urban science

MDPI

Article

Optimization of Embodied Energy and Construction Cost of Low-Income Housing in Urban India

Deepak Bansal [1], Sweta Byahut [2,*] and Yashika Bansal [3]

[1] Housing and Urban Development Corporation Ltd., Jammu 180001, India; deepak@hudco.org
[2] Department of Political Science, Auburn University, Auburn, AL 36849, USA
[3] Warwick Business School, Warwick University, Coventry CV47AL, UK; yashikabansal2022@gmail.com
* Correspondence: sweta.byahut@auburn.edu; Tel.: +1-3348448436

Abstract: India is the most populous country in the world, having a population of 1.42 billion in 2022. It is urbanizing rapidly, with the present urbanization level at about 35%, which is expected to reach about 40% by 2030. There was an estimated demand of 11.22 million homes in urban India in 2017, of which 95% was in the affordable housing sector. This demand is expected to increase with the current urbanization trends. The Indian government is promoting the construction of millions of affordable houses under its ambitious Prime Minister's Housing Program. These houses are planned, designed, and constructed using local materials and techniques, considering local climatic, geological, hazard, and socio-economic conditions. We examined the 30 most commonly applied housing typologies to determine which typologies and materials have minimum embodied energy and construction costs. The results indicate that load-bearing housing construction of up to three stories, with a plinth–carpet area ratio of 1.31, constructed with any of the blocks-based masonry techniques, has the lowest embodied energy and construction cost, and houses with a plinth–carpet area ratio of 1.51 have the highest. Further, houses constructed with Hollow CC block masonry have the lowest embodied energy, and HF Fly Ash block-based masonry has the lowest construction cost.

Keywords: Life Cycle Analysis (LCA); affordable housing; low-cost housing; embodied energy; alternative construction materials; urban India

Citation: Bansal, D.; Byahut, S.; Bansal, Y. Optimization of Embodied Energy and Construction Cost of Low-Income Housing in Urban India. *Urban Sci.* **2024**, *8*, 146. https://doi.org/10.3390/urbansci8030146

Received: 1 July 2024
Revised: 25 August 2024
Accepted: 9 September 2024
Published: 18 September 2024

1. Introduction

The construction and operation of buildings consume about 30–40% of primary energy, 16% of potable water, and emit about 40% of greenhouse gases (GHGs) globally [1–4]. Among various types of buildings, the housing sector is responsible for substantial consumption of energy and water and GHGs [5–9]. India's population was 1.42 billion in 2022 and is growing rapidly [10,11]. In 2023, it surpassed China to become the most populous country in the world. It is also fast-urbanizing and will require a vast amount of urban housing [11–15]. There was an estimated shortage of 18.78 million houses in urban India in 2012, of which 18 million were in the low-income category [12,13]. This assessment was based on the number of households that were homeless and included those households that were inadequately housed and lived in unserviceable, temporary, or obsolete housing or in congested conditions [11,12]. Almost this entire shortfall (95%) was in the low-income category [11–13]. To meet this demand, the Government of India (GOI) launched an ambitious nationwide affordable housing program in 2015 [15] called the *Pradhan Mantri Awas Yojana* (PMAY, or the Prime Minister's Housing Program), with an initial target to build or enhance about 20 million homes. The PMAY promised to deliver "Housing for All" by the year 2022 to all households that were homeless or living in substandard or dilapidated housing. Based on the number of applications approved by the PMAY, this target was revised to 11.22 million in 2017 [13,16]. Recently, the implementation period for completion of the PMAY program was extended from 2022 to 2024.

Affordable housing in the urban Indian context includes naturally ventilated houses constructed with local construction materials for the poor (economically weaker section and low-income groups), with approximately 20–30 sqm of carpet area (floor area of the unit/building within external walls), two habitable rooms, a toilet, a bath, and a kitchen with bare minimum furnishings. In the nine-year period between 2015 and 2024, approximately 8.4 million homes were constructed, and a total of 11.4 million homes were grounded for construction, making the PMAY the largest affordable housing program in the world. This massive construction of affordable housing across India is generating massive GHGs, which are expected to increase further as large numbers of houses are built [3]. There is an urgent need to analyze the sustainability of this large-scale housing construction program with the objective of reducing climate impacts.

The focus of the PMAY is on the optimization of construction costs and not on the optimization of energy embedded in them [16,17]. In this study, we analyzed 30 design typologies of load-bearing, low-rise (Ground + 2 stories) affordable housing to determine their efficiencies in planning, design, and the requirements of construction materials. These 30 design typologies are the most commonly applied in affordable housing projects built by the public sector agencies in urban India under the PMAY. The construction cost and embodied energy of these designs have been estimated based on the type and amount of construction materials required for construction. The recurring embodied energy and the recurring maintenance costs of these houses have also been estimated, assuming a life span of 50 years. An analysis of housing constructed with conventional construction materials as well as with alternative materials was undertaken to understand their effect on construction cost and the embodied energy footprint. Our objective is to identify the optimum design typologies and construction materials for minimum embodied energy and construction costs.

It is understood that the LCA approach is fundamental to assessing the sustainability of building and construction systems and increasing the productivity and competitiveness of green construction markets [18]. The LCA approach considers the environmental impact of all stages of a building (cradle to cradle), including the embodied energy consumed during the extraction of raw materials, manufacturing of building materials, transportation of raw materials to the construction site, on-site construction process, building operations and maintenance over its lifespan, building demolition, and finally, the recycling of building materials and building debris disposal [19–23]. The application of LCA in the Indian context can be difficult due to the lack of detailed inventory data on quantities of building materials, transportation modes and distances, construction systems, and information on the environmental footprint of individual processes [24,25].

Buildings consume a significant amount of energy in their construction (embodied energy) and operation (operational energy), which can vary from 10 to 20% and 80 to 90%, respectively, of their LCA [1,2,14,21,26,27]. The percentage of operational energy is much higher in conventional buildings, but with the advent of energy-efficient construction materials, efficient facades, energy-efficient electrical and electronic appliances, and the use of renewables such as solar and wind energy-harnessing devices, the requirement for operational energy is reducing [14,22,23]. Generally, the share of transportation and demolition energy in LCA of housing is insignificant [28–31]. Research shows that in milder climates, embodied energy can represent as much as 25% of the total life cycle energy of a building and can be up to 100% in zero-energy houses [27–29]. In residential buildings without air-conditioning, construction or embodied energy is a significant component of the life cycle energy, making it as important as operational energy [27,30]. Hence, in the LCA of buildings, the share of construction or embodied energy is increasing, which needs to be optimized through planning, design, and construction materials [19,31–33].

The amount of energy consumed in various types of buildings varies significantly due to their location, site conditions, building use, typologies, construction materials used, construction systems, maintenance level, loading conditions, number of stories constructed, local climatic conditions, occupant behavior, and desired indoor comfort, along with the type of primary energy used [5,34]. Many studies have analyzed different types of buildings in various locations in different zones and presented their LCA on a floor area basis [26,32,34–37]. However, some studies do not clarify whether the floor areas are plinth areas or carpet areas [26]. There is a significant difference between them [5,26], which results in a different understanding of boundary conditions, typologies, and building components considered [19,34]. The building components considered in many LCA studies are also not explained [37,38]. Foundation systems considered in research are unclear in the work by Reddy et al. [32]. Pinky devi et al. [26,27] considered RCC foundations in low-rise housing, SriLaxmi [4] considered pile foundations, Debnath et al. [37] and Chani et al. [35] focused on masonry system/walling, and Das [36] did not provide a detailed typology of the buildings used in their analysis. Consequently, there are large variations in these LCA values because of these variables, which need to be studied further to optimize these factors in Indian affordable housing. Choudhary and Akhtar [39] suggest using the building bill of quantity data with an analysis of rate documents to develop a materials inventory, which, when combined with the environmental footprint of construction materials, can be used to calculate the impact of a building during its life cycle stages.

Few studies have examined different types of construction materials to understand their effect on embodied energy. Jyosyula et al. [40] found that emissions from lightweight construction materials in a reinforced concrete building could be lower than conventional materials. Kurian et al. [41] found that the most carbon-producing construction material in the construction stage is cement. Aerated concrete blocks in the construction of walls and covering roofs have the potential to reduce the life cycle energy demand of a multifamily residential building by 9.7% [21]. Depending on the building envelope and climatic conditions, alternative wall materials without insulation can reduce the life-cycle energy demand of a residential building by up to 5%, and adding insulation to walls and roofs can reduce it by up to 30% [42]. Shukla et al. [38] considered earthen buildings, which have a different life span and typology than load-bearing or RCC-framed, structure-based buildings. Some studies only considered embodied energy, and some analyzed both embodied and operational energy [21,27–29,34,38,42,43]. Praseeda et al. [34] also studied various types of Indian buildings and presented their LCAs.

The effect of the number of floors on its embodied energy was studied by Bansal et al. [5,24,43], who found that low-rise (up to four stories) load-bearing construction is the most optimum. An analysis of various architectural designs shows that a plinth–carpet area ratio in the range of 1.28–1.62 has a close relationship between the cost of construction materials and embodied energy of construction materials—a lower ratio generally corresponds to lower construction costs and lower embodied energy [5,24]. Houses constructed with hollow cement concrete, AAC, Fa-L-G, and HF Fly Ash blocks-based masonry are optimum in two-storied construction in terms of embodied energy, and houses with other blocks-based masonry have the lowest construction cost in four-story constructions [24]. However, there is little difference in the construction cost and embodied energy in two- and four-story houses constructed with any of the construction materials analyzed [24]. Chani et al. [35] also studied various types of masonry using various building blocks. A component-wise analysis of Indian affordable housing showed that walling/masonry, roofing, foundations, flooring, finishing, and terracing are the six major building components primarily responsible for construction costs and embodied energy [43,44]. The analysis of recurring embodied energy and recurring maintenance costs found that these are in the range of 80–90% of the initial embodied energy and initial construction costs over a service life of 50 years [20].

As evident, considerable research is available on affordable housing in India with respect to their planning, construction materials, and embodied energy. However, the available research does not clarify important factors such as the design typologies, building components, floor areas, construction system, design efficiencies, and the construction materials studied. The first research objective of this study is to analyze which housing design typologies in low-income housing currently under construction in urban India have the most optimum construction cost and embodied energy. The second objective is to investigate if there is any variation in the embodied energy and construction cost with the use of alternative building materials.

2. Materials and Methods

In this study, the most commonly adopted housing typologies of affordable housing in India were selected for analysis, along with the most commonly used construction materials. The methodology followed several steps. First, thirty design typologies that are load-bearing, low-rise, 3-story structures (G + 2, ground floor, and 2 additional upper floors) in low-income housing design typologies were selected and obtained from the Ministry of Housing and Urban Affairs (MoHUA), Government of India (GOI) [15,17]. These selected typologies are representative of the large-scale affordable housing being built in urban India under the PMAY program by public sector agencies such as the Housing and Urban Development Corporation (HUDCO). The individual units have carpet areas varying from 20.02 to 29.99 sqm and plinth areas varying from 28.47 to 42.06 sqm. Each unit has two habitable rooms, a kitchen, a toilet, and a bath. The typical housing designs of low-income housing have 2–12 units on each floor and are 3 floors (G + 2), resulting in 6–36 housing units in each typology. These typologies have been designed according to the guidelines provided for the PMAY [16,17], and the technical specifications are as per the provisions of the National Building Code of India (NBC) [45]. While designing these, safe bearing capacity of soil was considered as 11 MT/m^2 at 1.0 m depth from natural ground level, seismic zone III, and basic wind speed of 47 m/s as specified in the NBC [45]. Few design typologies are illustrated in Figures 1–4, showing clusters of 1, 4, 5, and 12 housing units on each floor in G + 2 buildings.

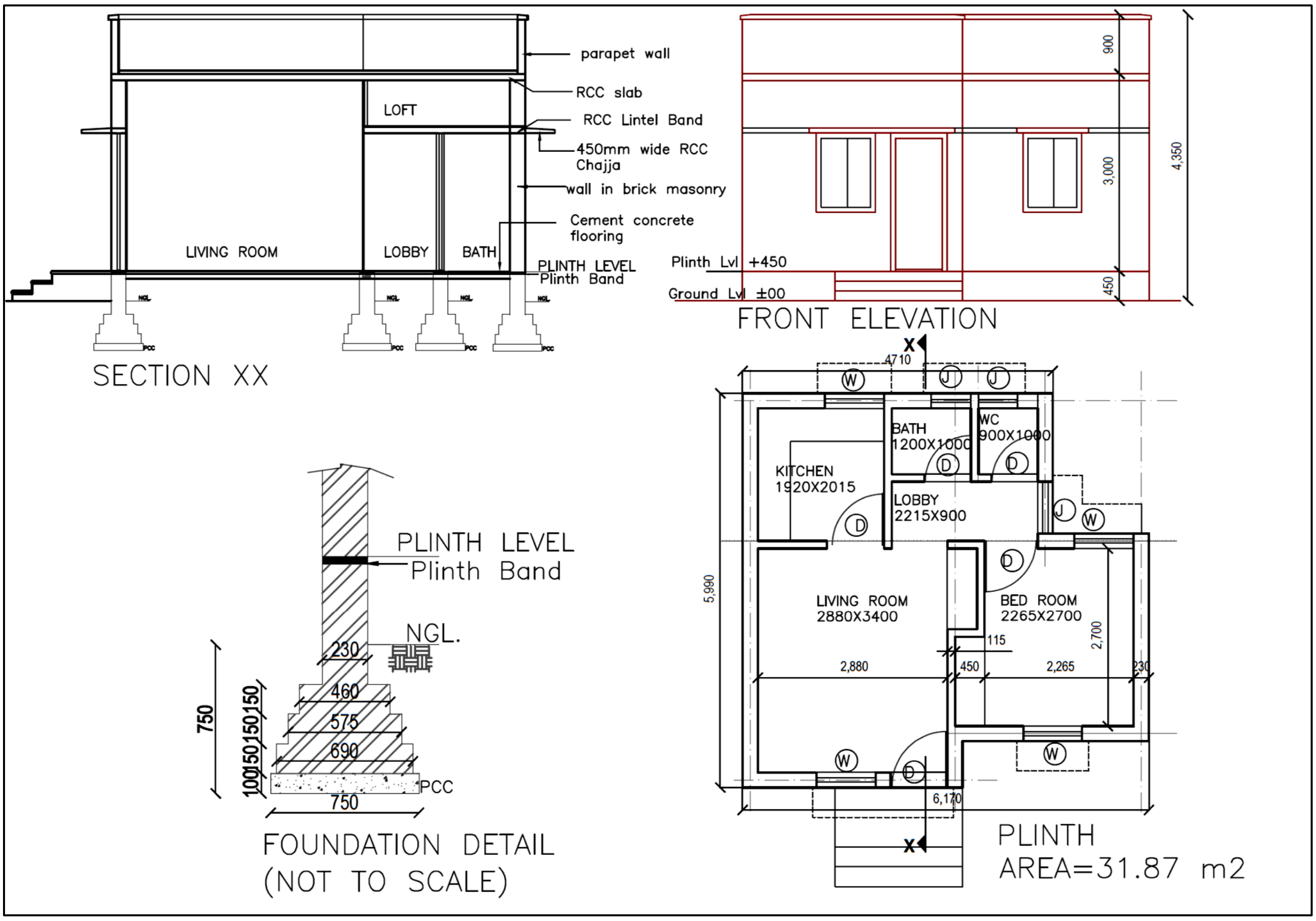

Figure 1. Illustration showing affordable housing with 1 unit on a floor. Source: MoHUA [15].

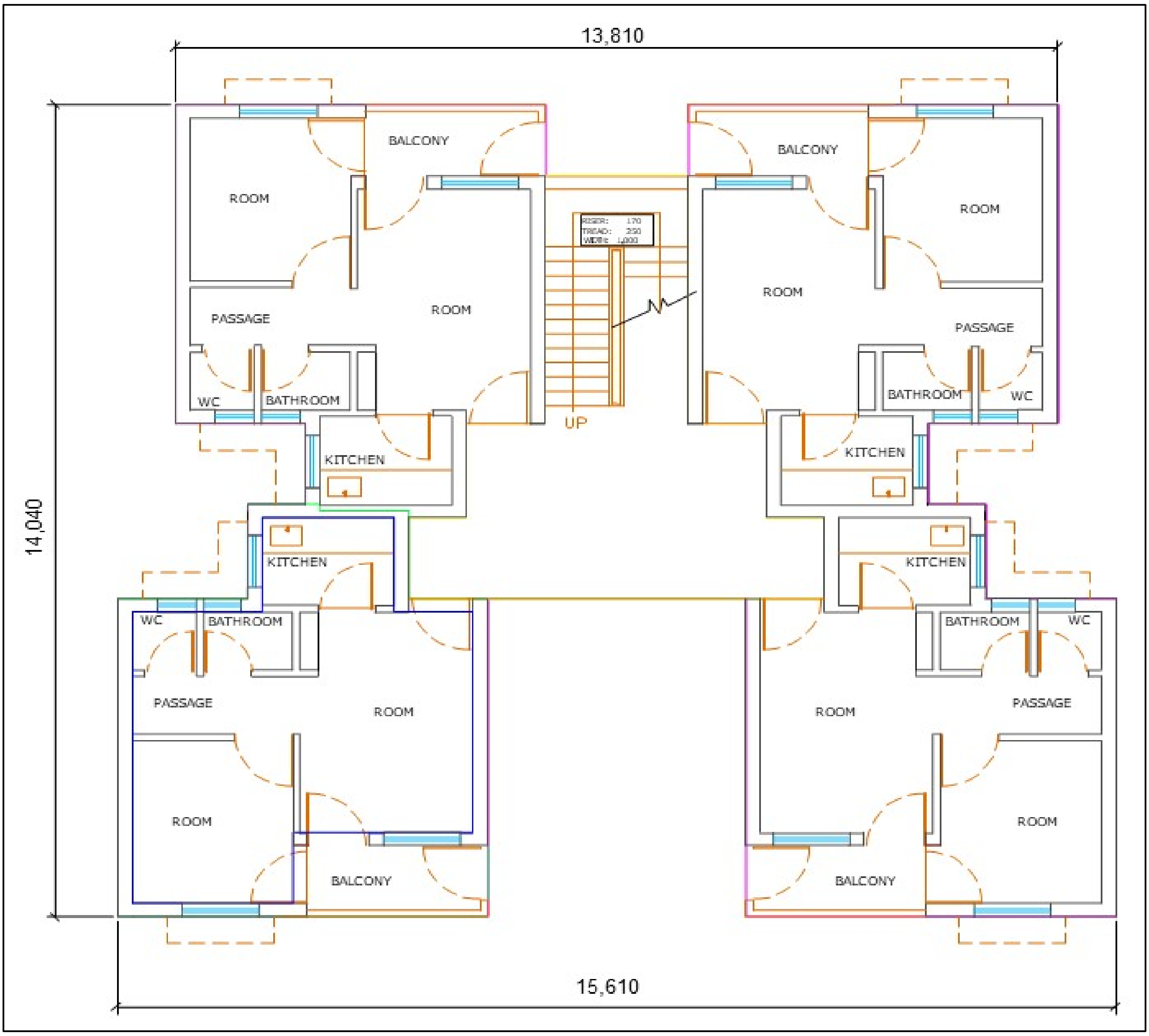

Figure 2. Illustration of an affordable housing cluster with 4 units on a floor. Source: MoHUA [15].

In the second step, design details, such as the number of units on a floor and the plinth–carpet area ratio for each of the 30 housing typologies, were determined. The carpet area is the total floor area of the unit/building within external walls, whereas the plinth/built-up area includes the carpet areas plus the floor area occupied by external walls, all proportional common/circulation areas, and proportional areas under elevators and staircases. The bills of quantities (BOQ) were estimated for the 30 typologies by applying standard procedures adopted in civil engineering [45–48]. These estimates are based on three-story (G + 2) load-bearing constructions with standard construction materials (cement, steel, bricks/blocks, sand, and coarse aggregates), which constitute 90% of construction cost based on construction materials [5,48]. The process includes estimating the quantities of various materials consumed, which in turn depends on the perimeter, width, depth, and height of the buildings determined from the drawings. The amount of various construction materials used in each typology is first estimated based on the construction specifications—whether reinforced cement concrete, load-bearing masonry, or another type of structure. Assumptions for soil, wind speed, and earthquake risks have been considered in analysis. Detailed specifications of the selected 30 housing typologies are presented in Table 1.

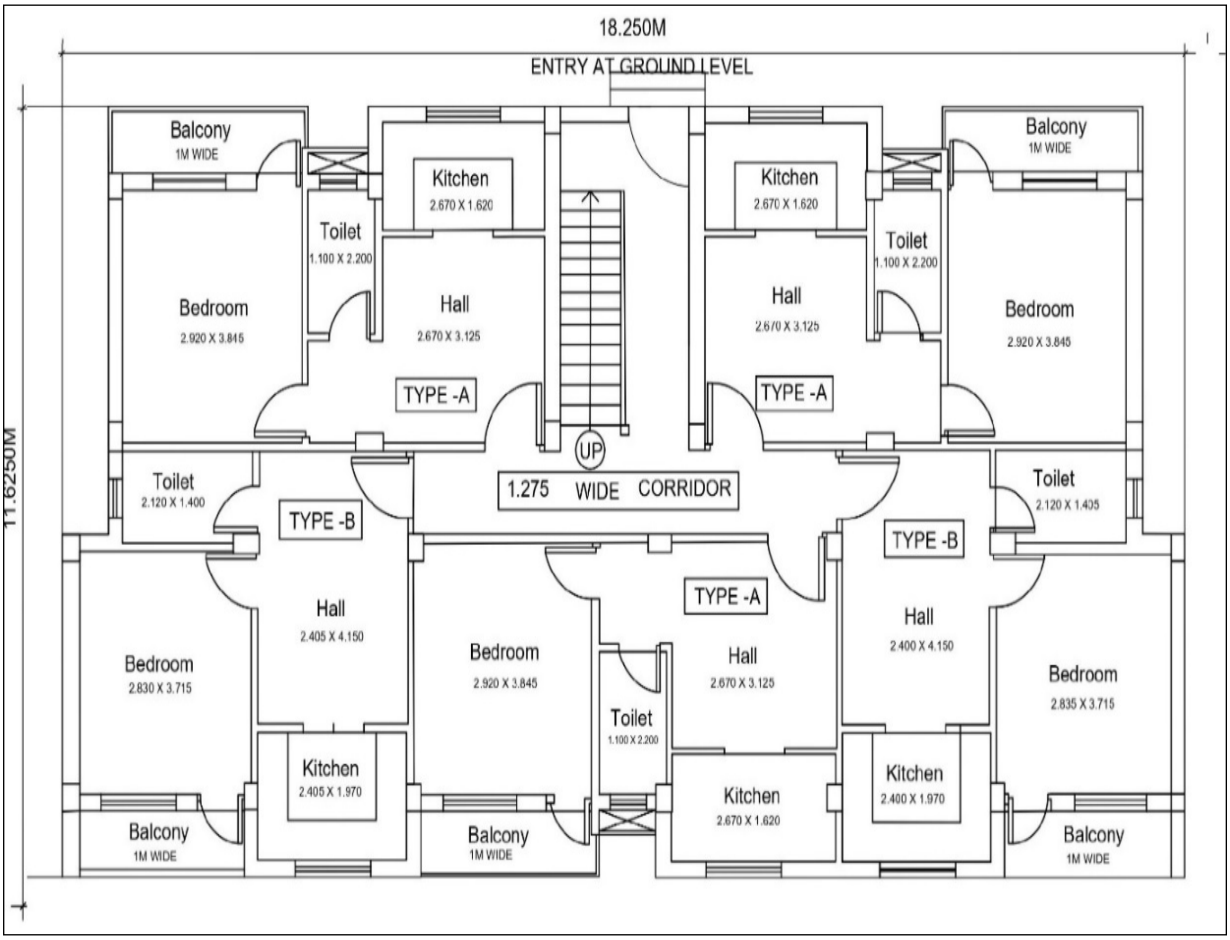

Figure 3. Illustration of an affordable housing cluster with 5 units on a floor. Source: MoHUA [15].

Figure 4. Illustration of an affordable housing cluster with 12 units on a floor. Source: MoHUA [15].

Table 1. Detailed specifications for selected housing design typologies.

No.	Building Component	Detailed Specifications
1	Structure	Load-bearing, G + 3 Structure
2	Wall	230 mm thick brick masonry in mortar of cement and coarse sand in 1:6 proportion
3	Roof	115 mm thick flat reinforced cement concrete (RCC) roof with concrete of M25 grade and with TMT Fe 500D-grade reinforcement, 1% by volume of RCC
4	Flooring	40 mm thick Plain Cement Concrete (PCC) of M15 grade
5	Skirting/Dado	12 mm thick, 100 mm/1200 mm high, in mortar of cement and coarse sand in 1:6 proportion
6	Plaster/Rendering	12/15 mm thick with in mortar of cement and coarse sand in 1:6 proportion
7	Terrace finishing	100 mm thick (average) with brick tiles and mud phuska (treatment with clay and mud to reduce solar heat gain)
8	Parapet	900 mm high, 115 mm thick brick masonry in mortar of cement and coarse sand in 1:4 proportion
9	Joinery	Mild steel frames with steel grills and float glass (4 mm thick) panels
10	CC Gola/Khurrah/Coping	CC Gola (over-the-deck treatment at junction of parapet wall and roof slab to prevent seepage) in PCC of M15 grade. Khurrah (rainwater spout)/coping (PCC over parapets to protect it from rainwater)

Source: BIS [45] and CPWD [48].

The third step involved estimating the embodied energy consumed during construction for the 30 typologies based on the BOQ of various construction materials used in each design. The rates adopted in estimating embodied energy were obtained from literature [33,36,46–48] and presented in Table 2. The cost of construction materials and the cost of construction per unit area were estimated based on the materials specified. The construction cost estimates are based on CPWD DSR 2016 [48], and market rates were collected for some of the construction materials that are not included in CPWD DSR 2016. In addition, recurring energy and recurring costs related to building maintenance have been estimated, considering the service life of housing to be 50 years [45,48].

Table 2. Embodied energy and cost of construction materials as per 2016 prices [33,47–50].

Construction Materials	Unit	Size (mm)	EEV(MJ)/Unit	Rates (INR)/Unit	Rates (INR)/Unit
Fired Clay Bricks	Nos	230 × 115 × 75	4.70	5.20/Nos	-
Cements	Bag	50 Kg Bags	342.50	285.00/Bags	-
Steel	Kg	-	35.10	37.30/Kg	-
Sand	Quintal (Q *)	-	15.00	80.00/Q *	1200/Cum
Aggregate	Quintal (Q *)	-	40.00	74.20/Q *	1300/Cum
Hollow CC Blocks	Nos	400 × 200 × 200	11.20	35.00/Nos	-
AAC Blocks	Nos	400 × 200 × 200	11.52	41.60/Nos	-
Fa-L-G Blocks	Nos	300 × 200 × 150	7.92	22.50/Nos	-
Solid CC Blocks	Nos	300 × 200 × 150	10.37	32.40/Nos	-
HF SEB Blocks	Nos	230 × 220 × 115	6.05	11.64/Nos	-
HF Fly Ash Blocks	Nos	230 × 220 × 115	5.32	10.47/Nos	-

* 1 Quintal (Q) is 100 Kg. or 220 lbs. USD 1 is equivalent to INR 84 in August 2024.

In the fourth step, an additional set of drawings for 122 affordable houses being built under PMAY was obtained from the MoHUA [15] to broaden the scope of this study. These were analyzed to understand if there is any variation in the embodied energy with the use of alternative construction materials. The design of these houses is consistent with the provisions of NBC and BIS [45], and they have similar design typologies and specifications.

However, these are constructed with 7 different types of widely used materials, including conventional fired clay bricks and 6 alternatives to fire clay bricks. Their BOQ, embodied energy, and construction costs were estimated following similar methodology. Finally, their recurring or maintenance costs were estimated to determine recurring energy requirements considering a life span of 50 years.

In the fifth and final step, the relationships between the plinth–carpet area ratio, the number of units on a floor, embodied energy, construction cost, construction materials, and other variables are analyzed using multivariate analysis to determine relationships between them and identify the most sustainable typologies and materials.

3. Results

There is a significant variation observed in the plinth–carpet area ratio in various typologies (A1–A30 in Table 3) and the number of housing units on a floor (ranging from 1.30 to 1.62). For a given floor area ratio (FAR), the plinth–carpet area ratio, along with the number of units on a floor, determines the sustainability of design typologies with respect to their embodied energy and construction cost. The plinth–carpet area ratio and the number of units on each floor for these 30 design typologies, along with their estimated values of the cost of construction materials, cost of construction, and embodied energy, are given in Table 3. Costs are given in Indian Rupees (INR) per sqm of plinth area.

Table 3. Plinth–carpet area ratio, cost of construction, cost of construction materials, embodied energy, and number of units on a floor.

No.	Design Typology	Plinth–Carpet Area Ratio	Construction Cost (INR)/Plinth Area (Sqm)	Materials Cost (INR)/Plinth Area (Sqm)	Embodied Energy (MJ)/Plinth Area (Sqm)	Units on a Floor
1	A1	1.42	11,927.16	4076.70	3558.06	8
2	A2	1.47	11,487.56	3993.45	3483.36	12
3	A3	1.34	12,902.10	4637.34	4048.83	4
4	A4	1.40	12,272.83	4388.28	3831.47	4
5	A5	1.41	12,092.39	4312.85	3766.21	4
6	A6	1.44	11,477.83	4046.48	3528.23	12
7	A7	1.46	11,371.10	4028.09	3511.74	12
8	A8	1.38	11,108.88	3928.48	3429.99	4
9	A9	1.50	11,684.46	4147.22	3620.30	6
10	A10	1.54	12,406.63	4552.34	3966.77	7
11	A11	1.51	13,294.85	4906.98	4290.29	2
12	A12	1.46	11,219.80	3989.92	3477.91	12
13	A13	1.30	11,684.69	4161.10	3634.69	4
14	A14	1.36	10,687.47	3753.78	3276.09	4
15	A15	1.55	12,236.02	4477.61	3904.63	6
16	A16	1.62	11,507.40	4189.72	3651.60	4
17	A17	1.56	12,518.13	4583.78	4005.69	2
18	A18	1.33	11,928.50	4301.93	3751.28	8
19	A19	1.38	12,332.31	4547.92	3967.89	4
20	A20	1.43	11,759.53	4269.52	3724.90	6
21	A21	1.44	11,287.00	4097.48	3570.92	12
22	A22	1.31	10,269.58	3592.60	3135.80	8
23	A23	1.48	10,336.23	3633.63	3168.57	8
24	A24	1.51	12,350.00	4638.66	4039.82	12
25	A25	1.35	10,443.51	3732.01	3254.44	8
26	A26	1.41	10,880.51	3962.96	3457.44	3
27	A27	1.39	11,692.36	4342.83	3785.25	12
28	A28	1.42	11,023.18	4025.70	3506.76	12
29	A29	1.46	11,241.31	4167.20	3637.30	3
30	A30	1.54	11,760.95	4535.06	3962.85	6
	Average	1.44	11,639.48	4200.72	3664.97	6.97

Source: MoHUA [15] and authors' estimates. USD 1 is equivalent to INR 84 in August 2024.

In Table 3, it is evident that the construction cost and embodied energy vary with the plinth–carpet area ratio—lower values are generally associated with lower ratios, with a few exceptions. Design A13, having the lowest ratio of 1.30, with four units on a floor, does not have the lowest construction cost and embodied energy, but design A22, with a ratio of 1.31, with 8 units on a floor, has the lowest construction cost and embodied energy. Similarly, design A16, with a ratio of 1.62 and four units on a floor, is not the most inefficient. Similarly, designs A17, A15, and A10, with ratios of 1.56, 1.55, and 1.54, respectively, and with two, six, and seven units per floor, respectively, are not the most inefficient, but design A11, with a ratio of 1.51 and two units on a floor, has the most inefficient embodied energy and construction cost. It is observed that the higher the number of units on a floor, the lower the embodied energy (correlation coefficient r = −0.31) and construction cost (r = −0.31), as more units share common resources and circulation areas. Similarly, the higher the plinth–carpet area ratio, the higher the embodied energy (r = 0.38) and construction cost (r = 0.30). The cost of construction materials, the cost of construction, and–embodied energy based on construction materials have a strong direct relationship with each other. The cost of construction materials constitutes approximately 36% of the total construction cost; electrical/PHE works constitutes 7%; labor cost constitutes 30%; the contractors' profit constitutes 15%; and the rest is constituted by sundries, tools, and plants. Hence, the share of the cost of construction materials in the total construction cost is quite high. These results are presented in Figure 5 on a distorted scale for improved clarity (plinth–carpet area ratio multiplied by 2000 and number of units multiplied by 100).

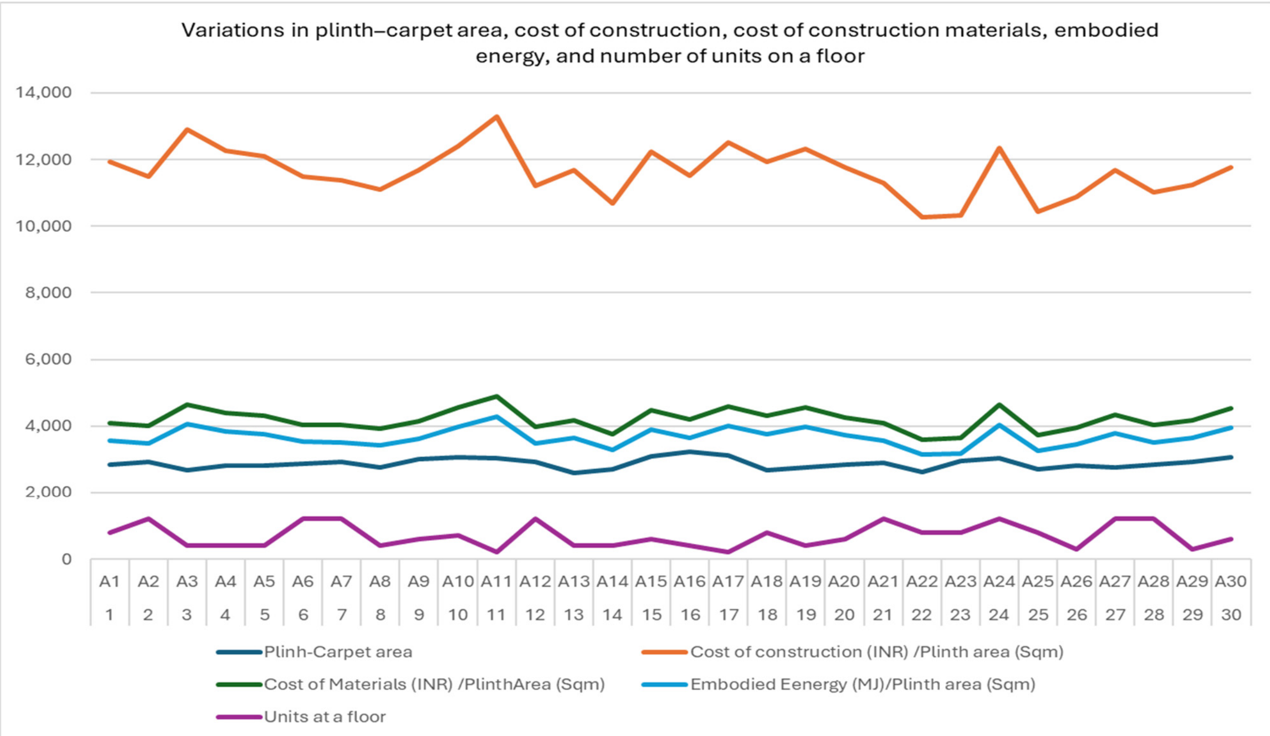

Figure 5. Variations in plinth–carpet area, cost of construction, cost of construction materials, embodied energy, and number of units on a floor.

There is a strong positive correlation between embodied energy and the cost of construction (r = 0.95). Similarly, there is a strong positive correlation between embodied energy and the cost of construction materials (r = 0.99). This is because the construction cost mainly depends on the cost of construction materials. An OLS regression model with 30 observations, keeping embodied energy as the dependent variable with the plinth–carpet area ratio, cost of construction, cost of materials, and number of housing units on the floor as independent variables, is found to be highly significant (adjusted R-square of 0.99). The regression results are presented in Table 4. The cost of materials and the number of units on each floor are highly significant. However, the plinth–carpet area ratio and the cost of construction were not found to be significant, but their relationships with embodied energy are in the expected direction.

Table 4. Relationship of embodied energy with plinth–carpet area ratio and other variables.

Variables	Coefficients	Standard Error	t Stat	*p*-Value
Intercept	1.1852	12.4865	0.0949	0.9251
Plinth–carpet area ratio	−5.2447	7.0527	−0.7436	0.4640
Cost of construction (INR)/plinth area (sq.m.)	0.0025	0.0023	1.1146	0.2756
Cost of materials (INR)/plinth area (sq.m.)	0.8681	0.0054	161.1469	0.0000
Number of units on a floor	−0.7275	0.1499	−4.8539	0.0001

As expected, there is a direct relationship between the cost of materials and embodied energy—a higher cost of materials is positively associated with higher embodied energy (Table 4). When the cost of materials per unit plinth area increases by 1 INR, there is a corresponding increase of 0.87 MJ in the embodied energy per unit plinth area. There is also a significant inverse relationship between the number of units on a floor and embodied energy. When the number of units on a floor increases by one unit, there is a corresponding decline in embodied energy of 0.73 MJ. When there are more units on a floor, there is less embodied energy required per unit to construct common areas and facilities (corridors, access staircases, elevators, etc.). This is because the cost of construction of the facilities and building foundation is distributed among the more units on a floor sharing them, thereby reducing the proportional share of embodied energy required per unit.

An analysis of a separate set of drawings for 122 low-cost houses that are of similar typologies and specifications was undertaken to understand whether there is variation in the embodied energy and construction cost when alternative building materials are used. These houses were constructed with fired clay bricks and six alternatives: Hollow CC Blocks, AAC Blocks, FaL-G Blocks, Solid CC Blocks, HF SEB Blocks, and HF Fly Ash Blocks. The estimated quantities of various construction materials and their construction costs based on construction materials are presented in Table 5. Cost estimates are based on construction materials only and are given in Indian Rupees (INR) per sqm of plinth area.

Table 5. Estimated construction cost of low-rise, load-bearing affordable housing built with various construction materials (in INR).

Low-Cost Housing Construction Materials	Single-Story House	Two-Story House	Three-Story House	Average Construction Cost
Burnt Clay Bricks	4758.55	3924.41	4004.02	4229.00
Hollow CC Blocks	4520.92	3607.99	3688.12	3939.01
AAC Blocks	4883.28	3883.68	3956.25	4241.07
Fal G Blocks	4879.90	3881.11	3953.75	4238.25
Solid CC Blocks	5883.34	4644.56	4696.27	5074.73
HF SEB Blocks	4319.60	3454.82	3539.14	3771.19
HF Fly Ash Blocks	4146.95	3323.94	3411.85	3627.58

Source: MoHUA [15] and authors' estimates. USD 1 is equivalent to INR 84 in August 2024.

The embodied energy of these 122 affordable houses is estimated and presented in Table 6. The embodied energy is given in MJ per sqm of plinth area.

Table 6. Estimated embodied energy of low-rise, load-bearing, low-cost housing with various construction materials (cost only based on construction materials).

Construction Material	Embodied Energy (MJ per sqm of Plinth Area)			
	Single-Story House	Two-Story House	Three-Story House	Average Embodied Energy
Burnt Clay Bricks	3937.13	3227.70	3281.36	3482.06
Hollow CC Blocks	2317.06	1932.48	2038.97	2096.17
AAC Blocks	2344.47	1953.33	2059.25	2119.02
Fal G Blocks	2514.75	2082.89	2185.25	2260.96
Solid CC Blocks	2762.88	2271.67	2368.86	2467.80
HF SEB Blocks	2606.10	2152.39	2252.85	2337.11
HF Fly Ash Blocks	2498.57	2070.57	2173.28	2247.47

Source: MoHUA [15] and authors' estimates.

As seen in Tables 5 and 6, the average construction cost (INR 4229) based on construction materials) and the average embodied energy (MJ 3482 per sqm of plinth area of houses constructed with fired clay bricks) obtained are very similar to those for the 30 design typologies analyzed earlier (Table 3). Further, houses constructed with HF Fly Ash-based blocks have the lowest construction cost among all three-story houses (Table 5), and houses constructed with Hollow CC blocks have the lowest embodied energy among all storied constructions (Table 6). It is also evident that there is little variation in the construction costs for FaL-G and AAC block-based houses and embodied energy in Hollow CC and AAC and Fal-G and HF Fly Ash block-based houses on all three floors. These findings are also applicable to the 30 design typologies (A1–A30) analyzed (Table 3). Design A22 (a plinth–carpet area ratio of 1.31 and eight units on a floor) has the most efficient construction cost with HF Fly Ash based block masonry, and design A22 is the most efficient in embodied energy when constructed with Hollow CC blocks-based masonry among the seven options. Recurring energy will be required for the maintenance houses, along with recurring maintenance costs. The churn-out rates of major construction materials were analyzed for plastering/rendering, flooring, and terracing, which are the three main building components requiring frequent maintenance. Their embodied energy is calculated for these 122 affordable houses and presented in Table 7.

Table 7. Estimated recurring embodied energy with a 50-year housing service life (average of all floors).

No.	Construction Material	Initial Embodied Energy (MJ/sqm)					% of Initial Embodied Energy of 3 Components	Recurring Embodied Energy of 3 Components (MJ/sqm)	% of Recurring Embodied Energy of 3 Components to Total
		Total	Plastering/ Rendering	Flooring	Terracing	Total of 3 Components			
	Churn out Rates		**3 Times**	**4 Times**	**9 Times**				
1	Burnt Clay Bricks	3390.03	144.36	212.43	156.19	512.98	15%	2688.53	79%
2	Hollow CC Blocks	2060.03	148.18	187.56	69.16	404.9	20%	1817.24	88%
3	AAC Blocks	2081.81	148.18	187.56	70.55	406.29	20%	1829.74	88%
4	Fal G Blocks	2217.15	148.18	187.56	79.17	414.91	19%	1907.28	86%
5	Solid CC Blocks	2414.37	148.18	187.56	91.73	427.47	18%	2020.36	84%
6	HF SEB Blocks	2289.76	148.18	187.56	82.8	418.54	18%	1939.94	85%
7	HF Fly Ash Blocks	2204.29	148.18	187.56	78.31	414.05	19%	1899.58	86%
	Average						18%	2014.67	85%

Source: MoHUA [15,20] and authors' estimates.

Similarly, the recurring or maintenance cost for these 122 affordable houses is estimated based on 2016 prices and presented in Table 8.

Table 8. Estimated recurring costs when considering a 50-year service life of affordable housing (average of all floors).

No.	Construction Material	Cost of Construction (INR/sqm)					Share of Initial Cost of 3 Components to Total	Recurring Cost of 3 Components	Share of Recurring Cost of 3 Components to Total
		Total	Plastering/ Rendering	Flooring	Cost of Terracing	Total of 3 Components			
	Churn out Rates		**3 Times**	**4 Times**	**9 Times**				
1	Burnt Clay Bricks	4124.31	208.44	427.67	165.27	801.38	19%	3823.42	93%
2	Hollow CC Blocks	3823.61	212.78	340.1	147.87	700.74	18%	3329.52	87%
3	AAC Blocks	4111.62	212.78	340.1	166.2	719.07	17%	3494.52	85%
4	Fal G Blocks	4108.93	212.78	340.1	166.03	718.9	17%	3492.96	85%
5	Solid CC Blocks	4906.49	212.78	340.1	216.79	769.67	16%	3949.85	81%
6	HF SEB Blocks	3663.59	212.78	340.1	137.7	690.57	19%	3238.01	88%
7	HF Fly Ash Blocks	3526.71	212.78	340.1	128.95	681.82	19%	3159.27	90%
	Average						18%	3498.22	87%

Source: MoHUA [15] and authors' estimates. 1 USD is equivalent to 84 INR in August 2024.

It is evident in Tables 7 and 8 that the share of maintenance-related energy and maintenance-related costs are almost the same as the initial embodied energy and initial construction costs (85% and 87%, respectively) in almost all houses constructed with any of the seven construction materials analyzed. This is due to the long service life (assumed to be 50 years) and related weathering of the three major components (plastering/rendering, flooring, and terracing) of these houses in composite climates.

4. Discussion

In this research, several low-rise (up to three stories) load-bearing housing designs were analyzed. Generally, for a given FAR, a low-rise construction performs better, as its plinth–carpet area ratio varies from 1.28 to 1.62, whereas in high-rise construction, this ratio varies from 1.30 to 2.48, resulting in more floor area being utilized for circulation and wall/masonry. In our analysis of low-rise housing, the plinth–carpet area ratio is found to be related to the cost of construction materials, construction cost, and embodied energy, and a ratio of 1.31 is found to be the most optimum. In the construction of Indian affordable housing, cement, steel, bricks/blocks, sand, and coarse aggregates are the five main construction materials used, contributing to 36% of the total construction cost. There is considerable potential to improve the sustainability of affordable housing in the design stage itself by adopting an optimal plinth–carpet area ratio and better materials. Of these five main construction materials, bricks/blocks may be substituted by alternative energy and cost-efficient materials. Further, the construction cost and embodied energy of houses built with few construction materials are almost the same. Hollow cement concrete blocks masonry-based houses were found to have the lowest embodied energy in all three-story housing designs, along with AAC block masonry-based houses. HF Fly Ash block masonry-based houses were found to have the lowest construction cost of all three-story housing. However, the construction cost and embodied energy are the lowest in two-story housing, irrespective of the construction materials used. The analysis of the recurring embodied energy and recurring maintenance costs shows that terracing, plastering/rendering, and flooring are three major components consuming a significant share, which could be optimized by using durable materials and/or better monitoring. The number of units in each design typology also has a relationship with the cost of construction materials, the construction cost, and embodied energy, but this relationship could not be fully established in this study.

5. Conclusions

The results of the analysis based on plinth areas are tabulated in Tables 3–8. It is evident that architectural design typologies (the plinth–carpet area ratio and the number of units on a floor) contribute to the requirements of construction materials, carpet areas, construction costs, and embodied energy. A lower ratio is found to be the most optimum. There are a few exceptions due to different numbers of units on a floor, and more analysis is required to understand this further. The application of alternative construction materials, such as Solid CC blocks, Hollow CC blocks, AAC blocks, Fal-G blocks, HF SEB blocks, and HF Fly Ash blocks, further reduces the construction cost and embodied energy of various storied housing constructions without affecting the functionality. Constructions with the same architectural design with a few select materials have similar construction costs (AAC Blocks and Fal-G blocks) and embodied energy (Hollow CC blocks, AAC blocks, and Fal-G and HF Fly Ash blocks). The construction cost was the minimum in HF Fly Ash block-based houses, and the embodied energy was the lowest in Hollow CC block-based houses with a plinth–carpet area ratio of 1.31. Further, the recurring embodied energy and recurring costs are primarily attributed to replacing terracing, plastering/rendering, and flooring and can be as high as 85–87% of the initial cost and initial embodied energy.

This research has considered specific typologies of load-bearing, low-cost housing construction in urban India, which is currently implementing the largest affordable housing program in the world. All assumptions and considerations are therefore made with the most commonly used construction materials and specifications, as well as assumptions adopted in the development of low-cost housing by the public sector agencies in urban India. Changes in any of these parameters will result in variations in the results. These findings are most relevant to the urban Indian context and other South Asian countries where similar building materials and similar building typologies are used extensively, including Nepal, Bangladesh, Sri Lanka, and Pakistan.

Author Contributions: Conceptualization, D.B.; methodology, D.B. and S.B.; formal analysis, D.B. and S.B.; investigation, D.B. and S.B.; resources, D.B. and S.B.; data curation, D.B. and Y.B.; writing—original draft preparation, D.B. and S.B.; writing—review and editing, D.B., S.B. and Y.B.; visualization, D.B. and S.B.; supervision, D.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Restrictions apply to the availability of these data. Data were obtained from the Ministry of Housing and Urban Affairs (MoHUA), Government of India, and are available from the authors with the permission of the MoHUA.

Acknowledgments: The authors are thankful for the support and assistance provided by Manju Safaya in data analysis, as well as Vijay K and Shailesh K. Agarwal for highlighting the environmental aspects of this study.

Conflicts of Interest: Deepak Bansal was employed by the company Housing and Urban Development Corporation Ltd., the remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations of Building Materials

HF Fly Ash blocks = Hydra Form Fly Ash blocks; HF SEB blocks = Hydra Form Soil Stabilized blocks; Hollow CC blocks = Hollow Cement Concrete blocks; Solid CC Blocks = Solid Cement Concrete blocks; AAC Blocks = Aerated Autoclaved blocks; Fal-G blocks = Fly Ash Lime Gypsum blocks; Fired clay Bricks = conventional building bricks/blocks.

References

1. Asif, M.; Muneer, T.; Kelley, R. Life cycle assessment: A case study of a dwelling home in Scotland. *Build. Environ.* **2007**, *32*, 1391–1394. [CrossRef]
2. Keoleian, G.A.; Blanchard, S.; Reppe, P. Life-cycle energy, costs, and strategies for improving a single-family house. *J. Ind. Ecol.* **2000**, *4*, 135–156. [CrossRef]
3. IPCC (Intergovernmental Panel on Climate Change). Climate Change 2007: Mitigation, Contribution of Working Group III to the Fourth Assessment Report of the IPCC. 2007. Available online: https://www.ipcc.ch/site/assets/uploads/2018/03/ar4_wg3_full_report-1.pdf (accessed on 1 November 2019).
4. Srilakshmi, S. Embodied Energy Analysis. *Archit. Time Space People* **2013**, *13*, 34–42.

5. Bansal, D.; Minocha, V.K.; Kaur, A. Embodied energy, CO_{2e}, and construction cost of Indian housing: Model of low-rise versus high-rise development. *J. Archit. Eng.* **2021**, *27*, 04021017. [CrossRef]
6. Hu, S.; Yan, D.; Guo, S.; Cui, Y.; Dong, B. A survey on energy consumption and energy usage behavior of households and residential building in urban China. *Energy Build.* **2017**, *148*, 366–378. [CrossRef]
7. UNEP Sustainable Building and Construction Initiative. *The Kyoto Protocol, the Clean Development Mechanism, and the Building and Construction Sector: A Report for the UNEP Sustainable Buildings and Construction Initiative*; UNEP/Earthprint: Hertfordshire, UK, 2008.
8. Huovila, P. *Buildings and Climate Change: Status, Challenges, and Opportunities*; UNEP: Panama City, Panama, 2007.
9. Tiwari, P. Energy efficiency and building construction in India. *Build. Environ.* **2001**, *36*, 1127–1135. [CrossRef]
10. NBO (National Building Organization). Housing data. Available online: http://nbo.nic.in/pdf/housing_data_table.pdf (accessed on 11 March 2021).
11. Census of India. Housing data of Urban and Rural. Available online: https://censusindia.gov.in/nada/index.php/catalog/42617 (accessed on 2 March 2020).
12. Roy, D.; Meera, M.L. Housing for India's Low-Income Urban Households: A Demand Perspective. 2020, Working Paper, No. 402, Indian Council for Research on International Economic Relations (ICRIER), New Delhi. Available online: https://hdl.handle.net/10419/242881 (accessed on 21 December 2021).
13. Report of The Technical Group (11th Five-Year Plan: 2007-12) on Estimation of Urban Housing Shortage. Available online: http://mhupa.gov.in/ministry/housing/HOUSINGSHORTAGE-REPT.pdf (accessed on 5 April 2020).
14. Sengupta, N.; Roy, S.; Guha, H. Assessing embodied GHG emission reduction potential of cost-effective technologies for construction of residential buildings of Economically Weaker Section in India. *Asian J. Civ. Eng.* **2018**, *19*, 139–156. [CrossRef]
15. MoHUA (Ministry of Housing and Urban Affairs). Annual Report 2014–15. Available online: http://mohua.gov.in/upload/uploadfiles/files/3Annual_Report_2014_15_MHUPA_English.pdf (accessed on 11 May 2021).
16. Prime Minister Awas Yojna. Available online: https://pmay-urban.gov.in/ (accessed on 19 January 2023).
17. MoHUA (Ministry of Housing and Urban Affairs). Affordable Housing. 2019. Available online: http://mohua.gov.in/w_new/AffordableHousing.pdf (accessed on 11 May 2021).
18. Ortiz, O.; Castells, F.; Sonnemann, G. Sustainability in the construction industry: A review of recent developments based on LCA. *Constr. Build. Mater.* **2009**, *23*, 28–39. [CrossRef]
19. Dixit, M.K. Life cycle embodied energy analysis of residential buildings: A review of literature to investigate embodied energy parameters. *Renew. Sustain. Energy Rev.* **2017**, *79*, 390–413. [CrossRef]
20. Bansal, D.; Vijay K, M.; Arvinder, K. Initial or recurring embodied energy: Importance in Indian affordable housing. *J. Build. Eng.* **2022**, *49*, 104072. [CrossRef]
21. Talakonukula, R.; Ravi, P.; Karunesh, K.S. Life cycle energy analysis of a multifamily residential house: A case study in Indian context. *Open J. Energy Effic.* **2013**, *2*, 34–41.
22. Utama, A.; Gheewala, S.H. Life cycle energy of single landed houses in Indonesia. *Energy Build.* **2008**, *40*, 1911–1916. [CrossRef]
23. Cabeza, L.F.; Rincón, L.; Vilariño, V.; Pérez, G.; Castell, A. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renew. Sustain. Energy Rev.* **2014**, *29*, 394–416. [CrossRef]
24. Bansal, D.; Minocha, V.K.; Kaur, A.; Dakwale, V.A.; Ralegaonkar, R.V. Reduction of embodied energy and construction cost of affordable houses through efficient architectural design: A case study in Indian scenario. *Adv. Civ. Eng.* **2021**, *1*, 5693101. [CrossRef]
25. Bureau of Energy Efficiency. Energy Conservation Building Code, BEE-ECBC. Available online: https://beeindia.gov.in/sites/default/files/BEE_ECBC%202017.pdf (accessed on 11 March 2020).
26. Devi, P.; Palaniappan, S. A case study on life cycle energy use of residential building in Southern India. *Energy Build.* **2014**, *80*, 247–259. [CrossRef]
27. Devi, P.; Palaniappan, S. Life cycle energy analysis of a low-cost house in India. *Int. J. Constr. Educ. Res.* **2019**, *15*, 256–275. [CrossRef]
28. Ramesh, T.; Prakash, R.; Shukla, K.K. Life cycle energy analysis of buildings: An overview. *Energy Build.* **2010**, *42*, 1592–1600. [CrossRef]
29. Winistorfer, P.; Chen, Z.; Lippke, B.; Stevens, N. Energy consumption and greenhouse gas emissions related to the use, maintenance, and disposal of a residential structure. *Wood Fiber Sci.* **2005**, *37*, 128–139.
30. Ramesh, S. Appraisal of vernacular building materials and alternative technologies for roofing and terracing options of embodied energy in buildings. *Energy Procedia* **2012**, *14*, 1843–1848. [CrossRef]
31. Baird, G.; Alcorn, A.; Haslam, P. The energy embodied in building materials-updated New Zealand coefficients and their significance. *Trans. Inst. Prof. Eng. N. Z. Civ. Eng. Sect.* **1997**, *24*, 46–54.
32. Reddy, B.V.; Jagadish, K.S. Embodied energy of common and alternative building materials and technologies. *Energy Build.* **2003**, *35*, 129–137. [CrossRef]
33. Stephan, A.; Crawford, R.H.; De Myttenaere, K. Multi-scale life cycle energy analysis of a low-density suburban neighbourhood in Melbourne, Australia. *Build. Environ.* **2013**, *68*, 35–49. [CrossRef]
34. Praseeda, K.I.; Reddy, B.V.; Mani, M. Embodied energy assessment of building materials in India using process and input–output analysis. *Energy Build.* **2015**, *86*, 677–686. [CrossRef]

35. Chani, P.S.; Najamuddin; Kaushik, S.K. Comparative analysis of embodied energy rates for walling elements in India. *J. Inst. Eng. (India) Archit. Eng. Div.* **2003**, *84*, 47–50.
36. Das, P.K. A Sustainability Impact-Assessment Tool for Selected Building Technologies in Rural India-The Case of Andhra PRADESH Education Project. Ph.D. Thesis, School of Architecture, Planning and Landscape, Newcastle University, Newcastle upon Tyne, UK, 2006.
37. Debnath, A.; Singh, S.V.; Singh, Y.P. Comparative assessment of energy requirements for different types of residential buildings in India. *Energy Build.* **1995**, *23*, 141–146. [CrossRef]
38. Shukla, A.; Tiwari, G.N.; Sodha, M.S. Embodied energy analysis of adobe house. *Renew. Energy* **2009**, *34*, 755–761. [CrossRef]
39. Chaudhary, A.; Akhtar, A. Template for Evaluating Cradle-to-Site Environmental Life Cycle Impacts of Buildings in India. *ACS Environ. Au* **2022**, *3*, 94–104. [CrossRef] [PubMed]
40. Jyosyula, S.K.R.; Surana, S.; Raju, S. Role of lightweight materials of construction on carbon dioxide emission of a reinforced concrete building. *Mater. Today Proc.* **2020**, *27*, 984–990. [CrossRef]
41. Kurian, R.; Kulkarni, K.S.; Ramani, P.V.; Meena, C.S.; Kumar, A.; Cozzolino, R. Estimation of carbon footprint of residential building in warm humid climate of India through BIM. *Energies* **2021**, *14*, 4237. [CrossRef]
42. Ramesh, T.; Prakash, R.; Shukla, K.K. Life cycle energy analysis of a residential building with different envelopes and climates in Indian context. *Appl. Energy* **2012**, *89*, 193–202. [CrossRef]
43. Bansal, D.; Minocha, V.K.; Kaur, A. Componentwise-embodied energy analysis of affordable houses in India. *Asian J. Civ. Eng.* **2020**, *21*, 137–145. [CrossRef]
44. Rawal, R.; Shukla, Y.; Shivani, S.; Nathani, S.; Kumar, S.; Asrani, S. Developing an Embodied Energy Database for Construction Materials in India. In Proceedings of the Energise 2023—Lifestyle, Energy Efficiency, and Climate Action, Goa, India, 31 October–4 November 2023; pp. 136–145, Alliance for an Energy Efficient Economy. [CrossRef]
45. BIS (Bureau of Indian Standards). National Building Code. Delhi, India. Available online: https://www.bis.gov.in/standards/technical-department/national-building-code/ (accessed on 19 January 2023).
46. Saka, A.B.; Chan, D.W. Knowledge, skills and functionalities requirements for quantity surveyors in building information modelling (BIM) work environment: An international Delphi study. *Archit. Eng. Des. Manag.* **2020**, *16*, 227–246. [CrossRef]
47. Development Alternatives, Energy in Building Materials: Final Report. BMTPC. Available online: www.bmtpc.org (accessed on 15 March 2019).
48. Central Public Works Department (CPWD), Plinth Rates. Available online: https://cpwd.gov.in/Publication/PLINTH_AREA_RATES_2019.pdf (accessed on 5 November 2020).
49. Hammond, G.; Jones, C. Inventory of Carbon and Energy, ver. 20. 2011. University of Bath. Available online: https://greenbuildingencyclopaedia.uk/wp-content/uploads/2014/07/Full-BSRIA-ICE-guide.pdf (accessed on 15 March 2019).
50. BMTPC (Building Materials and Technology Promotion Council). Vulnerability Atlas of India, 3rd Edition. 2020. Available online: www.bmtpc.org (accessed on 5 November 2020).