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Comparative Assessment of a Residential Building's Envelope Based on Embodied Energy

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Highlights

- Determination of life cycle embodied energy for a mid-rise building in the Indian context
- Comparative assessment of the determined embodied energy to existing studies and highlighting the variation in findings
- Comparative assessment of building's envelope based on embodied energy, identifying the most and least efficient materials

Abstract

This paper addresses the estimation of a residential building's embodied energy through real-time data and evaluates the influence of diverse infill wall materials on its embodied energy. The investigation centers on a 10storey residential structure situated in Roorkee, India's composite climate. The study encompasses initial embodied energy from the bill of quantities and recurring embodied energy from maintenance and replacement cycles. Calculated at 11630 MJ/m², the determined lifetime embodied energy comprises 98.6% initial and 1.4% recurrent energy. A comparative analysis is conducted against existing literature and extended to alternative building envelopes. Findings indicate that using fly ash lime brick for infill walls minimizes embodied energy, potentially saving around 515MJ/m² across the building's lifespan. This research provides valuable insights into estimating and comparing the embodied energy of residential buildings and highlights the potential energy efficiency benefits of specific building envelope choices.

Keywords: Life cycle embodied energy, Initial Embodied energy, Recurrent Embodied energy

Introduction

In recent years, the impact of buildings on global energy consumption and greenhouse gas emissions has become a growing concern in the context of climate change. According to the 2019 Global Report for Buildings and Construction [1], buildings accounted for a staggering 36% of global energy consumption and contributed 39% of global emissions. This alarming data highlights the urgent need to address the energy efficiency of buildings to mitigate climate change and global warming.

The energy consumption of buildings occurs in two key domains over their lifetime: operational energy, which is the energy consumed by the building's electrical load, and embodied energy, which is the energy embedded in the construction materials used. To achieve significant reduction in the life cycle energy of buildings, it is crucial to minimize both operational energy and embodied energy. This paper focuses specifically on the determination of the embodied energy in a real-time building situated in the composite climate of Roorkee. Additionally, it undertakes a comparative analysis of embodied energy for the same building, considering a range of nine different building envelopes. Each envelope represents an alternative infill wall material, offering insight into the potential energy savings achievable through the use of different materials in terms of embodied energy.

By shedding light on the embodied energy of buildings and the energy-saving potential associated with alternative materials, this study contributes to our understanding of sustainable practices in the construction industry. Ultimately, it aims to inform decision-makers and stakeholders about the importance of reducing embodied energy as part of comprehensive efforts to create energy-efficient and environmentally conscious buildings.

Methodology

The study was conducted following the methodology outlined in Figure 1. The research consisted of two main parts, each addressing a specific aspect of embodied energy in buildings.

In the first part of the study, the calculation of embodied energy was performed for a residential case building located in the composite climate of Roorkee. To determine the initial embodied energy, the bill of quantities for the building was utilized. This involved quantifying the energy embodied in the construction materials used in the building's construction phase. Additionally, the recurrent embodied energy for a 50-year period was calculated by considering the maintenance and replacement cycles observed in the previous years. The calculated values of embodied energy were then compared to the findings of the existing studies in the field of assessing the relative magnitude of the embodied energy for the case building.

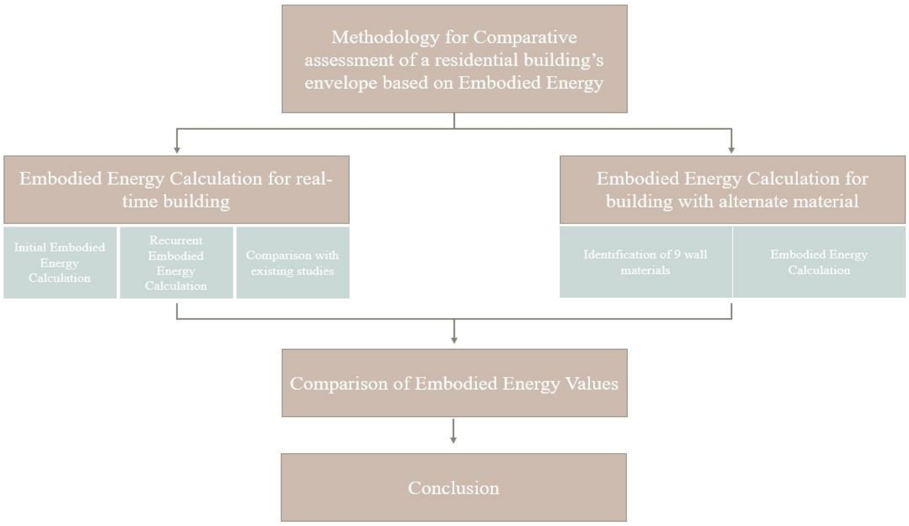

Figure 1: Methodology for the study

The second part of the study focused on investigating the impact of different wall materials on embodied energy. Nine wall materials, identified according to the list provided by NBCC [2], were selected as alternate materials for analysis. For each material, the initial and recurrent embodied energy values were calculated for the residential building, accounting for the specific variation in the building envelope. A comparative analysis of the embodied energy values associated with the different wall materials was performed, allowing for meaningful conclusions to be drawn regarding the energy-saving potential offered by these materials.

By following this methodology, the study aimed to provide a comprehensive understanding of embodied energy in buildings, both in the context of a specific case building and the influence of various wall materials. The findings of this research contribute to the body of knowledge in the field and offer valuable insights for decision-makers and stakeholders seeking to promote sustainable practices in the construction industry.

Introduction to the case study building

The case study building, depicted in Figure 2, is a real-time building situated in the composite climate of Roorkee. Table 1 provides an overview of the specifications for this particular building. Constructed in 2022, the building is a G+10 residential apartment building with a reinforced concrete frame structure and pile foundation serving as its structural system. It is part of an apartment complex consisting of three identical building blocks, as illustrated in Figure 2. The ground floor of each block is allocated for stilt parking.

Table 1: Specifications of the building

Specifications	
Building Name	River View Apartment
Location	Roorkee, Uttarakhand, India
Year of Construction	2022
Climate	Composite (as per ECBC)
Structural System	Reinforced concrete frame structure with pile foundation
Building Typology	Residential building
User Typology	Staff and Faculty Housing for IIT Roorkee

No. of floors	Stilt + 10
No. of blocks	3
No. of residences	60x3 blocks
Typology of residences	3 bhk
Built up area of 1 block	14850 m^2 approx.
Built up area of 1 residential unit	204 m^2 approx.

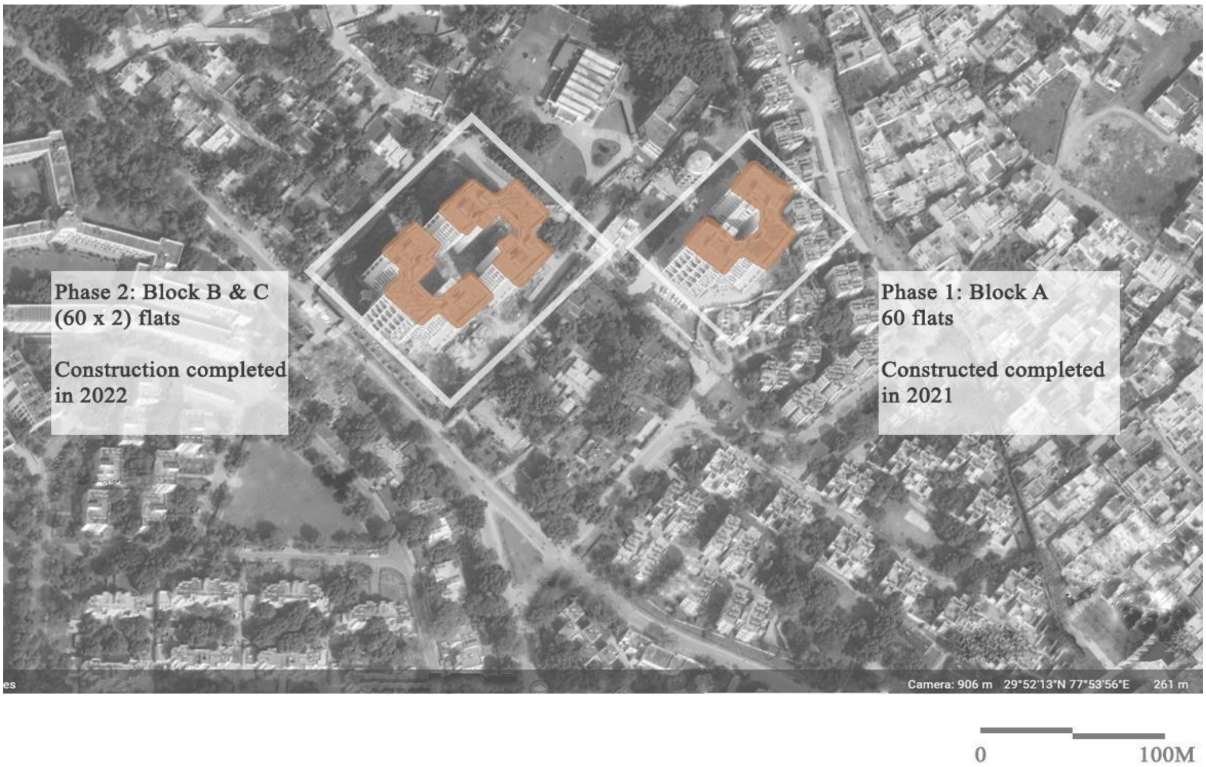

Figure 2: Apartment complex consisting of the case study building

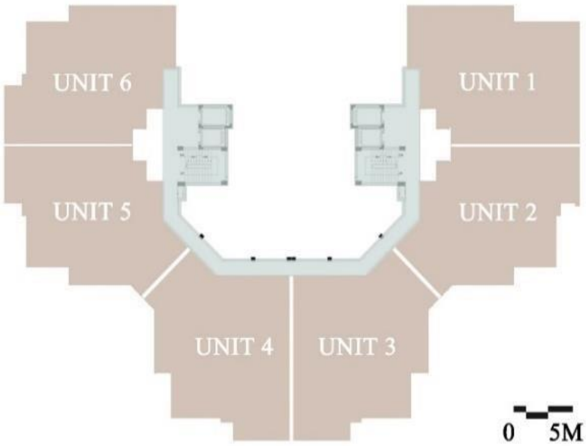

Figure 3: Typical floor plate of the apartment building.

Each typical floor plate of the building contains six residential units, as showcased in Figure 3. The total area of a typical floor plate is approximately 1485m^2, with approximately 18% of the space dedicated to circulation. Each residential unit is a 3 bhk apartment encompassing an area of around 204 m^2 and featuring balconies on three sides. A visual representation of a typical residential unit layout can be seen in Figure 4. For the purposes of this study, the anticipated life span of the building is considered to be 50 years, aligning with established industry standards [2].

Embodied Energy Calculation for the real time building

Initial Embodied Energy Calculation ($EE_{initital}$)

The $EE_{initital}$, which represents the embodied energy of the construction materials, is determined for the case study building. The bill of quantities is used to calculate the $EE_{initital}$. The embodied energy values are sourced from the "Indian Construction Materials Database of Embodied Energy and Global Potential" [3], a report published in 2017 by the International Finance Corporation and European Union. The embodied energy values consider the "cradle to gate" system boundaries and do not include transportation from production to the building site. All embodied energy values are expressed in Mega Joules per unit area.

The calculation of embodied energy covers various aspects of civil work, including concrete work, reinforced concrete work, masonry work, marble and granite work, wood and PVC work, steel work, flooring, roofing, finishing, pile work, and aluminum work. The specific scope for calculating embodied energy is outlined in Table 2.

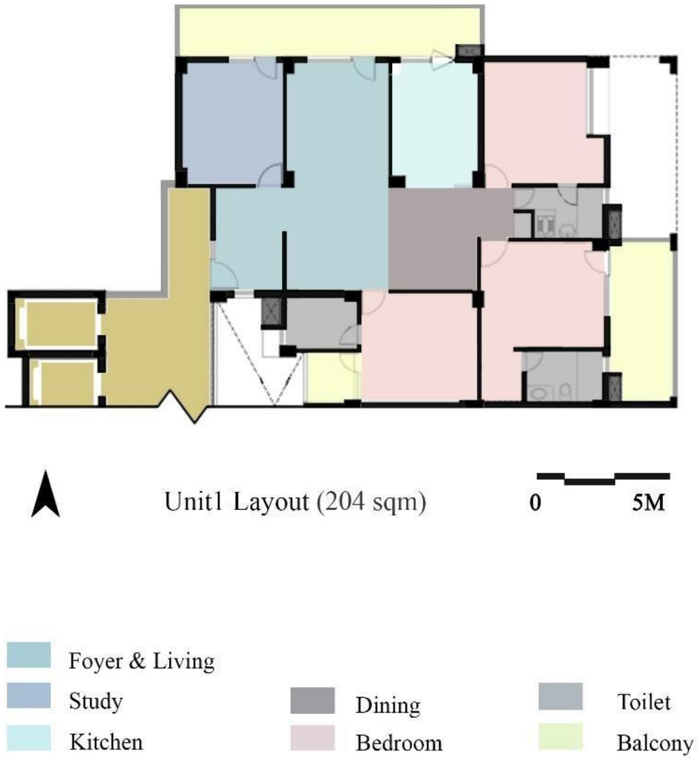

Figure 4: Typical layout of the residential unit

Table 2: Scope of embodied energy calculation

S.No.	Works considered for Embodied Energy Calculation	Works not considered for Embodied Energy calculation
1	Concrete Work	Earthwork
2	Reinforced Cement Concrete	Road work
3	Masonry/ brick work	Sanitary Installations
4	Marble and granite	Water Supply
5	Wood and PVC	Drainage
6	Steel Work	Water Proofing
7	Flooring	Extra (New technology/materials)
8	Roofing	Horticulture and landscape
9	Finishing	Lightings
10	Pile Work	Fire Alarm and PA System
11	Aluminum Work	Lifts/ Elevators
12		Sub-station
13		DG Set
14		Earthing and Miscellaneous Items

15		CCTV Surveillance
16		Fire Fighting Work
17		Pumps, Solar Hot Water System and Equipment

The $EE_{initital}$ for each block of the case study building is determined to be 170321035.50 MJ, equivalent to 2838683.92 MJ per residential unit. The calculated $EE_{initital}$ per unit area is approximately 11469.43 MJ. Table 3 provides details on the amount of building materials and the associated energy consumed per unit area. It is worth noting that cement and steel account for nearly 90% of the initial embodied energy consumption despite comprising only 31% of the total material quantity.

Table 3: Initial Embodied Energy consumed per unit area

S.No.	Building Material	Quantity (kg/ m^2)	Embodied Energy values reported in the database (MJ/kg)	$EE_{initital}$ (MJ/m^2)	Percent $EE_{initital}$ consumed by the material
1	Cement	1052.96	6.40	6738.98	58.76%
2	Steel	108.00	24-30	3255.08	28.38%
3	AAC	42.45	11.5	488.17	4.26%
4	Aluminum	0.64	330.00	211.52	1.84%
5	Tile	21.30	7.8-8.2	174.63	1.52%
6	Bricks	42.87	3.6-4.4	154.32	1.34%
7	Sand	1383.64	0.11	152.20	1.32%
8	Stone Aggregate	1069.00	0.11	117.59	1.02%
9	Kiln Dried Timber	7.81	15.00	117.21	1.02%
10	Cement based plaster	8.43	4.80	40.45	0.35%
11	Float Glass	0.60	17.00	10.10	0.08%
12	Stone Floor Tile	13.53	0.44	5.95	0.05%
13	Glass Reinforce Concrete	2.71	1.30	3.52	0.03%
		3753.94	**-**	**11469.43**	

It is important to recognize that there is currently no globally accepted standard or method for determining embodied energy [4]. Consequently, an attempt is made to benchmark the calculated values of the case study against existing studies conducted within the Indian context. Table 4 presents a compilation of such studies that have estimated the initial embodied energy in various buildings. Notably, Figure 5 illustrates the absence of a clear pattern or relationship between the height of the building and the initial embodied energy per unit area. The wide variability observed in different studies can be attributed to the use of different databases, inventories, methods, and scopes employed when determining the initial embodied energy. Achieving consistency in study outcomes demands the adoption of a shared boundary and standardized embodied energy value. However, practical implementation poses challenges due to the substantial material diversity inherent in various construction projects. Buildings draw materials from diverse sources, spanning both local and international origins. Furthermore, the manufacturing processes for identical products can diverge significantly based on geographical context. Consequently, deriving a universal embodied energy value for the same material, produced across distinct locations, risks oversimplification in the face of intricate contextual nuances.

This underscores the inherent unpredictability and breadth of variations observed in studies. It accentuates the call for standardized methodologies in assessing embodied energy within construction—an endeavor rife with practical complexities, yet ongoing efforts strive for advancements in this realm.

Table 4: Initial Embodied Energy per unit area of existing studies in Indian scenario

S.No.	Number of floors	Structural System/ Specifications	$EE_{initital}$ (MJ/m^2)	Climate	Source
1	1	Load bearing	4550.00	-	[5]
2	2	Load bearing system with alternate or low energy materials	1610.00	-	[6]
3	2	Load bearing system with conventional materials	2920.00	-	[6]
4	2	Load bearing system	3950.00	-	[5]
5	2	Load bearing system with alternate materials	4700.00	Warm-Humid	[7]
6	2	Load bearing system with conventional materials	5600.00	Warm-Humid	[7]
7	4	Reinforced concrete frame system	3700.00	-	[5]
8	4	Reinforced concrete frame system	7358.00		[8]

9	7	Reinforced concrete frame system	10800.00	Warm-Humid	[9]
10	8	Reinforced concrete frame system	4210 .00	-	[6]
	8	Reinforced concrete frame system	4250.00	Moderate	[2]
11	River-View Apartments (S+10)	Reinforced concrete frame system	11138.6	Composite	
12	14	Reinforced concrete frame system	3472.22	Warm-Humid	[10]
13	34	Reinforced concrete frame system	10510.00	Moderate	[2]

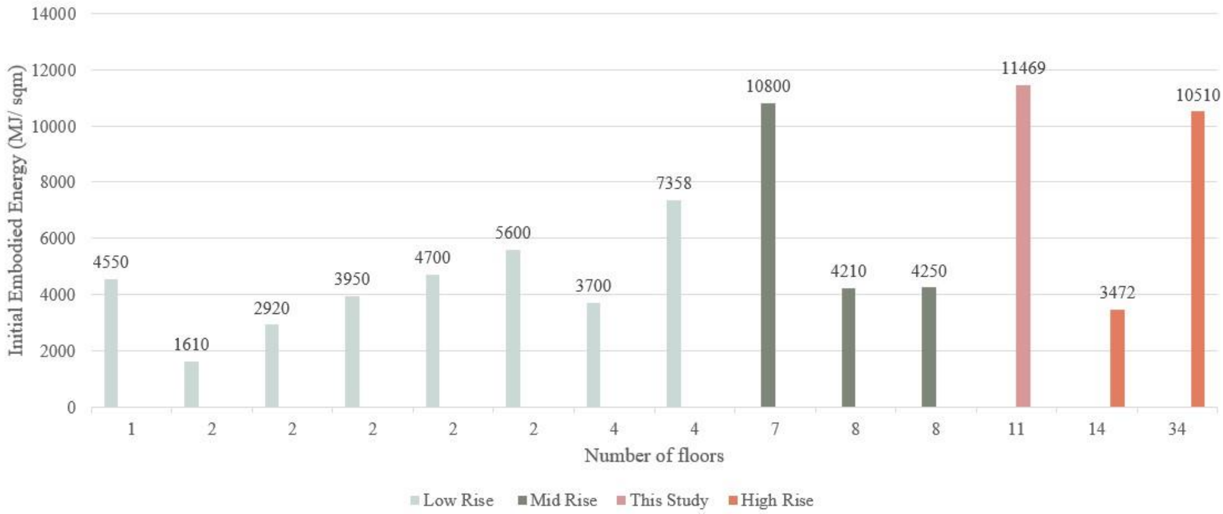

Figure 5: Initial Embodied Energy per unit area of existing studies in Indian scenario.

Recurrent Embodied Energy Calculation ($EE_{recurrent}$)

The $EE_{recurrent}$ is determined by the embodied energy associated with the maintenance work carried out on similar buildings within the campus that have been constructed in the past. Specifically, three apartment buildings – HillView Apartment, Canal-View Apartment, and Shivalik Apartment- are selected for this analysis. These buildings share similarities with the case study building in terms of resident type, floor area, and maintenance practices. Detailed specifications of these buildings can be found in Table 5.

Table 5: Specifications of buildings considered for recurrent embodied calculation

S.No.	Building's Name	Year of Construction	Built up area per block (m^2)	Number of floors	Floor area of a typical residential unit (m^2)
1	Hill View Apartment	2005	15192.50	Stilt + 7	181.12
2	Shivalik Apartment	2012	12126.75	Stilt + 6	163.08
3	Canal View Apartment	2014	12126.75	Stilt + 6	163.08
4	River-View Apartment	2022	148500.00	Stilt + 10	200.00

The calculation of $EE_{recurrent}$ incorporates the embodied energy of both scheduled and unscheduled maintenance works. Scheduled maintenance activities, such as internal painting, external painting, and varnish work, are performed at regular intervals. On the other hand, unscheduled maintenance works encompass civil work carried out based on specific requirements. By averaging the embodied energy values of the maintenance work performed on these similar buildings, the recurrent embodied energy for the case study building is determined. The results, as presented in Table 6, indicate an annual $EE_{recurrent}$ per unit area of approximately 3.27MJ. It is noteworthy that the $EE_{recurrent}$ accounts for only 1.40% of the $EE_{initial}$ over the building's lifetime.

Table 6: Annual Recurrent Embodied Energy consumed per unit area

S.No.	Building's Name	Type of maintenance work	$EE_{recurrent}$ (MJ/m2/year)		Average $EE_{recurrent}$ for the case study building (MJ/m^2/year)
1	Hill View Apartment	Painting Work	1.97	3.29	3.27
		Civil work and maintenance work	0.87		
		Tiling work	0.45		
2	Shivalik Apartment	Painting Work	1.97	2.73	
		Tiling work	0.76		
3	Canal View Apartment	Painting Work	2.06	3.77	
		Tiling work	1.71		

Comparing the findings with existing studies [4], it is important to note that the range of recurrent embodied energy reported varies widely, spanning from 0.6 to 294.3 MJ/m^2/year. In this context, the $EE_{recurrent}$ for the case study building falls on the lower end of the spectrum, showcasing relatively efficient maintenance practices and lower embodied energy requirements. This observation highlights the significance of appropriate maintenance strategies and their potential to minimize the recurrent embodied energy, contributing to the overall energy efficiency and sustainability of the building.

Comparison of embodied energy with varying building envelope using alternative building material

In order to explore the impact of different wall materials on the embodied energy of the building, the study considers a set of nine alternative infill wall materials. Given the potential for a considerable shift in a building's operational energy due to changes in infill wall materials, the study delves into the extent to which such adjustments impact embodied energy. These 9 materials endorsed by NBCC [11] are thoughtfully curated for their lower embodied energy values, making them viable options for building construction in the Indian context. For determining the Life Cycle Embodied Energy with alternate infill material, $EE_{initial}$ is derived for each material, followed by the determination of $EE_{recurrent}$. $EE_{recurrent}$ for the alternate materials is determined considering recurrent embodied energy at 1.4% of the initial embodied energy (established for the reference building). Table 7 provides an overview of the life cycle embodied energy for the building envelope using the selected set of alternative materials, as well as the life cycle embodied energy for the case study building.

Table 7: Life cycle Embodied Energy consumed per unit area for different building envelopes

S.No.	Alternate Material	$EE_{initial}$ (MJ/m^2)	$EE_{recurrent}$ (MJ/m^2)	Life cycle Embodied Energy (MJ/m^2)	Savings in life cycle Embodied Energy compared to the real time building (MJ/m^2)
1	Machine molded modular clay bricks, designation 7.5	11363.60	159.09	11522.69	107.31
2	Machine molded non-modular clay bricks, designation 12.5	11199.78	156.80	11356.58	273.42
3	Machine molded modular clay bricks, designation 12.5	11148.59	156.08	11304.67	325.33
4	Hollow concrete block	11765.45	164.72	11930.17	-300.17
5	Sand lime bricks	11036.82	154.52	11191.34	438.66
6	Clay Fly Ash Bricks	11024.88	154.35	11179.23	450.77
7	Solid concrete block	11714.26	164.00	11878.26	-248.26
8	Fly Ash lime bricks	10959.18	153.43	11112.61	517.39
9	Aerated Autoclave Concrete Block	11808.11	165.31	11973.42	-343.42
10	Brick and AAC block (Case Study Building)	11469.43	160.57	11630.00	-

By evaluating the embodied energy associated with these different wall materials, the study aims to quantify the potential energy savings that can be achieved by making informed choices regarding the building envelope. Comparing the life cycle embodied energy of the case study building with the alternative wall materials; the result shed light on the energy efficiency benefits that can be achieved by opting for lower embodied energy materials. The findings in Table 7 highlight the variations in embodied energy values across the different building envelope options, allowing for a comprehensive understanding of the potential energy savings achievable through the material selection.

Conclusion

In conclusion, the life cycle embodied for the G+10 real-time building is determined to be 11630MJ/m^2, comprising approximately 98.6% initial embodied energy and 1.4% recurrent embodied energy. The analysis reveals that the initial embodied energy is higher compared to existing studies, while the recurrent embodied energy is relatively lower. The research also emphasizes the wide variation in embodied energy found across different studies, which can be attributed to the absence of a globally accepted standard method or determination along with different system boundaries and embodied energy values considered while determining the embodied energy.

By examining nine different building envelopes based on their infill wall materials, the study demonstrates the significant impact of the building envelope on embodied energy. Among the investigated envelopes, the use of fly ash lime bricks is found to be the most favourable, resulting in a minimum life cycle embodied energy with a savings of approximately 517.39MJ/m^2 (equivalent to 4.45% of the total life cycle embodied energy of the actual building). Conversely, the building envelope utilizing aerated autoclave concrete blocks is identified as the least efficient, contributing an additional 343.42 MJ of embodied energy per unit area (representing an extra 2.95% of the total cycle embodied energy).

These findings underscore the importance of carefully selecting building envelope materials to achieve significant energy savings. It is crucial to note that changes in embodied energy through the building envelope will inevitably impact the operational energy consumption of the building. Therefore, a comprehensive approach is necessary to optimize life cycle energy and reduce embodied energy simultaneously in order to achieve sustainable building practices.

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