated upfront emissions. Scenario analysis demonstrates an approximately 48.0% reduction potential between the pessimistic and optimistic supply-chain trajectories, confirming that material selection is as critical as design geometry in reducing embodied carbon. Notably, the Optimistic Scenario indicates that utilizing existing low-carbon technologies could reduce the upfront embodied carbon by 32.2% compared with the baseline without altering architectural practices. However, a readiness paradox exists in which advanced materials produced for EU CBAM compliance are not sufficiently incentivized in the domestic market due to legislative inertia. This study concludes by proposing a phased regulatory roadmap that begins with embodied carbon disclosure and progressively integrates mandatory WLCA reporting, thereby aligning the Turkish construction sector with the EU EPBD and improving economic resilience against future carbon taxes.

1. Introduction

The rapid pace of global urbanization and the escalating climate crisis have positioned the building industry at the forefront of international decarbonisation efforts. According to the 2024 Global Status Report for Buildings and Construction, the industry accounts for approximately 37% of global energy-related carbon dioxide (CO$_2$) emissions, a figure that encompasses both operational energy and the embodied carbon from materials [1]. This environmental burden is further aggravated by the Urban Heat Island (UHI) effect, which significantly drives up cooling demand and operational energy consumption in cities [2]. While advanced heat mitigation technologies are essential to reduce these operational loads [3], strategies such as vertical extensions are increasingly explored to accommodate urbanization while minimizing the embodied carbon footprint of new infrastructure [4]. More broadly, sustainability challenges associated with rapid urban transformation and urban development have increasingly highlighted the environmental impacts of the built environment [5].

The transition to low-carbon materials to mitigate this burden remains constrained by perceived risks and a lack of incentives within the construction industry [6]. In response to these challenges, the concept of nearly Zero Energy Buildings (nZEB) has gained global traction as a primary strategy for strictly reducing operational emissions in the built environment [7]. Improving energy efficiency in buildings is widely recognized as one of the most effective strategies to reduce energy consumption and greenhouse gas emissions in the construction sector [8]. In line with the terminology of the European Union Energy Performance of Buildings Directive (EPBD), the nZEB concept refers to buildings with very low energy demand, where a significant share of the required energy is supplied from renewable sources produced on-site or nearby. In Türkiye, this operational focus has been progressively incorporated into national policy instruments. The Regulation on Energy Performance in Buildings (BEP-TR) requires all new buildings to obtain at least a Class C Energy Identity Certificate (EKB), which primarily evaluates operational energy demand related to heating, cooling, ventilation, and lighting [9]. Similarly, the TS 825 Thermal Insulation Standard establishes maximum permissible heat transfer coefficients (U-values) for building envelope components in order to limit annual heating energy demand and improve the thermal performance of buildings [10]. In addition, Türkiye has recently adopted the Energy Efficiency 2030 Strategy and the second National Energy Efficiency Action Plan (2024–2030) [11], which expand national targets for energy savings and emissions reduction. In parallel, policy instruments such as the YeS-TR [12] system have further introduced the concept of nZEB into the national regulatory discourse. These initiatives aim to reduce operational energy demand while increasing the share of renewable energy systems in buildings. However, despite the inclusion of nZEB principles in strategic policy documents, their practical implementation in Türkiye remains limited and progresses relatively slowly within the construction sector [13]. Similar observations have been noted in studies examining the broader environmental performance of residential buildings and the economic implications of carbon emissions in the housing sector [14]. Consequently, the current regulatory framework continues to prioritize operational energy performance, while the life-cycle carbon implications of construction materials remain largely outside the regulatory scope.

However, as operational energy efficiency improves toward nZEB standards, the relative importance of embodied carbon increases. Embodied carbon refers to emissions associated with material extraction, manufacturing, and construction processes. Recent international research has demonstrated this shift clearly. Röck et al. [15] showed that while stricter energy performance standards reduce operational emissions, the relative contribution of embodied emissions grows substantially, reaching approximately 45–50% of total life cycle emissions in highly energy efficient buildings and exceeding 90% in extreme cases. This trend reveals a critical challenge for climate mitigation and contributes to what can be described as a hidden carbon gap in current policy frameworks [16]. Ignoring these emissions can lead to ineffective climate strategies [17]. Therefore, leading international organizations have standardized the Whole Life Carbon Assessment (WLCA) methodology as a comprehensive reference framework. The Life Cycle Assessment (LCA) approach provides a basis for evaluating environmental impacts across the building life cycle, including production, use, and end-of-life stages [18]. While European nations like Norway have already actively developed whole-life carbon benchmarks to monitor and regulate these impacts [19], the RICS Professional Standard provides a consistent framework for calculating carbon across all life cycle modules: from the Product stage (A1–A3) and Construction Process (A4–A5) to the Use stage (B1–B7) and End-of-Life (C1–C4) [20].

This shift towards a life cycle perspective is critical for Türkiye, which has committed to a net-zero emission target by 2053 [21]. The Turkish construction industry is a major producer of carbon-intensive materials like ready-mixed concrete and steel [22]. Previous local research, such as the study by Atmaca and Atmaca [23], identified these materials as the primary drivers of embodied energy while simultaneously highlighting operational energy as the dominant life cycle phase. This historical context supported the initial regulatory focus on operational efficiency.

However, recent studies indicate a paradigm shift. Kayaçetin and Tanyer [24] revealed that at the neighborhood scale, embodied carbon constitutes a critical burden that can no longer be ignored, particularly when infrastructure is included in the assessment. The growing body of LCA research in Türkiye reflects a diversifying focus beyond operational energy. Recent studies have successfully applied life cycle principles to niche typologies, including post-disaster temporary housing [25], heritage building restoration [26], and educational facility retrofits [27]. Furthermore, component-specific analyses have investigated the embodied carbon trade-offs of insulation materials [28] and reinforced concrete grades [29]. Studies addressing broader sustainability dimensions in the built environment also highlight the importance of resource efficiency strategies in building design and operation [30]. While these studies provide critical data points for specific cases or materials, they often remain isolated from the broader legislative context. There is a notable scarcity of research that holistically evaluates the regulatory gap for standard multi-story residential buildings, which constitute the vast majority of the national building stock, and quantifies the carbon burden that remains legally permissible under current codes.

Based on the reviewed literature, the key research gaps related to embodied carbon assessment and WLCA integration in the Turkish construction sector can be summarized as follows:

- Existing studies in Türkiye predominantly focus on material-level or component-level embodied carbon assessments rather than evaluating the regulatory implications of these emissions.
- The mismatch between Turkish building regulations (e.g., BEP-TR and TS 825) and international life-cycle carbon frameworks has been acknowledged qualitatively but rarely quantified through empirical case studies.
- There is limited research quantifying the embodied carbon burden of typical code-compliant residential buildings, which represent the dominant typology within the national housing stock.

The potential impact of supply-chain choices and low-carbon material alternatives on reducing this regulatory carbon gap has not been systematically evaluated in the Turkish context.

The transition to a whole-life carbon approach is no longer solely an environmental aspiration but a commercial imperative. As Aktaş Çimen [31] emphasizes, the European Green Deal and Carbon Border Adjustment Mechanism (CBAM) are transforming sustainability from a voluntary preference into a prerequisite for industrial competitiveness. However, current Turkish legislation lacks the mechanisms to monitor or mitigate the embodied carbon of construction materials (specifically cement and steel) leaving the sector vulnerable to these emerging international carbon taxes. Despite these environmental and economic imperatives, current Turkish legislation remains narrowly focused on operational energy and lacks a mandatory framework to monitor or mitigate the embodied carbon of construction materials.

This study aims to evaluate the misalignment between international WLCA principles and the current Turkish construction legislation to bridge this identified regulatory gap. Specifically, the research pursues three interconnected inquiries. First, it performs a comparative gap analysis to determine the extent to which existing regulations (BEP-TR, TS 825) address the life-cycle modules defined in international standards such as EN 15978. Second, it quantifies the hidden embodied carbon gap by conducting a scenario-based embodied carbon assessment of a typical multi-story residential building, focusing on material-related modules including the product stage (A1–A3), construction process stage (A4–A5), and end-of-life stage (C1–C4). A persistent challenge identified in the literature is the absence of a comprehensive national Life Cycle Inventory (LCI) database, which hinders precise carbon accounting as noted by Kuzgunkaya [32]. This study addresses this limitation by utilizing verified Bill of Quantities (BoQ) data from a realized project to ensure high precision. Furthermore, to account for supply chain uncertainties and demonstrate the potential for decarbonisation, the assessment was structured around three distinct scenarios: Pessimistic (Business-as-Usual), Baseline (Standard Practice), and Optimistic (Low-Carbon Transformation). Finally, based on these empirical findings, it proposes a phased regulatory framework for the future integration of WLCA into the national legislative system.

Beyond bridging the theoretical gap, the outcomes of this study aim to provide actionable evidence for a broad spectrum of stakeholders. For policymakers and regulators, the findings offer a quantitative basis to amend national codes like BEP-TR and develop a roadmap for aligning Turkish legislation with the WLC mandates of the EU EPBD. For industry professionals and material manufacturers, the study illuminates the economic urgency of decarbonisation, demonstrating how low-carbon production strategies are essential to maintain competitiveness against the tax liabilities of the EU CBAM. Furthermore, for the academic and scientific community, it addresses the chronic data scarcity by establishing a verified embodied carbon baseline and a replicable scenario-based methodology, serving as a reference point for future national inventory development.

2. Literature Review

The construction industry is widely recognized as a critical industry for achieving global climate goals due to its high resource consumption and carbon emissions. To align with the Paris Agreement, the focus of environmental assessment has shifted from a singular emphasis on energy efficiency to a comprehensive life cycle approach. This section critically reviews the theoretical evolution from operational to whole-life carbon, analyses the comparative regulatory landscapes in Europe and Türkiye, discusses the methodological challenges inherent in carbon assessment, and highlights the economic imperatives driven by the CBAM.

2.1. Theoretical framework: From operational optimization to burden shifting

Historically, building regulations prioritized operational carbon, emissions from energy used for heating, cooling, ventilation, and lighting, driven by the immediate need to reduce fossil fuel consumption [33]. This focus led to the proliferation of nZEB strategies, which rely heavily on high-performance envelopes and renewable energy integration [7]. While effective in reducing power demand, recent literature identifies a critical paradox known as burden shifting. As buildings become more energy-efficient through thicker insulation and triple glazing, the embodied carbon associated with the production (A1-A3) and transport (A4) of these materials increases significantly [1, 19].

Studies by Santamouris et al. [2] and Santamouris [3] emphasize that while addressing operational loads, exacerbated by urban heat islands, is vital, ignoring the material footprint leads to suboptimal climate strategies. Ghorbany et al. [17] argue that in high-performance buildings, embodied carbon can account for over 50% of the total lifecycle emissions, rendering purely operational strategies insufficient for total decarbonisation. There is a wide range of embodied carbon values for residential buildings depending on structural systems, methodological assumptions, and system boundaries. A comprehensive meta-analysis by Röck et al. [15] shows that embodied emissions represent a significant share of total building life-cycle emissions, particularly as operational energy demand decreases in energy-efficient buildings. In European contexts, upfront embodied carbon values for reinforced concrete residential buildings are often reported in the range of approximately 250–500 $kgCO_2e/m^2$ for modules A1–A5, while whole life-cycle values can reach 400–800 $kgCO_2e/m^2$ depending on building typology and assessment scope [34]. These ranges provide a useful reference framework for interpreting embodied carbon assessments in different regional contexts.

2.2. Global standardization and mandatory WLCA regulations

To address the dominance of embodied carbon, international frameworks have moved towards standardization. The RICS Professional Standard [20] and the European Union's Level(s) framework [35] are established consistent methodologies covering all lifecycle modules (A1–C4). However, the translation of these standards into mandatory legislation varies significantly across geographies, creating a diverse regulatory landscape.

In Europe, several nations have pioneered mandatory WLCA. France's RE2020 regulation represents a paradigm shift, introducing dynamic LCA calculations and strict caps on embodied carbon per square meter [36]. Similarly, the Netherlands utilizes the Milieu Prestatie Gebouwen (MPG) to limit the shadow cost of materials, while Denmark's Building Regulations (BR18) have introduced CO_2 limit values for new construction starting in 2023 [37]. Recent comparative studies highlight that these regulations not only enforce reporting but drive market transformation by penalizing carbon-intensive materials [38].

In parallel with these regulatory developments, several international research initiatives have played a critical role in advancing WLCA methodologies. Notably, the International Energy Agency Energy in Buildings and Communities Programme (IEA EBC) launched Assessing Life Cycle Related Environmental Impacts Caused by Buildings (Annex 72), which aimed to harmonize building LCA practices in the building sector and improve the comparability of environmental assessments across the building life cycle [39]. Building on this work, the more recent Annex 89 initiative focuses on pathways for implementing net zero whole life carbon buildings by integrating life cycle carbon considerations into policy, design, and construction practices [40]. These initiatives highlight the growing international consensus that operational energy efficiency alone is insufficient to achieve long term decarbonisation goals in the built environment.

2.3. Methodological challenges and data uncertainty

Despite the regulatory progress, the academic literature highlights significant methodological challenges that affect the reliability of WLCA. A primary concern is the discrepancy between different LCI databases. Studies comparing databases such as Ecoinvent, Ökobaudat, and ICE have shown that variations in background data can lead to significantly different carbon results for identical building elements [41]. Furthermore, the issue of truncation error in Environmental Product Declarations (EPDs) and the selection of functional units (e.g., $kgCO_2e/m^2$ vs. $kgCO_2e$/occupant) remain critical debates in ensuring comparable results. These methodological limitations suggest that any gap analysis should be grounded in verified, local material data rather than generic global averages.

2.4. The Turkish context: Operational focus and the CBAM imperative

In contrast to the evolving European landscape, the Turkish regulatory framework remains predominantly focused on the operational phase. The BEP-TR and TS 825 strictly mandate insulation properties and operational efficiency but lack mechanisms to measure or limit embodied carbon [10, 9]. While the National Energy Efficiency Action Plan and Climate Council Decisions commit to net-zero targets [11, 42], they do not yet enforce WLCA, creating a significant regulatory blind spot. Recently, Karanfil et al. [43] classified Türkiye's decarbonisation maturity at Level 2: Emerging, noting that while awareness is rising, the policy landscape lacks the holistic WLCA integration seen in Level 4: Developed nations like France or Denmark.

Existing academic research in Türkiye mirrors this evolving understanding. Early foundational studies, such as the comprehensive assessment by Atmaca and Atmaca [23] the historical dominance of the operational phase (accounting for ~86-93% of emissions), justifying the regulator's initial focus on energy efficiency. However, recent studies indicate a paradigm shift with varying benchmarks depending on scope and typology. Kayaçetin and Tanyer [24] demonstrated that at the neighborhood scale, embodied carbon reaches 409.2 $kgCO_2e/m^2$ when infrastructure is included, revealing a hidden urban burden. Conversely, Kayaçetin and Hozatlı [44] found that while new nZEB regulations reduce operational emissions, they inadvertently increase embodied carbon by 15% due to material intensity.

Further complexity is added by material-specific studies. Somer [45] analysed the existing residential stock and identified a high concrete intensity of ~720 kg/m^2, estimating the embodied carbon of the rough construction alone at 121–137 $kgCO_2e/m^2$. Similarly, Altun et al. [28] and Keleş & Yazıcıoğlu [46] highlighted how design choices, such as insulation thickness and facade systems, create significant trade-offs between embodied and operational impacts. Despite these valuable data points ranging from 150 to over 400 $kgCO_2e/m^2$ across different studies (Table 1), there remains a gap in quantifying the specific regulatory gap for a standard, code-compliant residential building using a consistent module-based embodied carbon assessment framework.

The urgency for this transition is further driven by external economic factors. The EU's CBAM poses a direct financial risk to Türkiye's export-oriented construction materials industry. As noted by Beder [47] and Bahçekapılı [48], without aligning with international WLC standards, the Turkish steel and cement industries, which Atmaca and Atmaca [23] identified as the primary contributors to embodied emissions, face severe tax liabilities and loss of competitiveness.

Table 1. Summary of key LCA studies on buildings in Türkiye (Embodied Carbon Benchmarks)

Study	Building Typology	Location	Scope / Modules	Embodied Carbon (kgCO$_2$e/m^2)	Key Findings / Notes
Atmaca & Atmaca [23]	Residential (Urban & Rural)	Gaziantep	Cradle-to-Grave (A-C)	~198 – 215* *(Construction Phase)*	Operational energy dominates (86-93%). Concrete is the largest contributor to embodied carbon.
Atmaca [25]	Temporary Housing (Container)	Türkiye (General)	A1–A5 (Construction)	~300 – 350	Temporary shelters have high embodied carbon intensity due to steel-heavy structure relative to their lifespan.
Kayaçetin & Tanyer [24]	Mass Housing (Tunnel Form)	Ankara	A1–A4 (Cradle-to-Site)	272.4 *(Building Only)*	When infrastructure and landscape are included, the value rises to 409.2, highlighting the hidden urban burden.
Keles & Yazicioglu [46]	Primary Schools (Facades)	Istanbul	A1–A3, B4 (50 Years)	181 – 450 *(Floor area basis)*	High variation due to different facade materials. Reinforced concrete frame is the main contributor.
Altun et al. [28]	Residential	Ankara	A1–A5, B6, C1–C4	~180 – 300 *(Embodied share)*	Focuses on insulation trade-offs. Embodied carbon constitutes ~10-15% of the total life cycle emissions.
Kayaçetin & Hozatlı [44]	Residential (Apartment)	4 Climate Zones	A1–A5, B4, C1–C4	145 – 191	nZEB regulations increase embodied carbon by ~15% due to material intensity, creating a trade-off.
Karanfil et al. [43]	Office (nZEB)	Türkiye (General)	Whole Life Carbon (WLC)	182 – 201	Categorizes Türkiye as Emerging (Level 2) in decarbonisation maturity. nZEB offices carry significant upfront loads.
Somer [45]	Residential Stock (RC-Frame)	Türkiye (General)	A1–A3 (Product Stage)	295 – 334 *(Estimated Total)*	Analyzes existing stock. Identifies high concrete intensity (~720 kg/m^2) as a major driver of embodied carbon.

Note: Values for Atmaca [25] are derived from the reported total emissions and construction phase percentages

Thus, for Türkiye, progressing toward mandatory embodied carbon disclosure and future WLCA implementation is not merely an environmental concern but also a commercial necessity [31].

As summarized in Table 1, previous studies in Türkiye have established a wide range of embodied carbon benchmarks, typically varying between 150 and 450 kgCO$_2$e/m^2 depending on the building type and assessment scope. While Kayaçetin & Tanyer [24] highlighted the significance of urban infrastructure and Somer [45] quantified the material intensity of the existing stock, a critical gap remains regarding the regulatory compliance aspect. Most studies analyze what is or what could be (nZEB), but few quantify what is legally missed (the regulatory gap) in standard residential projects under current codes. This study aims to fill this specific void.

2.5. Identification of the scientific gap

A critical review of the literature reveals a distinct research gap. While international studies have extensively analyzed the impact of mandatory WLCA regulations (e.g., RE2020), the Turkish literature remains fragmented. Foundational local studies have successfully established material baselines [23] or highlighted urban-scale carbon burdens [24]. However, there is a lack of research that quantitatively maps the specific disconnect between these empirical findings and the current Turkish building codes. Existing literature identifies the political absence of regulation qualitatively, but fails to quantify the magnitude of the hidden carbon burden that legally compliant Turkish buildings continue to emit. This study bridges this scientific gap by performing a scenario-based embodied carbon assessment of a reference building constructed under current codes (BEP-TR), using the EN 15978 modular structure as a reference framework. In doing so, it provides empirical evidence on the material-related carbon burden that remains outside the current Turkish regulatory framework and supports the future alignment of national regulations with international life-cycle carbon standards.

3. Material and Methods

3.1. Research design and system boundary

This study adopts a case study–based research design to investigate the misalignment between Turkish building regulations and international WLCA principles, with a specific focus on material-related embodied carbon emissions. The methodological framework combines a regulatory gap analysis with a scenario-based embodied carbon assessment to a representative multi-story residential building. Within this framework, the regulatory gap analysis evaluates the extent to which existing Turkish regulations address life-cycle modules defined in EN 15978, while the scenario-based assessment quantifies the embodied carbon burden under different material production and supply-chain conditions (Fig. 1).

While the overall research design focuses on identifying regulatory misalignments, the carbon calculations follow the methodological principles defined in ISO 14040 and the modular framework of EN 15978.

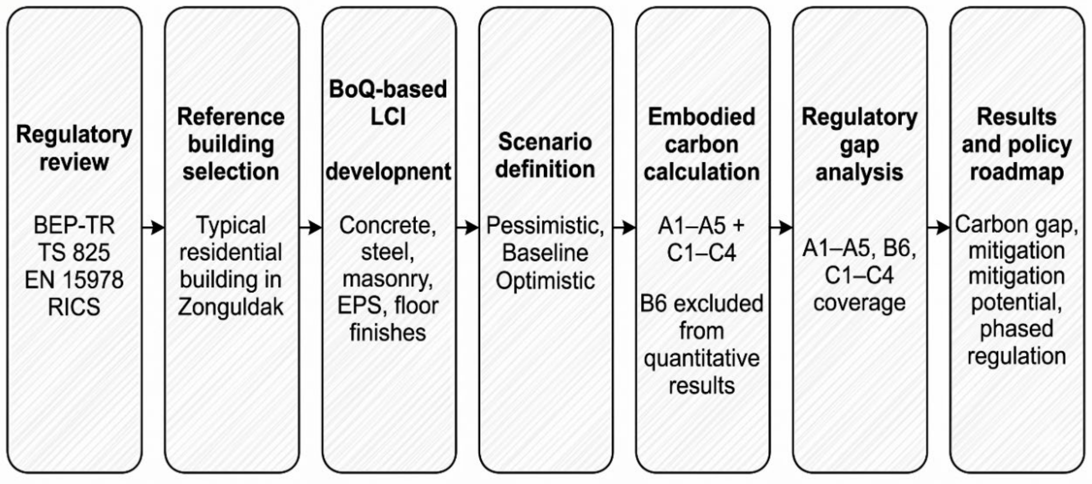

Fig. 1. Work flow of the study

In this context, ISO 14040 provides the general life-cycle assessment principles, while EN 15978 defines the life-cycle module structure used for building environmental assessments. However, the quantitative assessment does not represent a complete whole-life carbon assessment, as use-stage modules were excluded from the scenario-based calculations.

Fig. 2 illustrates the system boundary adopted in this study based on the EN 15978 module structure. The quantitative embodied carbon assessment includes the product stage (A1–A3), construction process stage (A4–A5), and end-of-life stage (C1–C4). Use-stage modules (B1–B7), including operational energy use (B6), were excluded from the quantitative carbon calculations. Module B6 was retained only in the regulatory gap matrix because operational energy is already addressed by BEP-TR through Energy Identity Certificate requirements. Module D was excluded because it represents potential benefits and loads beyond the system boundary and depends on uncertain future recycling, recovery, and substitution scenarios.

3.2. Goal and scope definition

The primary goal of this study is to quantify the unaccounted material-related embodied carbon burden resulting from the systemic exclusion of material-related emissions in current Turkish building regulations. The functional unit was defined as 1m^2 of Gross Floor Area (GFA) of the residential building. Unlike a complete whole-life carbon assessment, the quantitative assessment does not include use-stage modules; instead, it focuses on embodied carbon emissions associated with the product stage (A1–A3), construction process stage (A4–A5), and end-of-life stage (C1–C4).

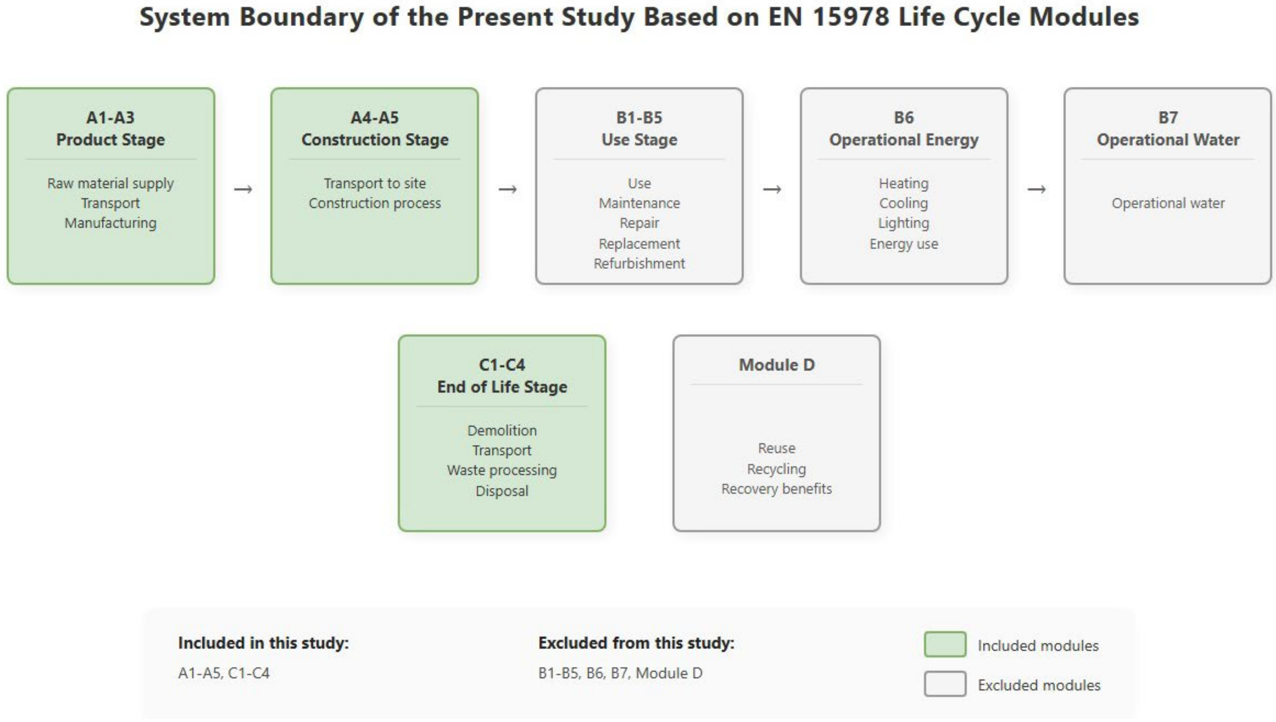

Fig. 2. System boundary of the study based on EN 15978 life cycle modules (Authors' own work)

The system boundaries follows the modular structure of EN 15978 [49] and includes the following life-material-related embodied carbon modules:.

- Product stage (A1–A3): raw material supply, transport, and manufacturing.
- Construction stage (A4–A5): transport of the materials to the site and construction waste.
- End-of-life stage (C1–C4): demolition, waste transport, waste processing, disposal.

All use-stage modules (B1–B7) were excluded from the quantitative assessment. This decision was made to avoid presenting the study as a complete whole-life carbon assessment and to focus specifically on material-related embodied carbon emissions that remain outside current Turkish regulations. Module B6 was retained only in the regulatory gap matrix because operational energy is already regulated through BEP-TR and Energy Identity Certificate requirements. Module D, which represents potential benefits and loads beyond the system boundary, was also excluded because it depends on uncertain future recycling technologies, substitution assumptions, and market conditions [20]. Therefore, the quantitative assessment focuses on modules A1–A5 and C1–C4.

3.3. Life cycle inventory

The LCI was developed using verified construction data obtained from a completed residential building project located in Zonguldak, Türkiye. The selected building represents a typical mid-rise reinforced concrete residential typology commonly observed in urban transformation projects across Turkish cities.

The building consists of a detached five-story residential apartment block (two basement floors, one ground floor, and three upper floors) with a total GFA of 1,120 m². The structural system is composed of a reinforced concrete frame (C30/37 concrete and B420C reinforcement steel) with hollow brick infill walls and conventional finishing materials.

Material quantities used in the LCI were derived directly from the verified BoQ and construction documentation of the project. This approach ensures that the analysis is based on actual construction data rather than simplified or hypothetical building models, thereby improving the reliability of the life-cycle assessment results.

The main construction materials included in the inventory are summarized in Table 2, which presents the quantities of structural, envelope, and finishing materials used in the building. These quantities were subsequently used as input parameters in the scenario-based embodied carbon calculations described in Section 3.4.

Due to its structural system, construction materials, and scale, the selected building typifies the plot-based reconstruction model widely used in Turkish urban transformation practices, making it a suitable case study for evaluating the regulatory carbon gap within the national construction sector.

3.4. Calculation methodology

Embodied carbon emissions were calculated by multiplying material quantities with the corresponding emission factors and module-specific assumptions defined within the quantitative system boundary. The assessment includes the product stage (A1–A3), construction process stage (A4–A5), and end-of-life stage (C1–C4). Use-stage modules, including operational energy use (B6), were excluded from the scenario-based carbon calculations. Accordingly, the study does not claim to provide a complete whole-life carbon calculation; rather, it quantifies the material-related embodied carbon gap that remains outside the current Turkish regulatory framework.

The total embodied GWP assessed in this study was calculated by summing upfront embodied carbon and end-of-life embodied carbon, as expressed in Eq. (1):

$$GWP_{embodied,total} = GWP_{A1-A5} + GWP_{C1-C4} \tag{1}$$

Upfront embodied carbon was calculated as the sum of product-stage, transport-stage, and construction-stage emissions, as shown in Eq. (2):

$$GWP_{A1-A5} = GWP_{A1-A3} + GWP_{A4} + GWP_{A5} \tag{2}$$

Product-stage emissions were calculated by multiplying the quantity of each material by its corresponding A1–A3 emission factor, as given in Eq. (3):

$$GWP_{A1-A3} = \sum_{i=1}^{n} Q_i x EF_{i,A1-A3} \tag{3}$$

Transport emissions were calculated using material quantities, transport distances, and the transport emission factor, as shown in Eq. (4):

$$GWP_{A4} = \sum_{i=1}^{n} Q_i x D_i x EF_{transport} \tag{4}$$

Construction waste impacts were calculated by applying material-specific waste rates and waste-related emission factors, as presented in Eq. (5):

$$GWP_{A5} = \sum_{i=1}^{n} Q_i x WR_i x EF_{waste,i} \tag{5}$$

Table 2. LCI of the reference residential building derived from the verified BoQ

Building Component	Material	Quantity	Unit	Data Source
Structure	Ready-mixed concrete (C30)	425	m³	BoQ
Structure	Reinforcement steel	40.5	t	BoQ
Envelope	Hollow brick walls	155	t	BoQ
Envelope	EPS insulation	850	m²	BoQ
Finishes	Laminate flooring and floor finishes	1,120	m²	BoQ

End-of-life emissions were estimated using material-specific scenario factors assigned to each material group, as defined in Eq. (6):

$$GWP_{C1-C4} = \sum_{i=1}^{n} GWP_{A1-A5,i} \; x \; r_{C,i} \tag{6}$$

Finally, total embodied carbon intensity and upfront embodied carbon intensity were calculated by normalizing the corresponding GWP values by the gross floor area of the reference building, as shown in Eqs. (7) and (8), respectively:

$$CI_{embodied} = \frac{GWP_{embodied,total}}{GFA} \tag{7}$$

$$CI_{upfront} = \frac{GWP_{A1-A5}}{GFA} \tag{8}$$

where Q_i is the quantity of material i derived from the BoQ, $EF_{i,A1-A3}$ is the product-stage emission factor of material i; D_i is the transport distance; $EF_{transport}$ is the transport emission factor; WR_i is the construction waste rate; $EF_{waste,i}$ is the waste-related emission factor; $GWP_{A1-A5,i}$ is the upfront embodied carbon of material group i; $r_{C,i}$ is the end-of-life scenario factor assigned to material group i; and GFA is the gross floor area of the reference building.

For A1–A3, emissions were calculated by applying cradle-to-gate emission factors to the material quantities derived from the BoQ. In the baseline scenario, the emission factors corresponding to CEM II blended cement concrete and electric arc furnace (EAF) reinforcement steel were applied to the material quantities reported in Table 2.

For A4–A5, additional emissions from transportation and construction waste were incorporated. Transport emissions (A4) were calculated using the material quantities from Table 2, transport distances defined in Table 3, and emission factors for heavy-duty diesel trucks reported in the literature [13, 41]. Construction waste impacts (A5) were incorporated by applying material-specific waste rates defined in Table 3.

For C1–C4, end-of-life emissions were calculated using literature-based factors for demolition activities, waste transport, waste processing, and final disposal. These emissions were reported separately from upfront embodied carbon to distinguish immediate construction-related impacts from end-of-life impacts.

Module B6 was not quantified as part of the scenario-based carbon results because the objective of this study is to quantify the material-related carbon gap that remains outside the current Turkish regulatory framework. Operational energy is already addressed by BEP-TR through Energy Identity Certificate requirements; therefore, B6 was included only in the regulatory gap matrix to indicate existing regulatory coverage, not in the embodied carbon calculations. All calculations were performed using spreadsheet based modelling in Microsoft Excel, rather than dedicated LCA software, in order to maintain transparency and allow flexible scenario parameter adjustments [50].

3.5. Assumptions and scenario parameters

To ensure transparency and reproducibility of the assessment, the main modelling assumptions applied in the scenario-based embodied carbon calculations are summarized in Table 3. These parameters reflect the logistical and infrastructural conditions observed in the Zonguldak region and were applied consistently across the scenario calculations. Due to the absence of project-specific demolition and waste-processing data, C1–C4 impacts were estimated using simplified material-specific scenario factors. These factors were applied to the A1–A5 embodied carbon impact of each material group and reflect the assumed end-of-life treatment routes summarized in Table 3. The resulting C1–C4 values should therefore be interpreted as scenario-based estimates rather than product-specific end-of-life LCA results.

Transport distances used in the analysis represent typical supply chains observed in regional construction practices. Materials were categorized according to their typical sourcing scale, including local supply for ready-mixed concrete, district-level supply for masonry materials, regional supply for timber-based finishing materials, and national supply for reinforcement steel. Transport processes were modelled using heavy-duty diesel trucks (Euro 5 class), assuming one-way distances between production facilities and the construction site.

Construction waste factors were applied to account for material losses during installation and on-site construction activities.

Table 3. Key LCA parameters and assumptions for modules A4–A5 and C1–C4

Material Group	Representative Material	A4 Transport Distance	A5 Waste Rate	C1–C4 Treatment Route	C1-C4 Scenario Factor $r_{C,i}$
Structural (Concrete)	Ready-Mixed Concrete (C30/37)	20 km (Local / Zonguldak)	5%	100% landfill / inert waste	3%
Structural (Steel)	Reinforcement Steel (B420C)	650 km (National / Çanakkale)	5%	95% recycling / 5% landfill	1%
Envelope / Masonry	Hollow Bricks & Mortar	50 km (District / Çaycuma)	3%	100% landfill	3%
Envelope	EPS insulation	50 km (District / Çaycuma)	3%	100% landfill	5%
Finishes	Laminate flooring and floor finishes	200 km (Regional / Kastamonu)	3%	100% landfill / incineration	5%

Waste rates of 5% were assumed for structural materials such as concrete and reinforcement steel, while a waste rate of 3% was applied to finishing materials. These values are consistent with construction waste benchmarks reported in previous studies [20].

End-of-life scenarios were defined based on current waste management practices observed in the region. Reinforcement steel was assumed to have a high recovery rate due to its economic value and the established scrap collection network. In contrast, concrete and masonry waste were assumed to be disposed of in landfill facilities due to the lack of large-scale concrete recycling infrastructure in the region. These assumptions provide the contextual basis for modelling the construction stage and end-of-life embodied carbon process within the scenario-based assessment framework.

The emission factors used for the main construction materials are summarized in Table 4. These values represent literature-based emission intensities corresponding to the dominant production technologies considered in the scenario analysis. For concrete, emission factors were differentiated according to cement clinker content, with higher values associated with CEM I Portland cement and lower values for blended cements such as CEM II and CEM III. For reinforcement steel, different emission factors were applied to represent primary steel production through the basic oxygen furnace (BOF) route and scrap-based production through the EAF route. An additional low-carbon EAF value was included to represent high-recycled steel production scenarios. The factor for laminate flooring and floor finishes was treated as a conservative area-based assumption for the floor finish assembly rather than for laminate boards alone, as product-specific laminate flooring factors may vary substantially depending on thickness, substrate, underlay, and installation layers.

3.6. Regulatory gap analysis framework

To evaluate the alignment between Turkish building regulations and international WLCA principles and standards, a Regulatory Compliance Matrix was developed. This matrix compares the scope of national regulations, primarily the BEP-TR and the TS 825, with the modular life-cycle framework defined in EN 15978 and RICS Professional Standard.

Since legislative texts typically describe energy performance requirements in qualitative terms, a three-level scoring rubric was developed to translate regulatory provisions into a measurable analytical framework. Each relevant life-cycle module, including (A1–A5), B6, and, C1-C4 was evaluated according to the extent to which it is addressed within the national regulatory framework.

The scoring system is defined as follows:

- Level 0, Regulatory Void: The life-cycle module is not addressed in the legislation. No requirements exist for calculating, reporting, or limiting emissions associated with the module.
- Level 1, Partial Alignment: The module is indirectly addressed through related regulatory parameters such as energy efficiency or insulation requirements, but no explicit carbon-based metric is defined.
- Level 2, Mandatory Regulation: The module is explicitly regulated with quantitative performance requirements, and compliance is required for obtaining building permits or certification.

This framework allows the identification of regulatory gaps between current Turkish building regulations and the life-cycle carbon accounting structure defined in international WLCA standards.

Table 4. Product-stage emission factor assumptions for key construction materials used in the embodied carbon scenarios

Material	Production Route / Type	Emission Factor	Unit	Source
Concrete	CEM I	0.40	tCO_2e/m^3	Gan et al. [51], Turner and Collins [52]
Concrete	CEM II	0.32	tCO_2e/m^3	THBB [22]
Concrete	CEM III	0.22	tCO_2e/m^3	MPA [53]
Reinforcement Steel	BOF	1.80	tCO_2e/t	Rumsa et al. [54]
Reinforcement Steel	EAF	1.15	tCO_2e/t	Rumsa et al. [54]
Reinforcement Steel	High-recycled EAF	0.60	tCO_2e/t	Rumsa et al. [54]
Hollow brick walls	Standard masonry	0.24	tCO_2e/t	Olsson et al. [55]
EPS insulation	Standard EPS board	6.5	$kgCO_2e/m^2$	Schmidt and Chertack [56]
Laminate flooring and floor finishes	Standard floor finish	15.0	$kgCO_2e/m^2$	Literature-based conservative assumption for floor finish assembly

Note: The emission factors in this table were used for product-stage A1–A3 calculations. A4–A5 transport and waste assumptions and C1–C4 scenario factors are provided separately in Table 3.

3.7. Scenario analysis framework

To address uncertainties related to material production technologies, supply-chain conditions, and end-of-life assumptions, a scenario-based assessment approach was adopted. Previous studies indicate that embodied carbon values for residential buildings can vary significantly depending on material composition, production technologies, logistics, and system boundaries. Reported values in the literature typically range between 150 to over 400 $kgCO_2e/m^2$. Three scenarios were defined to represent different levels of carbon intensity in construction practices (Table 5).

Scenario 1: Business-as-Usual (Pessimistic Case): This scenario reflects the high-carbon intensity profile of the existing building stock. It aligns with the findings of Somer [50], who identified a high concrete material intensity (720 kg/m^2) in Turkish residential buildings. It assumes the use of traditional, carbon-heavy materials (e.g., CEM I Portland cement, virgin or low-recycle steel) and inefficient logistics, representing the upper bound of emissions.

Scenario 2: Standard Practice (Baseline Case): This scenario represents the current market reality for a typical construction project compliant with BEP-TR. The parameters are calibrated to match the embodied carbon intensities reported by Kayacetin and Tanyer [24].

Scenario 3: Low-Carbon Transformation (Optimistic Case): This scenario models a future trajectory where the sector aligns with EU Green Deal targets. It adopts the best available technologies (e.g., Green Concrete, high-recycle steel) to achieve the lower-bound emission targets suggested by Karanfil et al. [22] for Developed decarbonisation maturity. The specific parameters defining these scenarios were summarized in Table 5.

The specific parameters defining these scenarios are summarized in Table 5. These scenarios affect the embodied carbon modules included in the quantitative assessment, namely A1–A5 and C1–C4. Operational energy module B6 is not included in the scenario calculations and is retained only in the regulatory gap matrix.

4. Findings

The analysis of the Turkish construction regulatory framework against international WLCA principles and standards reveals a critical dichotomy between operational mandates and embodied carbon realities. his section presents the results of the regulatory gap analysis, the calculated embodied carbon burden of the reference building across three defined scenarios, and the sensitivity of these findings to supply-chain variations. The scenario-based results distinguish between upfront embodied carbon (A1–A5) and end-of-life embodied carbon (C1–C4), while use-stage modules, including B6, are excluded from the quantitative carbon totals.

4.1. Regulatory framework mapping: The compliance gap

The comparative analysis between the national regulations (BEP-TR, TS 825) and the international EN 15978 and RICS Professional Standard reveals a significant regulatory imbalance. While operational energy is explicitly regulated, embodied carbon emissions associated with construction materials remain largely unaddressed. To quantify this divergence, the scoring framework described in Section 3.6 was applied to each life-cycle module. Table 6 shows that Türkiye has achieved Level 2 regulatory maturity for operational energy (B6) through mandatory energy performance certification requirements. However, all upfront embodied carbon modules (A1–A5) remain at Level 0, indicating that these emissions are not explicitly addressed within the current legislative framework. Similarly, end-of-life processes (C1–C4) are also absent from the regulatory scope.

4.2. Quantification of the hidden carbon gap

LCI analysis of the reference residential building provides empirical evidence of the emissions ignored by the current framework.

Table 5. Definition of scenario parameters affecting embodied carbon modules in the assessment

Parameter	Scenario 1 (Pessimistic) (Business-as-Usual)	Scenario 2 (Baseline) (Standard Practice)	Scenario 3 (Optimistic) (Low-Carbon Future)
Primary Focus	Maximum Risk Assessment	Current Market Reality	Best Available Technology
Concrete Type	CEM I *(High Clinker Factor)*	CEM II *(Standard Mix)*	CEM III *(High Slag/Ash Content)*
Steel Production	Global Avg. / BOF Route *(Low Recycled Content)*	TR Avg. / EAF Route *(~70% Recycled)*	High Efficiency EAF *(>95% Recycled)*
Transport (A4)	Long Distance (>100 km) *(National Supply)*	Regional Distance (50 km) *(District Supply)*	Local Distance (<20 km) *(Optimized Logistics)*
Waste Rate (A5)	High (5-10%)	Standard (3-5%)	Optimized / Prefab (<2%)
End-of-Life Scenario (C1–C4)	Landfill dominant	Recycling + landfill mix	Improved recycling
Benchmark Ref.	Somer [45] Stock Data	Kayacetin and Tanyer [24] Mass Housing	Karanfil et al. [43] nZEB Targets

Table 6. Comparative gap analysis of carbon regulation scope (Score, 0: None, 1: Partial, 2: Mandatory)

Life Cycle Module	BEP-TR / TS 825	RICS / EN 15978	Gap Status
A1–A3 (Product)	0	2	Critical Gap
A4 (Transport)	0	2	Critical Gap
A5 (Construction)	0	2	Critical Gap
B6 (Operational Energy)	2 (EKB Class C Limit)	2	Aligned
C1–C4 (End-of-Life)	0	2	Critical Gap

Scenario 1: Assuming high-carbon traditional practices, the building generates 363.7 tCO_2e, of upfront embodied carbon (A1–A5), resulting in a carbon intensity of 324.8 $kgCO_2e/m^2$. This figure aligns with the upper bounds of the existing heavy stock identified by Somer [45].

Scenario 2: Under current standard practices, the total upfront carbon (A1–A5) is 278.9 tCO_2e. When normalized by the GFA, the specific carbon intensity is 249.0 $kgCO_2e/m^2$. This represents the unreported embodied carbon associated with a typical code-compliant building.

Scenario 3: By adopting best available technologies and optimized logistics, emissions drop to 189.2 tCO_2e (168.9 $kgCO_2e/m^2$), demonstrating a potential reduction of 32.2% compared to the baseline.

To clarify the contribution of different life-cycle modules, Table 7 presents the module-level embodied carbon results for the Baseline Scenario. The results show that upfront embodied carbon dominates the assessed impact, while end-of-life emissions represent a smaller but still unregulated material-related carbon burden.

To analyze the anatomy of this unregulated carbon burden, a detailed breakdown of the Baseline Scenario (Scenario 2) is presented in Table 8. This scenario was selected for granular analysis as it represents the current standard practice in the Turkish construction sector, compliant with BEP-TR energy codes but utilizing conventional materials (e.g., CEM II cement, standard steel) and regional supply chains. The table dissects the contribution of specific building components to the total upfront carbon, highlighting the disproportionate impact of structural elements compared to architectural finishes.

Table 8 shows that structural materials dominate the building's upfront embodied carbon footprint. Ready-mixed concrete alone accounts for 146.9 tCO_2e, while reinforcement steel contributes 52.2 tCO_2e. Together, these structural elements account for 71.4% of total upfront emissions. The building envelope accounts for 16.2%, while finishes and auxiliary materials contribute the remaining 12.5%. The distribution of emissions across building components is illustrated in Fig. 3.

These results highlight a structural mismatch in current decarbonisation policies. Existing regulations focus primarily on envelope performance through insulation requirements, while the structural frame, which generates the largest share of emissions, remains outside the regulatory scope.

Table 7. Module-level embodied carbon results for the Baseline Scenario

Life-cycle module	Description	Emissions (tCO_2e)	Intensity ($kgCO_2e/m^2$)	Reporting note
A1–A5	Upfront embodied carbon	278.9	249.0	Quantified from BoQ, product-stage emission factors, transport assumptions, and waste rates
C1-C4	End-of-life embodied carbon	7.8	7.0	Scenario-based estimate using $r_{c,i}$ factors
A1-A5+C1-C4	Total assessed embodied carbon	286.7	256.0	Excludes B1–B7 and Module D

Table 8. Breakdown of Upfront Carbon (A1-A5) for the Baseline Scenario (Scenario 2)

Building Component	Material	Quantity	Embodied Carbon Factor (A1-A3)	Transport & Waste Impact (A4-A5)	Total Emissions (tCO_2e)	Intensity ($kgCO_2e/m^2$)
Structure	Ready-Mixed Concrete (C30)	425 m^3	0.32tCO_2e/m^3	+8%	146.9	131.1
Structure	Reinforcement Steel	40.5 Ton	1.15 tCO_2e/t	+12%	52.2	46.6
Envelope	Hollow Brick Walls	155.0 Ton	0.24 tCO_2e/t	+5%	39.1	34.9
Envelope	Thermal Insulation (EPS)	850 m^2	6.5 $kgCO_2e/m^2$	+10%	6.1	5.4
Finishes	Laminate flooring and floor finishes	1,120 m^2	15.0 $kgCO_2e/m^2$	+8%	18.1	16.2
Others	Mortar, Windows, etc.	Various	-	+5%	16.6	14.8
TOTAL	Upfront Carbon				278.9	249.0

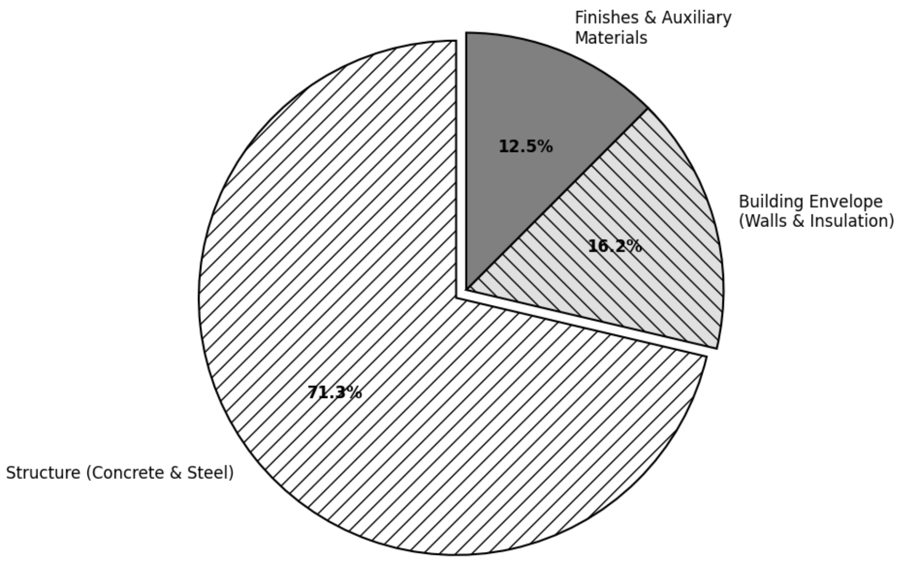

Fig. 3. Distribution of upfront carbon by building component

4.3. Scenario analysis and mitigation potential

The scenario analysis moves beyond static accounting to illustrate the potential impact of supply chain decisions and technological choices on the building's carbon footprint. Table 9 summarizes the variation across the three defined trajectories.

The comparison indicates that the adoption of lower-carbon material technologies could reduce embodied emissions by 32.2% relative to current construction practices. The primary drivers of this reduction are the substitution of Portland cement with blended cements and the use of scrap-based electric arc furnace steel production. The difference between the pessimistic and optimistic scenarios corresponds to a 48.0% reduction relative to the pessimistic scenario, confirming that supply-chain decisions and material production routes significantly affect building-level embodied carbon outcomes. To evaluate the robustness of the baseline results, a sensitivity analysis was conducted by varying key input parameters. Fig. 4 presents the effects of changes in material emission factors (±10 percent) and transport distances (±50 percent) on the total carbon intensity. These results indicate that decarbonisation policies targeting material production processes (A1–A3) are likely to be significantly more effective than measures focusing solely on transport logistics.

4.4. Industrial readiness assessment

To evaluate the feasibility of addressing this regulatory carbon gap, a qualitative readiness assessment was conducted based on current policy landscape and market indicators. The assessment synthesizes the findings of recent sectoral analyses [43, 47] to map the sector's capacity for transition. The results, summarized in Table 10, reveal a disjointed landscape where external pressure is high, but internal regulatory mechanisms are immature.

The assessment reveals a structural mismatch between industrial capability and regulatory incentives. On the one hand, major Turkish construction material manufacturers already produce lower-carbon products, particularly blended cements and recycled steel, largely driven by export requirements related to the EU CBAM. On the other hand, the absence of a domestic regulatory mandate for embodied carbon reporting limits the adoption of these materials in local construction projects [45]. This imbalance suggests that while technological capacity exists to reduce embodied carbon emissions, the current regulatory framework does not yet provide sufficient incentives to support widespread implementation.

Table 9. Comparison of upfront embodied carbon results across scenarios

Parameter	Scenario 1 (Pessimistic)	Scenario 2 (Baseline)	Scenario 3 (Optimistic)
Upfront embodied carbon (tCO_2e)	363.7	278.9	189.2
Upfront carbon intensity (A1–A5, $kgCO_2e/m^2$)	324.8	249.0	168.9
% Change vs. Baseline	+30.4%	0%	-32.2%
Driver of Change	High-clinker cement & long transport	Standard practice	Low carbon cement & local supply

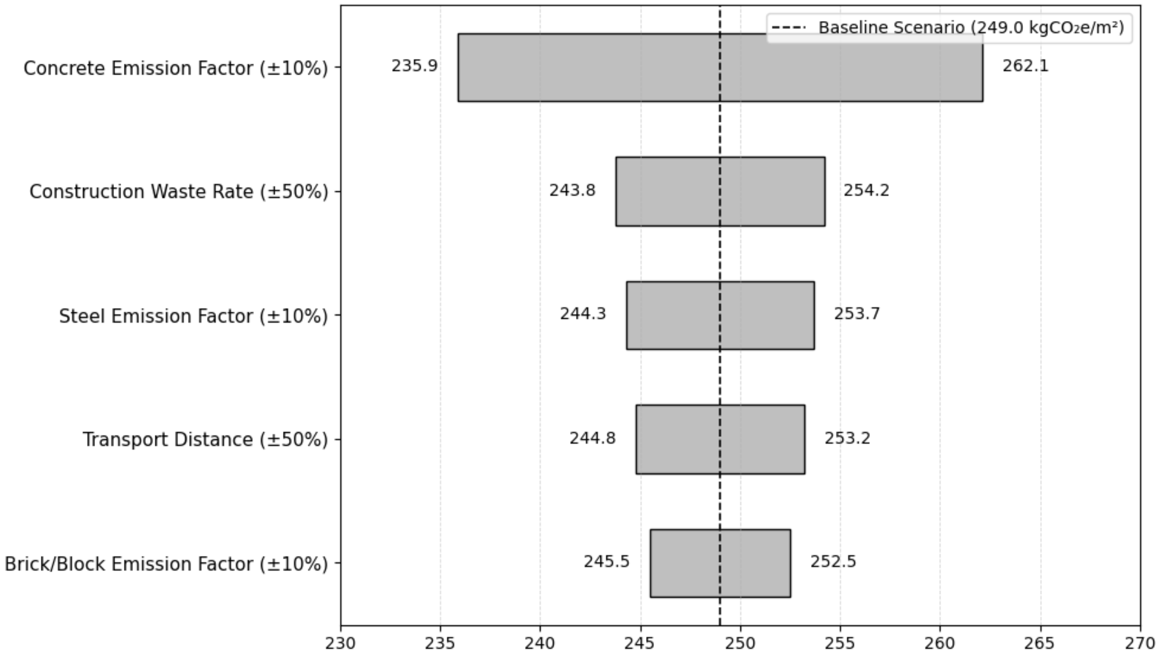

Fig. 4. Sensitivity analysis of key parameters on total upfront carbon intensity

Table 10. Industrial readiness assessment for mandatory embodied carbon disclosure and future WLCA transition

Indicator	Current Status	Readiness Level	Assessment
Economic Pressure	High Risk	Critical	The EU CBAM poses immediate tax liabilities, estimated to reach billions of Euros for the steel and cement sectors by 2034 [48].
Data Infrastructure	Fragmented	Medium	While YeS-TR infrastructure exists, a comprehensive national LCI database remains incomplete, creating reliance on foreign data [32].
Regulatory Mandate	Non-Existent	Low	No legal requirement for embodied carbon reporting exists in BEP-TR. Türkiye is classified at Level 2: Emerging maturity, lacking holistic WLC policies
Industry Capability	Mixed	Medium	Large manufacturers (Steel/Cement) have EPDs and low-carbon products (Scenario 3 capability), but SMEs and contractors lack WLCA literacy.

5. Discussion

This study quantified the unregulated embodied carbon within the Turkish construction regulatory framework by analyzing a typical residential building under three distinct supply-chain scenarios. The results provide empirical evidence that the current focus on operational energy efficiency leaves a significant portion of material-related climate impacts unregulated. The baseline scenario produced an upfront embodied carbon intensity of 249.0 $kgCO_2e/m^2$ for A1–A5 and a total assessed embodied carbon intensity of 256.0 $kgCO_2e/m^2$ when C1–C4 end-of-life emissions were included.

5.1. Contextualizing the national baseline

The calculated upfront embodied carbon intensity for Scenario 2 is 249.0 $kgCO_2e/m^2$ for modules A1–A5. When the scenario-based end-of-life estimate for C1–C4 is included, the total assessed embodied carbon intensity increases slightly to 256.0 $kgCO_2e/m^2$. This figure serves as a critical benchmark for the current standard practice in Türkiye. This range remains close to the findings of Kayaçetin and Tanyer [24], who estimated an embodied carbon intensity of approximately 272 $kgCO_2e/m^2$ for mass housing projects using tunnel formwork systems in Ankara. The proximity of these results confirms that despite differences in construction techniques, the carbon intensity of the structural frame remains the dominant factor in the Turkish residential sector. However, the Scenario 1, which yielded 324.8 $kgCO_2e/m^2$, reveals a concerning proximity to the historical stock values. Somer [45] estimated the existing Turkish residential stock and identified a high material intensity, estimating the embodied carbon of rough construction to be around 334 $kgCO_2e/m^2$. This proximity suggests that without mandatory regulations, new constructions risk mimicking the high-carbon profile of the legacy building stock, failing to contribute to the national decarbonisation targets. Conversely, the Scenario 3 demonstrates that a reduction to 168.9 $kgCO_2e/m^2$ is technically feasible. This value is consistent with the ambitious nZEB targets suggested by

Karanfil et al. [43], who classified Türkiye as an emerging market in decarbonisation maturity.

5.2. Methodological robustness and variability

A key methodological contribution of this study is the use of scenario-based modelling rather than relying on a single deterministic carbon value. Previous research has shown that embodied carbon estimates can vary substantially depending on material sourcing and production parameters. Marsh et al. [50], demonstrated that variations in mixture design and supply chains can alter embodied carbon results by more than 30%, while Zheng et al. [51] found that buildings with identical typologies could exhibit up to a twofold variation in embodied carbon due to differences in supply chains.

The results obtained in this study confirm a similar variability within the Turkish context. The difference between the pessimistic and optimistic scenarios corresponds to approximately a 48.0% reduction relative to the pessimistic scenario. This finding indicates that supply-chain decisions and material production technologies can significantly influence building-level emissions. Consequently, policies targeting embodied carbon should focus on material production processes and emission factors, rather than regulating building typologies alone.

Although the analysis primarily focuses on operational energy within Module B6, other use-stage modules such as maintenance, repair, and replacement (B1–B5) may also influence life-cycle emissions. From an integrated life-cycle perspective, material selection may create trade-offs between upfront embodied carbon and long-term durability. Materials with higher initial carbon intensity may offer longer service life and reduced replacement cycles over the building life span. Previous studies have shown that maintenance and replacement cycles can significantly affect life-cycle emissions depending on material durability and service life assumptions [15, 34]. While these processes were beyond the scope of the present analysis, future WLCA studies in Türkiye could incorporate detailed maintenance scenarios to better capture long-term life-cycle trade-offs.

5.3. International benchmarking and future risks

When compared with international studies, the baseline embodied carbon intensity identified in this study remains relatively moderate. The calculated A1–A5 upfront embodied carbon intensity is 249.0 $kgCO_2e/m^2$, while the total assessed embodied carbon intensity increases to 256.0 $kgCO_2e/m^2$ when C1–C4 end-of-life emissions are included. Soust-Verdaguer et al. [52] reported embodied carbon ranges for residential buildings in Spain between 205 and 1463 $kgCO_2e/m^2$, placing the Turkish baseline values toward the lower end of this spectrum. This difference can partly be explained by the structural typology commonly used in Türkiye, characterized by reinforced concrete frames with relatively simple architectural finishes. Similarly, Tozan et al. [37] proposed a limit value of approximately 9.0 $kgCO_2e/m^2/year$ for new constructions in Denmark, corresponding to roughly 450 $kgCO_2e/m^2$ under a 50-year benchmark framework.

However, this apparent advantage may be temporary. Several studies indicate that as operational energy efficiency improves and electricity grids decarbonize, embodied carbon becomes the dominant source of life-cycle emissions. Torabi et al. [53] found that embodied emissions may account for up to 80% of total building emissions in highly energy-efficient buildings. A similar trend may emerge in Türkiye. Kayaçetin and Hozatlı [44] suggest that stricter operational energy regulations associated with nZEB policies may increase embodied carbon by up to 15%, primarily due to increased insulation requirements and system complexity. Therefore, without regulatory mechanisms addressing embodied carbon, future improvements in operational efficiency could unintentionally shift emissions toward material production stages.

5.4. Policy implications and industrial alignment

The results highlight the material intensity of the carbon gap within the current regulatory framework. Structural materials alone account for 71.4% of the total upfront embodied carbon, confirming previous findings by Atmaca and Atmaca [54]. Sensitivity analysis further indicates that the results are highly responsive to changes in concrete carbon intensity. This finding is particularly relevant for policy design in Türkiye, where structural requirements defined by the Turkish Seismic Code (TBDY-2018) often necessitate higher concrete strength classes and increased cement content [29]. Highlighted that the high strength classes of concrete required by the Turkish Seismic Code (TBDY-2018) However, the optimistic scenario demonstrates that the use of blended cements such as CEM II or CEM III can substantially reduce emissions without compromising structural performance.

At the same time, the Turkish construction materials industry already possesses the technological capacity required for such a transition. As noted by Aktaş Çimen [31], the Türkiye is a major exporter of cement and steel products to the European Union, and manufacturers are increasingly adapting production processes to comply with the CBAM. Economic analyses by Bahçekapılı [48] and Beder [47] suggest that failure to align with these standards could expose Turkish industries to significant financial risks in international markets. Despite this technological capability, the domestic regulatory framework currently provides no mandatory requirements for embodied carbon assessment, creating a structural disconnect between industrial capability and regulatory incentives.

Based on these findings, this study proposes a phased regulatory roadmap for integrating WLCA into Turkish building legislation. As illustrated in Fig. 5, the proposed transition begins with voluntary WLCA reporting and the development of a national life-cycle inventory database.

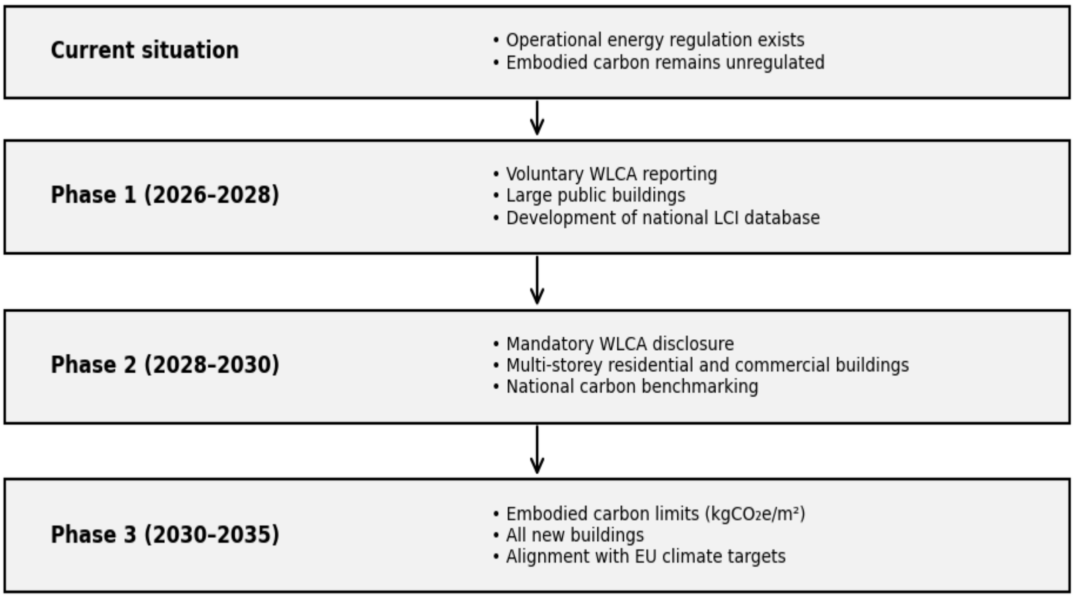

Fig. 5. Proposed phased roadmap for integrating WLCA into Turkish building regulations

In the medium term, mandatory carbon disclosure and benchmarking mechanisms could be introduced for large residential and commercial buildings. Ultimately, this process could culminate in the implementation of quantitative embodied carbon limits for new buildings, aligning national regulations with European climate targets.

In addition to regulatory gaps, several market-related barriers may also contribute to the continued use of carbon-intensive materials. Cost differences between conventional and low-carbon materials remain a significant constraint, particularly in price-sensitive housing projects [6]. Furthermore, limited familiarity with WLCA methodologies among contractors and developers may hinder the adoption of low-carbon alternatives [55]. Similar barriers have been documented in other construction markets, where regulatory mandates and financial incentives were required to accelerate the adoption of low-carbon construction practices [15, 55]. These findings suggest that effective decarbonisation policies should combine regulatory requirements with economic incentives and capacity-building initiatives.

5.5. Generalizability and regional variability

Although the reference building analysed in this study represents a common mid-rise reinforced concrete residential typology in Turkish urban transformation projects, several contextual factors may influence the generalizability of the results. First, regional variations in cement production technologies and clinker ratios can lead to differences in the embodied carbon intensity of ready-mixed concrete across Türkiye [56]. Second, structural design requirements imposed by TBDY-2018 may increase material quantities through higher reinforcement ratios and stronger concrete classes [23]. Third, climatic differences across the country influence both operational energy demand and envelope design, potentially altering the balance between operational and embodied emissions [15]. Finally, urban transformation projects in Türkiye include a wide range of building typologies, including variations in building height, structural systems, and construction techniques. These factors may result in different embodied carbon intensities across projects. Despite these contextual variations, the selected case study provides a representative baseline for understanding the regulatory carbon gap within the dominant reinforced concrete residential construction model currently prevalent in Turkish cities.

6. Conclusions

This study scrutinized the Turkish construction regulatory framework through the lens of WLCA, exposing a systemic misalignment between national building codes and the strategic 2053 net-zero targets. While current regulations (BEP-TR, TS 825) have successfully standardized operational energy efficiency, the analysis confirms that they remain blind to embodied carbon. The resulting hidden carbon gap, quantified in this study as 256.0 kgCO$_2$e/m^2 for a standard code-compliant building, represents a critical unmonitored emission source. This figure aligns with the national mass-housing benchmarks but remains significantly lower than the heavier legacy stock identified, indicating a gradual but insufficient market evolution.

6.1. Scientific contributions and policy implications

This study contributes to the literature and policy debate in three main ways.

1. For Policymakers and Regulators: The findings provide a quantitative basis for integrating whole life carbon considerations into national building regulations. The identified baseline values 249.0 kgCO$_2$e/m^2 for upfront embodied carbon and 256.0 kgCO$_2$e/m^2 when C1–C4 end-of-life emissions are included, offer reference points for future

embodied carbon benchmark, comparable to regulatory frameworks implemented in countries such as Denmark and Spain.

2. For Industry Professionals and Manufacturers: The findings highlight the economic implications of decarbonisation within the context of the CBAM. The analysis demonstrates that the adoption of existing low-carbon material technologies could reduce upfront embodied carbon by approximately 32.2% compared with the baseline, without requiring changes in architectural design. This indicates that technological capability already exists within the Turkish construction materials industry, although regulatory incentives remain limited.

3. For the Academic and Scientific Community: Addressing the chronic data scarcity highlighted by Kuzgunkaya [32], this work establishes a verified embodied carbon baseline and a replicable scenario-based methodology. By revealing an approximately 48.0% reduction potential between the pessimistic and optimistic supply-chain scenarios, it serves as a reference point for future national inventory development and validates the necessity of managing uncertainty in data-scarce environments as suggested by Marsh et al. [50].

4. Benchmarking for Policy Alignment: The calculated upfront baseline of 249.0 $kgCO_2e/m^2$ and the aspirational low-carbon level of 168.9 $kgCO_2e/m^2$ provide specific quantitative targets for future legislation. These figures are consistent with the developed maturity levels described by Karanfil et al. [43] and offer a roadmap similar to the INDICATE initiative in Spain described by Soust-Verdaguer et al. [52].

6.2. Limitations

The findings of this study should be interpreted in light of several methodological limitations:

1. Static LCA approach: The analysis relies on static emission factors and scenario-based assumptions. It does not account for temporal changes in material production technologies, electricity grid decarbonisation, demolition practices, or waste management infrastructure. Dynamic LCA approaches may provide more accurate long-term projections in future studies.

2. Limited national LCI data: Due to the absence of a comprehensive national life cycle inventory (LCI) database in Türkiye, a hybrid dataset combining local industry reports, EPDs, and international databases was used. This limitation, also highlighted by Kuzgunkaya [32], may introduce uncertainties in emission factors.

3. Exclusion of certain building components: The system boundary excludes some building service systems, particularly HVAC equipment. However, previous studies indicate that the embodied carbon of HVAC systems is relatively modest (approximately 10–20 $kgCO_2e/m^2$) compared to the structural frame in conventional reinforced concrete buildings [57].

4. Single-building case study: The quantitative assessment is based on a single residential building typology representing a typical mid-rise reinforced concrete apartment block. While this typology reflects the dominant pattern of urban transformation projects in Türkiye, variations in regional construction practices, climate zones, and structural systems may influence the absolute carbon intensity values.

Despite these limitations, the scenario-based framework captures a sufficiently wide range of material production and supply-chain conditions to provide meaningful insights for policy development and regulatory reform.

6.3. Future research directions

To bridge the identified gaps and support evidence-based policymaking, future research should focus on the following lines of inquiry:

1. National Database Creation: Developing a localized and verified database for carbon factors specific to Turkish construction materials is urgent to replace generic data proxies.

2. Dynamic LCA Integration: Future studies should adopt dynamic LCA methodologies to account for the changing carbon intensity of the energy grid over the building's lifespan.

3. Renovation vs. Demolition: Applying WLCA to compare the carbon footprint of retrofitting the existing stock versus new construction is essential, particularly for the urban transformation of the aging stock analysed by Somer [45].

4. Broader Typologies: Expanding the simulation to include schools, hospitals, and commercial offices will create a comprehensive national benchmark, building on the sector-specific work of Moazzen et al. [27].

In conclusion, this study argues that the era of regulating buildings solely based on energy consumption has passed. Transitioning to a holistic carbon management approach is not merely a technical adjustment but a strategic imperative to ensure that the Turkish construction industry remains environmentally resilient and economically competitive in a decarbonizing world.

Declarations

Conflict of Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Author Contributions

V. Arslan: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. Ş. H. Papila: Data curation, Writing – original draft, Writing – review & editing, Visualization, Validation, Formal analysis.

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Data Availability Statement

The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy restrictions regarding the specific construction project details.

Ethics Committee Permission

Not applicable.

Use of Generative AI and AI-assisted Technologies

The authors confirm the authors did not use any AI tools in the preparation of this study.

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