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Ecological Footprint of Residential Buildings in Composite Climate of India—A Case Study

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Abstract: Buildings are accountable for waste generation, utilization of natural resources, and ecological contamination. The construction sector is one of the biggest consumers of resources available naturally and is responsible for significant CO_2 emissions on the planet. The effects of the buildings on the environment are commonly determined using Life Cycle Assessments (LCA). The investigation and comparison of the Life Cycle Ecological Footprint (LCEF) and Life Cycle Energy (LCE) of five residential buildings situated in the composite climatic zone of India is presented in this study. The utilization of resources (building materials) along with developing a mobile application and a generic model to choose low emission material is the uniqueness of this study. The utilization of eco-friendly building materials and how these are more efficient than conventional building materials are also discussed. In this investigation, the two approaches, (a) Life Cycle Energy Assessment (LCEA) and (b) Life Cycle Ecological Footprint (LCEF), are discussed to evaluate the impacts of building materials on the environment. The energy embedded due to the materials used in a building is calculated to demonstrate the prevalence of innovative construction techniques over traditional materials. The generic model developed to assess the LCEA of residential buildings in the composite climate of India and the other results show that the utilization of low-energy building materials brings about a significant decrease in the LCEF and the LCE of the buildings. The results are suitable for a similar typology of buildings elsewhere in different climatic zone as well. The MATLAB model presented will help researchers globally to follow-up or replicate the study in their country. The developed user-friendly mobile application will enhance the awareness related to energy, environment, ecology, and sustainable development in the general public. This study can help in understanding and thus reducing the ecological burden of building materials, eventually leading towards sustainable development.

Keywords: life cycle energy assessment; ecological footprint; embodied energy; residential building; operational energy; composite climate; mobile application

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1. Introduction

In developing countries, there is rapid urbanization taking place that requires a large amount of energy with a compelling substantial impact through the generation of waste, emissions of greenhouse gases, etc. [1]. The building industry is at fault for the total primary energy utilization of about 45% and CO_2 emissions of about 40% globally [2]. The preceding decade has seen a rapid rise in the Indian construction industry. From 2001 to

2011, the housing stock in India has increased tremendously [3], and the "Housing for All" scheme of the Government of India targets two million Pucca houses for all by the year 2023 [4]. About 40% of the electrical energy is utilized in buildings in India [5]. The previous research indicates that the operational energy primarily used to maintain good indoor environmental quality in building stock is majorly responsible for energy and natural resource consumption followed by the construction industry [6,7]. The results presented by Praseeda and Reddy [8] show that annual operational energy in the composite climate is 0.04–0.22 GJ/m^2/yr., in the warm humid climate is 0.03–0.04 GJ/m^2/yr., in the moderate climate is 0.01 GJ/m^2/yr., and in the cold climate is 0.06 GJ/m^2/yr. In India, the amount waste generated annually is about 64 million tons, including construction and demolition (C&D) waste [9]. However, most of the waste produced after the demolition of buildings is not recycled and is disposed of in a landfill [10]. So, the recycling and re-utilization of the aforesaid waste can potentially help in energy-saving, thus resulting in protecting the environment and resource efficiency. Therefore, buildings materials that form the major components of civil constructions play an important role in reducing the ecological footprint. Praseeda and Reddy [8] compared the embodied energy of masonry buildings and the alternate masonry materials. According to the study, finding renewable alternative materials for construction and minimising energy expenditure in the construction sector in general is necessary, but the challenge is to develop techniques to convert solid wastes and biomass (both woody and non-woody) into construction products with minimal energy expenditure. Therefore, the Life Cycle Energy Assessment (LCEA) of buildings is important in reducing the ecological footprint of buildings. Zhixing et al. [11] studied carbon emissions in various types of buildings, in which the carbon emissions of the residential buildings are 514.66 kg CO_2 e/m^3; office buildings, 533.69 kg CO_2 e/m^3; and commercial buildings, 494.19 kg CO_2 e/m^3.

The Life Cycle Energy (LCE) of various house types has been studied by Ramesha and Prakasha [12]. Ten single and multi-story houses were analyzed in the Indian context in view of their energy-saving potential. Accordingly, the LCE of buildings varied between 230 and 360 kWh/m^2 depending on their type and the environmental conditions. The results indicate that the use of energy-efficient appliances helps in the reduction of LCE. Albeit, in several research studies, inadequate sample data is gathered, hindering the expected findings. Garg and Kumar [13] investigated the current energy utilization patterns in the residential buildings of India. It likewise follows the different activities by the government to decrease dependence on petroleum derivatives, rating frameworks of green structures, etc., which influences the energy demand management. Additionally, the various challenges such as technological barriers, regulatory policy barriers, and financial barriers are also discussed. Kapoor and Tegar [14] investigated the energy consumption perception of residents of residential buildings in Bhopal, India. The results show that more than 80% of residents spend a good amount of energy maintaining the indoor environment in their homes. Bastianoni et al. [15] focus on calculating the environmental pressure of the building construction through the use of the Ecological Footprint (EF) by studying and comparing two types of buildings situated in Italy. It shows that the EF can be reduced by the use of environment-friendly inexpensive materials, renewable energy resources, etc. Due to the difficulty in computing, the EF in certain residential building studies does not include indirectly occupied land areas, construction and demolition waste dumps, and demolition energy. As a result, the total EF computed may contain some inaccuracies. Additionally, when performing life cycle evaluations of buildings for EF calculation, the most often utilized factor is the estimated service life. Because the expected maintenance and repair intervals and usage stages may change depending on the building materials utilized, LCA evaluations are subject to uncertainty.

Raj et al. [16] reviewed the relation among energy, the environment, and the economy to achieve the energy-efficiency in buildings. Architects, designers, and researchers will be able to consider various building energy optimization scenarios using the framework presented in this study. Kurian et al. [17] estimated the carbon footprints of residential buildings using BIM in the warm-humid climate zone of India and found that the operational stage is responsible for the largest portion of carbon emission in buildings. Kumar and Suman [18] investigated the building materials used in composite climate to insulate the building for maintaining thermal comfort and thus reducing operational energy requirements in buildings. According to this study's findings, 50-mm-thick Elastospray with conventional roof and walls meets the ECBC standards, but alternative insulation materials require additional thickness to meet the specified values. Authors construct two prototype buildings at the CSIR–CBRI campus to confirm the results: one with a typical burned clay brick wall with reinforced cement concrete roof and 50-mm-thick exterior thermal insulation, and the other without insulation. The six-month period outcomes for the winter and summer seasons are taken to find the best case in reducing operational energy with more thermal comfort in a building. In another study, Kumar et al. [19] investigated low embodied energy sustainable building materials and technologies to reduce the total LCE of buildings to maintain sustainability. Kumar et al. [20] tested insulation material in buildings as it is regarded as one of the most efficient methods of achieving energy savings in buildings. More effective insulation having low thermal conductivity is beneficial in new construction and upgrading old structures. Authors concluded that better insulating materials can potentially reduce the operational phase energy in any building irrespective of the age of the building. Saini et al. [21] nudge the idea of developing more net-zero energy buildings in India for fewer emissions during the building life-cycle. For a brighter, greener, and cleaner future, this study proposes expanding researchers' emphasis beyond direct energy usage and opting for hybridized clean energy sources, and improving constructional characteristics. Therefore, by reducing the operational energy, associated emissions will definitely be reduced and the sustainability goals can be achieved easily. Hussain and Prakash [22] focus on finding an academic building's Life Cycle Ecological Footprint (LCEF), which is found to be 4426.47 gha. The study mentions that the 'Grid-Connected Rooftop Solar Photovoltaic' System (GRSPV) has the potential to decrease the total LCEF of a structure. Reddy and Jagadish [23] assess the Embodied Energy (EE) of both general building materials and their alternatives. The authors mention that through efficient utilization of alternative materials used in buildings, the total EE can be cut down by 50%.

The previous study has largely found that the lack of a defined framework and calculation technique frequently results in a wide range of findings in LCEA assessments [24]. Several European standards created by Technical Committee TC350, including EN 15643-2 [25] and EN 15,978 [26], as well as worldwide standards, including ISO 21931-1 [27] and ISO 21929-1 [28], have been established in recent decades to standardize the use of LCA in buildings. However, there is a lot of evidence that the findings of LCEA analyses vary a lot [29–32].

Most studies in the literature focus solely on embodied energy calculations, with relatively little work done on operational energy calculations and combined effect of OE and EE on ecological footprint. The system boundaries set need to consider the life cycle of all the building components and of the building itself in order to assess the overall total EF and the impacts of the building throughout its entire life cycle. There have been very few studies to evaluate the TBL sustainability performance of residential structures. The Life Cycle Sustainability Evaluation (LCSE) of residential structures may be improved further by identifying important stakeholders, establishing appropriate TBL indicators, and gathering site-specific data to construct TBL inventories for sustainability assessment. So far, the sustainability evaluation frameworks in use have lacked a comprehensive strategy to addressing the shortcomings. As a result, a comprehensive LCSE framework is necessary to combine environmental, social, and economic goals in order to reduce the ecological impact and achieve sustainability.

Earlier studies on ecological footprint reduction in tropical and warm climates have been conducted, but no proper study on ecological footprint reduction of housing developments in composite climates has been conducted. The National Building Code (NBC) of

India [33] classified India into five climatic zones, namely, hot and dry, warm and humid, cold, temperate, and composite zones. In India, many regions experience two or three types of climates during the course of a year, with varying degrees of intensity and duration. Such regions are said to have a composite climate. The features of a composite environment include hot and dry, warm and humid, and cold climates. Season to season, the features alter. This type of climate is most common in India's central region, as well as in the plains of Northern India.

This paper presents a novel study of the Life Cycle Energy Assessment and Life Cycle Ecological Footprint Assessment of five buildings located in two northern states, namely, Uttarakhand and Haryana, along with one union territory, i.e., Jammu and Kashmir, falling under the composite climatic region of India. The comparison between the most energy efficient buildings has been performed using low energy building materials and star-rated household appliances (plug loads) for determining the operational energy of the buildings in this climatic region. The building's maintenance and recurring phases are examined, but the demolition phase is excluded.

A novel user-friendly LCEF mobile application and a program on MATLAB is also developed to calculate the life cycle energy and life cycle ecological footprints of the buildings by putting the huge amount of building materials inventory data along with their embodied energies data in digital format. The generic model and mobile App can help in choosing the best building material responsible for reducing the associated GHG emissions and finding the LCE of any building simultaneously. The mobile App is dynamic and user can also add on any new materials used in any building along with their properties and embodied energy to find the best optimized LCE and Life Cycle Ecological Footprint Assessment of any building in any part of the country.

2. Materials and Methods

The methodology adopted in this research is split into two parts. The first part discusses LCE, and the second part covers the LCEF of buildings.

2.1. *Building's Life-Cycle Energy (LCE)*

LCE is defined as "the energy that is answerable for the entire energy contributions to a building during its life cycle". The manufacturing, use, and demolition phases of any building are included in the total LCE. The Embodied Energy (EE) and Operational Energy (OE) are calculated first in order to estimate the LCE of any building. The EE is calculated for initial and recurring building materials [34] for the overall calculation of building LCE. Equation (1) represents the formula for calculating LCE of a building:

$$\mathrm{LCE} = \mathrm{EE}_{(i)} + \mathrm{EE}_{(r)} + \mathrm{OE} + \mathrm{DE}, \tag{1}$$

where $\mathrm{EE}_{(i)}$ = building's initial embodied energy; $\mathrm{EE}_{(r)}$ = building's recurring embodied energy; OE = building's operational energy throughout its lifespan; DE = building's demolition energy.

2.1.1. Building's Initial Embodied Energy ($\mathrm{EE}_{(i)}$)

$\mathrm{EE}_{(i)}$ is the exemplified energy [34] that is utilized for the underlying development of the building. It is computed by Equation (2):

$$\mathrm{EE}_{(i)} = \sum \mathrm{m}_{(x)}\mathrm{M}_{(x)} + \mathrm{E}_{(c)}, \tag{2}$$

where $\mathrm{M}_{(x)}$ = energy content of the material (x) per unit quantity; $\mathrm{m}_{(x)}$ = quantity of building material (x); $\mathrm{E}_{(c)}$ = energy consumed at the site for creation of the building; $\mathrm{EE}_{(i)}$ = building initial embodied energy.

Examples of low $\mathrm{EE}_{(i)}$ building materials are sand, aggregate, wood, Kota stone, prefabricated brick panel roof, soil cement block masonry, etc. [35].

2.1.2. Building's Recurring Embodied Energy ($EE_{(r)}$)

$EE_{(r)}$ is the energy that is utilized for the repair and replacement of building materials that have a lifespan less than the life span of the building [34]. It tends to be assessed by Equation (3):

$$EE_{(r)} = \sum m_{(x)} M_{(x)}\ [L_{(b)}/L(m_{(x)}) - 1], \quad (3)$$

where $L_{(b)}$ = building life span; $EE_{(r)}$ = building recurring embodied energy; $L(m_{(x)})$ = material (x) life span.

Examples of EE(r) building materials involve sand, wood, aggregate, and other materials used during the repair works after some time interval in a building.

2.1.3. Building's Operational Energy (OE)

The energy consumed in heating, ventilation, lighting, and operating equipment and machines in the building can be termed as OE [34]. OE is communicated as:

$$OE = E(OA) \times L_{(b)}, \quad (4)$$

where $L_{(b)}$ = building life span; E(OA) = yearly operating energy; OE = operating energy throughout the building life span varying from 50 years to 100 years.

The example of building OE is the energy consumed by various electrical and electronic equipment in a building such as fans, bulbs, tube lights, air conditioners, etc.

2.1.4. Building's Demolition Energy (DE)

The demolition energy is "the energy required for obliterating the structure and moving the generated waste to the landfill destinations or recycling the waste in plants for its further re-use" [34]. It may be communicated as:

$$DE = E(D) + E(T), \quad (5)$$

where E(T) = energy consumed in transporting waste materials; E(D) = energy utilized in the destruction of a building; DE = demolition energy.

2.2. Building's Life-Cycle Ecological Footprint (LCEF)

The concept of EF created by Wackernagel and Rees [36] in the mid-1990s is used to examine the usefulness of resource consumption, the natural resources distribution around the world, and the sustainability of the system. The LCEF methodology of a building project is presented in Figure 1.

The expression for calculating the EF(gha) according to [22] is as follows:

$$EF = C_{(x)}/Y_{(x)} \times e_{(x)}, \quad (6)$$

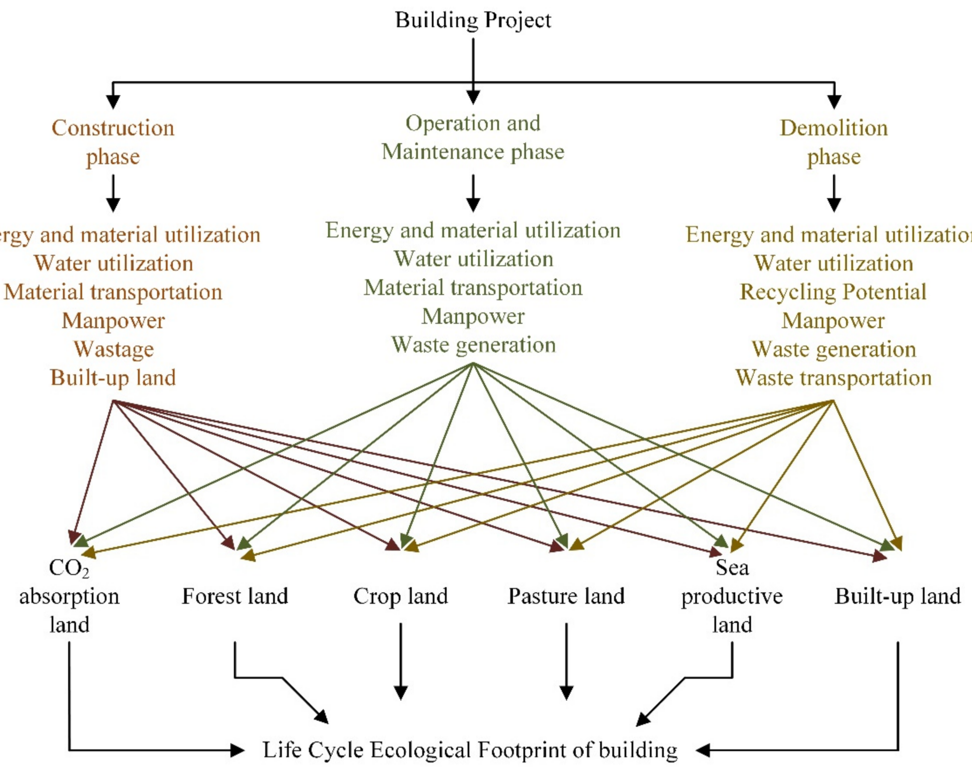

Figure 1. LCEF of a building project [22].

where $Y_{(x)}$ = Yearly item productivity (kg/year); $C_{(x)}$ = Yearly item consumption (kg/year); $e_{(x)}$ = equivalence factor. The equivalence factor for various land types is determined as follows, taken from [37]:

$$e(x) = \frac{\text{Net primary productivity of specific land type(kg/ha)}}{\text{Average Net primary productivity of all land types(kg/ha)}} \times \text{gha/ha}, \tag{7}$$

This work shows the adaptation of the EF indicator with the use of LCA to determine the building's total LCEF. The LCA of the building is utilized to explore and quantify the natural results during their life, creation of materials, development stage, use, repair stage, and destruction stage. This project is a cradle-to-grave approach.

The parameters taken into account for the LCEF of the building are related to the consumption of materials, electricity consumption, manpower, waste disposal, etc., and are defined as:

$$\sum \text{LCEF} = \text{LCEF}_{(e\ \&\ m)} + \text{LCEF}_{(t)} + \text{LCEF}_{(we)} + \text{LCEF}_{(m)} + \text{LCEF}_{(built\text{-}up)}, \tag{8}$$

where $\text{LCEF}_{(built\text{-}up)}$ represents the LCEF of built-up land utilization; $\text{LCEF}_{(m)}$ represents the LCEF of manpower; $\text{LCEF}_{(w)}$ represents the LCEF of construction and demolition waste disposal; $\text{LCEF}_{(t)}$ represents the LCEF of transportation; $\text{LCEF}_{(we)}$ represents the LCEF of water utilization; and $\text{LCEF}_{(e\ \&\ m)}$ represents the LCEF of utilized energy and materials in the building [22].

2.2.1. LCEF of Energy Consumption and Material ($\text{LCEF}_{(e\ \&\ m)}$)

The relation for calculating the LCEF associated with consumption of energy and materials is derived from [22]:

$$\text{LCEF}_{(e\ \&\ m)} = \{L_{CO_2} \times ((1 - S_{OC})/A_f)\} \times e_{CO_2\ land} + \{\sum C_{wi}/Y_{wi}\} \times e_{forest}, \tag{9}$$

where L_{CO_2} is the total emissions during the building's life cycle. It is noted that 30% of the global emissions of CO_2 were absorbed by oceans from 2002 to 2012 [38]. A_f is the absorption factor of forests, which is considered to be 2.68 T_{CO2}/gha. The sequestration by oceans (S_{OC}) of the anthropogenic emissions is 0.30. The wood production yield (Y_{wi}) in India is 73 m^3/ha [39]. The $e_{CO_2\ land}$ is the equivalence factor for CO_2 land, ith wooden material's life-cycle consumption is the C_{wi} [40], and e_{forest} is the equivalence factor of forest land (1.28 gha/ha).

2.2.2. Transportation LCEF ($LCEF_{(t)}$)

The LCEF of transportation comprises of three stages:

- Stage I: The materials for the building construction and their transportation to the site of the project;
- Stage II: The transportation of labor from their homes to the site of the project;
- Stage III: Construction and demolition waste removal from the project site to the landfill zone.

The LCEF of transportation is calculated by the following Equation [22]:

$$LCEF_{(t)} = \{(\sum C_{mi} \times D_{mi}/T_c + \sum C_{wj} \times D_{wj}/T_c) \times E_{tr} + \sum M_k \times D_{mk}/T_b \times E_{bus}\} \times \lambda_{diesel} \times (1 - S_{oc}/A_f) \times e_{CO_2\ land}, \quad (10)$$

where D_{mi} represents the average distance covered by a material during transportation, and C_{mi} represents the weight of the transportable material. M_k represents the number of laborers, and D_{mk} represents the distance traveled by the laborers. T_b and T_c are the capacities of the bus and truck, respectively. λ_{diesel} represents the diesel fuel emission factor (3.17 CO_2 kg per kg of diesel) [41]. The average fuel efficiencies of E_{bus} and E_{truck} are taken as 0.238 and 0.222 kg of fuel per kilometer, respectively [42].

2.2.3. LCEF of Manpower ($LCEF_{(m)}$)

The LCEF related to labor is generally centered on food and portability. In this segment generally, food utilization is considered to survey its LCEF. To estimate the $LCEF_{(m)}$ [43], only food consumption during working hours is taken into consideration. The LCEF of manpower [22] is estimated as:

$$LCEF_{(m)} = d_w/365 \times f_d\{\sum(C_{fi}/Y_{fi}) \times e_i + \sum(C_{fuelj} \times \lambda_j) \times (1 - S_{oc})/A_f \times e_{CO_2\ land}, \quad (11)$$

where d_w represents the labor day counts for the building life span; f_d represents the fraction of food intake (i.e., 60%) for lunch and breakfast of an Indian adult; Y_{fi} represents the ith food production yield (kg/hectare/year); C_{fi} is food consumption category j in the building life (kg/person/year); C_{fuelj} represents fuel consumption category j for the building life cycle (kg/person/year); λ_j represents category j fuel emission factor. Yearly EF of the utilization of goods per capita in India is decided as per the report of the product utilization of India by NSSO [44].

2.2.4. LCEF of Construction and Demolition Waste Disposal ($LCEF_{(we)}$)

The wastage during the development period of the building is reported as 45–65 kg/m^2 by the Energy and Resources Institute (TERI) [45]. It is assessed that 12 to 14.7 million tons of C&D waste is accumulated every year from the construction industry [46]. The life of the construction and demolition (C&D) waste is considered to be around 75 to 80 years. The $LCEF_{(we)}$ can be calculated as:

$$LCEF_{(we)} = (\sum W_{dwi}/Y_{dwi}) \times e_{landfill}, \quad (12)$$

where Y_{dwi} is the bio-productive land area per unit waste; W_{dwi} is the quantity of waste (m^3); $e_{landfill}$ (0.43 gha/ha pasture-land) is the equivalence factor of the type of bio-productive land for the waste to be disposed of (gha/ha) [40].

2.2.5. LCEF of Consumption of Water ($LCEF_{(w)}$)

In India, water consumption data is not well documented. A study [47] shows that water demand for the production of material and the construction is about 27 kl/m^2. The $LCEF_{(w)}$ can be calculated by using the following Equation (13):

$$LCEF_{(w)} = C_w \times E_w \lambda_I \times \{(1 - S_{oc})/A_f\} \times e_{CO_2\ land}, \tag{13}$$

where C_w represents the total consumption of water for the lifespan of a building (m^3); E_w represents the energy consumption rate/liter to extract water up to the requisite height from the underground level; λ_i represents the ith fuel (i.e., electricity and diesel) emission factor that is used to extract water.

2.2.6. LCEF of Built-Up Land ($LCEF_{(built\text{-}up)}$)

Built-up lands are associated with different classifications such as cropland, forestland, pasture-land, CO_2 land, and sea productive land. The $LCEF_{(built\text{-}up)}$ can be evaluated by:

$$LCEF_{(built\text{-}up)} = A_b \times e_{built\text{-}up\ land}, \tag{14}$$

where A_b = built-up land in total (ha); $e_{built\text{-}up\ land}$ represents built-up land equivalence factor (2.52 gha/ha) [40].

2.2.7. Average Annual EF of Residential Building

The life expectancy of a building is considered as hundred years. The normal yearly EF of a building is determined by the given formula:

$$EF_{avg} = \frac{\text{Total LCEF of a Building}}{\text{Building Life Span}}, \tag{15}$$

The normal yearly $ef_{avg/floor}$ area of the structure is:

$$EF_{avg/floor\ area} = \frac{\text{LCEF of a Building}}{(\text{Building Life Span} \times \text{Floor Area of a Building})}, \tag{16}$$

The normal yearly EF per person ($EF_{avg/person}$) of a building is as follows:

$$EF_{avg/person} = \frac{\text{LCEF of a Building}}{(\text{Building Life Span} \times \text{Number of Persons in a Building})}, \tag{17}$$

3. Case Studies

India is divided into five climate zones [33], and the climate types range from extreme summers to extreme winters. The scope of this study is limited to residential buildings of composite climatic regions in which the minimum winter temperature (Dec.–Jan.) reaches 1.0 °C with maximum temperatures (May–June) touching 45 °C. The EE, LCE, and LCEF have been calculated. The places considered in this case study have been marked in Figure 2. These include (i) Roorkee (R_1), (ii) Kurukshetra (K_1), (iii) Jammu (J_1), (iv) Jammu (J_2), and (v) Ambala (A_1). The detailed information of all the considered cases is presented in Table 1.

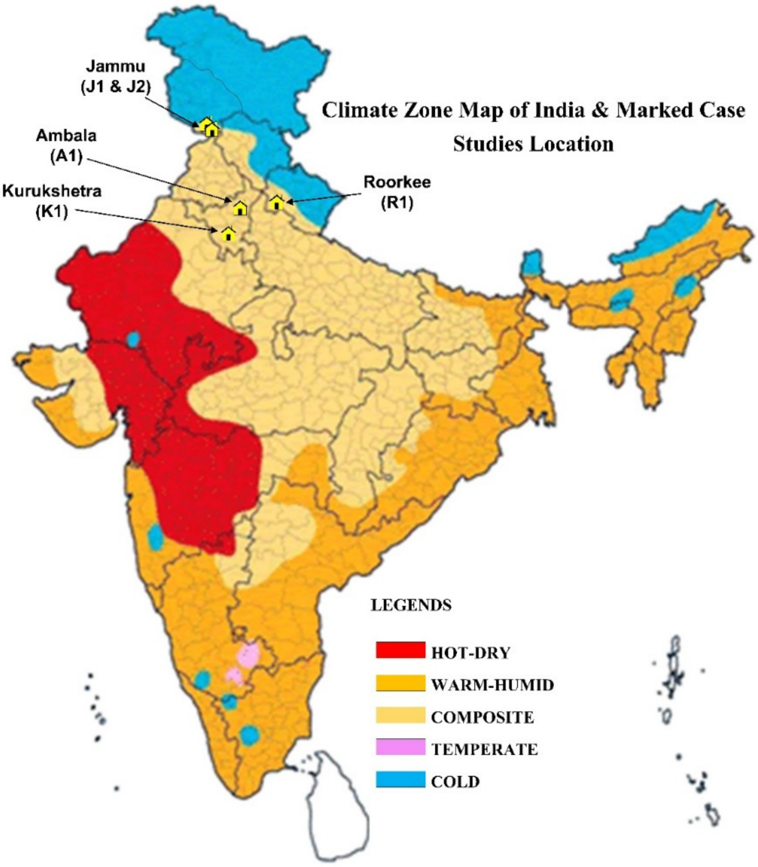

Figure 2. Indian map with marked case study locations.

Table 1. Detailed information of the cases considered in this study.

Parameter		Roorkee (R_1)	Kurukshetra (K_1)	Jammu (J_1)	Jammu (J_2)	Ambala (A_1)
Age of Building (in yrs.)		*30*	*36*	*32*	*30*	*38*
Building Occupants (nos.)		*4*	*5*	*10*	*5*	*6*
Area (m^2)		*165*	*160*	*157*	*163*	*166*
Volume (m^3)		*495*	*478*	*470*	*509*	*518*
Height Regime		*Single storied*	*Single storied*	*Single storied*	*Single storied*	*Single storied*
Rooms (nos.)		*4*	*3*	*3*	*4*	*4*
Details (size)	Room 1	*3.00 m × 3.05 m*	*3.53 m × 3.96 m*	*3.38 m × 3.38 m*	*4.26 m × 3.65 m*	*3.47 m × 4.63 m*
	Room 2	*4.75 m × 3.35 m*	*3.77 m × 3.048 m*	*3.62 m × 4.29 m*	*4.26 m × 3.65 m*	*3.62 m × 5.05 m*
	Room 3	*4.20 m × 3.23 m*	*3.77 m × 4.26 m*	*3.62 m × 2.46 m*	*3.93 m × 3.65 m*	*3.53 m ×3.81 m*
	Room 4	*5.35 m × 4.00 m*	-	-	*4.87 m × 5.88 m*	*4.08 m × 4.57 m*
Lat./Bath (nos.)		*Lat:2, Bath:2*	*Lat:1, Bath:1*	*Combined Lat-Bath:2*	*Lat:1, Bath:1*	*Combined Lat-Bath:2*
Details (size)	Lat.	*2.10 m × 1.30 m*	*1.60 m × 1.46 m*	*2.40 m × 1.79 m*	*2.40 m × 1.82 m*	*1.82 m × 2.74 m*
	Bath.	*2.10 m × 1.30 m*	*1.05 m × 0.95 m*		*2.74 m × 2.40 m*	
Kitchen Size		*2.40 m × 4.50 m*	*3.13 m × 3.35 m*	*2.40 m × 2.34 m*	*3.35 m × 3.35 m*	*3.65 m × 2.74 m*
Energy Consumption (kwh/day)		*18.05*	*7.19*	*7.08*	*8.48*	*12.85*

Table 1. *Cont.*

Parameter		Roorkee (R_1)	Kurukshetra (K_1)	Jammu (J_1)	Jammu (J_2)	Ambala (A_1)
Details (nos.)	Tube- lights	*10*	-	*2*	-	*5*
	CFL/LED	*12*	*10*	*5*	*14*	*6*
	Fan	*7*	*5*	*3*	*5*	*6*
	AC	2	*1*	*1*	*1*	2
	Other Appliances	*8*	*5*	*5*	*7*	*6*
Maintenance Time (in yrs.)		*15*	*15*	*15*	*15*	*15*
Building Life Span (in yrs.)		*100*	*100*	*100*	*100*	*100*
Structure Typology		*Load-Bearing Structure*	*Load-Bearing Structure*	*Load-Bearing Structure*	*Load-Bearing Structure*	*Load-Bearing Structure*

All the selected buildings have an approximately similar building occupancy of five occupants, except the Jammu (J_1) case. Additionally, all the buildings lie in the same age group of 30–40 years, which means the material used in construction is primarily Burnt Clay Brick (BCB), as all the other materials did not exist at the time of construction. All selected houses are single-storied load-bearing structures. The area of the buildings is around 160 sqm. with a deviation of 3 percent on both upper and lower sides. Room sizes vary in all the cases, and the detailed size and count of rooms and lat./bath are presented in Table 1. All the houses contain a single family, and there is only one kitchen in each house, although the size of kitchen varies, and the related information is also mentioned in the table below.

In this study, the life span of the residential buildings is considered to be 100 years. For the computation of embodied energy, the impact of transportation and separation to move building materials from one place to another is not considered. This study does not include the cost of shipping and handling. The transportation's life cycle ecological footprint is based on prior studies and data available on the Internet. The possible impact of the different building products and fuels used on embodied energy is also not considered. For the computation of operational energy, this study is centered on the buildings as they are. In this manner, the conceivable commitment from the metropolitan scale is not mulled over. It is assumed that the residential buildings taken here are partly occupied during the daytime from 9 am to 5 pm and are completely occupied during nights, weekends, and other public holidays for energy calculations. The yearly operational energy is viewed as steady all through the life expectancy of the building. Because of changes in climatic conditions and tenants' conduct, the building's operational energy may vary in the future; however, this is not contemplated in the investigation. For calculating the ecological footprint, some data, which were not available for the studied buildings, are taken from the previous studies [35,48].

There are various plumbing and sanitary fittings and fixtures installed in the kitchen, bathroom, or toilets of the houses. Due to the non-availability of data of the type of sanitary fixtures and fittings used in the houses, it is, therefore, omitted for the interest of the study. Due to consideration of building aging, it is important to include a maintenance period. The maintenance of any construction is dependent on the condition of the structure at the moment, and it varies from one structure to another. However, to make predictions easier, we used a 15-year maintenance/replacement interval for the structure. The structure's maintenance is highly reliant on the quality of material used. Plastering might require 4–5 years to supplant while flooring might take 10–15 years to supplant. It completely relies upon the part of the structure as well as the materials. The embodied energy of the building materials used in the construction of the structure is calculated for the overall

LCE of the house. The embodied energy embedded in the appliances used in the house is not included in this study.

4. Results and Discussion

4.1. Alternative Building Materials

The determination of materials and advances for the building development ought to the benefit the environment. The construction sector of India accounts for about 22% of the emissions of CO_2 in the atmosphere [49]. In the Indian construction industry, steel, bricks, and cement are the biggest and mass utilized materials. The use of conventional building materials should be minimized. The usage of a conventional brick, steel, and cement should be reduced by using alternative materials as identified, and the energy preservation measures must be adopted.

4.1.1. Basic Building Materials

The estimations of energy are utilized by the materials' producers in India (Appendix C). These can be used for the calculations of energy. For decreasing the EE of buildings, substitute building technologies can be used. These are: filler slab roofs, prefabricated roofing systems, Stabilized Mud Blocks (SMB), Lime-Pozzolana (LP) cements, Clay Fly-ash Brick (CFB), Reinforced Concrete (RC) slab using PPC, etc.

Table 2 presents the embedded energy in basic building materials. The LP cement can be used as an option to the conventional cement particularly for applications such as plastering, masonry mortar, etc. Steel and aluminum are both high-energy metals, so they can be avoided as building materials and replaced in PVC or UPVC and wood substitutes.

Table 2. Common building materials with their embedded energy.

Materials	Cement	Lime	LP	Steel	Aluminum	Glass
Thermal energy (MJ/kg)	*5.85*	*5.63*	*2.33*	*42.0*	*236.8*	*25.8*

4.1.2. Materials Used in Masonry Walls and Energy in Masonry

The masonry walls are important energy-expending parts of a building. Various types of materials are being utilized in masonry wall construction. The building block types which can be used are analyzed in Table 3. The stone block has the least amount of energy when compared with other masonry materials and is followed by Soil-cement block.

Table 3. Masonry materials with their embedded energy.

Material	Burnt Clay Brick (BCB)	Stone Block	Concrete Block (Hollow)	Soil-Cement Block	Steam-Cured Block
Size (mm)	*230 × 105 × 70*	*180 × 180 × 180*	*400 × 200 × 200*	*230 × 190 × 100*	*230 × 190 × 100*
Energy in one brick/block (MJ)	*4.45*	*0*	*12.30 (7% cement)*	*2.52 (6% cement)*	*6.65 (10% lime)*
Energy/brick equivalent (MJ)	*4.45*	*0*	*1.32*	*1.00*	*2.60*

Masonry is the congregation of different types of masonry units. It includes the energy substance of brickwork units just as mortar, which shows the energy content for it. Table 4 shows different masonry types and the energy embedded in them.

Table 4. Different masonry types and their embedded energy.

Type of Masonry	Hollow Concrete Block		Burnt Clay Brick	Steam Cured Mud Block	Soil Cement Block	
Energy/m^3 of Masonry (MJ)	818 (7% cement blocks)	972 (10% cement blocks)	*2141*	1397 (10% lime blocks)	644 (6% cement blocks)	811 (8% cement blocks)
Equivalent of brick masonry energy (%)	*38.3*	*43.4*	*100*	*63.2*	*30.2*	*36.5*

4.1.3. Energy in Mortars

Mortar is made up of materials having cement-like properties by mixing sand and lime. The different types of mortars used are cement-soil mortar, cement mortar, LP mortar, and cement-pozzolana mortar. The energy content/m^3 of these mortars is studied. It shows that the LP mortars have the least energy esteem when contrasted among different mortars. In addition, if pozzolana replaces 20% cement, it can lead to a drop of about 25% in the energy of the cement mortar [23].

4.1.4. Energy in Flooring and Roofing

The different typologies of roofs and floor systems can be summarized as follows:

1. The RC section rooftop or floor expends the most noteworthy measure of energy while the ferroconcrete tile rooftop devours the least energy;
2. The 20% energy reduction in the RC slab is due to the use of SMB fillers;
3. The Mangalore tile roof is the lowest energy-expending roofing material when compared with the conventional material frameworks. Its energy content is 30% of the RC sections;
4. The RC ribbed chunk rooftop frameworks devour around 66% of energy in the RC section rooftop/floor. This is the other suitable method of decreasing the energy of the RC solid piece.

Various substitutes are accessible for the development of the floor/rooftop of a building. These choices are being utilized for the development of Indian residential buildings. The roofing and flooring energy as per materials used are presented in Table 5.

Table 5. Roofing and flooring energy.

Type of Roof/Floor	RC Slab	SMB Filler Slab	BCB Masonry Vault	Composite Brick Panel	RC Ribbed Slab	Mangalore Tile	Ferro-Concrete
Energy/m^2 of plan area (MJ)	732	589	565	558	487	237	160
Equivalent of RC solid slab (%)	*100*	*81.8*	*79.8*	*77.7*	68.3	32.1	22.6

4.1.5. LCE and LCEF Reduction Using Solar Photovoltaics

There is different research [50–56] concerning the Life Cycle Analysis of various kinds of Solar Photovoltaic (SPV) modules that decrease ecological impact. In India, generally, monocrystalline SPV modules are utilized as housetop SPV frameworks since their proficiency is high when contrasted with different kinds of modules [51,57,58]. It has been assessed that the normal lifecycle ecological footprint per m^2 of the solar photovoltaic framework is 0.0694 gha/m^2. If the network power utilization is replaced by 100%, 85%, 60%, and 35% through the 'Grid-Connected Rooftop Solar Photovoltaic' (GRSPV) framework, it can decrease up to 60%, 45%, 30%, and 12% of the all-out LCEF of the buildings individually [14]. Agarwal et al. [59] found that during the lockdown in COVID-19 pandemic situation, the operational energy demand was increased in residential buildings. Kapoor et al. [60] stated that the increase in operational energy demand is obvious due to the productivity, health, and comfort perspectives in buildings. However, it must be optimized to enhance the sustainable use of available energy without much wastage. Power utilization during the operational period of the building can be decreased to bring down its life cycle energy to make it economically feasible. To meet the need for hot water in residential structures, the most basic and inexpensive solar water heater is a flat plate solar collector (FPSC), which absorbs solar radiation to enhance the thermal energy of fluid. In the near future, this can be an appropriate technology to reduce buildings' operational energy [61]. Phase changing materials are also one of the rapidly growing building materials to reduce electricity load in buildings while maintaining thermal comfort in the buildings [62,63]. Building-Incorporated Photovoltaic (BIPV) boards generally decrease the LCE utilization of the building. Even though the building's embodied energy accounts for just 25–49% of the building's LCE, the chance for its reduction through low embodied energy materials needs to be thought of.

4.2. Building Life-Cycle Energy (LCE)

For determining the total LCE, both the initial and recurring embodied energy is worked out separately using the Equations (2) and (3), respectively, and then summed up to find out the total embodied energy. The electricity bills paid by the residents for their residential buildings are collected by visiting the sites to calculate the total electricity consumption. Figure 3 represents the total EE of the five studied houses.

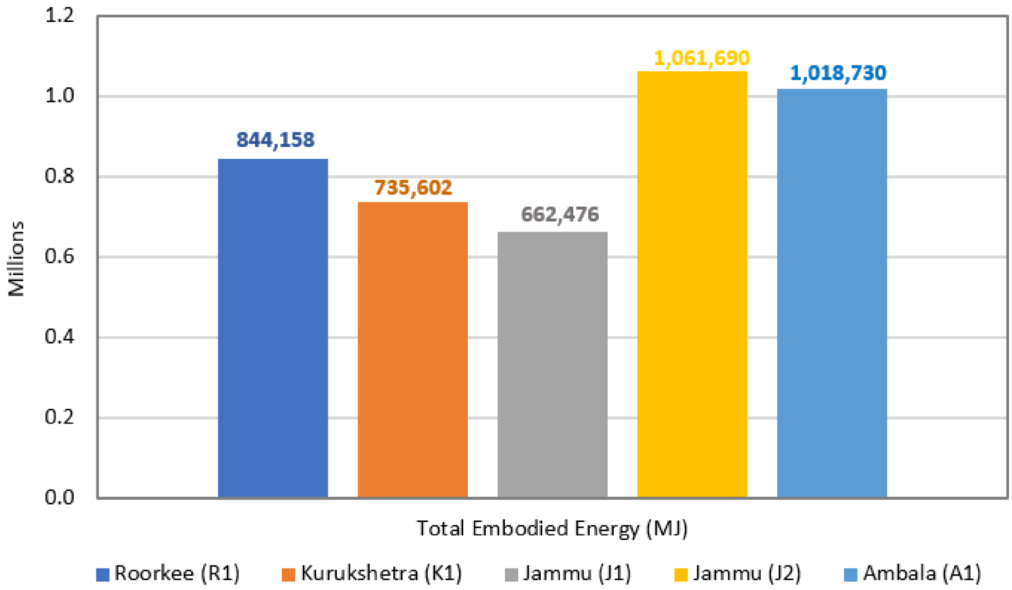

Figure 3. Comparison of the total embodied energies of the five studied houses.

Approximately, the areas of all the considered residential building cases are equal (155–165 sqm). It was seen that the residential house in Jammu (J_2) has the maximum amount of EE, while the residential house in Jammu (J_1) has the minimum amount of EE among the five cases. For the OE of the house, Roorkee (R_1) has the maximum OE, and the OE of Jammu (J_1) is the minimum among the five cases. These results are shown in Figure 4.

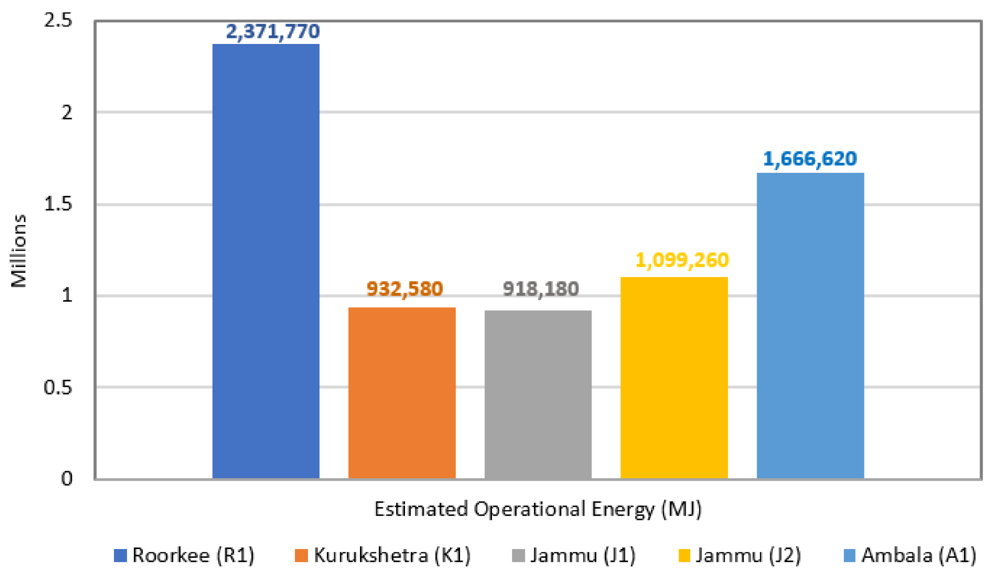

Figure 4. Comparison of the operational energy for the five studied houses.

Considering the LCE analysis of these houses, it can be seen that the Roorkee house has the highest LCE but less EE, and Jammu (J_2) has the highest EE but less LCE when compared to the Roorkee (R_1) case as shown in Figure 5.

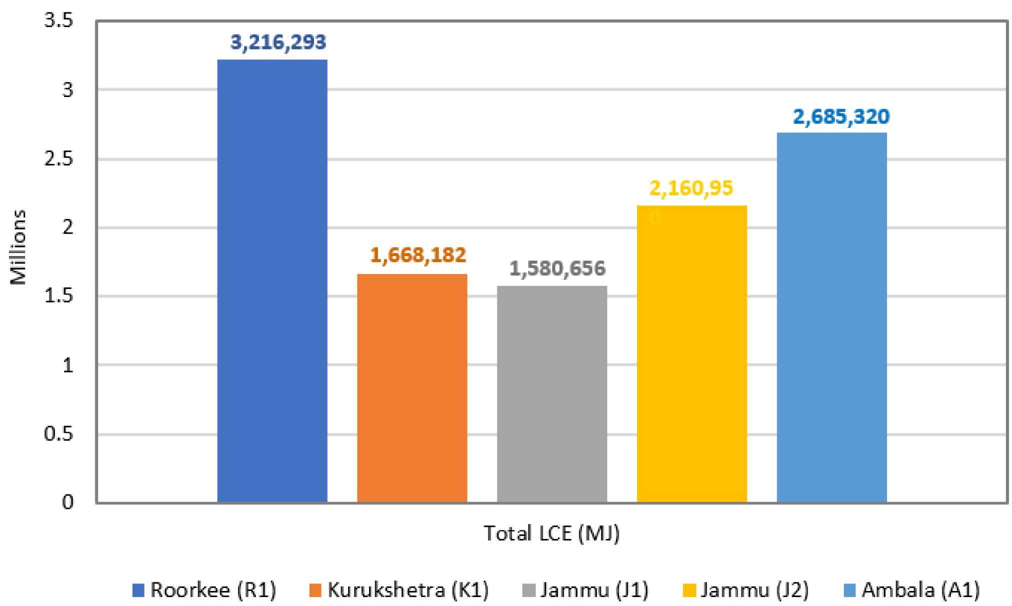

Figure 5. Comparison of the total LCE of the five studied residential buildings.

From the studied houses, it is also observed that the EE generally takes 25–49% of the total life cycle energy depending on the materials used, and the OE may fluctuate from 50–75% (based on the appliances/equipment used) of the total LCE. The operational energy split for the studied houses uncovers that energy for heating, ventilation, and cooling (52–62%) is majorly responsible for the operating energy followed by artificial lighting and the use of appliances. The average share of OE and EE in the LCE of buildings is presented in Figure 6.

4.3. Ecological Footprint of the Building Life Cycle (LCEF)

For determining the total LCEF of Buildings, all factors, i.e., $LCEF_{(m)}$, $LCEF_{(built\text{-}up\ land)}$, $LCEF_{(w)}$, $LCEF_{(we)}$, and $LCEF_{(e\ \&\ m)}$, are calculated separately. From the studied houses, the total LCEF of buildings is calculated in the range of 242–401 gha, which is shown in

Figure 7, and the average annual EF per person of the five buildings studied is shown in Figure 8.

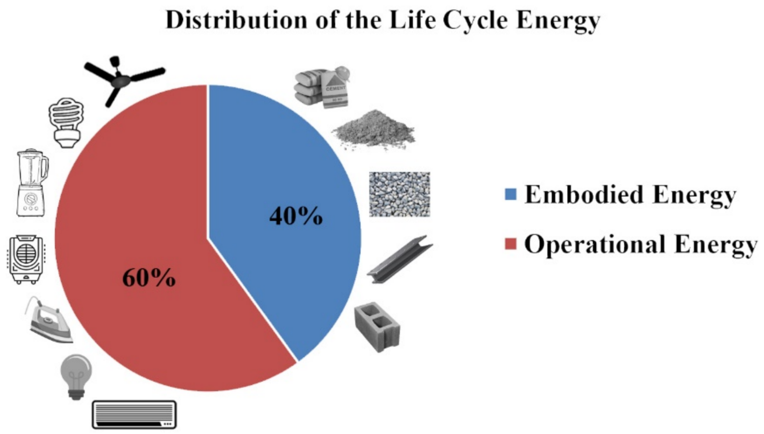

Figure 6. Detailed distribution of Life Cycle Energy of the Ambala (A_1) Case.

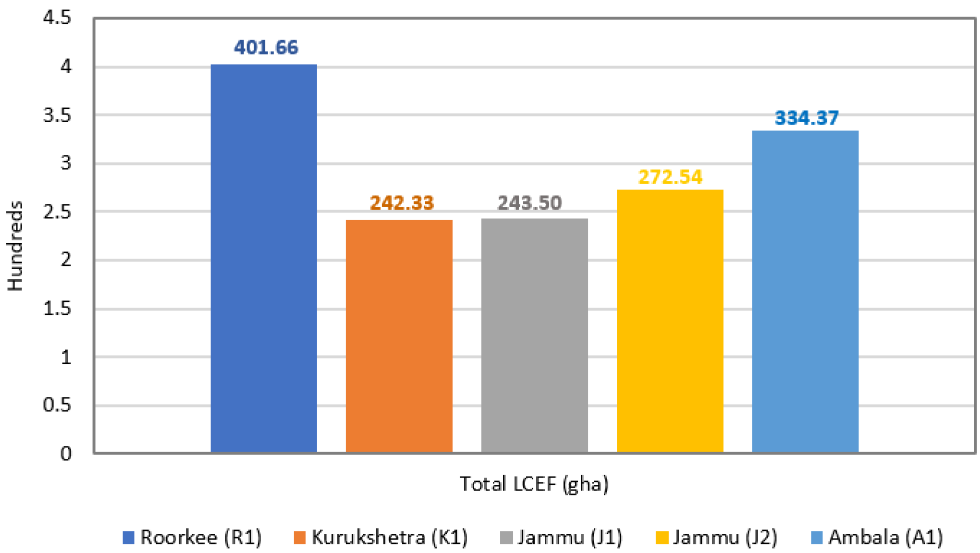

Figure 7. Total LCEF of the five studied houses.

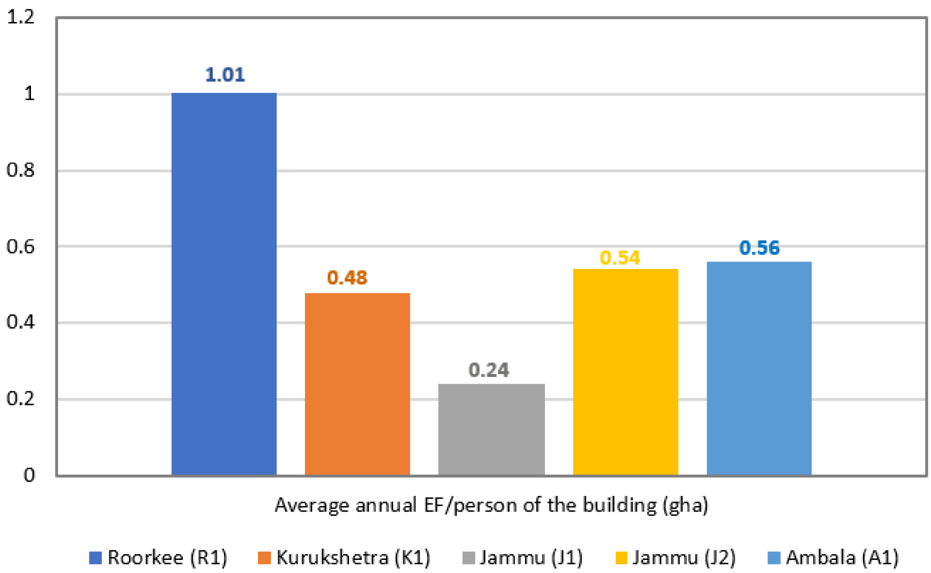

Figure 8. Average annual EF/person of the five studied buildings.

The LCEF of the utilization of energy and materials is determined by the inventory of the construction materials, OE, and demolition energy (DE) of the building during its life cycle. It is highest for Roorkee (R_1) and lowest for Kurukshetra (K_1). This is majorly due to the $LCEF_{(t)}$ calculation, but construction site location also plays a major role. The transportation of workers, materials, and the construction and demolition waste in the life cycle of the building depends on the site location. The LCEF of the manpower is calculated through the food consumed in the working hours by the laborers. The monthly consumption of goods per person in urban areas of India is estimated through the National Sample Survey Organization (NSSO) report [44]. The construction and demolition waste in the whole building life is evaluated by the use of real data of the type of buildings and the built-up area. For the estimation of the $LCEF_{(w)}$, the CO_2 absorption land is taken into consideration. The building construction phase requires a huge amount of water. Water consumption is worked out by means of building per floor area basis data [47]. Water consumed in the use phase, demolition, and maintenance of the building is not considered due to the lack of available data. It is seen that out of all the footprint types, CO_2 absorption by land has the supreme fraction, which is 99% of the total land impact.

4.4. Generic Model for Life Cycle Energy

A generic model for the life cycle energy has been developed in MATLAB and is explained with the example of the Roorkee building case R_1. The plan of the Roorkee building is presented in Figure 9.

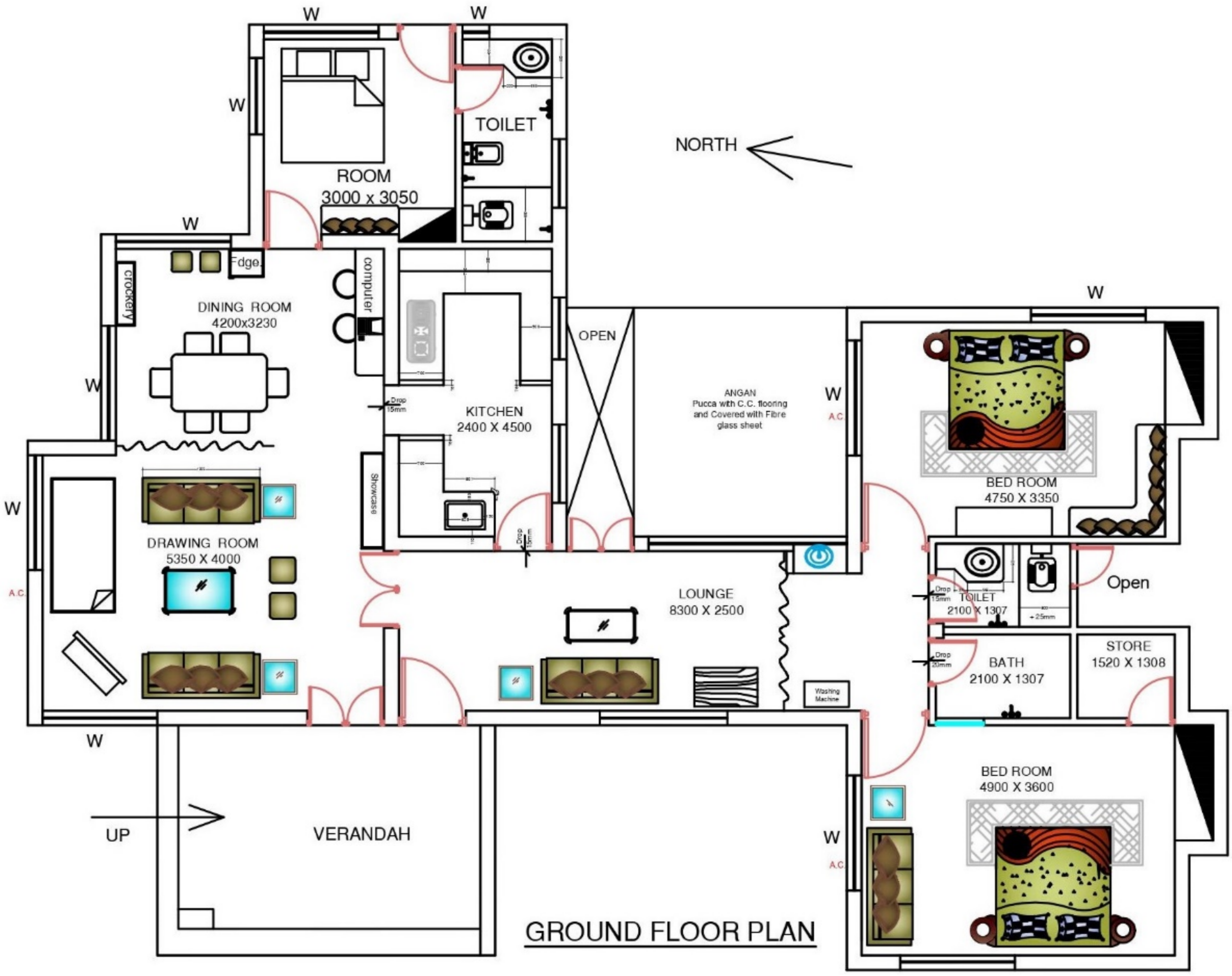

Figure 9. Plan of a residential building in Roorkee—Case (R_1).

The code written is applicable to any building located in any city in India and only the input parameters of the "data file" are to be replaced by the data file of the building whose life cycle energy we are intending to calculate. In the present case, R_1, the data file denotes the data prepared by the authors manually for the life cycle energy calculation, where "m" stands for the lifespan of the building and "n" stands for the operational energy of the building in a year. The eei (i,j) stands for the initial embodied energy in which e1 (i,j) is the data of the quantity of building materials and e2 (i,j) is the data of the energy content of the materials. The data is to be entered to calculate the eei (i,j). Moreover, eer (i.j) is the recurring embodied energy in which eei(i,j) stands for the initial embodied energy, and e3 (i,j) stands for the data of the life span of the building materials used. OE is the operational energy in which "n" stands for the operational energy of the house in a year and "m" stands for the life span of the building taken. LCE (i,j) is the total life cycle energy, which is the sum of all the energies calculated. In the same way, the life cycle energy of other residential buildings can be calculated by entering the data of that particular building whose LCE we want to calculate. The comparison of the calculations performed manually (analytically) and by the use of the generic model is shown in Figure 10. The results from the analytical calculations show a much smaller error percentage. This validated our study for the calculation of the LCE of the residential buildings using the MATLAB program. The mobile application developed is presented in Appendix A.

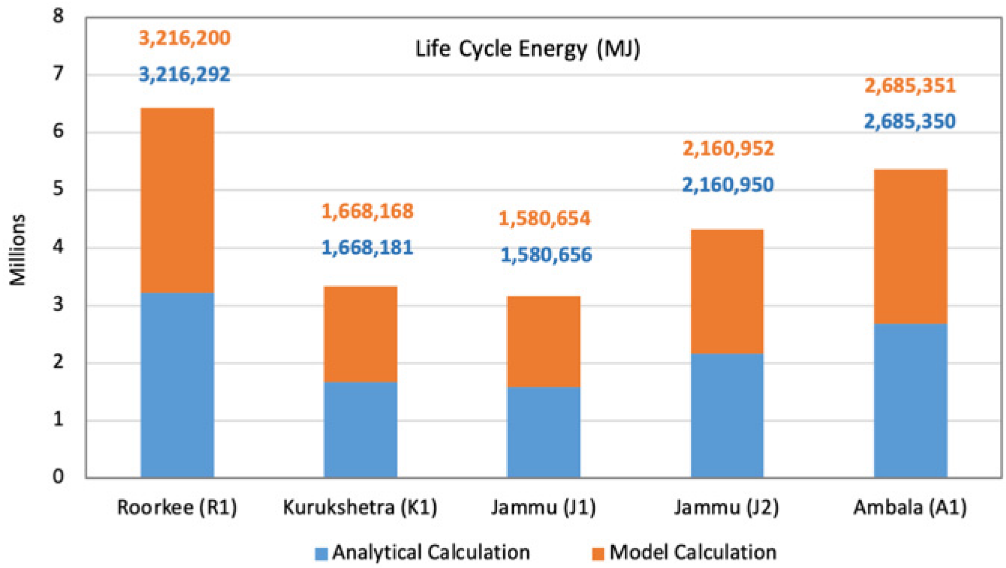

Figure 10. Comparison of LCE calculations for validation (Unit: MJ).

The MATLAB explanations (Appendix B) are provided to help the multidisciplinary audiences to easily follow up this work or replicate this study in their countries and enhance the knowledge at the global level. The source code is not included in this article due to privacy concerns, and the mobile application uses a broad database that is based on deep literature review, extreme research, and rigorous calculations of real-time materials. However, when the authors complete their study totally, after receiving permission from a competent authority, all the data will be shared.

The mobile app section is included in this article as an Appendix to inform the readers about it so in the future they can download it from the appropriate platforms and use it widely. The general public needs some easy-to-use calculation tool to find out the impacts of different building materials in real-time. This mobile application related to the study will help in enhancing the subject knowledge in an interesting manner in the general public, who are not subject experts. While considering the real-time application of the developed model, users can easily compare the impact of the building materials in terms of energy and ecological impact on the Earth. Users with zero or little knowledge can also use the developed mobile app to find out the impacts of their selected building material (purchased for constructing their homes) on nature. Sustainability goals can only be achieved in real-time when simple mobile apps (such as the developed one) help non-expert users to contribute to the same direction. This noble effort (model and mobile application) can also enlighten the knowledge of the subject in residents and all in a state-of-the-art manner, i.e., a mobile application. Residents can practically download the mobile app based on the model to find out the energy and ecological impacts of their selected building materials. Furthermore, the app is designed to update the energy data as users can also add material and energy after downloading the app on mobile.

Finally, some of the materials and technologies recommended to reduce the ecological footprint of buildings include the following: strategic use of continuous insulation throughout the envelope, installation of energy efficient lighting fixtures, use of smart appliances, and the utilization of renewable energy to reduce the OE-associated ecological footprint in the building. Concrete can be manufactured partly from secondary raw resources such as municipal solid wastes, used plastic, and electrical equipment to decrease EE and thus reduce the associated ecological footprint. Furthermore, bio-composite materials and resins made from agricultural waste and feedstock, as well as the stems of tough plants such as flax and jute, can be used to replace concrete. In addition, new types of cement are being developed based on low carbon binders to replace existing varieties such as Portland cement. New concrete casting techniques, 3D printing replacing traditional materials, and the conversion of excavation waste into building materials are all expected to transform the EE-associated ecological footprint scenario during the construction of future buildings.

5. Conclusions

This manuscript is based on the study of five residential buildings in the composite climate of India. The ecological impact of residential buildings during their lifespan is evaluated in this case study. The alternative building materials have been studied, which shows that the utilization of low-energy building materials brings about a significant decrease in the EF and the LCE of the buildings. The following conclusions emerge from this study:

- Cement blocks mixed with soil are the most energy-efficient material for walling, which expends only a little amount of energy of consumed mud block. Concrete blocks and steam-cured bricks additionally expends less when contrasted with the burnt clay brick;
- LP mortars have the most reduced energy content in comparison with the different mortars such as cement mortar, concrete pozzolana mortar, etc.;
- The SCB masonry is the most energy productive at around 33% of the energy of the BCB masonry;
- The utilization of energy-productive alternative building advancements can bring about a decrease in the EE of the buildings. The embodied energy can be reduced to 62% when we use SMB fillers. It is then compared with the burnt clay brick masonry, which shows a 45% decrease in the embodied energy;
- Other than the solar PV frameworks, the buildings may need to embrace extra green buildings advancements such as sun-powered cooling/warming frameworks, lime-calcined clay concrete for altogether decreasing the CO_2 ingestion land, which brings about the decrease in the LCEF of the buildings;
- The study shows the contribution of operational and embodied energy in total LCE. A significant contribution of embodied energy in total LCE is noted due to the type of building materials used during construction and maintenance;
- The alternative building materials and technologies were to be developed and researched more as it can potentially affect the total LCE;
- The results indicate that the LCE can be reduced substantially by using low-energy materials and using low-energy-star-rated appliances and lighting fixtures.
- The Life-Cycle Energy Assessment (LCEA) and Life-Cycle Ecological Footprint (LCEF) are two management methods used to assess energy, ecological impact, as well as environmental issues. In the construction industry, the value of LCEA and LCEF as a

decision-making tool are growing continuously every day. It is difficult to measure and explain the relative weighting of diverse ecological consequences caused by variations in Life-Cycle Energy (LCE). The proposed model will help stakeholders to identify the LCEF via calculating the LCE. Thus, users can reduce the coming ecological burden due to the building materials. Users can also compare different materials and their impact simultaneously and can decide to choose alternative low-energy material that suits them, as well as nature. By the above-mentioned mechanism, this proposed model can help in reducing the ecological burden of building materials and leads towards sustainable development.

Author Contributions: Conceptualization, A.K. and P.S.; methodology, A.K., C.S.M. and R.C.; software, N.R.K., C.S.M. and K.J.; validation, K.S.K., C.S.M. and N.R.K.; formal analysis, A.K.; investigation, P.S.; resources, A.K.; data curation, P.S.; writing—original draft preparation, A.K., P.S., N.R.K., C.S.M. and R.C.; writing—review and editing, A.K., N.R.K., C.S.M. and R.C.; visualization, N.R.K., C.S.M. and R.C.; supervision A.K., C.S.M. and R.C.; project administration, A.K., C.S.M. and R.C. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Mobile Application for LCE

As the world is focusing more on the sustainable type of development, the LCA tools such as life cycle energy and ecological footprint will play a major role in the development of the world sustainably. Building-integrated photovoltaic systems are found to be generally encouraging for the decrease in LCE, and hence, more studies should be conducted on them for a clearer picture of this system. In addition, more work should be done on alternative building materials so that environmental sustainability can be attained. These life cycle assessment tools have a wide scope for measuring the sustainability of the system and hence more parameters should be considered for the wider research of these tools.

Therefore, looking into the complexity of the subject of LCE, a smart mobile application (App) is developed to assess Life Cycle Energy levels (OE, EE, DE) of residential buildings. The App uses Java Programming Language (Android 10), with the help of MySQL Database with the inheritance of data analytics by Tableau. The app dynamically models the data and can take user geographic location as well as Indian climatic zone automatically. The application is capable of capturing the carpet area by the use of the intense camera (Deep Learning Camera). Users can feed customized data to obtain the exact energy values with high precision. In addition, users can manually select the climate and typology of building according to their location, and select building area, foundation type, building envelope materials, and lifespan of the building, etc. Built-in formulas will calculate the initial and recurring embodied energy, as well as operational energy. Furthermore, with an option, users can see the pie-chart division of the various energy types. Users can also find bar charts providing the dynamic forecast of upcoming years with the time interval of five years. Forecasting data will be embedded and the charts will dynamically change (every 5 years' gap) depending on changes in operational energy due to the adaptive behaviors of users. Increased energy usage in the future due to climate change is also considered in this App. A few screenshots and a schematic representation of the application are presented below in Figures A1 and A2, respectively. More of this type of user-friendly applications are under process at CSIR-CBRI Roorkee as per the societal requirement.

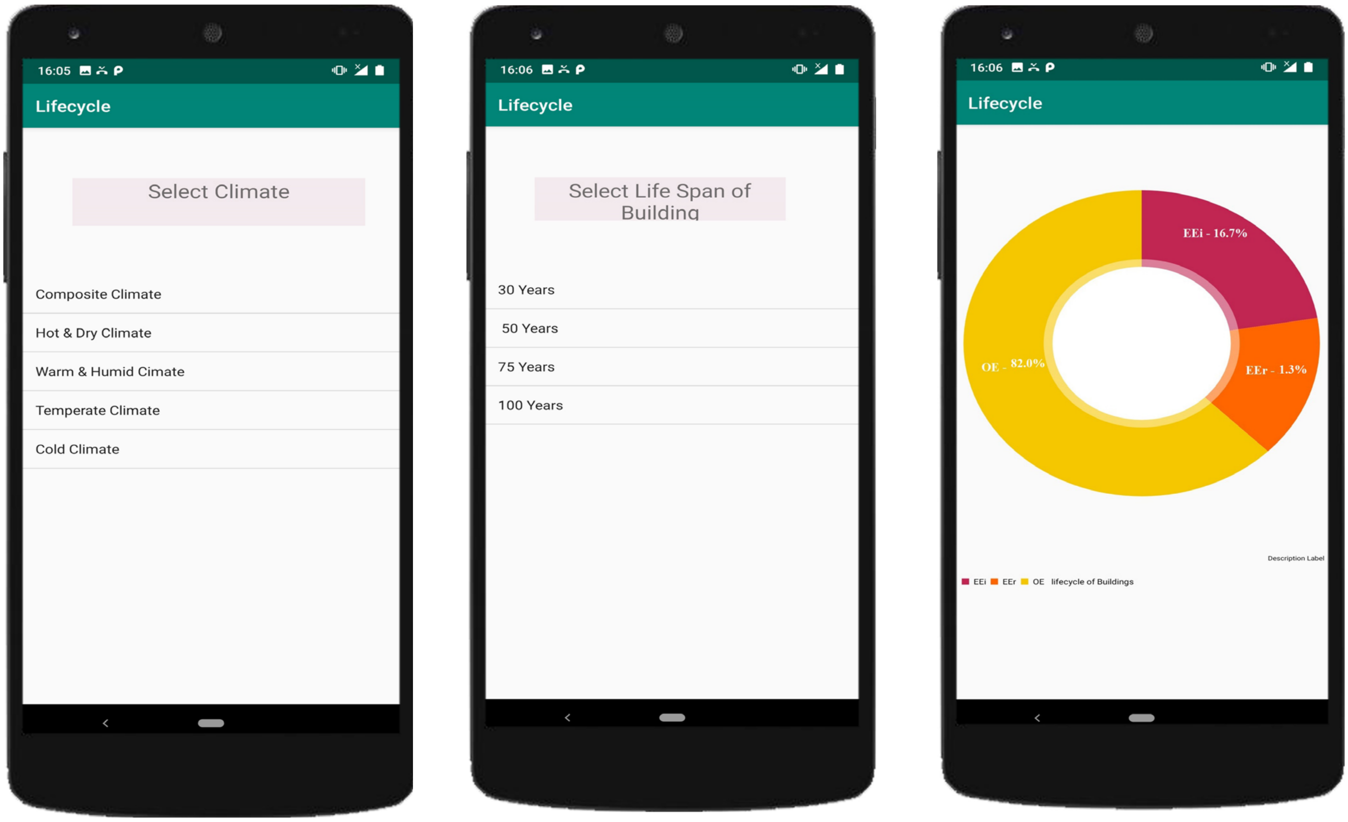

Figure A1. Screenshots of the developed mobile application (App) for life cycle energy.

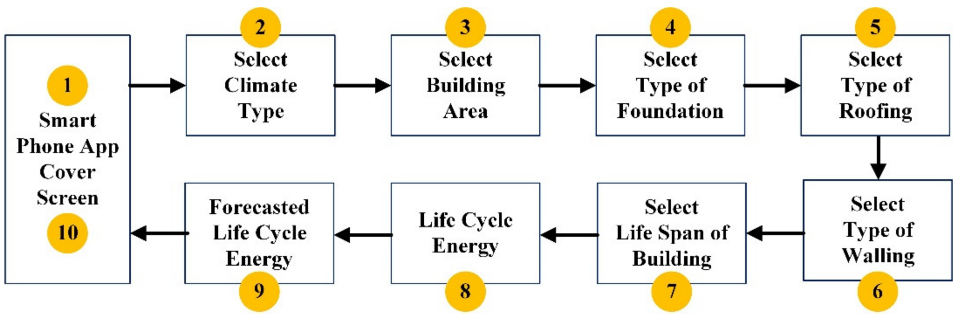

Figure A2. Schematics of the life cycle energy application.

Appendix B

MATLAB Code

```
clc
clear all
load('datafile1');
dtarorke = model;
m = 100; n = 23,723.15;

e1 = zeros(16,1);
e2 = zeros(16,1);
e3 = zeros(16,1);
```

```
e1 = dtarorke(:,1);
e2 = dtarorke(:,2);
e3 = dtarorke(:,3);

eei = zeros(16,1);
for i = 1:16
  for j = 1:1
    eei(i,j) = e1(i,j) × e2(i,j);
   end
end
eer = zeros(16,1);
for i = 1:16
  for j = 1:1
  eer(i,j) = eei(i,j) × [(m/e3(i,j)) − 1];
  end
end
OE = n × m;
eeisum = sum(eei);
eersum = sum(eer);
OEsum = sum(OE);
LCE(i,j) = sum (eei) + sum(eer) + sum(OE);
LCEsum = sum(LCE);
```

Appendix C

Table A1. Building materials' embedded energy and properties.

Materials	Praseeda et. al. 2015 [8]	Inventory of Carbon and Energy [64]	Properties of Different Building Materials
FCB	1.20–4.40 MJ/kg	-	They are yellowish-white in color. The compressive strength ranges from 200 to 220 kg/cm^2.They have good chemical resistance.
FAB	1341.00 MJ/cm^3	-	They have higher compressive strength and have good dimensional stability.
Cement (Portland)	2.38 MJ/kg	-	-
Steel (Gen)	32.24 MJ/kg	-	It has great formability and durability, good tensile and yield strength and thermal conductivity.
Sand	0.037 MJ/kg	-	Its properties include porosity, cohesiveness, adhesiveness and plasticity.
Aggregate	0.04 MJ/kg	-	The size of fine aggregate is 4.75 mm and that of coarse aggregate is bigger than 4.75 mm.
Polystyrene sheet	86.40 MJ/kg	-	These are rigid, brittle, and moderately strong.
Plywood	-	15.00 MJ/kg	It has high strength and dimensional stability.
Glass (float)	7.88 MJ/kg	-	These have high degree of light transmission and good chemical inertness.
Concrete (plain)	-	0.95 MJ/kg	This concrete is more durable and has high compressive strength.
Concrete (reinforced)	-	1.21 MJ/kg	This has high relative strength and high toleration of tensile strain.

Table A1. *Cont.*

Materials	Praseeda et. al. 2015 [8]	Inventory of Carbon and Energy [64]	Properties of Different Building Materials
Bricks (common)	-	3.00 MJ/kg	The standard size of brick taken in India is 190 mm × 90 mm × 90 mm
Marble	-	2.00 MJ/kg	It is durable, long lasting, and easy to maintain.
Timber	-	8.50 MJ/kg	A good timber gives good sound and is easy to work on. The texture of good timber is fine and even.
Clay tile	4.93 MJ/kg	-	It has low maintenance and is weather-resistant.
PVC	-	77.20 MJ/kg	It has good dielectric strength and is resistant to weathering, chemical rotting, corrosion, etc.
Iron	-	25.00 MJ/kg	It is capable of being shaped or bent. It has good transmission of heat and electricity.
Aluminium (Gen)	-	155.00 MJ/kg	It is a lightweight metal and is corrosion-resistant. It is an excellent heat and electricity conductor.
Stone	-	1.00 MJ/kg	Its property depends upon the stone type and climatic conditions which vary from place to place and where it is used.
Concrete precast	-	2.00 MJ/kg	It has great dimensional accuracy and design flexibility.
Cement mortar (1:4)	-	1.21 MJ/kg	The mortar should be water-resistant, and the deformability of mortar should be low. Its mobility should be good.
Ceramic tiles	10.63 MJ/kg	-	It does not retain dust and is skid as well as stain resistant.
Copper	-	42.00 MJ/kg	It has good corrosion resistance and has excellent heat and electrical conductivity.
Burnt clay bricks	1.30–4.05 MJ/kg	-	They have good resistance to moisture, insects, and erosion and create a good room environment.
Steel (reinforcing, sections)	8.90 MJ/kg	-	It possesses high tensile strength and elasticity, and its thermal coefficient is nearly equal to that of concrete.

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