Life Cycle Emission Analysis and Case Specific Mitigation Strategies for Hostel Buildings in the Lower Himalayan Region.

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ABSTRACT

Buildings account for a significant share of global carbon emissions, yet comprehensive lifecycle frameworks for assessing their full environmental impact remain limited in the Indian context. The study evaluates the environmental impact of a residential building in the lower region of north India. This case specific framework integrates life cycle assessment (LCA) in terms of operational energy analysis, embodied energy accounting, and carbon emission estimation. A detailed material and energy inventory was compiled, with embodied energy coefficients and emission factors sourced from peer-reviewed literature. Results indicate that the operational stage dominates the building's carbon profile, contributing 73% of total lifecycle emissions driven primarily by occupant metabolic CO_2 and electricity consumption. The total carbon footprint is estimated at 12.77 million kg CO_2 equivalent, with brick and reinforced cement concrete identified as the most energy and emission intensive materials. Three mitigation strategies were evaluated: replacing grid electricity with photovoltaic panels reduces electricity related emissions by 96%; substituting LPG with kitchen waste biogas achieves a 15.6% reduction in cooking emissions; and plantation of 90 mature trees enables full carbon sequestration. Collectively, these measures reduce the building's lifetime emissions by approximately 38%. The proposed framework offers a replicable, case specific approach to carbon assessment and mitigation planning, applicable to other residential buildings seeking to align with sustainable construction goals.

Keywords: emissions, embodied energy, hostel building, sustainability, operational stage.

INTRODUCTION

Sustainable development has now been embossed in human consciousness (Brandon & Lombardi, 2011). It has led to changes in the priorities of global agendas such as the Sustainable Development Goals and the 2015 Paris Agreement. Scholars and environmentalists have long warned of the consequences of unchecked human activity on the planet, including global warming, habitat loss, resource depletion, and widespread pollution (Gore & Gore, 1999; Jackson, 2009; Lovelock, 2009; Rees, 2009). Despite widespread awareness, no single solution has yet proven sufficient to reverse these complex trends.

Peter and Brandon (Brandon & Lombardi, 2011) have highlighted a spectrum of views for sustainable development. At one extreme is the ecological viewpoint that emphasizes harmony with nature, urging radical lifestyle changes and curbs on urban expansion. At the other is the techno-centric perspective, which advocates technological innovation to mitigate environmental harm while maintaining development trajectories.

India, ranked as the third-largest emitter of greenhouse gases (GHGs) among the world's leading economies (World Bank: Washington, DC, USA, 2021), exemplifies the scale of this challenge. In 2022 alone, its CO_2 emissions rose by 6.52%, adding over **164 million metric tons** to previous levels (*India CO2 Emissions*, 2024). Acknowledging this trajectory, India pledged at **COP26** to achieve net-zero emissions by 2070 (Ministry of Environment, Forest and Climate Change, 2023).

The building construction industry is a crucial sector for achieving these climate targets. It is one of the world's largest energy consumers, accounting for 40% of total energy consumption (Mathumitha et al., 2024) and 37% of energy and process-related CO_2 emissions globally (United Nations Environment Programme, 2021). Consequently, sustainable construction methods are increasingly prevalent to alleviate the environmental and energy crises. Although sustainable construction involving new materials may incur higher initial costs, they offer longer economic value in the long run. Sustainable buildings can save money by reducing carbon emissions, optimizing input usage, and lowering operation costs. Moreover, good design enhances the comfort and natural living experience of occupants. Materials used in sustainable construction tend to be more environment friendly and harmless, safeguarding occupants from harmful substances (Y. Wang, 2023). A triple-bottom-line approach is important for any design and construction practice where social, environmental, and economic principles are integrated to achieve more sustainable outcomes (Goh et al., 2020).

Assessing the sustainability involved in the life cycle of any construction helps in identifying the scope and direction of improvement for sustainable and cost-effective decision-making (Chen et al., 2025; Y. Dong et al., 2023; Fan et al., 2025; Figueiredo et al., 2024; Milić & Bleiziffer, 2024; Ullah et al., 2023). ISO 14040:2006 provides a detailed framework for Life Cycle Assessment of any construction (ISO, 2006). It is an intricate process involving various phases, viz., setting up the goal and scope, the life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase, interpretation, and reporting phase. The sub-processes involved may differ in importance due to the specific characteristics of the built environment project (Moncaster & Song, 2012).

Studies have also suggested broadening the scope of LCA by considering factors like indoor environmental quality, building location, and social factors (Chau et al., 2015). LCA also offers a framework for evaluating buildings' resource use and enviromental impacts (W. Dong et al., 2024), and its early application can greatly improve sustainability (Hansen et al., 2023; Schneider-Marin & Lang, 2020).

The construction and management of built environment utilize enormous resources and energy, affecting the environment and human health in numerous ways (Ioppolo et al., 2019). These concerns must be understood from a life cycle perspective (Asdrubali et al., 2013; Chau et al., 2015). Several approaches have been proposed to appraise the environmental impacts of any product or process. These can be classified into three major streams viz. Life Cycle Assessment (LCA), Life Cycle Energy Assessment (LCEA), and Life Cycle Carbon Emissions Assessment (LCCO2A) (Chau et al., 2015). LCA evaluates the all-inclusive environmental impacts of products in terms of their energy consumption, material usage, and discharges into the atmosphere (Eq. 1). It encompasses entire cradle-to-grave phase of the product, viz., extraction and processing of raw materials, their transportation, application (re-application), maintenance, and disposal.

$$I = I_{Extraction} + I_{Manufacture} + I_{Onsite} + I_{Operation} + I_{Demolition} + I_{Recycling} + I_{Disposal} \qquad (1)$$

Where,

I = life cycle environmental impact, and

Ij = environmental impacts of j^{th} building phase.

LCEA assesses the total energy used by a building in its lifespan (Eq. 2). However, it fails to present a genuine picture of the negative impacts as it does not segregate the renewable and non-renewable energies.

$$E = E_{Extraction} + E_{Manufacture} + E_{Onsite} + E_{Operation} + E_{Demolition} + E_{Recycling} + E_{Disposal} \qquad (2)$$

Where, E = total energy consumed during the whole life cycle of a building,

Ej = energy consumed during the j^{th} building phase.

LCCO2A determines the total CO_2 emitted by the building in its lifespan.

LCA approach is adopted for comprehending the environmental impacts of built environment round the globe, viz. India (Varun et al., 2012), China (Hao et al., 2020; J. Wang et al., 2018; Yang et al., 2018), Taiwan (Chou & Yeh, 2015), Japan (Endo & Takamura, 2021). Australia (Shahana Y. Janjua et al., 2019), United States (Ben-Alon et al., 2021; Hasik et al., 2019; S. Liang et al., 2020), Canada (Rezaei et al., 2019) Netherlands (Santos et al., 2020), Norway (Rabani et al., 2021) Sweden (Österbring et al., 2019; Petrovic et al., 2019), Argentina (Arena & de Rosa, 2023), Italy (Ardente et al., 2008; Blengini, 2009), Nigeria (Adeyeye et al., 2023), Thailand (Kofoworola & Gheewala, 2008).

METHODOLOGY

A building consumes energy and emits harmful pollutants during all processes involved in its construction and operation. Several materials are required for its construction, which must be extracted or prepared and transported to the site. All these processes consume energy, contributing to their embodied energy and associated carbon emissions as shown in Figure 1. Post-construction and during building occupancy, various operations run for its functioning, each consuming energy and resources in some form or another. These operations, alongside repairs and refurbishments, run throughout the building's lifespan. The End-of-Life stage addresses demolition, waste transport, recycling, and disposal. Finally, Beyond the Lifecycle includes reuse and recovery opportunities to mitigate further emissions.

To reduce the carbon footprint of building structures, it is essential to evaluate embodied carbon during the early design stages, since the structural framework often reflects the initial conceptual form of the building (Torabi & Evins, 2024). The study calculates the emissions and embodied energy in both the phases of the building, starting from the preparation (extraction, transportation, and manufacturing) of various building materials such as cement, brick, and MS frames to operational activities such as energy (electricity) usage, water consumption, cooking, and human respiration. The life span of the building for this case study is taken as 50 years. Emissions due to construction processes, and maintenance is not considered in the study. On-site construction activities (ISO, 2006 - stage A5), including equipment fuel use and site energy, were excluded from the system boundary due to the absence of site-specific machinery records. Literature indicates that material production and transportation together dominate 82-96% of construction-period emissions, with on-site activities contributing the remaining fraction (B. Surekha et al., 2016); their exclusion is thus expected to introduce a minor underestimation in total lifecycle emissions (Y. Liang et al., 2023). Maintenance-related emissions were similarly excluded; reviews of LCA case studies for 650+ buildings indicate that maintenance and renovations during the use phase can contribute approximately 22% to implied building carbon (Röck et al., 2020), and this is acknowledged as a limitation of the present study. Furniture emissions were also excluded due to the absence of standardized emission factors for the specific items procured and lack of procurement records; this is acknowledged as a limitation that may marginally underestimate total embodied emissions.

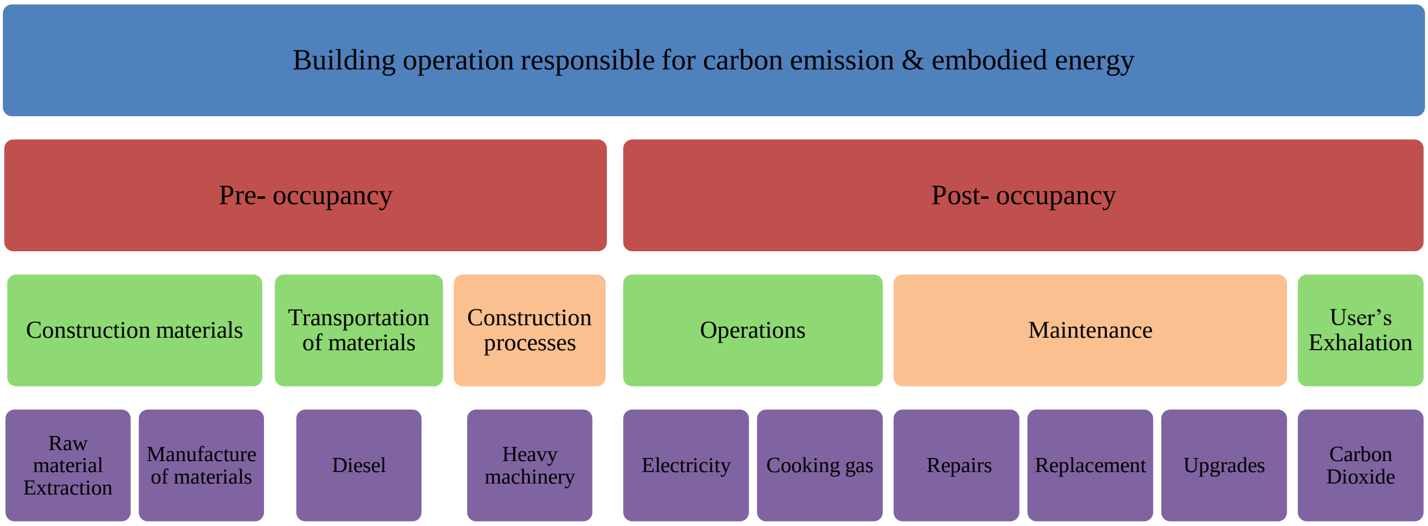

Fig. 1 Building Operations responsible for carbon emissions ans embodied energy

Carbon Emission

The total environmental impact of building in terms of carbon emissions of any building is the total pollutant (CO_2, CH_4, N_2O, SO_2, etc.) released to the atmosphere during the construction and operation of the building. It is the sum of the emissions due to all the materials used and activities involved during its construction and operation (Eq.3).

For each material or activity, emissions were estimated using:

$$E = Q \times EF \qquad (3)$$

Where:

E = total emissions (kg CO_2- eq.)

Q = quantity used or consumed

EF = emission factor specific to the material or activity

Emission factor (EF) is used to calculate the GHG emissions of a process or activity. An EF of any material is a value that represents the amount of a pollutant released to the atmosphere during the activity or manufacturing of the material. The potential impact of all the GHG gases is converted into an equivalent effect of carbon dioxide (CO_2) and is cumulatively expressed in terms of CO_2 equivalent (CO_2- eq.) which is a unit of measurement used to express the impact of different GHGs on global warming.

Emission factors for individual materials and operational carbon (electricity, Liquified Petroleum Gas (LPG), and user's exhalation) were derived from a review of relevant literature with similar research (Shams et al., 2011) and Inventory of Carbon & Energy (ICE) database.

Embodied energy

Embodied Energy encompasses the total energy consumed throughout the lifecycle of a building material from extraction and processing to transportation and installation at the construction site. This measure accounts for all direct and indirect energy inputs, including those associated with manufacturing, logistics, on-site assembly, and eventual renovation or demolition. It is a key parameter in evaluating the environmental footprint of construction practices (Almusaed et al., 2024).

Materials such as cement and steel contributes upto 30% of a building's lifetime energy demand (Ding et al., 2004). Beyond carbon output, the extraction and production of these materials can lead to habitat loss, resource depletion, and soil degradation (Hammond & Jones, 2008).

The embodied energy of a material or activity is calculated as the product of its quantity and its specific energy intensity, typically expressed in megajoules per kilogram (MJ/kg):

$$\text{Embodied Energy (EE)} = Q \text{ x Embodied Energy per unit} \qquad (4)$$

Where:

- EE = total embodied Energy (MJ/kg)
- Q = quantity used or consumed (kg)
- Embodied Energy per unit: Specific energy intensity for the material/process (MJ/kg)

Embodied energy per unit data for individual material was derived from recognized databases and peer-reviewed studies to ensure accuracy and consistency (Singh* et al., 2019; Varun et al., 2012).

By quantifying and analyzing embodied energy, practitioners can make informed decisions about construction materials prioritizing approaches that minimize environmental harm and resource consumption. This ultimately facilitates the selection of sustainable alternatives and encourages continuous improvement in building practices.

Case Study

The case study focuses on the Parvati Girls' Hostel at the National Institute of Technology (NIT), Hamirpur. The region falls under the 'subtropical highland' category of the Köppen climate classification ('Köppen-Geiger Climate Classification', 2010). It experiences hot summers and cold winters. Solar radiation is available throughout the year, ranging from 3.45 kWh/m²/day in December to 7.42 kWh/m²/day in May. The hostel building was constructed in 1998 and has a total built-up area of 3,522 m². It accommodated 160 students in total. The building is organized into six blocks (A, B, C, D, E, and F), offering various accommodation options tailored to meet the diverse needs of its residents. Blocks D, E, and F feature 54 single-seated rooms, and Blocks A, B, and C comprise 36 triple-sharing rooms.

Apart from 90 residential rooms, there are nine common washrooms, a dining hall, common room facilities, guest rooms and administrative rooms. Figure 2 represents the ground floor plan of the building and Figure 3 represents the typical floor plan for the first and second floors.

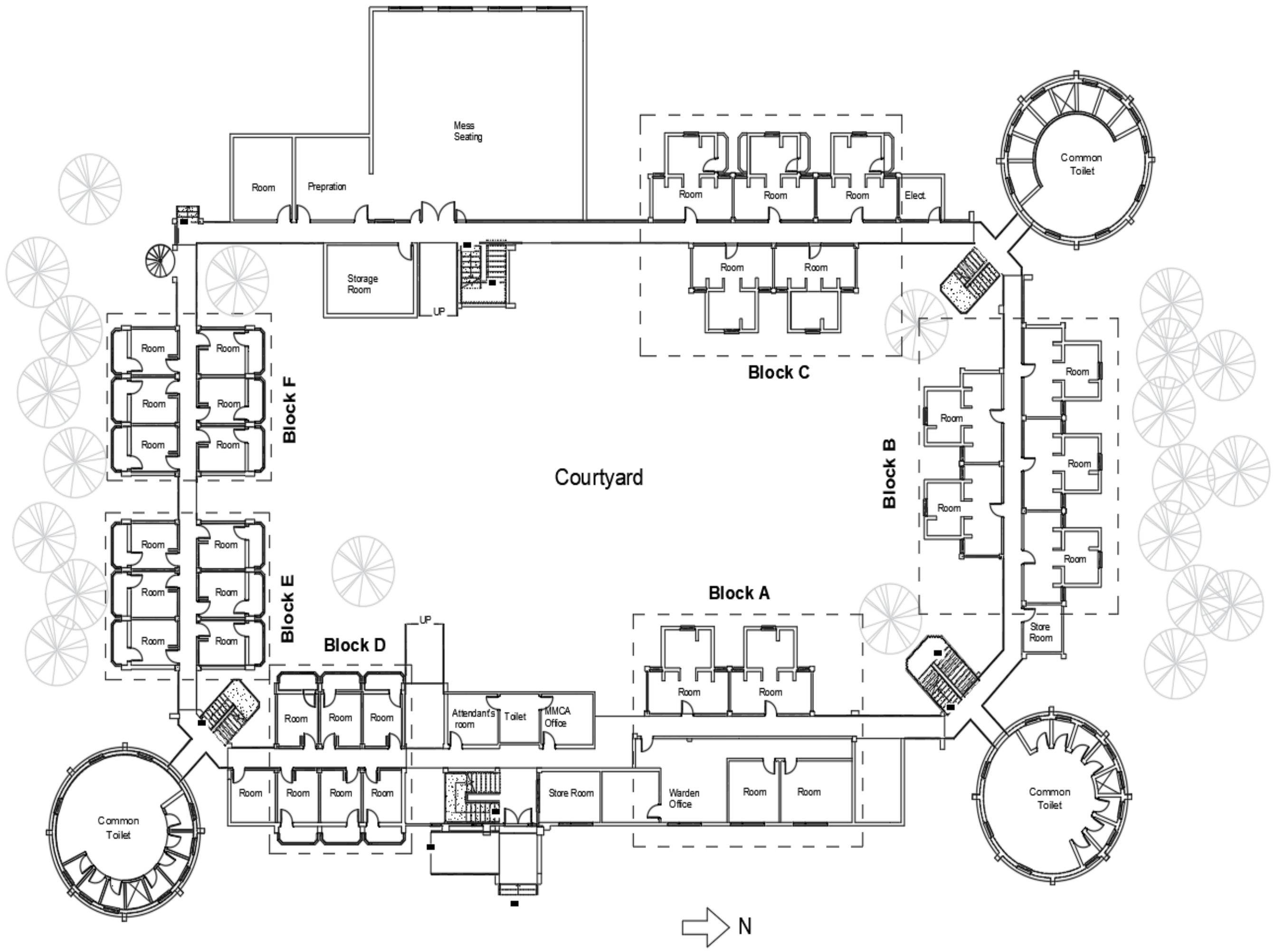

Fig. 2 Ground floor plan of the building

The external walls are constructed using stone masonry with a thickness of 300 mm. The internal partitions are built with 230 mm-thick brick. Fenestration includes external windows fitted with 4 mm-thick clear glass, supported by mild steel (MS) frames. Doors are positioned at a lintel height of 2,000 mm and are fabricated from wood, reinforced with MS angles for durability. Safety considerations are addressed through railings composed of MS channels, set at a standard height of 600 mm. Flooring throughout the building is finished in terrazzo.

The architectural plans and bill of quantities of the hostel were sourced from the Institute's Engineering Office, providing a detailed blueprint of the building design and materials used. Additionally, data on water and electricity consumption were acquired from the monthly expense bills maintained by the hostel office. These bills offered insights into their usage patterns, enabling a comprehensive analysis of resource consumption. The collected data were meticulously organized and validated to ensure accuracy and reliability for the study's objectives.

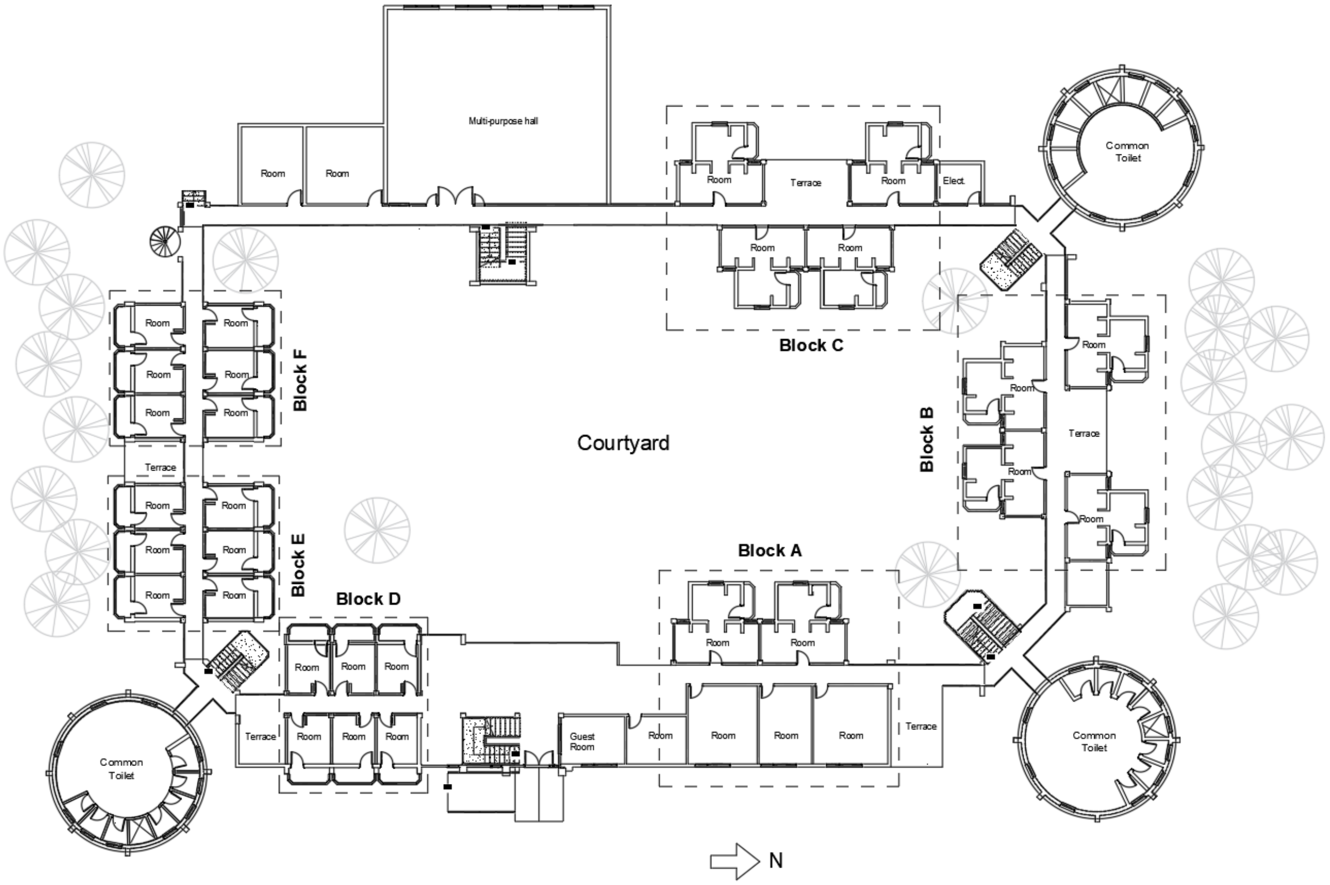

Fig. 3 Typical floor plan of Building

Transportation-related carbon emissions were quantified through calculations based on vehicle mileage, payload, trip frequency, and distance from the source. The total trips were calculated by dividing the material quantity by the vehicle payload. The diesel consumption is based on the total trips, where each trip consumes a set amount of diesel. Carbon emissions (kg CO_2- eq.) are calculated based on the diesel consumed. The emission factor for diesel is a constant that converts diesel consumption into carbon dioxide equivalents (B. Surekha et al., 2016). The source of the building materials, such as bricks, MS frames, etc., is Una (Himachal Pradesh), which is 67 km away from the site.

RESULTS

A comprehensive assessment of embodied energy and carbon emissions was conducted for the primary construction materials used in the project. The results reveal significant variations in environmental impact across materials, reflecting differences in processing intensity, unit quantities, and emission factors.

Pre-Occupancy stage (Construction stage)

Embodied energy during the pre-occupancy stage is due to the materials. The total embodied energy for the building materials is estimated to be approximately 10.93 million megajoules (MJ), as mentioned in Table 1. The most energy-intensive materials were brick and limestone, contributing 4.22 million MJ and 2.90 million MJ, respectively. This is attributed to their high embodied energy per unit mass and the magnitude of their usage. Reinforced Cement Concrete (RCC) and cement also contributed significantly, with total embodied energies of 1.78 million MJ and 1.25 million MJ, respectively. Despite their moderate per unit embodied energy, their bulk usage resulted in high cumulative energy demand.

Other materials with notable embodied energy contributions include vitrified tiles (113,057 MJ), MS grill (247,564 MJ), and glass panes (21,097 MJ). In contrast, materials such as paver blocks, granite, CPVC and PVC pipes, paints, and cement putty exhibited comparatively lower total energy impacts due to smaller usage volumes or lower energy intensities.

Pre-occupancy stage: Construction stage

Carbon emissions during this stage arise primarily due to raw material extraction, manufacturing, and transportation. Heavy construction vehicles and equipment also contribute significantly to greenhouse gas emissions, but are not considered in the study. Energy-intensive processes like cement and steel production generate substantial amounts of CO_2, both directly from chemical reactions (e.g., calcination in cement) and indirectly from the use of fossil fuels.

The total carbon emissions associated with the building materials amount to 3.4 million kilograms of CO_2- eq., as mentioned in Table 1. Brick emerges as the highest emitter, responsible for 1.7 million kg CO_2- eq., which corresponds to over 50% of total emissions. This is a direct result of its high emission factor (0.48 kg CO_2- eq./kg) and substantial volume. RCC is the second-largest contributor, with emissions amounting approximately to 1.0 million kg CO_2-eq. owing to its high emission factor (410 kg CO_2- eq./Cu.m) and considerable usage.

Table 1 Materials with quantities, emissions, and embodied energy

Materials	Quantity	Units	Emission factor (kg CO_2-eq./ unit)	Total emissions (kg CO_2- eq.)	Embodied Energy (MJ/Unit)	Total Embodied Energy (MJ)
Earth Work	9,032.9	Cu.m	0.02	181	NA	NA
RCC	2,447.8	Cu.m	410	1,003,610	730	1,786,894
Cement	272,272.0	kg	0.967	263,287	4.6	1,252,451.2
Concrete	3,696.0	kg	0.159	588	5.6	20,697.6
Brick	3,548,023.0	kg	0.48	1,703,051	2,141	4,220,167.92
Limestone	208,216.0	kg	0.015	3,123	34,860	2,903,489.4
Paver Blocks	24,024.0	kg	0.159	3,820	1.5	36,036
Granite	1,647.0	kg	0.04	66	5.908	9,730.476
Terrazzo flooring	4.8	Cu.m	237	1,127	2,450	11,760
Vitrified Tiles	20,555.9	Sqm	18.33	376,790	5.5	113,057.45
Wood	8,200.5	kg	1.5	12,301	10.8	88,565.4
MS Grill	5,894.4	kg	2.75	16,209	42	247,564.8
Glass Panes	817.7	kg	1.735	1,419	25.8	21,096.66
CPVC Pipes	971.7	kg	3.96	3,848	71.2	69,185.04
PVC Pipes	365.8	kg	3.23	1,181	80	29,264
Paints	762.3	litre	2.86	2,180	98.1	74,781.63
Cement Putty	9,287.0	kg	0.78	7,244	4.8	44,577.6
Total				3,400,025		10,929,319.2

Other significant sources of emissions include tiles (376,790 kg CO_2- eq.), cement (263,287 kg CO_2- eq.), and MS grill (16,209 kg CO_2- eq.). Glass panes and CPVC pipes also represent non-negligible emission sources due to their relatively high emission factors (1.735 and 3.96 kg CO_2- eq./kg, respectively), despite being used in lower quantities.

In contrast, materials such as limestone, granite, and wood contributed minimally to total carbon emissions, reflecting low emission factors.

Transporting these materials from production sites to construction locations adds to the carbon footprint. Together, these stages make construction materials a major source of carbon emissions. Transportation-related emissions were assessed based on the number of delivery trips, diesel consumption, and an emission factor of 3.14 kg CO_2- eq./ litre of diesel. 15.2 litre of diesel is consumed in 1 trip from Una to the site.

The total emissions due to transportation of the materials from Una to the site were estimated to 63,169 kg CO_2- eq. (Table 2). The highest contributor was Reinforced Cement Concrete (RCC) with 756 trips, consuming 11,491.2 litres of diesel, and emitting 36,427 kg CO_2- eq. Brick followed with 438 trips, consuming 6,559.7 litres of diesel, and emitting 21,105 kg CO_2- eq. Other notable materials included cement and tiles, contributing 1,638 kg CO_2- eq. and 1,976 kg CO_2- eq., respectively.

Table 2 Materials with emissions due to their transportation

Materials	Quantity	Units	Trips	Diesel Consumption (in litres)	Emissions by transportation (kg CO_2- eq.)
Earth Work	9,032.9	Cu.m	NA	NA	NA
RCC	2,447.8	Cu.m	756	11,491.2	36,427
Cement	272,272.0	kg	34	516	1,638
Concrete	3,696.0	kg	1	15.2	48
Brick	3,548,023.0	kg	438	6,559.7	21,105
Limestone	208,216.0	kg	27	394.7	1,253
Paver Blocks	24,024.0	kg	3	45.6	145
Granite	1647.0	kg	1	15.2	48
Terrazzo flooring	4.8	Cu.m	2	30.4	96
Vitrified Tiles	20,555.9	Sqm	41	623.2	1,976
Wood	8,200.5	kg	2	30.4	96
MS Grill	5,894.4	kg	1	15.2	48
Glass Panes	817.7	kg	1	15.2	48
CPVC Pipes	971.7	kg	1	15.2	48
PVC Pipes	365.8	kg	1	15.2	48
Paints	762.3	litre	1	15.2	48
Cement Putty	9,287.0	kg	2	30.4	96
Total emissions					63,169

Materials like glass, pipes, wood, paints, and concrete had minimal impact (≤96 kg CO_2- eq. each) due to fewer trips and smaller quantities. Although materials such as limestone and paver blocks were used extensively, their transportation emissions remained moderate. Earthwork had no associated transport emissions due to on-site excavation. The total emissions are 34,00,025 kg CO_2- eq., with an additional 63,169 kg CO_2- eq. from transportation. Major contributors to total emissions are RCC and Brick, comprising approximately 79% of the total emissions from building materials.

During occupancy, several mechanical processes run inside the building, consuming Energy from LPG, water, and electricity, thus releasing carbon or equivalent pollutants. Biological processes like respiration are also a major source of carbon dioxide emissions.

Post Occupancy stage: Operational stage

LPG is used for cooking in the mess. The Annual consumption of LPG is 4,750 kg. Emissions due to 1kg of LPG are 3kg CO_2- eq. (Eggleston, 2006). Thus, the annual emission due to cooking gas is 14,250 kg CO_2- eq.

There are 160 students in the hostel and 175 in total, including mess workers, attendants, and others. Generally, an individual emits 1kg of carbon daily (Baste & Thakare, 2023). Thus, the annual average emission is 63,875 kg CO_2- eq.

Electricity use is the primary source of carbon dioxide emissions, playing a dominant role in fueling climate change (Li et al., 2025). In 2022, power generation accounted for 53% of total energy-related CO_2 emissions in India (*International Energy Agency*, 2025). This highlights the significant role of the electricity production sector in the country's overall emissions profile. Electricity sourced from the national grid powers all operations within the building, including the functioning of air conditioners, computers, heavy machinery, and lighting systems.

The emission factor for 1kWh is 0.921 (Varun et al., 2012). Figure 4 represents the monthly electricity consumption (use of geyser, ceiling fans, lights, iron, hair styling appliances, etc.) and emissions for 2022, 2023, and 2024.

Peak electricity consumption is seen in April, attributed to the simultaneous use of geysers and fans. In 2022, the lowest consumption was recorded in March, primarily due to reduced occupancy resulting from COVID-19 restrictions.

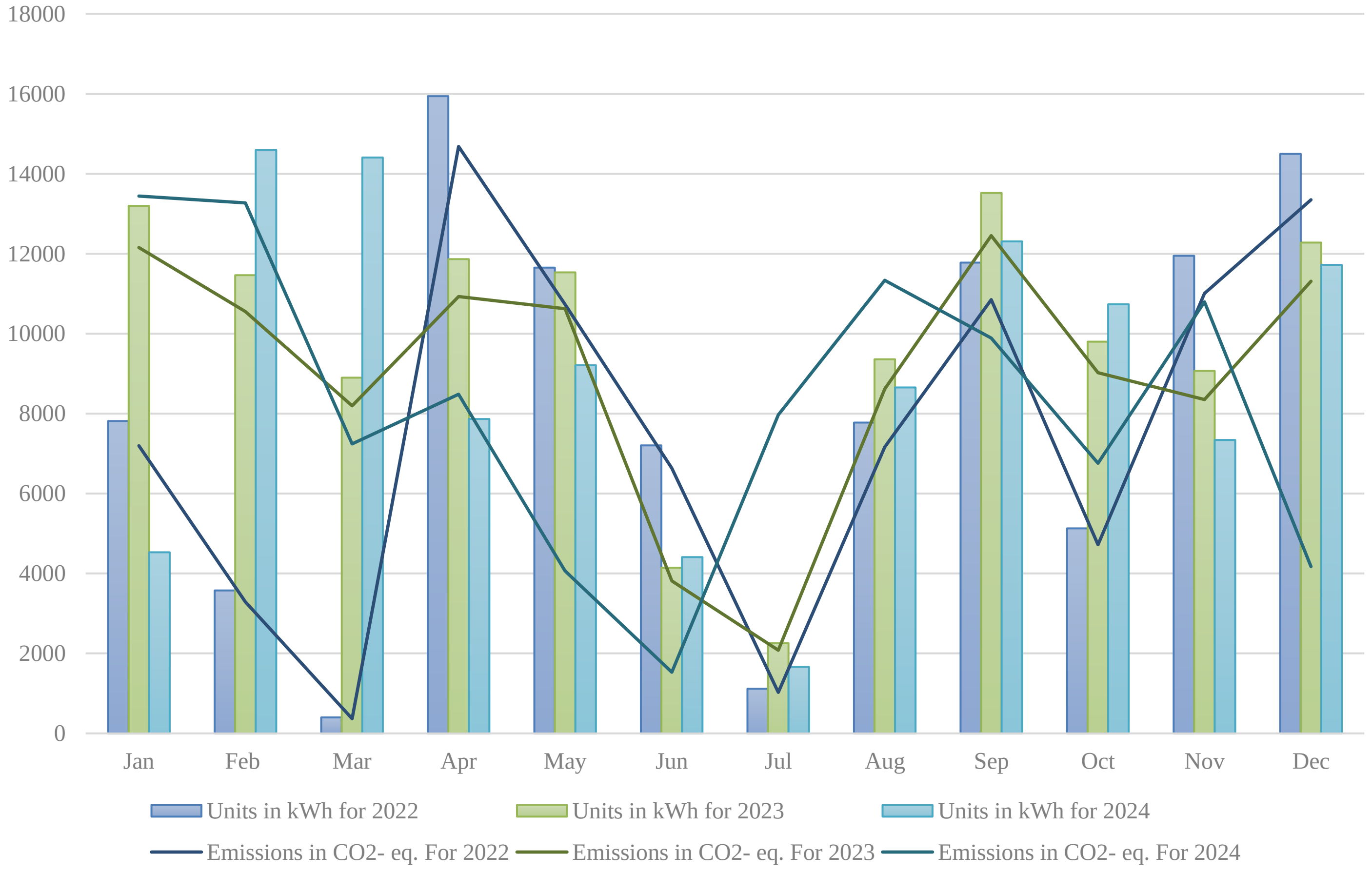

Fig. 4 Electricity consumption and its emissions

In contrast, the minimum consumption for 2023 and 2024 occurred in July, coinciding with the semester break vacation, which led to fewer users. The total electricity consumption for the years 2022, 2023, and 2024 is 98,835 kWh, 117,390 kWh, and 107,444 kWh, respectively. The total emissions due to electricity for the years 2022, 2023, and 2023 are 91,027.04 kg CO_2- eq., 108,116.2 kg CO_2- eq., and 98,955.92 kg CO_2- eq. respectively.

Sensitivity Analysis: Grid Emission Factor Trajectory

The study assumes a constant grid electricity emission factor of 0.921 $kgCO_2$-eq./kWh (Varun et al., 2012) throughout the 50-year building lifespan. However, India's grid is undergoing rapid decarbonisation driven by expanding renewable energy capacity under its Nationally Determined Contributions (NDC) and the target of achieving net-zero emissions by 2070 (Ministry of Environment, Forest and Climate Change, 2023). Historical data from the Central Electricity Authority (CEA) show that the national grid emission factor declined from 0.774 $kgCO_2/kWh$ in FY 2013-14 to 0.710 $kgCO_2/kWh$ in FY 2024-25 (Bhawan & Puram, 2025) . Modelling studies project a further decline to approximately 0.369 tCO_2/MWh by 2050 under an ambitious decarbonisation pathway (Bisht & Sharma, 2025). To quantify the sensitivity of lifecycle results to this assumption, three scenarios were evaluated as presented in Table 3.

In S1 (BAU), the EF is held at 0.921 $kgCO_2/kWh$ throughout, yielding a total lifecycle emission of 12.78 million $kgCO_2$-eq., consistent with the main result of this study. In S2 (NDC-aligned, moderate decline), the EF is assumed to decrease linearly from 0.921 to 0.50 $kgCO_2/kWh$ by 2075, reflecting India's commitments under the Paris Agreement and historical CEA grid emission trends (Bhawan & Puram, 2025). This reduces the total lifecycle emission to 11.64 million $kgCO_2$-eq., a reduction of 8.9%. In S3 (ambitious decarbonisation), the EF declines from 0.921 to 0.369 $kgCO_2/kWh$ by 2075 based on published low-carbon energy transition modelling for India (Bisht & Sharma, 2025), yielding a total of 11.29 million $kgCO_2$-eq., a reduction of 11.7%. The narrow spread across scenarios (11.29-12.78 million $kgCO_2$-eq.) confirms that the study's core findings are robust to the emission factor assumption; however, the BAU scenario represents a conservative upper bound, and actual future emissions are likely to be lower as India's grid progressively decarbonises.

Table 3 Sensitivity analysis of total lifecycle emissions under three grid emission factor scenarios. EF is applied as a linearly declining average over 50 years for S2 and S3.

Scenario	**EF Start ($kgCO_2/kWh$)**	**EF End ($kgCO_2/kWh$)**	**50-yr Total Lifecycle Emissions (million $kgCO_2$-eq.)**	**Change from S1**
S1 - Business As Usual (BAU)/ Constant (paper assumption)	0.921	0.921	12.78	-
S2 - Moderate Decline (NDC-aligned)	0.921	0.50	11.64	-8.9%
S3 - Ambitious Decline (decarbonisation pathway)	0.921	0.369	11.29	-11.7%

The study investigates the greenhouse gas (GHG) emissions linked to the water supply system. The water supply system includes the extraction, treatment, and distribution of potable water (Lahmouri et al., 2019). The calculations are based on the monthly user data provided by the hostel. The emission factor for water consumption varies by region due to differences in supply systems and energy sources. For greater accuracy, this research references a study from Dehradun, which provides a locally derived emission factor based on the city's specific water supply and energy usage. Using this region-specific data ensures the assessment reflects the actual environmental impact of water use in that context. Water production including extraction, treatment, and delivery to storage contributes to the GHG emissions. The related emission factor for water consumption is 0.00112 kg CO_2- eq. per liter of water (Medha, 2020). The total annual water consumption amounts to 7,814,070 liters, resulting in an associated emission of 8,751.75 kg CO_2- eq.

Overall Emissions

Over a span of 50 years, the building's total GHG emissions can be categorized into embodied and operational emissions. Pre-occupancy emissions for the entire life span refer to the cumulative emissions due to the preparation and transportation of building materials and construction-related activities. The total is calculated to be 3,463,194 kg CO_2- eq., accounting for 27% of emissions.

Post-occupancy emission for building's life span includes the emissions due to major building operations, viz cooking, water, and electricity consumption. In this study, the operations considered are electricity usage, water consumption, users' exhalation, and LPG consumption, amounting to 186,242 $kgCO_2$- eq annually and 9,312,100 $kgCO_2$- eq in the entire life span. Thus, 73% of the total lifespan emissions are due to operational stage (Fig. 5). Also, maximum weightage in emissions in the operational stage is due to user's exhalation and electricity, which is 87% of the total in the operational stage (Fig.6).

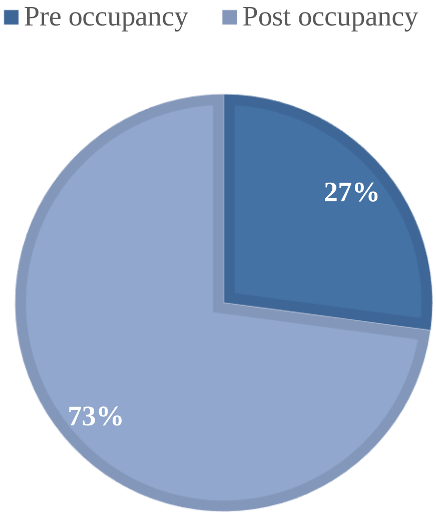

Fig. 5 Distribution of total emissions in pre- occupancy and post- occupancy

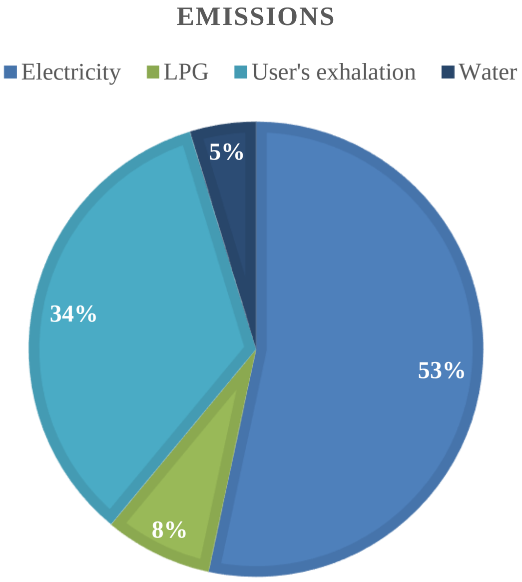

Fig. 6 Share of Emissions due to different operations in Post- Occupancy phase

Total emissions for the life span include pre-occupancy and post-occupancy emissions, which are calculated to be 12,775,294 $kgCO_2$- eq.

RECOMMENDATIONS

The LCA quantifies the carbon emissions generated by a building throughout its entire life cycle. Given that the building considered for study is already constructed and operational, the emissions that have already occurred cannot be reversed. While achieving absolute zero carbon emissions is not feasible, it is possible to attain net-zero carbon through compensatory measures.

Consequently, selecting materials with lower embodied energy becomes critical for sustainable design (Kibert, 2016). Furthermore, integrating sustainable practices during the pre-construction phase, such as energy-efficient machinery and waste reduction strategies, can significantly lower the embodied energy associated with construction activities (Zuo & Zhao, 2014). By adopting a comprehensive approach to embodied energy, stakeholders can enhance the sustainability of the built environment, ultimately contributing to climate change mitigation and resource conservation.

To identify pathways for sustainable construction practices, it is crucial to assess the environmental impact of buildings. Since construction processes vary based on factors like building type, climate, topography, location, and soil conditions, tailored solutions are needed. For instance, sloping roofs are commonly used in hilly regions to protect buildings from heavy rain and snow. By adopting this site-specific approach, key construction and operational areas can be identified, and targeted actions can be implemented.

Electricity

The annual average consumption of electricity in the building is 107,889 kWh. As mentioned, the source of electricity here is a thermal power plant. The associated emission factor of thermal sources and renewable sources (PV panels) is 921g CO_2- eq.per kWh and 35g CO_2- eq. per kWh, respectively (Varun et al., 2012). The difference between them is 886g CO_2- eq. per kWh. Therefore, the implementation of solar photovoltaic panels for electricity generation can reduce carbon emissions by 95,589.65 kg CO_2- eq. annually which accounts to 96 % of the emissions due to electricity. To support institutional decision-making, a preliminary cost-benefit assessment of the proposed PV installation is presented. Based on the annual average electricity consumption of 107,889 kWh and a site solar availability of approximately 4.5–5 kWh/m²/day for Hamirpur, Himachal Pradesh, the required PV system capacity is estimated at approximately 59 kWp. At current MNRE benchmark costs for institutional rooftop solar of approximately ₹45,000–48,000 per kWp (Ministry of New and Renewable Energy, 2024), the total installed cost would be in the range of ₹26.5–28.5 lakh. It is noted that Central Financial Assistance (CFA) under PM Surya Ghar: Muft Bijli Yojana is not applicable to government/institutional buildings; the above costs reflect the unsubsidised benchmark for institutional installations. At the applicable institutional electricity tariff for Himachal Pradesh of approximately ₹6–7 per kWh (HPSEBL, 2024), annual savings in electricity expenditure would be approximately ₹6.5–7.5 lakh, implying a simple payback period of 4–5 years. Over the 50-year building lifespan, the net financial saving is estimated to exceed ₹3 crore, in addition to the 96% reduction in electricity-related carbon emissions, positioning the PV installation as a high-impact, economically viable intervention for the institution.

Cooking gas

Biogas has been identified as the most effective alternative fuel, exhibiting the minimal adverse environmental impacts throughout its entire life cycle (Kumar et al., 2024). The building consumes an annual average of 4,750 kg of LPG for cooking, with an emission factor of 3 kg CO_2- eq., while Biogas has a lower emission factor of 0.3 kg CO_2- eq. Although LPG consumption cannot be entirely replaced, installing a biogas plant can reduce emissions and can also improve waste management efficiency. Past studies have worked on the methods of estimating food wastage from hostel mess. In 2017, food wastage at IIT Mandi averaged 27g and 32g per capita per meal in two messes, amounting to 118g per capita daily. At IIT Bombay, a 2011 waste audit showed an average daily mess hall waste of over 950 kg, with per capita waste ranging from 100g to 160g, averaging 130g (Dash A, 2015).

At Parvati Girls' Hostel, with an average food waste of 124g per capita daily and a total capacity of 160 people, the total waste generated is 19.84 kg per day. According to Pathak et al. (2022), 1 kg of kitchen waste can produce 0.3 m³ of Biogas, resulting in 5.952 m³ of Biogas daily and 178.56 m³ monthly in the hostel. Since 1 m³ of Biogas is equivalent to 0.46 kg of LPG, biogas production would replace 82.14 kg of LPG monthly and, thus 821 kg annually. Thus, by using this alternate, annual carbon emissions can come down to 12,031 kg CO_2- eq. from 14,250 kg CO_2- eq. by using LPG gas. The biogas plant can reduce 2,219 kg CO_2- eq. (15.56%) of emissions annually in terms of cooking gas (considering the current waste production in the kitchen) as mentioned in Table 4. The technical feasibility of the proposed biogas plant is consistent with institutional-scale installations supported under India's National Biogas Programme (*Biogas Programme*, 2022) A daily waste input of 19.84 kg corresponds to a biogas yield of approximately 5.95 m³/day. Based on standard anaerobic digestion design guidelines, a fixed-dome or floating-drum digester (KVIC type) of 6-10 m³ capacity with a hydraulic retention time of 30-40 days would be required to process this waste volume (Rajendran et al., 2012). This scale of installation is well within the range of systems successfully deployed in institutional settings across India, confirming the practical viability of this recommendation for PGH.

Table 4 Comparison of the LPG and the Combination of LPG and biogas for cooking gas

	LPG	LPG+ Biogas
Annual average consumption (in kg)	4,750	3,928.6 (LPG) + 821.4(Biogas)
Annual emissions (in kg CO_2- eq.)	14,250	12,031.4

Beyond the Lifecycle: End-of-Life Recovery Opportunities

While the present study adopts a cradle-to-grave system boundary in line with ISO 14040, the end-of-life stage offers meaningful recovery opportunities that can reduce the net environmental burden of the building. Two materials present the most significant potential. First, the 5,894 kg of mild steel (MS) grills used in the building (embodied emissions: 16,209 kgCO_2-eq.) are highly recyclable; steel recycling recovers approximately 85-90% of embodied energy compared to primary production (Hammond & Jones, 2008), implying a potential avoided emission of 13,778-14,588 kgCO_2-eq. at end of life. Second, the 2,447.8 m^3 of reinforced cement concrete (RCC) can be crushed at demolition to produce recycled coarse aggregate (RCA), which substitutes for virgin aggregate extraction in future construction and reduces associated quarrying emissions. The use of RCA in structural and non-structural applications is recognised under IS 383:2016. Incorporating these beyond-lifecycle recovery pathways in future design decisions for comparable buildings can contribute to a more circular, cradle-to-cradle approach to construction in the Himalayan region.

Carbon sequestration by trees

The process of carbon uptake and storage involves the absorption of atmospheric carbon dioxide by vegetation through photosynthesis. In this process, trees and plants release oxygen while retaining carbon within their biomass. Fossil fuels, which originate from ancient biomass, also act as long-term carbon reservoirs until their combustion releases the stored carbon back into the atmosphere (*UNFCCC*, 2010).

Thakare in his study presented that after the full growth of 765 trees, 367.81 tons of carbon were sequestered per year (Baste & Thakare, 2023). This gives a rate of approximately 0.481 tons of carbon per fully grown tree per year and 24 tons of carbon per fully grown tree in 50 years. Trees found in the area are pine, oak, deodar, etc. The average carbon sequestration of pine is 0.44 tons per year, as per a study (Pant & Tewari, 2013). Following is the detailed calculation of trees required to carbon sequestration required after change in cooking gas and electricity source.

Step 1:

Molecular weight of CO_2 = 44 g/mol

(Carbon = 12, Oxygen = 16 x 2; 12+32 =44)

Molecular weight of Carbon = 12

Fraction of Carbon in CO_2 = 12/44 = 0.2727

Therefore, 1 kg CO_2 x 12/44 = 0.2727 of Carbon

Step 2:

Total emissions through the lifetime of building after recommendations = (Materials) + (transportation of materials to the site) + (Cooking gas as Biogas+ LPG) + (Electricity through solar panels) + (Water consumption) + (User's Exhalation)

= 3,400,025 + 63,169 + 601,570 + 188,806 + 437,587.5 + 3,193,750

= 7,884,907.5 kg CO_2- eq.

Which is equals to 2,149,585.7 kg of Carbon or 2,149.59 tons of Carbon

Step 3:

1 tree = 0.481 tons/ year

Over 50 years = 24 tons of Carbon / tree

Step 4:

Total number of trees = 2,149.59 / 24

=89.54 (approximately 90) trees

Thus, 90 fully grown trees are required to sequester the carbon emitted by the building in the entire life span in PGH. This approach helps offset or potentially neutralize the building's total carbon emissions over its lifecycle.

Comparison between existing case and recommended case

Figure 7 presents a comparison of annual carbon emissions during the operational phase for the existing case and the recommended case, across electricity, cooking gas, water usage, and user exhalation, along with carbon sequestration by trees, shown as a negative value.

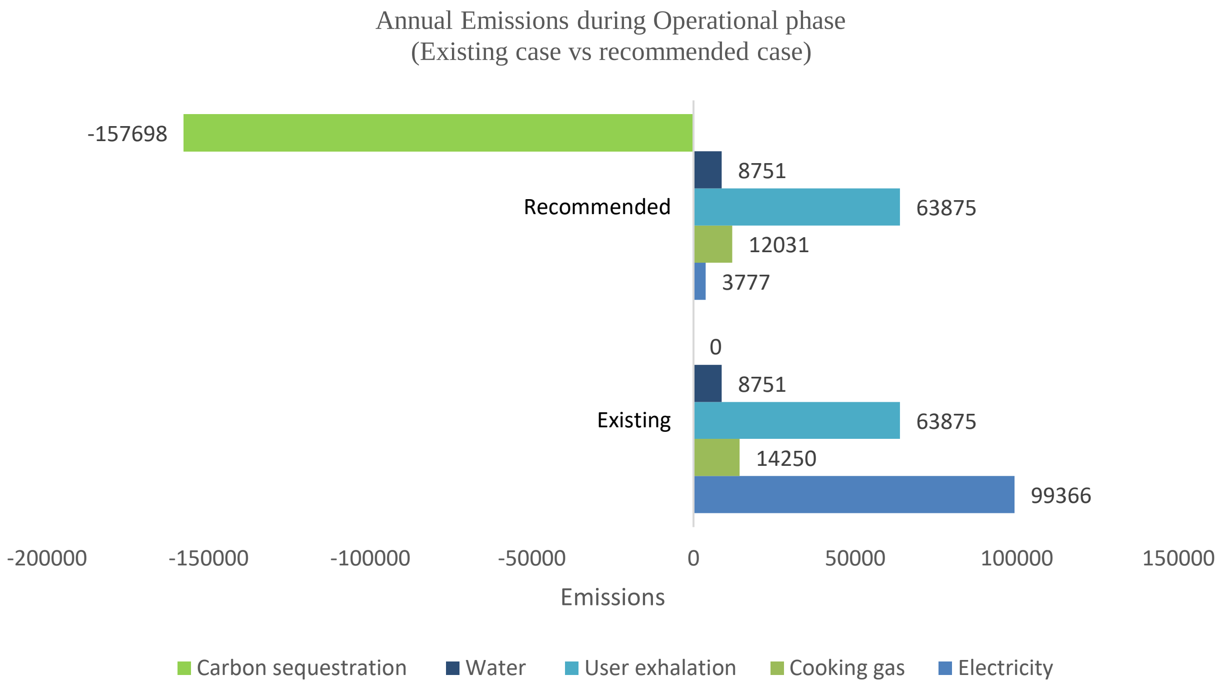

Fig. 7 Emissions during operational phase for Existing case and recommended case

In the existing case, total operational emissions are substantially higher, dominated by electricity and user exhalation, which together account for the 87% of emissions. Water usage and cooking gas also contribute, though to a lesser extent which is 13%.

The recommended strategies demonstrate a significant reduction in net emissions. While emissions from electricity, and cooking gas persist, they are considerably lower than the existing case indicating improved energy and resource efficiency. Notably, the inclusion of carbon sequestration, depicted as a large negative value, offsets a substantial portion of the operational emissions. This sequestration, attributed to strategic planting of trees or green cover, shifts the overall carbon balance in favour of a more sustainable outcome. The data underscores the effectiveness of the recommended interventions in reducing net annual emissions, primarily through demand-side efficiency measures and natural carbon offset mechanisms.

For buildings that are already constructed, emission reduction efforts must focus on the operational phase, which accounts for 73% of total emissions. This study was conducted on an existing, operational building, but similar methods could also be applied during the design phase once the construction materials and operational plans are finalized.

One effective strategy to reduce operational emissions is transitioning to renewable energy sources, such as installing solar photovoltaic (PV) panels to replace conventional electricity. Similarly, using Biogas as a substitute for LPG in cooking can significantly lower emissions. While emissions from human exhalation are unavoidable, they can be offset through carbon sequestration measures like planting trees. By integrating these strategies, this research aims to pave the way for more sustainable and environmentally responsible building practices.

CONCLUSION

This study provides a comprehensive LCA associated with the Parvati Girls' Hostel at NIT Hamirpur, offering an evidence-based understanding of the environmental burden imposed by both the construction and operation of a residential building in a subtropical highland climate. The primary objective was to quantify and analyse the embodied energy, material- and transport-based emissions, and post-occupancy emissions to identify actionable pathways toward a low-carbon built environment.

The analysis revealed that over a 50-year life span, the building is responsible for a total of 12.77 million kg CO_2 equivalent, with emissions split across the construction phase (27%) and operational phase (73%). Operational emissions were dominated by electricity usage and human respiration, contributing 87% of annual emissions during building occupancy. Construction materials such as brick, RCC, and cement emerged as major contributors to both embodied energy and emissions, primarily due to their high usage volumes and energy-intensive production processes. Additionally, transportation of materials added a notable yet secondary layer of emissions, totalling 63,169 kg CO_2- eq.

Another finding is that 34% of post-occupancy emissions are linked to human exhalation, emphasizing the importance of **passive ventilation strategies** to maintain indoor air quality. Furthermore, the study demonstrates that the total lifetime emissions of the building can potentially be **offset by planting 90 fully grown pine trees**, offering a nature-based solution for carbon sequestration. The embodied energy of construction materials is also significant, with steel and brick being the major contributors.

This research contributes a **replicable, data-driven methodology** for evaluating sustainability in institutional residential buildings. It can inform **architects, engineers, and policymakers** seeking to implement **net-zero or low-emission strategies** in both new and retrofitted structures. Moreover, it aligns with India's commitment to **achieve net-zero emissions by 2070**, as announced at COP26, and supports global climate goals under the Paris Agreement and the UN Sustainable Development Goals (SDGs).

While this study identifies high exhalation-related emissions as a key driver recommending improved passive ventilation, a detailed technical evaluation of fenestration retrofitting and its impact on thermal performance and energy loads falls beyond the scope of the current lifecycle carbon assessment. The quantitative assessment of how modifications to the existing hostel’s window-to-wall ratio, ventilator sizing, or envelope configuration would affect indoor thermal comfort, air change rates, and resultant operational energy demand requires dedicated building energy simulation and is being addressed in a subsequent study by the authors. This follow-up investigation will employ simulation tools to evaluate passive design interventions specific to the Lower Himalayan climate zone and will complement the lifecycle carbon findings presented here.

As a way forward, the study recommends expanding research on next-generation materials such as **geopolymer concrete, hempcrete, recycled steel, biobased flooring like cork and bamboo**. It also encourages to integrate smart metering and real time monitoring for energy optimization. The study also recommends to leverage decentralized renewable systems, such as hydrogen fuel cells and hybrid microgrids. With advancements in **transportation, production, and resource extraction**, new possibilities for reducing the carbon footprint across a building's lifecycle can be realized.

In conclusion, this work demonstrates that **holistic assessment and intervention strategies** can not only mitigate environmental impacts but also pave the way toward **climate-resilient and resource-efficient buildings**. As climate change accelerates, such analytical tools and localized actions will be essential for transforming the built environment into a catalyst for ecological balance and sustainability.

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Author Contribution

Monika Garg was responsible for the conceptualization of the study, development of the methodology, simulation work, data curation, analysis, visualization, and preparation of the original draft. Dr. Swechcha Roy contributed through supervision, validation of results, critical review, and editing of the manuscript, as well as providing guidance on research design and overall project administration. All authors have read and approved the final version of the manuscript.

Data Availability

The authors declare that all data generated or analyzed during this study are included in this paper.

Declarations

Competing Interests The authors declare no competing interests.

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