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A systematic review of methods for reducing embodied energy in building materials: a quantitative cradle-to-gate analysis

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Abstract
Reducing embodied energy (EE) in building materials is a critical aspect of achieving sustainable building construction. Embodied energy refers to the total energy consumed in the extraction, processing, transportation, and manufacturing of building materials before they reach the construction site. In conventional buildings, total energy consumption is predominantly influenced by operational energy (OE), which includes energy used for heating, cooling, lighting, and ventilation throughout the building's lifespan. However, in energy-efficient buildings, the proportion of EE to total energy demand becomes more significant, sometimes equaling or surpassing OE. This shift highlights the growing importance of minimizing EE in sustainable building design. This study conducts a systematic review using the PRISMA framework, extracting relevant data from the Scopus database to categorize methods for reducing EE within cradle-to-gate systems. These methods are classified into three phases: the material phase, the construction method phase, and the design phase. The material phase includes three approaches: mixed material intervention, production process intervention, and material substitution. The construction method phase encompasses two approaches: building component substitution and process or method substitution. Finally, the design phase focuses on interventions at the building design level. Despite these classifications, the findings suggest that no single phase or approach demonstrates a significantly greater impact on EE reduction than the others. Each approach contributes comparably to reducing EE, highlighting that while notable progress has been made, the relative effectiveness of individual methods remains consistent across phases. Integrated approaches combining strategies across multiple phases hold promise for substantial reductions in EE, emphasizing the need for future research to refine and innovate these methodologies.

Keywords:
Building lifecycles;
Cradle-to-gate;
Embodied energy;
Sustainable building design;
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INTRODUCTION

The reduction of embodied energy (EE) in building materials is a crucial yet often underexplored aspect of sustainable building construction, particularly within the cradle-to-gate system boundary. While global efforts have increasingly focused on enhancing buildings' energy efficiency and sustainability, much of this attention has centered on reducing operational energy. However, the growing demand for construction, driven by population growth and technological advancement, continues to escalate overall building energy use. In this context, the role of building materials becomes increasingly critical, as the processes involved – such as raw material extraction, manufacturing, and on-site construction – are estimated to contribute nearly 11% of global carbon emissions [2]. Therefore, carefully selecting and optimizing building materials can significantly minimize a building's total environmental impact [3].

In a building's life cycle, there are two main types of energy, namely embodied energy (EE) and operational energy (OE) [4]. Embodied energy consists of initial embodied energy (IEE), recurrent embodied energy (REE), and demolition energy (DE). IEE represents the initial energy, which includes upstream, manufacturing, and downstream processes. This IEE is also equivalent to the production stage. REE pertains more to the maintenance of materials, while DE relates to the demolition of buildings and the reuse and processing of materials.

Dixit et al. (2012) identified parameters responsible for causing significant variations in building embodied energy (EE), such as system boundaries, EE analysis methods, geographic location, data age, data sources, and data completeness [5]. To address these challenges, a life cycle assessment (LCA) analyses a material's life cycle and associated energy demands within the cradle-to-gate system boundary [6]. This system covers the initial production stages, A1-A3, as shown in Figure 1, where the initial embodied energy is consumed. Stage A1 involves raw material acquisition, including extraction and preliminary processing, which require energy for operating machinery and equipment. Stage A2 addresses transporting these raw materials to factories, which depends on various fuel sources and emits associated emissions. Stage A3 focuses on manufacturing, where materials are processed into finished products, a stage that also demands substantial energy [3]. Given this context, this study will focus solely on the EE values in the cradle-to-gate system (stages A1-A3) and exclude stages A4-5, B1-5, and C1-4.

Ramesh et al. (2010) concluded that in conventional residential and office buildings, operational energy (OE) accounts for 80-90% of the total energy demand during the building life cycle, while embodied energy (EE) only contributes 10-20% [7]. Additionally, Karimpour et al. (2014) reviewed case studies of 24 residential buildings across ten countries. They found that EE can account for up to 25% of the total building energy life cycle in colder climates, a figure projected to increase to 35% [8].

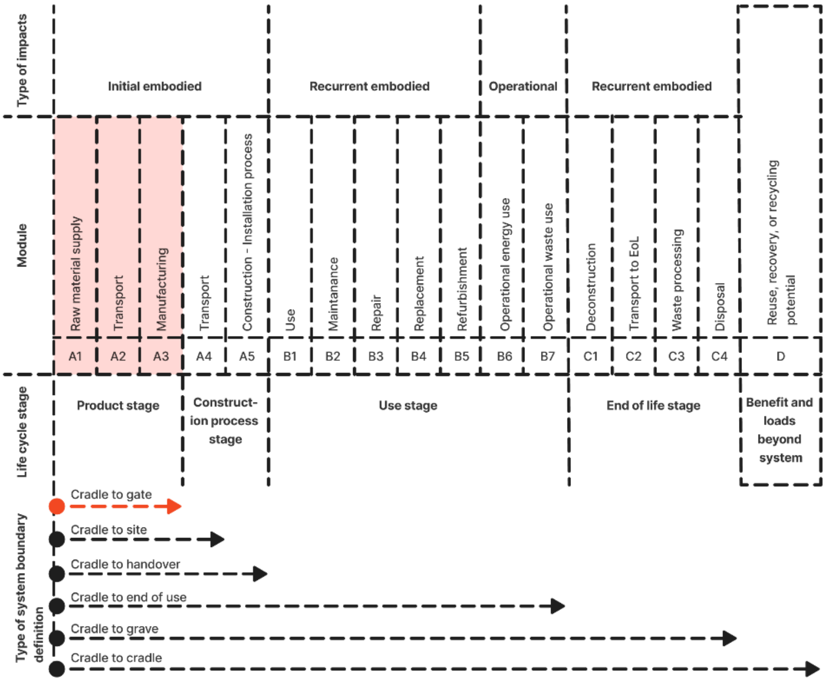

Figure 1. The Module Selected in This Study. Life Cycle Stage According to Standard EN 15804:2012+A2 2019 – Adapted from [1]

However, the proportion of EE becomes increasingly essential compared to operational energy (OE) as building energy efficiency improves. Chastas et al. evaluated 90 case studies covering conventional, passive, low-energy, and nearly zero-energy buildings (nZEB) [9]. In low-energy-consumption buildings, EE contributes between 26% and 57% of the total energy consumption during the building life cycle. Meanwhile, in nearly zero-energy buildings (nZEB), the proportion of EE is even more significant, ranging from 74% to 100% of the total energy consumption. This indicates that as buildings become more efficient in terms of operational energy use, the contribution of EE to total energy increases. This shift highlights the importance of reducing embodied energy (EE) in sustainable building design.

Previous studies reveal significant variation in reported embodied energy (EE) values, primarily due to a range of influencing factors such as the choice of building materials, construction techniques, and regional practices (Hu, 2020). These variations highlight a lack of detailed information on how and in which specific phases of the building lifecycle these factors are addressed. Within the cradle-to-gate system, such variables span multiple stages, including the extraction and processing of raw materials, manufacturing production processes, and design interventions. This broad application of variables complicates the understanding of where and how embodied energy can be most effectively minimized.

To address these gaps, this paper focuses on two primary objectives. First, it aims to systematically categorize methods for reducing embodied energy within cradle-to-gate systems, providing a structured framework for understanding these approaches. Second, it seeks to identify the specific phases within the building lifecycle where these methods have the most significant impact on reducing embodied energy.

By achieving these objectives, this study aims to enhance the understanding of effective embodied energy reduction strategies. It also seeks to refine existing methodologies for building assessments, enabling a more targeted and efficient approach to sustainable construction practices. This research contributes to advancing knowledge in the field and supports the development of more sustainable building designs and practices.

DATA COLLECTION AND ANALYSIS METHOD

This study employs a systematic review approach to identify, evaluate, and synthesize relevant research findings on methods for reducing embodied energy. The systematic review process follows a structured framework involving several critical steps. First, a well-defined and focused research question is established to guide the review and ensure clarity in its objectives. Next, appropriate databases and search terms are carefully selected to comprehensively identify relevant academic literature.

After the literature is collected, a screening process is applied using predefined inclusion and exclusion criteria to eliminate studies that do not meet the scope or quality requirements of the review. This step ensures that only relevant and high-quality studies are retained for further analysis. Following the screening, a methodological assessment is conducted to evaluate the robustness, validity, and reliability of the included studies, ensuring the integrity of the findings.

The synthesis phase involves systematically analyzing and summarizing the findings of the selected studies to extract key insights and patterns. This comprehensive process is guided by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology, which provides a standardized framework for conducting systematic reviews. The workflow of these processes is illustrated in Figure 2, ensuring transparency and replicability in the research methodology [10].

The Scopus database was selected as the primary source for material collection to address the research question: *What is the most influential phase of the method in reducing embodied energy from cradle to gate?* The database search was conducted on April 25th, 2024. It is important to note that repeating the search later could yield additional documents due to the continuous addition of new publications. The search query was carefully constructed using relevant keywords and parameters to ensure specificity, as follows: “TITLE-ABS-KEY("embodied energy" AND "cradle-to-gate") AND PUBYEAR > 2009 AND PUBYEAR < 2025 AND (LIMIT-TO(LANGUAGE, "English"))”.

This query targeted studies published in English from 2010 to 2024 that focus on embodied energy within cradle-to-gate systems. The initial search returned 86 articles. During the screening process, three duplicates were identified and removed, leaving 83 unique articles. A secondary screening was conducted based on specific inclusion and exclusion criteria, such as accessibility and relevance to the research topic. This process eliminated nine articles, reducing the count to 74.

Further evaluation was performed to refine the selection. Eleven articles were excluded as they did not explicitly mention embodied energy or embodied carbon values. The final inclusion criteria required the studies to explicitly address methods for reducing embodied energy and provide quantitative data on embodied energy reduction, either in percentage or absolute terms. Additionally, studies reporting embodied carbon values were included, given the strong correlation between embodied energy (EE) and embodied carbon (EC). Reducing EE generally results in lower EC, as reduced energy consumption typically translates to fewer greenhouse gas emissions.

After completing the screening and selection processes, a total of 63 relevant articles were identified and included in the review. These articles form the basis for analyzing the most impactful phases and methods for reducing embodied energy within cradle-to-gate systems.

Furthermore, the inventory data was obtained through several steps. Firstly, the initial and alternative materials with each embodied energy value must be identified. Initial materials refer to conventional materials that contribute to greenhouse gas emissions, such as concrete, steel, fired clay brick, and Portland cement. Secondly, the approaches category was identified by analyzing how the alternative materials replaced the conventional ones.

These lead to phase categories. Subsequently, the percentage reduction in EE when using the alternative materials is calculated compared to the initial material. However, the unit of measurement (e.g., MJ/kg, MJ/m², MJ/t) does not affect the calculation as the percentage is based on the relative difference between two values, not their absolute units. The calculation is shown in (1).

$$EEred = \left(\frac{EEi - EEalt}{EEalt}\right) \times 100\% \tag{1}$$

Where:

$EEred$ = EE Reduction value
EEi = EE of initial material
$EEalt$ = EE of alternative material

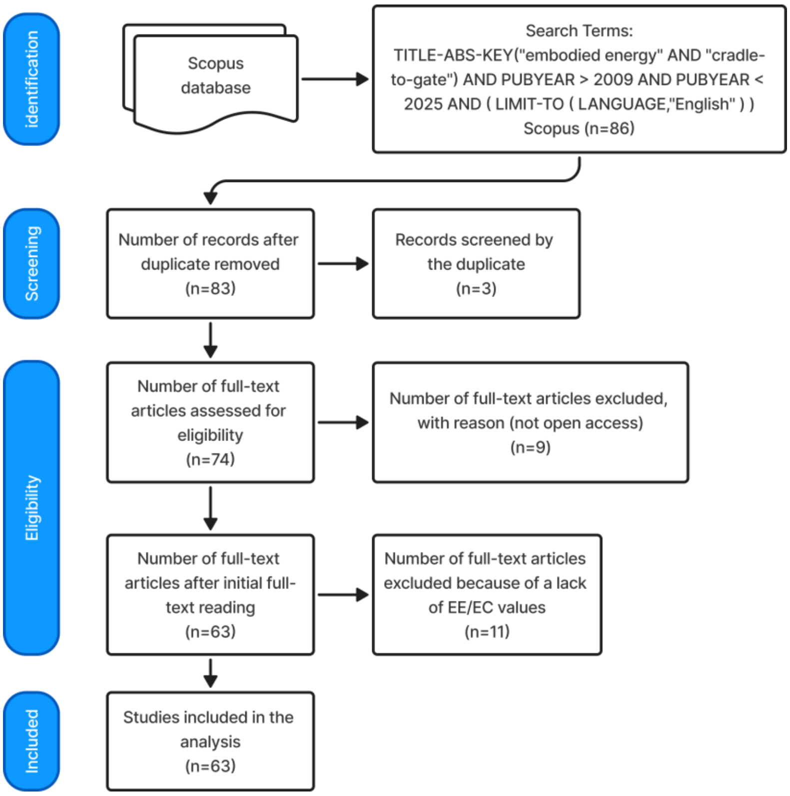

Figure 2. The Process of Selecting Studies in The Review

JMP's statistical modelling evaluates distribution analysis to identify the range and average of EE reduction values, and conducts an ANOVA test for comparing means (the average values). This is to determine if there are statistically significant differences between the means.

By adhering to this rigorous methodology, the study aims to provide a thorough and reliable analysis of embodied energy reduction methods, contributing valuable insights to the field of sustainable construction.

CATEGORIZATION OF EMBODIED ENERGY REDUCTION METHODS

Building on the research methodology outlined in the previous chapter, this paper identifies six approaches from existing literature that address the building lifecycle with a focus on reducing embodied energy. Given the significant variation in these approaches and their implementation across different lifecycle stages, this study categorizes the methods for reducing embodied energy into three distinct phases: the Material Phase, the Construction Method Phase, and the Design Phase. Each phase encompasses specific approaches to reduce embodied energy, which will be elaborated on in detail in the following sections.

An inventory of studies focusing on Life Cycle Assessment (LCA) from cradle to gate is presented in Table 1, which outlines the range of embodied energy reductions achieved through these approaches. The findings indicate that nearly 94% of the reviewed studies report positive results, demonstrating reductions in embodied energy when the identified approaches are applied.

Table 1. Inventory Data of EE Reduction

Phase	Approach	Author	EE Reduction (%)
Material	Mixed material intervention	[11] Xie et al (2023)	-10.2 – 98.23
		[12] Gursel & Ostertag (2019)	8 – 40
		[13] Jitsanigam et al. (2018)	2.4
		[14] Yu et al. (2022)	65
		[15] Fenoglio et al. (2018)	48.7
		[16] Dollente et al. (2021)	0
		[17] Zhang et al. (2015)	20
		[18] DeRousse et al. (2020)	17.16
		[19] Robati et al. (2016)	10 – 15.5
		[20] Giama & Papadopoulos (2020)	23 – 28
		[21] Henry & Lynam (2020)	15.3
		[22] Wijayasundara et al. (2017)	1.1
		[23] Jagadesh et al. (2024)	89
		[24] Brás & Gomes (2015)	81
		[25] Faridmehr et al. (2021)	45 – 68.45
		[26] Ricciardi et al. (2021)	20 – 60
		[27] Jain & Chandrappa (2024)	25.08 – 41.17
		[28] Almeida et al. (2024)	6.5
	Production process intervention	[29] Nadeem et al. (2022)	0 – 70.1
		[30] Luo et al. (2021)	72.1 – 72.8
		[31] Dahmen et al. (2018)	42 – 46
	Material substitution	[32] Huang et al. (2013)	10 – 20
		[33] Ricciotti et al. (2020)	30 – 40
		[34] Meek et al. (2021)	15 – 73
		[35] Cornaro et al. (2020)	40
		[36] Pomponi et al. (2018)	78.13
		[37] Beecham (2020)	50
		[38] Casas-Ledón et al. (2020)	8.7
		[39] Kumanayake & Luo (2018)	11 - 50
		[40] Jayawardana et al. (2021)	34.03 – 42.23
		[41] Reider & Meir (2019)	-66.67
		[42] Ahmed Reza et al. (2023)	54
		[43] Gehlot & Shrivastava (2024)	81.48
		[44] Jagadesh et al. (2024)	84.55
		[45] Berchowitz & Kwon (2012)	57.69
		[46] Sravani et al. (2024)	40 – 60
Construction method	Building component substitution	[47] Fernandes et al. (2019)	40.4 – 99.61
		[48] Iddon & Firth (2013)	-10 – 20
		[49] Livne et al. (2022)	73.33

Table 1. Inventory Data of EE Reduction

Phase	Approach	Author	EE Reduction (%)
		[50] Hamida et al. (2022)	-10.76 – 17.97$^{(1)}$ 5.94 – 18.03$^{(2)}$ 9.15 – 21.39$^{(3)}$
		[51] Švajlenka et al. (2017)	54
		[52] Larasati et al. (2023)	50
	Process or method substitution	[53] Reyhani et al. (2022)	40.4
Construction method		[54] Sedláková et al. (2015)	30.89 – 97.24
		[55] Jayasinghe et al. (2022)	12 – 65
		[56] Oval et al. (2023)	50
		[57] Punhagui & John (2022)	78.99
		[58] Gursel & Ostertag (2016)	31
		[59] Thinley & Hengrasmee (2023)	71
		[60] Pierobon et al. (2019)	8
		[51] Švajlenka et al. (2017)	54
		[61] Robertson et al. (2012)	– 43.90
Design	Building design intervention	[62] Sharma & Chani (2024)	14,7 – 33,1
		[63] Foraboschi et al. (2014)	20.1 – 35.8$^{(4)}$ 2.12 – 18.4$^{(5)}$ 80.6 – 82.8$^{(6)}$ 7.4 – 36.3$^{(7)}$ 85.9 – 87.3$^{(8)}$ 77.3 – 79.9$^{(9)}$
		[64] Jayasinghe et al. (2021)	37
		[65] Belizario (Silva et al. (2024)	42.3
		[66] Sedláková et al. (2014)	36.7
		[67] Kridlova Burdova et al. (2016)	60.9
		[68] Iuorio et al. (2019)	63
		[69] Slavković et al. (2015)	-33.33 – -8.2
		[70] Sierra- Pérez et al. (2016)	15 - 30
		[71] Jayasinghe et al. (2022)	8
		[72] Ferreira et al. (2023)	75
		[73] Wolfova et al. (2020)	25 – 41.67

(1) Wall
(2) Roof
(3) Glazing
(4) Building structure
(5) Building core
(6) Frames
(7) The horizontal structures
(8) Columns
(9) Beams

It is important to note, however, that not all studies explicitly quantify reductions in embodied energy as a percentage. As a result, the inventory data in this paper represents a quantified synthesis derived from the reported findings in previous studies. By consolidating this information, the paper provides a comprehensive overview of the effectiveness of various approaches, offering valuable insights for future research and practical applications in sustainable construction.

The Approach in the Material-Phase

Approaches in the Material Phase are predominantly applied in experimental studies and include three key strategies: mixed material intervention, production process intervention, and material substitution. These strategies focus on optimizing material properties and processes to reduce embodied energy (EE) while maintaining or improving material performance.

Mixed material intervention approach involves replacing some of the raw materials in a mix with alternative components, thereby altering the mix proportions to reduce EE. For example, Ricciotti et al. (2020) compared the energy consumption of aerated autoclaved concrete (AAC) with two geopolymer-based hybrid foams derived from fly ash (GHF-FA) and metakaolin (GHF-MK). The study demonstrated that GHF-FA exhibited the lowest environmental impact, achieving a 30–40% reduction in embodied energy compared to AAC systems [33]. This highlights the potential of mixed material interventions to provide substantial environmental benefits by optimizing material composition.

Production process intervention approach focuses on modifying conventional production systems without entirely replacing existing materials. For instance, Luo et al. (2021) investigated the incorporation of dewatered extracted soil (DES) into concrete blocks manufactured with either ordinary Portland cement (OPC) or alkali-activated slag (AAS). The study revealed that incorporating DES improved the structural strength of AAS concrete blocks (AASCBs) while significantly enhancing their environmental performance. Specifically, AASCBs achieved a remarkable 72.8% reduction in embodied energy compared to conventional fired clay bricks and OPC-based concrete blocks (OPCCBs) [30]. This demonstrates how process adjustments, such as integrating supplementary materials, can optimize resource use and reduce environmental impacts.

Material substitution entails replacing traditional building materials with alternative, low-impact materials to achieve greater reductions in energy consumption and greenhouse gas emissions. For example, modern Rammed Earth (RE) materials have been developed to replace conventional construction materials like cavity and veneer bricks. These RE materials incorporate recycled waste, such as crushed brick and concrete, as well as industrial by-products, resulting in a reduction of greenhouse gas emissions per vertical square meters of wall by 73% and 57%, respectively [34].

Another example of material substitution is the use of innovative Straw Wall (SW) systems. Cornaro et al. (2020) assessed the energy-saving potential of SW systems under various climate conditions across Italy and found that they outperformed nearly zero-energy building (NZEB) standards mandated by Italian regulations. The SW systems demonstrated excellent energy performance, with approximately 50% lower embodied energy compared to traditional wall systems, underscoring their potential as a sustainable construction alternative [35].

These Material Phase strategies are also consistent with broader green building principles, which emphasize the use of environmentally friendly materials and resource efficient construction practices. According to Omer (2021), green buildings prioritize life cycle-oriented design and low-impact materials, highlighting the need for innovative solutions such as hybrid foams, alkali-activated binders, and recycled earth systems to reduce embodied energy and meet sustainability standards [74].

The Material Phase approaches – whether through mixed material intervention, production process modifications, or material substitution – offer substantial opportunities for reducing embodied energy in construction. These strategies not only address environmental sustainability by lowering greenhouse gas emissions but also maintain or enhance material performance. By integrating innovative materials and processes, these approaches contribute to advancing sustainable construction practices and achieving significant environmental benefits.

The Approach in Construction Method-Phase

In the Construction Method Phase, two key approaches are utilized to reduce embodied energy: building component substitution and process or method substitution. Each targets distinct aspects of the construction process to minimize environmental impact.

Building Component Substitution strategy involves replacing existing building components, such as walls, roofs, windows, and other structural elements, with alternatives that have lower embodied energy. For example, Larasati et al. (2023) investigate the impact of using different prefabricated facade materials on the embodied energy (EE) and operational energy (OE) consumption of apartment buildings. The results show that solid precast concrete materials with thicknesses of 120 and 150 mm have EE and greenhouse gas emissions more than twice the average of all materials tested. In contrast, uninsulated Glass-Fiber Reinforced Concrete (GRC) removable walls exhibited the lowest EE, corresponding to 50% of the average [52]. This highlights the importance of component selection in reducing the environmental impact of construction materials.

The Process or Method Substitution approach focuses on replacing conventional processes or methods with alternative strategies to reduce embodied energy. Reyhani et al. (2022) conducted a life cycle assessment (LCA) of two green wall systems – plastic-based and felt-based structures. The analysis revealed that the production stage was the most significant contributor to environmental impacts for both systems. However, the felt-based green wall exhibited a higher overall environmental impact, despite achieving a 40.4% reduction in embodied energy compared to traditional systems [53].

Complementing this, Jayasinghe et al. (2021) explored carbon reduction strategies for concrete floors using parametric design optimization, alternative slab types, and novel optimized floor systems [64].

In addition, Keintjem et al. (2024) conducted a quantitative analysis of carbon emissions from cut and fill operations in construction, revealing that material transportation and the use of heavy equipment are the primary contributors to CO_2 emissions. These findings reinforce the urgency of optimizing construction methods as part of a cradle-to-gate strategy to lower the carbon footprint [75].

These strategies demonstrated the potential to reduce both embodied energy and carbon emissions. While this optimization method also intersects with the Design Phase, its inclusion in the Construction Method Phase emphasizes its role in improving construction efficiency through material and process innovation.

Both building component substitution and process or method substitution offer significant opportunities to reduce embodied energy in construction. By focusing on alternative materials and innovative production methods, these strategies enhance the sustainability of building systems. The findings underscore the importance of considering the environmental impact of individual components and processes throughout the construction phase to achieve meaningful reductions in embodied energy and carbon emissions.

The Approach in the Design-Phase

Building Design Intervention focuses on strategic decision-making during the design and construction phases to minimize the energy required for producing building materials. This approach aims to optimize building geometry, material use, and construction efficiency to reduce both embodied energy (EE) and carbon emissions. By addressing these aspects at the design stage, it is possible to influence the entire lifecycle of a building, achieving significant sustainability benefits.

For instance, Belizario-Silva et al. (2024) conducted an in-depth analysis using detailed industry data from the construction designs of 53 reinforced concrete structures for multifamily residential buildings in Brazil. The study employed Life Cycle Assessment (LCA) to examine the relationship between building geometry and material consumption. The findings highlighted that building height is a critical geometric parameter influencing material intensity and embodied CO2, especially for structural elements such as columns. As building height increases, the demand for reinforced concrete in columns grows disproportionately due to the structural requirements for stability and load-bearing capacity. This correlation underscores the need to carefully consider building geometry during the design phase to optimize material use and reduce embodied energy and emissions.

The importance of this approach lies in its ability to address embodied energy and carbon emissions at their source – during the design stage. Decisions regarding building height, structural design, material selection, and layout efficiency have a cascading effect on material requirements and energy consumption. By incorporating energy-efficient design strategies, architects and engineers can significantly reduce the environmental impact of a building before construction even begins.

This case highlights the broader potential of design interventions in improving sustainability outcomes. Strategies such as optimizing building geometry, using lightweight materials, or employing modular construction techniques can reduce not only embodied energy but also operational energy during the building's lifespan. These interventions also align with broader goals of sustainable urban development, particularly in densely populated areas where multifamily housing is prevalent.

By leveraging design interventions like those identified in Belizario-Silva et al.'s study [65], the construction industry can make informed decisions that lead to meaningful reductions in both embodied energy and carbon emissions, ultimately promoting more sustainable practices in the built environment.

DISCUSSION

This section discusses findings from the analyzed literature review on embodied energy. The following observations were made based on the inventory data of EE reduction in Table 1.

Distributions of The Approach

Among the three phases of embodied energy (EE) reduction methods, the Material Phase emerges as the most frequently studied, accounting for 51% of the total research. This phase focuses primarily on interventions related to the selection, modification, and substitution of materials to minimize their embodied energy content. The substantial representation of the Material Phase highlights its critical role in shaping the building's overall embodied energy, as material choices directly and significantly impact energy consumption throughout the structure's lifecycle.

The Construction Method Phase follows, comprising 29% of the studies. This phase encompasses strategies that optimize the processes and methods used during construction, including building component substitutions and adopting alternative construction practices. Though less studied than the Material Phase, the Construction Method Phase still plays an essential role in reducing embodied energy, particularly in how materials are processed, assembled, and utilized during the building process.

The Design Phase is the least represented, accounting for 20% of the research. This phase deals with the decisions made during the design and planning stages, such as optimizing building geometry, structural design, and material efficiency. While fewer studies focus on this phase, the importance of design decisions cannot be overstated, as they lay the foundation for subsequent material and construction method choices that will ultimately influence the building's embodied energy.

Within the Material Phase, Mixed material intervention is the most researched approach, accounting for 25% of the studies. This strategy involves integrating alternative materials into traditional building mixes, effectively reducing the embodied energy without sacrificing the performance or functionality of the materials. The prominence of this approach indicates its potential as a practical solution for improving sustainability in the building sector.

Following this, Material Substitution and Building Design Intervention each represent 20% of the studies. Material Substitution focuses on replacing conventional materials with those that have lower embodied energy, such as using recycled or alternative materials that require less energy to produce. Building Design Intervention, on the other hand, involves strategic design decisions aimed at minimizing the need for high-energy materials and optimizing the overall building layout to reduce energy consumption. These two approaches are widely recognized for their effectiveness in lowering embodied energy and improving the sustainability of buildings.

Building Component Substitution accounts for 15% of the research, focusing on replacing specific building components, such as structural elements, with more energy-efficient alternatives. This approach has shown promise in reducing energy demand, mainly when applied to high-impact components like walls, roofs, and windows. Process or Method Substitution, which makes up 14% of the studies, focuses on replacing traditional construction processes or methods with more energy-efficient alternatives, thus reducing the overall energy consumption during the construction phase.

Finally, Production process intervention represents the least studied approach, at only 6%. This approach involves modifying the production processes of materials to make them more energy-efficient, such as improving manufacturing techniques or using less energy-intensive production methods. Although valuable, it is less frequently addressed in the literature, likely due to the complexity and scale of changes required in manufacturing processes.

This distribution of research highlights the varying emphasis placed on different phases and approaches in reducing embodied energy. The Material Phase dominates, highlighting its direct impact on energy consumption and the various strategies available to reduce embodied energy through material choice and modification. The Construction Method and Design Phase**s**, while less frequently studied, are also crucial in achieving overall reductions in embodied energy. The findings suggest that a multifaceted approach addressing material selection, construction methods, and design strategies is essential for optimizing embodied energy reduction in buildings. Figure 3 compares each approach's frequencies, providing a visual representation of their relative importance in the context of EE reduction methods.

EE Reduction in Every Approach Category

Overall, the data collected from various studies indicate significant variability in the values for embodied energy (EE) reduction, as illustrated in Figure 4. Several factors, including the type of intervention and the specific materials or methods applied influence this variation. In particular, the Construction Phase demonstrates substantial potential for energy reduction, with Building Component Substitution emerging as one of the most impactful strategies. For instance, one study by Fernandes et al. (2019) shows that this approach can lead to an impressive reduction of up to 99.61%.

Fernandes et al. specifically examine the life cycle environmental impacts of earthen materials – rammed earth (RE) and compressed earth blocks (CEBs) – in the context of construction in Portugal. Their findings reveal that both RE and CEBs exhibit significantly lower embodied energy compared to conventional building materials. CEBs, for example, have an embodied energy value of just 3.94 MJ per block, while RE demonstrates an embodied energy value of 596 MJ per cubic meter [47].

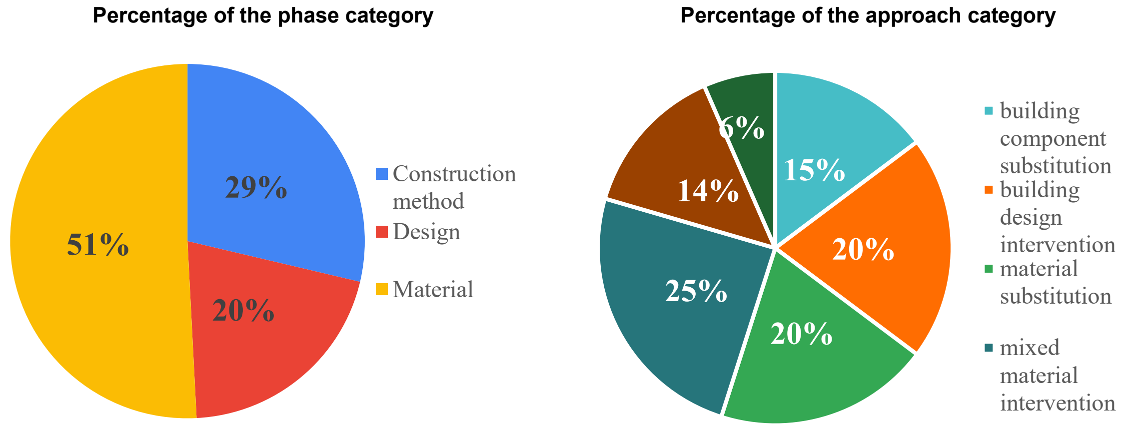

Figure 3. Comparison of the Frequencies Between the Phase Category and the Approach Category

These values highlight the potential of earth-based materials to significantly reduce embodied energy in construction, offering a promising alternative to more energy-intensive conventional materials like concrete and fired clay bricks.

In contrast, within the same approach, Hamida et al. (2022) revealed that the efficient block wall with marble has 10.7% more embodied carbon than the base case. Nevertheless, this wall type still has the potential for saving around a 6% carbon footprint resulting from operational energy [50].

A study using the Process or Method Substitution approach shows an impressive reduction in EE values of 97,24%. Sedláková et al. (2015) assessed alternative material solutions for the foundation, wall, and floor construction details. Extruded Polystyrene (XPS) Insulation, a versatile solution, is used in various thicknesses for foundation, floor, and wall insulation. It significantly reduces not only the embodied energy but also thermal bridging, thereby improving the overall thermal performance of the building [54].

Robertson et al. (2012) analyzed the environmental impacts of a typical North American mid-rise office building by comparing a laminated timber hybrid design with a traditional cast-in-place reinforced concrete frame. The process energy for both designs is nearly identical. Still, the cumulative embodied energy of construction materials is higher for the timber design due to the potential energy stored within the building materials, which is 43.90% [61]. Despite having a much higher embodied energy total (including both feedstock and process energy), it has superior environmental performance in almost all impact categories. This study highlights the importance of considering the full life cycle of building materials, not just their immediate energy use, to accurately assess their environmental impact [76].

In the approach of Design Building Intervention, Foraboschi et al. (2024) quantified the embodied energy in constructing tall building structures. The study considers a reference structure composed of a central core of reinforced concrete and rigid frames of either reinforced concrete or steel. The EE depends mainly on the flooring system, with steel consuming more EE than reinforced concrete. The total EE reduction values can be reachable to 87.3% [63].

Meanwhile, Slavković et al. (2015) examine the insulation materials used in the external walls of residential buildings in Sombor, Serbia. Their findings reveal that the incorporation of insulation materials into the external walls, aimed at optimizing energy performance, leads to an increase in embodied energy (EE). The initial EE of the walls is assessed, and adding various insulation materials – such as reed board, compressed straw, expanded polystyrene, and mineral wool – results in increases in total EE of 8.18%, 8.63%, 33.31%, and 13.24%, respectively.

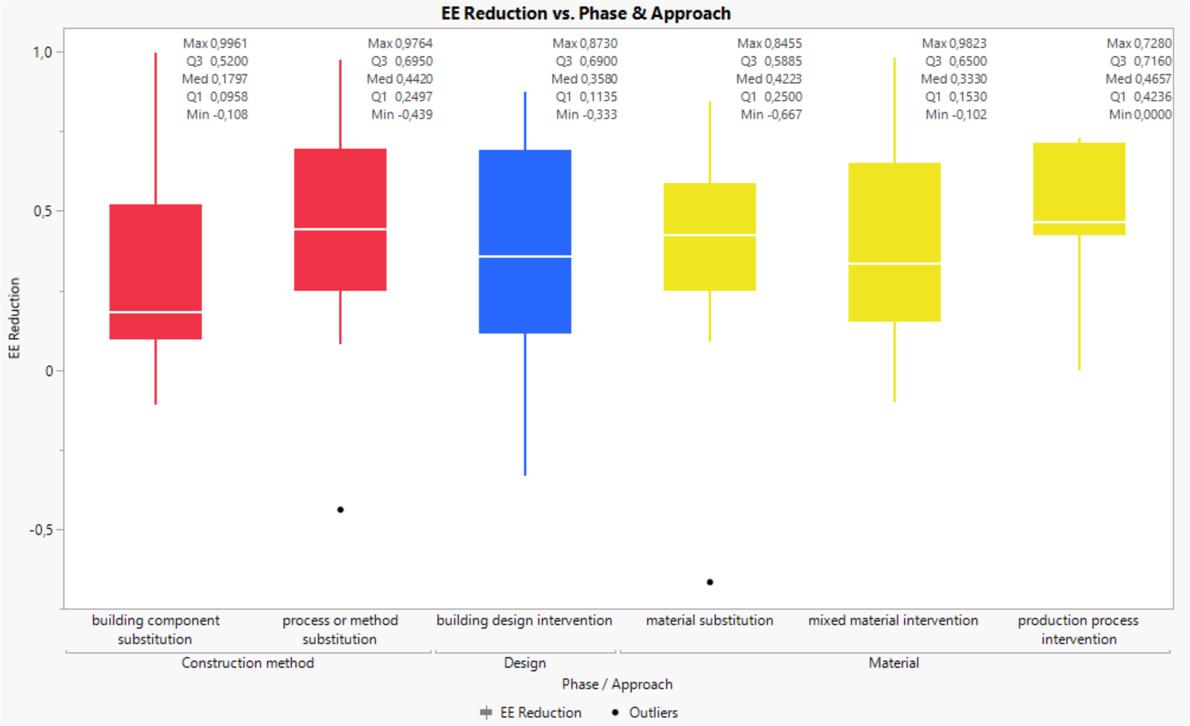

Figure 4. The Maximum and Minimum Values of EE Reduction from Each Phase and Approaches

However, this increase is warranted due to the substantial enhancement in thermal performance and the decrease in operational energy consumption, ultimately resulting in overall energy savings throughout the building's lifecycle [69].

Some studies that utilize the approaches focused on the Material Phase are equally significant in reducing embodied energy. Particularly in the Mixed material intervention approach, Xie et al. (2023) explore the use of fiber-reinforced polymers (FRPs) in constructing FRP-confined concrete columns (FCCs). The study finds that basalt and carbon fibers have superior environmental performance that can reduce EE up to 98.23%, compared to aramid and glass fibers [11].

Dollente et al. (2021) examined the cradle-to-gate environmental impacts of a localized geopolymer process in the Philippines, comparing them to those of Ordinary Portland Cement (OPC). The findings indicate that geopolymer concrete (GP) using a rice husk ash (RHA)-based activator has a Global Warming Potential (GWP) comparable to GP produced with a commercial activator, resulting in no reduction in embodied energy (EE) [16].

The same result happened in the Production process intervention approach when producing cellulose nanofibril (CNF) films using two different methods: spray deposition and vacuum filtration [29]. Although CNF films showed approximately 15%–20% higher environmental impacts compared to conventional plastic films like polyethylene terephthalate (PET), the expected impact could be much lower if cradle-to-grave or cradle-to-cradle cycles are considered, and the scale of production is increased.

Nonetheless, another study using this approach shows a positive result in environmental performance. Luo et al. (2021) investigate the feasibility of incorporating dewatered extracted soil (DES) in concrete blocks manufactured with ordinary Portland cement (OPC) or alkali-activated slag (AAS). The results indicate that AASCBs exhibit 72.80% EE reduction [30].

In the Material substitution approach, a reduction of 84.55% in embodied energy (EE) is achieved by using granite powder (GrP) as a partial replacement for Ordinary Portland Cement (OPC) in mortar production. The most sustainable and economically favorable results are observed at a 25 wt% GrP replacement level (Jagadesh, et al., 2024). Therefore, GrP has been demonstrated to be a sustainable construction material in the building sector.

After everything, Figure 5 shows the median of EE reduction values across three different phases.

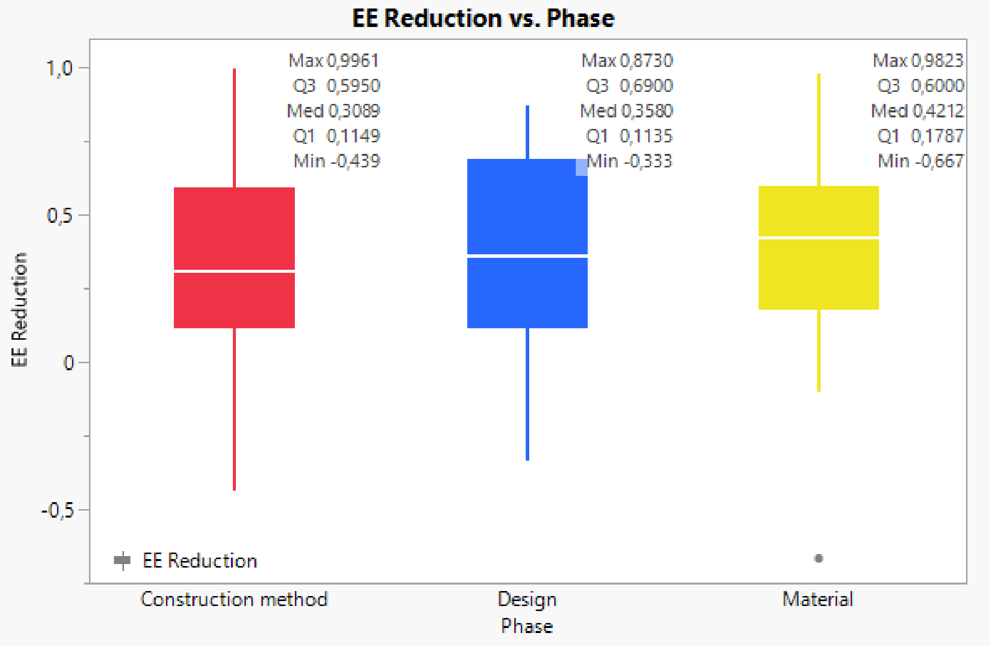

Figure 5. Median Values of EE Reduction from Each Phase Category

The median EE reduction values for each phase are as follows: Construction Method Phase: 30.89%, Design Phase: 36.50%, and Material Phase: 42.12%. These values represent the central tendency of EE reduction for each phase, indicating the typical reduction achieved in each category.

An outlier was noted in the Material Phase, with a dot reflecting a remarkably low value of -66.67%. In their study, Reider et al. (2019) assessed the energy performance of residential buildings made from Fiber Reinforced Polymer (FRP) compared to those built with conventional concrete in hot, arid climates. They found that although FRP materials have a higher embodied energy due to their manufacturing methods, they also offer superior thermal insulation and energy efficiency. As a result, buildings constructed with FRP tend to consume less energy for heating and cooling in these environments [41].

The Effectiveness of Phase Category

The analysis of variance (ANOVA) in Table 2 reveals that the mean EE Reduction varies across the three phases: Construction method, Design, and Material, with mean values of 0.3631, 0.3562, and 0.4039, respectively. The Material phase demonstrates the highest average EE Reduction (40.39%), followed by the Construction method phase (36.31%) and the Design phase (35.62%). However, the ANOVA test results, indicated by Prob > F value of 0.7342, suggest that these differences are not statistically significant at a 95% confidence level, as shown in Table 3. This high p-value indicates that the observed variations in EE Reduction are likely due to random rather than any inherent differences among the phases. Consequently, no single phase can be concluded to achieve significantly higher EE reduction than the others.

CONCLUSION

The motivation for this research stems from the urgent need to mitigate the environmental impact of the construction industry, which remains a significant contributor to global greenhouse gas emissions and resource consumption. As operational energy (OE) decreases in modern energy-efficient buildings, the role of embodied energy (EE) becomes increasingly important, particularly in low-energy and nearly zero-energy buildings where EE can represent a dominant share of total energy use [9].

The study categorizes methods for reducing EE into three phases: the material phase (mixed material intervention, production process intervention, and material substitution), the construction method phase (building component substitution and process or method substitution), and the design phase (design-level interventions). The findings suggest that no single phase or approach demonstrates a significantly greater impact on EE reduction than the others, and each approach contributes comparably to EE reduction.

Table 2. Comparison of means by ANOVA

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Construction method	37	0.363054	0.05260	0.25896	0.46715
Design	29	0.356176	0.05942	0.23860	0.47375
Material	64	0.403945	0.04000	0.32480	0.48309

Table 3. Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Phase	2	0.063426	0.031713	0.3097	0.7342
Error	127	13.003079	0.102386		
C. Total	129	13.066505			

To address the findings, the study recommends exploring integrated approaches that combine methods from multiple phases to enable more substantial reductions in EE [77]. Future research should focus on refining existing methodologies for assessing buildings and investigating innovative strategies to lower EE. These efforts are vital to enhancing the effectiveness of sustainable construction practices and expanding the knowledge base in this field.

The findings of this review align with several previous studies. For instance, Fernandes et al. (2019) demonstrated that earthen materials such as rammed earth and compressed earth blocks could achieve substantial EE reduction compared to conventional materials, consistent with this study’s observation that material-focused approaches are highly impactful [47]. Similarly, Luo et al. (2021) reported up to 72.8% EE reduction through production process interventions, supporting the conclusion that material and process modifications contribute significantly to lowering EE [30]. In line with this, Foraboschi et al. (2014) emphasized the role of structural design in reducing EE, echoing this review’s categorization of design interventions as critical to holistic strategies [63]. Conversely, Reider and Meir (2019) found that the use of fiber-reinforced polymer (FRP) materials could increase EE despite offering better thermal performance, highlighting the variability and trade-offs noted in this review [41]. These comparisons reinforce the need for integrated, context-specific approaches across material, construction, and design phases to achieve meaningful EE reductions.

The review acknowledges several limitations. First, its scope is restricted to studies that explicitly address methods for reducing EE and provide quantitative data on EE reduction. Second, significant variability in reported EE values is observed, influenced by factors such as geographic location, data sources, and analysis methods. These limitations highlight the need for further studies to address these challenges and provide more consistent and comprehensive data.

This study concludes that while notable progress has been made in reducing EE, the relative effectiveness of individual methods remains consistent across phases. The findings underscore the importance of integrated approaches to achieve more substantial reductions in EE, advancing the construction industry's commitment to sustainability and fostering a more environmentally responsible built environment.

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