Alliance for an™ Energy Efficient Economy

SAINT-GOBAIN

LIFE CYCLE ASSESSMENT OF CARBON EMISSIONS

Progress and Barriers in Indian Building Sector

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LIFE CYCLE ASSESSMENT OF CARBON EMISSIONS

Progress and Barriers in Indian Building Sector

Project

Di-Carb: Development of Integrated Carbon Assessment (Embodied and Operational) Framework for Reducing Building's Carbon Footprint

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Abbreviations

AAC	Autoclaved Aerated Concrete
AC	Air Conditioner
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BIM	Building Integrated Modelling
BIS	Bureau of Indian Standards
BOQ	Bill of Quantity
CARBSE	Centre for Advanced Research in Building Science Energy
CO2	Carbon Dioxide
COP	Coefficient of Performance
DOE	Department of Energy
ECBC	Energy Conservation Building Code
ECSBC	Energy Conservation and Sustainability Building Code
EE	Embodied Energy
ENS	Eco-Niwas Samhita
EPD	Environment Product Declarations
EPS	Expanded Polystyrene Insulation
EU	European Union
FAR	Floor Area Ratio
GFRG	Glass Fibre Reinforced Gypsum
GHG	Global Greenhouse Gas
GRIHA	Green Rating for Integrated Habitat Assessment
GSA	General Services Administration's
GWP	Global Warming Potential
ICE	Inventory of Carbon and Energy
IEA	International Energy Agency
IFC	International Finance Corporation
IOH	Input-Output-based Hybrid

ISO	International Standardization Organization
KPMG	Klynveld Peat Marwick Goerdeler
LCA	Life Cycle Analysis
LCC	Life Cycle Cost
LCCA	Life Cycle Cost Analysis
LCE	Life Cycle Carbon Emission
LCEA	Life Cycle Carbon Emission Analysis
LCI	Life Cycle Carbon Inventory
LEED	Leadership in Energy and Environmental Design
MJ	Mega Joule
NIUA	National Institute of Urban Affairs
NZEB	Net Zero Energy Building
OE	Operational Energy
OPC	Ordinary Portland Cement
OSB	Oriented Strand Board
PCR	Product Category Rules
PUF	Poly Urethane Foam
PVC	Polyvinyl Chloride
RCC	Reinforced Cement Concrete
RE	Renewable Energy
RH	Relative Humidity
RICS	Royal Institution of Chartered Surveyors
RMI	Rocky Mountain Institute
TJ	Tera joule
VOC	Volatile Organic Compound
WWR	Window-to-Wall Ratio
XPS	Extruded Polystyrene Insulation
ZEB	Zero Energy Building

Glossary

This glossary aims to clarify specific key terms utilized within this report. The definition of specific terms used in this report has been established in relation to the different life cycle stages outlined in ISO 14044, and EN 15978 as presented in Figure 0.1.

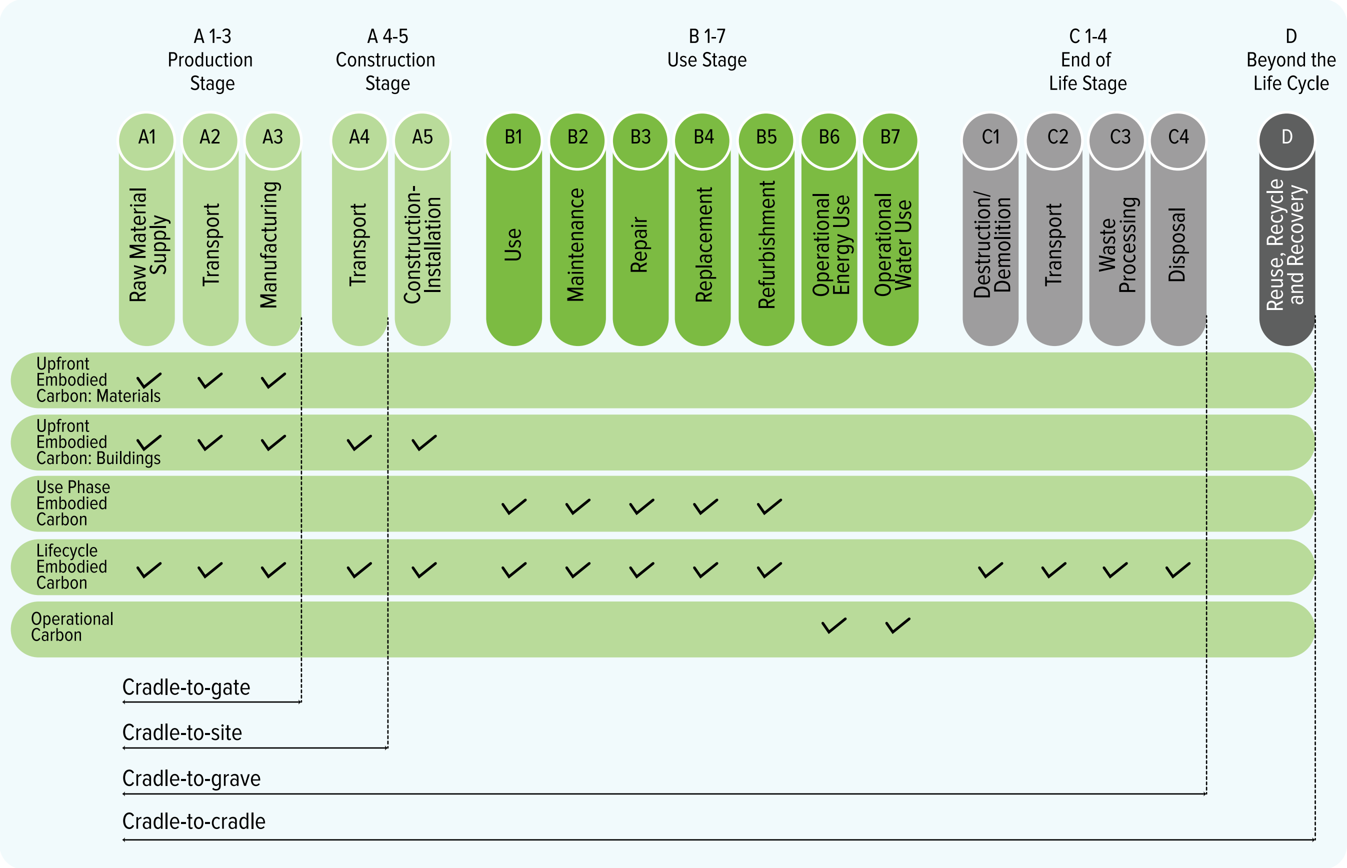


Figure 0.1: Different life cycle stages of buildings to perform life cycle assessment [1]

Carbon Emissions: In this report, any reference to “carbon emissions” refers to emissions of greenhouse gases (GHGs).

Global Warming Potential (GWP): This is a metric used to compare the global warming ability of different GHGs, and is measured in units of carbon dioxide equivalence. As carbon dioxide is being used as a reference gas, one kilogram of carbon dioxide carries a GWP of 1 kgCO2eq. Nitrous oxide, for instance, has a GWP of 273 $kgCO_{2eq}$.

Life Cycle Assessment (LCA): LCA refers to a methodical series of procedures for gathering and analysing the inputs and outputs of materials and energy, along with the related environmental impacts directly linked to a building, infrastructure, product, or material throughout its life cycle (ISO 14040:2006). LCA can be used to assess a range of environmental impacts including GHG emissions, acidification potential, eutrophication potential, abiotic depletion potential, etc. For the purpose of this report, the term LCA is used in the context of assessing the energy and carbon emissions associated with buildings or building materials/products over their life cycle.

Life Cycle Carbon: In this report life cycle carbon in reference to buildings entails carbon emissions from all life cycle phases, incorporating both embodied and operational carbon (i.e., stages A1 to C4).

Life Cycle Embodied Carbon: Life cycle embodied carbon encompasses carbon emissions linked with materials and construction processes across the entire life cycle of a building. This includes: material extraction (A1), transportation to the manufacturer (A2), manufacturing (A3), transportation to the site (A4), construction (A5), use phase (B1), maintenance (B2), repair (B3), replacement (B4), refurbishment (B5), deconstruction (C1), transportation to end-of-life facilities (C2), processing (C3), and disposal (C4). In this report, both the life cycle embodied carbon of buildings, as well as the life cycle embodied carbon of individual materials have been referred. The nomenclature in brackets used to refer to different life cycle stages is as per the widely-accepted ISO standards 14040/14044 and European standard EN 15978, as illustrated in Figure 0.1.

Upfront Embodied Carbon (Materials and Buildings): Upfront embodied carbon of building refers to carbon emissions generated during the materials' production and construction phases (A1-A5), occurring before the building becomes operational. Similarly, the upfront embodied carbon of the materials refers to carbon emissions generated during the material extraction (A1), transportation to the manufacturer (A2) and manufacturing (A3).

Use phase Embodied Carbon: Use phase embodied carbon refers to emissions related to use phase stage (e.g., concrete carbonation, emission related to refrigerant leakages) (B1), maintenance (B2), repair (B3), replacement (B4) and refurbishment (B5). It excludes emissions related to operational energy use (B6) and operational water use (B7).

Operational Carbon: In this report operational carbon refers to the carbon emissions attributed to the energy consumed during the use phase (B6) of buildings and associated with energy required for heating, cooling, lighting, powering appliances, and other functions necessary for the day-to-day operation and comfort of the building's occupants.

Upfront Embodied Energy: Upfront Embodied energy is the total energy required to produce a product (building) or material, from raw material extraction through manufacturing, transportation, and assembly, until the product is ready for use. It includes all energy used in mining, processing, manufacturing, and transporting materials, as well as constructing or assembling the final product.

Use phase Embodied Energy: Use phase embodied energy refers to energy associated with use stage (B1), maintenance (B2), repair (B3), replacement (B4) and refurbishment (B5). It does not include operational energy (B6) and energy related to water use (B7).

Life Cycle Embodied Energy: The life cycle embodied energy of buildings refers to the total energy consumed throughout the entire life cycle of a building (A1-C4), encompassing all phases from construction to demolition. It includes the energy used in extracting (A1), processing (A2), and transporting building materials (A3), the energy consumed during the transportation of materials to the site (A4), the energy consumed during the construction process (A5), and the energy involved in maintaining, renovating (B stages excluding B6 and B7), and eventually demolishing the building (C stages). Similarly, for materials it refers to the total energy consumed throughout the entire life cycle of a material, including the initial production phase (raw material extraction, processing, manufacturing, transportation, and assembly) as well as the energy used during the material's use, maintenance, and end-of-life stages (disposal, recycling, or reuse).

Operational Energy: Operational energy refers to the energy consumed during the use phase (B6) of a building. This includes all the energy required for heating, cooling, lighting, powering appliances, and other functions necessary for the day-to-day operation and comfort of the building's occupants.

Life Cycle Energy (LCE): In this report LCE has been used in reference to buildings. The life cycle energy of buildings refers to the total energy consumed by a building over its entire lifespan, encompassing all stages (A1-C4) from initial construction to demolition.

Environmental Product Declarations (EPDs): EPD refers to a standardized method for presenting data regarding the environmental impacts of a product throughout its life cycle.

Product Category Rules (PCRs): PCRs are standardized guidelines used in environmental labelling and declarations, such as Environmental Product Declarations (EPDs). They detail the rules and requirements for the LCA of a particular product category.

Executive Summary

In India, the building sector is the third-largest energy consumer, following the industry and transport sectors. It accounts for 25.6% of the country's annual greenhouse gas emissions currently. This percentage is anticipated to rise due to increasing building stock, which is projected to double by 2050 relative to the 2020 baseline.

Emissions throughout the building life cycle can be divided into upfront embodied carbon emissions (related to the production and transport of materials and construction), use phase carbon emissions (covering both embodied carbon emissions related to the operation and maintenance of buildings and operational related to day-to-day energy use for operating the buildings), and end-of-life carbon emissions (related to demolishing buildings after their life cycle).

In India, building sector policies primarily focus on reducing operational energy and associated carbon emissions, with little emphasis on embodied carbon emissions and life cycle carbon emission reductions. This oversight is due to a lack of awareness about life cycle carbon emissions, an absence of standardized frameworks for evaluation, an inadequate India-specifc embodied carbon dataset of materials, the exclusion of life cycle assessments in building codes, and insufficient financial incentives.

This report assesses current practices, challenges, and opportunities for using Life Cycle Assessment (LCA) as a tool to help decarbonize India's building sector. It explores international standards and practices for LCA of buildings, providing insights into the impact of different system boundaries, embodied carbon datasets, life cycle stages, and functional units. The report identifies challenges in conducting LCA for buildings through an analysis of published studies and suggests necessary action points. It serves as a critical resource for stakeholders in the construction and regulation of India's building sector. Key insights from the analysis presented in this report are noted below.

International standards and framework of LCA: International standards such as ISO 14040 and ISO 14044 provide a broad framework for LCA applicable to buildings. The European standard EN 15978 specifies calculation methods and system boundaries for building LCA, making it increasingly referenced in related literature. ISO 21930 and EN 15804 outline core rules for Environmental Product Declarations (EPDs) of materials, which provide the methodology to quantify the environmental impact, including GHG impact of specific materials and/or products, which in turn help create region-specific embodied carbon datasets for construction materials and products.

The report highlights that, despite the availability of these international standards for LCA of buildings and material EPDs, adherence to them remains mostly voluntary worldwide. However, countries like Denmark, the United States, Canada, France, and the United Kingdom are promoting LCA of buildings through initiatives such as the Buy Clean Act, limits on embodied carbon for new buildings, and various carbon accounting standards and labelling programs.

Challenges and opportunities for India: A lack of standardized methodologies for LCA of buildings, a limited India-specific, embodied carbon dataset for construction materials and products, and insufficient financial incentives for disclosing and reducing embodied carbon hinder developers from designing and constructing buildings using low-carbon materials. Bureau of Indian Standards' (BIS) guidelines for quantifying product carbon footprints using ISO 14044 represent another significant move toward standardizing the LCA framework.

A review of literature on LCA of buildings in India and around the world highlights the following key methodological aspects impacting the life cycle energy and carbon emissions of buildings embodied carbon dataset for Indian construction materials by CEPT University are notable steps toward mainstreaming LCA in India's building sector. Additionally, the Bureau of Indian Standards' (BIS) guidelines for quantifying product carbon footprints using ISO 14044 represent another significant move toward standardizing the LCA framework.

A review of literature on LCA of buildings in India and around the world highlights the following key methodological aspects impacting the life cycle energy and carbon emissions of buildings:

Variations in system boundaries: The review reveals inconsistencies in selecting system boundaries for LCA of buildings due to varying objectives. Studies focusing on upfront embodied carbon typically use boundaries A1-A3 (cradle-to-gate), while those examining life cycle embodied carbon use A1-C4 (cradle-to-grave), excluding B6 (operational carbon) and B7 (operational water use). Some studies focused on both embodied and operational carbon, selected A and B stages but excluded C stages. These variations cause discrepancies in reported life cycle carbon emissions, making result comparisons difficult.

Variations in embodied carbon dataset: Different methodologies for creating embodied carbon dataset for construction materials and products, such as process-based, input-output, and hybrid analyses, result in varying data. The report notes that process-based analysis is the most commonly used method in the literature. However, the absence of a standardized methodology, along with product-specific and regional material datasets, leads to significant variations in reported upfront embodied carbon results.

Variations in building design life: The report emphasizes that varying assumptions on the designed lifespan used for building life cycle assessments result in differences in reported life cycle energy and carbon emissions. Buildings with longer lifespan may show higher or lower embodied carbon emissions depending on material replacement or refurbishment cycles. It is important to fix the life span of buildings to avoid variations in life cycle carbon of buildings

Variations in functional unit: The use of different functional units—like volumetric (net volume of construction materials in m^3), area-based (average/net/gross floor area in m^2), serviceable area-based (conditioned floor area in m^2), and weight-based (quantity of materials in kg)—results in variations in reported life cycle energy and carbon emissions for buildings. It is recommended that all carbon emissions be reported using an area normalised metric (kgCO2eq/m2) to comply with internationally accepted practice for both operational and embodied carbon.

In addition to methodological variations, physical factors such as varying climatic conditions, types of construction materials available in that geography, building types (residential or commercial), operations, electrical loads, and electro-mechanical appliances significantly influence embodied and operational carbon emissions throughout the building life cycle. These variations pose challenges when benchmarking LCA results across different studies.

Insights from literature review of Indian LCA studies: The literature review on Indian building LCAs reveals a small number of studies focusing on residential buildings, and a few covering educational buildings. In these, there are significant variations in LCA system boundaries and datasets used for construction materials manufactured in India. Most studies assess upfront embodied energy (A1-A3) and operational energy (B6), neglecting other LCA phases, which can skew perceptions of building life cycle energy and associated carbon emissions. Differing datasets used for Indian material carbon intensities lead to substantial variations in upfront embodied energy and carbon results.

Insights from literature review of international studies: Insights from international studies reveal that life cycle embodied energy ranges from 4% to 75% of total building life cycle energy. Transport-related embodied energy, use phase embodied energy, and end-of-life energy vary from 2% to 23%, 1% to 1.8%, and 0.1% to 13% respectively. These wide-ranging results across life cycle stages are attributed to variations in building typologies, operational practices, appliance types, materials used, climatic conditions, embodied carbon datasets, and system boundaries used in different studies.

Further, to facilitate the comparison of LCA outcomes from different studies, the report recommends a bottom-up approach, starting from the materials level and progressing to the building level. Results should be normalized by floor area to ensure consistency and accuracy in reporting.

To quantify the factors influencing life cycle embodied carbon of buildings identified through the literature review, the report presents a case study of a small commercial office building. Factors such as different embodied carbon datasets for materials that are currently available, varying manufacturing process related emissions of materials by geographic location, transportation distances, and building lifespan are analysed for their impact on both upfront and use phase embodied carbon emissions. The report notes a 17% variation in upfront embodied carbon due to different datasets numbers. Geographic location indicates a 5% variation in upfront embodied carbon. The variations in transportation distances have a minor impact when emissions are compared to the combined upfront embodied and transport-related carbon emissions. Variations in building lifespan indicate a 5% increase in use-phase embodied carbon with a 20-year extension beyond the baseline of 50 years. UK specifies a standard lifespan of 100 years for LCA calculations and it will be good if Indian authorities also specify a suitable lifespan based on Indian experience. However, extending the building's design life helps defer carbon emissions associated with new construction that would result from demolishing the existing building.

Based on the literature review, the report recommends the following checkpoints to mainstream LCA in building sector:

- Standardize LCA framework for life cycle energy and emission analysis of buildings
- Indian policymakers should request voluntary disclosure of EPDs to help create embodied carbon dataset based on primary reporting by manufacturersEstablish standardized framework for manufacturers to calculate EPDs of materials
- Support development of India-specific embodied carbon dataset for most frequently used and most carbon-intensive construction materials and products
- Establish standardized framework for manufacturers to calculate EPDs of materials
- Lay the groundwork for reporting LCA results across standard building typologies.

CHAPTER

01

Policy Context and Barriers to Mainstreaming LCA

1.1 Introduction

Globally, the building sector accounts for about 35% of annual global CO_2 emissions [2]. This includes embodied carbon emissions from some of the key construction materials as well as carbon emissions from energy used for heating, cooling, lighting and appliances. Of those total carbon emissions, building operations are responsible for approximately 27% annually, and at the same time, the embodied carbon of just four materials used in buildings– cement, iron, steel, and aluminium – is responsible for an additional 7.7% annually [2] as shown in Figure 1.1.

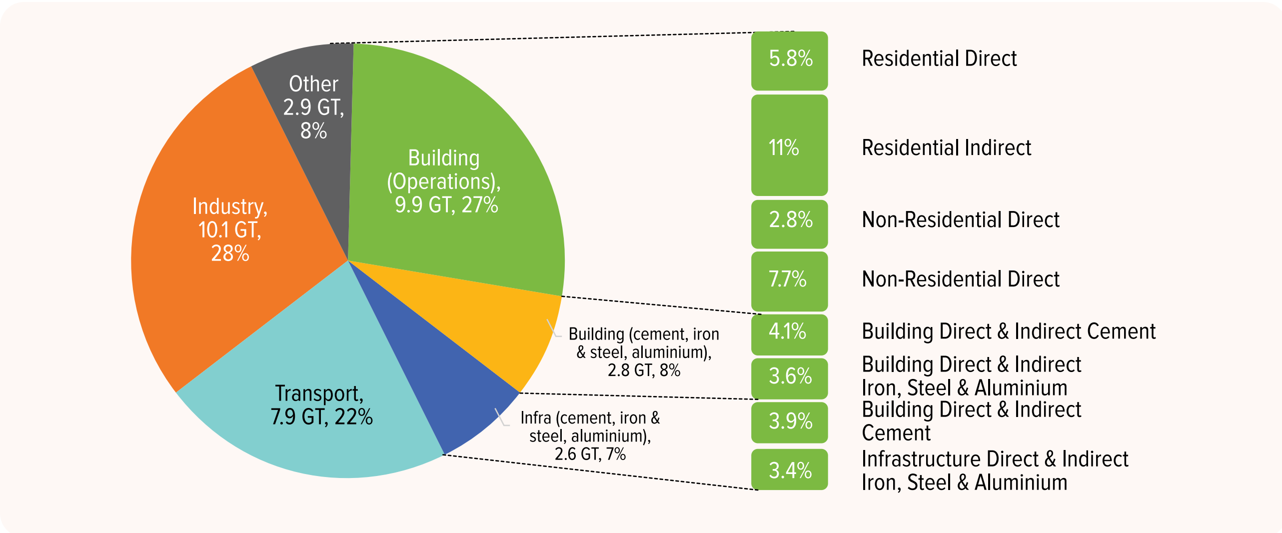


Figure 1.1: Total annual global CO_2 emissions broken by sector (Source: Image has been reproduced using data from [2])

To meet future demand, it is projected that the world will add approximately 2.6 trillion ft^2 (241 billion m^2) of new floor area to the global building stock between 2020 to 2060 [2]. Given that buildings are major consumers of energy-intensive materials like cement and steel, the contribution of these materials to total carbon emissions from the building sector is expected to increase significantly.

1.2 Overview of the Carbon Emissions from Indian Building Sector

By 2050, India's floor area is forecasted to surpass double its current size. This expansion, coupled with the anticipated retirement of a significant portion of existing buildings, suggests that the majority of the building stock expected to exist in 2050 has yet to be constructed [5] and hence presents significant opportunity for avoided carbon emissions, both embodied and operational.

India is projected to become the world's largest emitter of new embodied carbon emissions from the building sector by 2070 [3]. Currently, 42% of annual building-related carbon emissions are related to embodied carbon, which is expected to increase fourfold, in aggregate, by 2070 (Figure 1.2) [4].

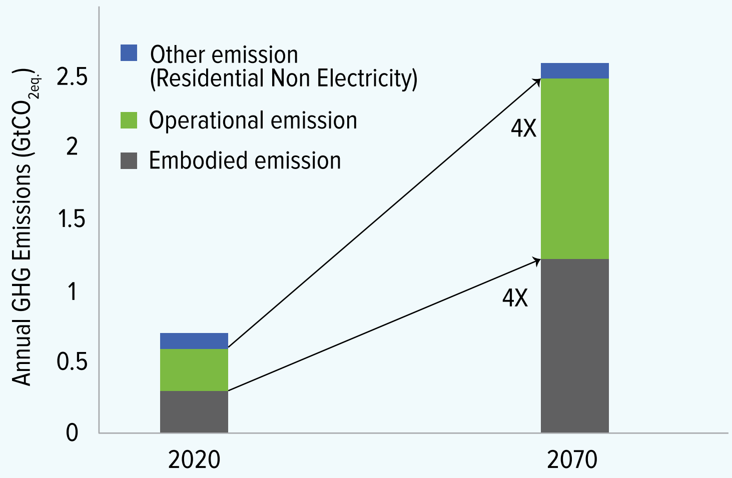


Figure 1.2: Projected operational and embodied carbon emissions from the Indian building sector. [Source: The figure has been repurposed using the data presented in CSTEP [4]]

The majority of embodied carbon in the building construction sector results from carbon emissions emitted from using fossil fuels in building material extraction and manufacturing, process emissions from manufacturing, transportation of building construction materials to the site and carbon emissions related to on-site energy use to construct the buildings.

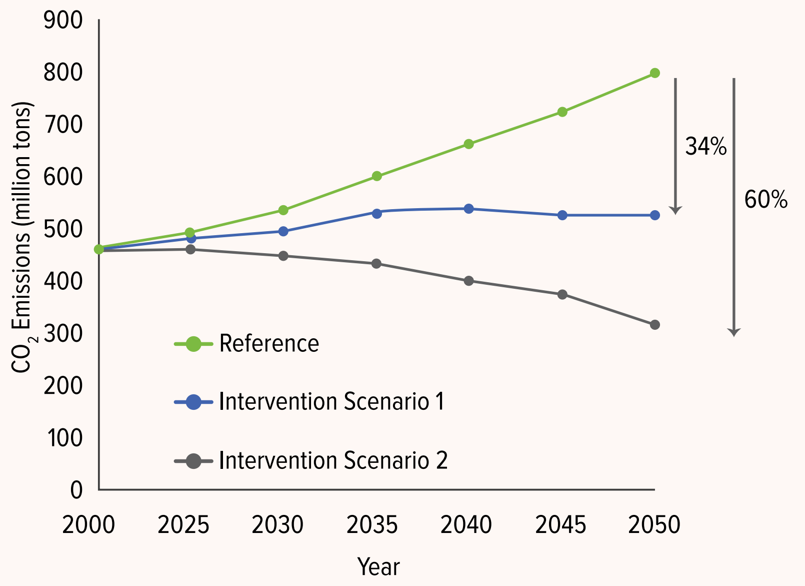
With rapid urbanization and a surge in purchasing power, coupled with a growing desire for enhanced thermal comfort, energy consumption for building operations is also projected to skyrocket by approximately fourfold by 2070 compared to 2020 levels (refer to Figure 1.2). Residential buildings are expected to contribute around 85% of the total operational carbon emissions, with commercial buildings accounting for the remaining 15% [5].

1.3 Policy Landscape

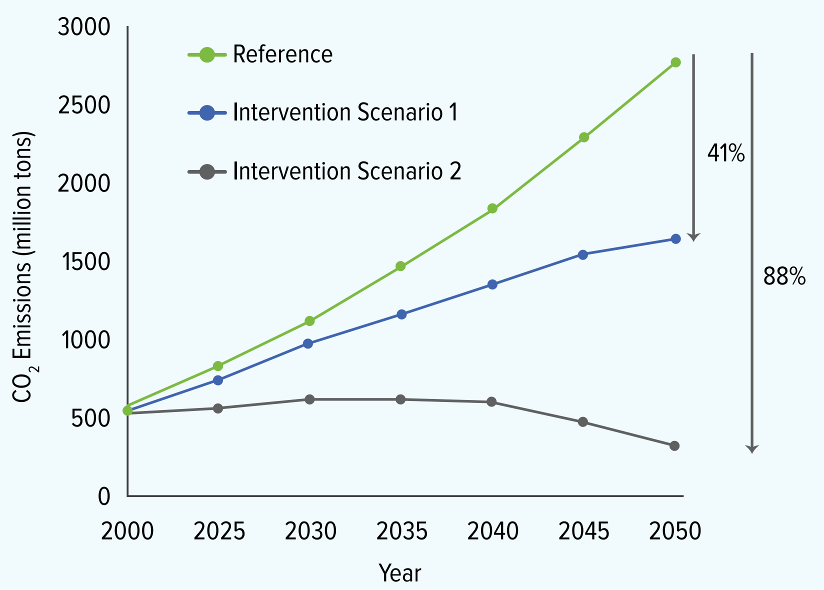
Currently, governments and private sector stakeholders are largely focused on reducing operational carbon emissions, while embodied carbon remains more challenging to track, record and report. In India, there are policies and programs to reduce building-related operational energy and carbon emissions, such as the ECBC (Energy Conservation Building Code) and ENS (Eco Niwas Samhita). However, neither of these codes talk about the embodied carbon of building.

Across the life cycle of a building, typically 50–70% of total embodied carbon is emitted before the building becomes operational, referred to as upfront embodied carbon [6]. Of the total upfront carbon, 85–90% of the carbon emissions arise during the manufacturing stage, 7–10% during transportation and 3–5% during the building construction [6]. Considering that typically more than 50% of the carbon emissions happen upfront, and given the time value of carbon, upfront carbon emissions are the most critical to address. Given the forecasted increase in new construction in the coming decades, unless embodied carbon emissions are regulated, India will likely spend a large share of its carbon budget on upfront carbon emissions.

With appropriate policy support and interventions, it is estimated that the operational and embodied carbon can be reduced by up to 60% and 88%, respectively, by 2050 relative to business-as-usual reference case scenario. Figure 1.3 shows the reduction potential by 2050 from a 2020 baseline under two intervention scenarios. Intervention scenario 1 reflects a scenario where interventions in the building sector are made as per the announced COP26 goals. Under this scenario embodied and operational carbon can be reduced by 34% and 40%, respectively, by 2050 compared to the reference case. Under intervention scenario 2, which deals with demand side efficiency and clean energy supply, the embodied and operational carbon from the building sector can be reduced by 60% and 88%, respectively, by 2050.



Reduction in embodied carbon from the reference building sector emission based on Scenario 1 and 2



Reduction in operational carbon from the reference building sector emission based on Scenario 1 and 2

Figure 1.3: Projected embodied and operational carbon for 2050 from the base year of 2020 under different intervention scenarios (Intervention scenario 1: interventions aligned with COP 26 goals, Intervention scenario 2: interventions related to demand side efficiency and clean energy supply)
[Source: The figure has been repurposed using the data presented in [1]]

1.4 Challenges and Barriers to Mainstreaming Building Life Cycle Assessment

While recent LCA research conducted in India has focused on various sectors including the handloom industry, waste management, rooftop solar PV systems, among others, building sector focussed LCA studies have been limited. Where the latter have been carried out, they rely primarily on non-Indian data sources in the absence of India-specific national and/or regional data on building materials and products.

The LCA of buildings allows building owners, users, developers, designers, researchers and performance rating agencies to understand the total carbon emissions, and therefore the life cycle impact of the building on environment. It enables them to make interventions to building design and specifications to mitigate carbon emissions while also allowing for performance benchmarking, which is increasingly of interest to asset owners, tenants and other stakeholders. However, there are some challenges and barriers which need to be overcome for mainstreaming the adoption of LCA of buildings, which are mentioned below:

1.4.1 Lack of Mandatory Requirements in Building Codes

Indian building codes do not currently have a prescribed standard for embodied carbon and/or a mandatory requirement for conducting and reporting on life cycle carbon in buildings as is the case in some other jurisdictions internationally. This interlinks with the other challenges such as standard LCA framework prescribed for Indian building sector, lack of India-specific embodied carbon dataset for construction materials and products, lack of market push and lack of awareness discussed below.

1.4.2 Unavailability of Standard LCA Framework for India

The absence of a standardized LCA framework tailored for India poses obstacles to its adoption in the building sector. This lack of standardization leads to inconsistency in LCA methodologies across projects, making it difficult to compare and interpret results accurately. Without clear guidelines, there is uncertainty about which parameters to include and how to integrate local environmental and economic factors. This variability in methodologies can result in unreliable data quality and undermines confidence in LCA as a reliable decision-making tool. The creation of India-specific and/or adoption of international framework and methodologies for LCA of buildings such as ISO 14040: 2006, ISO 21930: 2017, EN 15978: 2011, EN 15804: 2012 and ASHRAE/ICC 240 standard (currently in development [3]) will improve the consistency, comparability, and comprehensiveness of life cycle embodied carbon analysis.

1.4.3 Unavailability of Reliable India-specific Construction Materials Dataset

As mentioned earlier, India specific data on life cycle embodied carbon of building materials and products is a key constraint for reliable and consistent analysis. Data gaps occur in two distinct manners: gaps in some of the life cycle stages for some material categories and a lack of data for all life cycle stages for other material categories. Currently, cradle-to-gate (A1–A3) embodied carbon Dataset for Indian construction materials exists for key building material categories, including concrete, masonry, steel, aluminium, gypsum board, insulation, cladding, flooring, ceiling tiles, and paint published by International Finance Corporation (IFC). However, the data has been published in 2017 and no further revisions have happened. Variations arise due to differences in product category rules (PCRs) and/or the specificity of data used (factory-specific or generic). Although in the material categories mentioned above, A1–A3 carbon emission estimates fall within a relatively narrow range currently, as manufacturers innovate and adopt sustainable manufacturing processes (e.g. green steel or green concrete alternatives), the gap is expected to widen.

1.4.4 Lack of Market Push

At present, national or sub-national governments do not have established procurement guidelines and incentives to promote green products and sustainable construction practices, e.g., by setting a threshold (say in $kgCO_2/m^2$) for the carbon content of the materials used. There is also no requirement to disclose embodied carbon data of products listed on the Government e-marketplace, the national public procurement platform. The Indian Green Building Council (IGBC) has set a benchmark of 700 kgCO2eq./m^2 for net-zero buildings. However, this benchmark needs to be validated against the various types of current construction practices. Additionally, it is important to assess how the incentives provided can drive the adoption of this benchmark value in new construction. The financial incentives currently available to developers and or asset owners for constructing green buildings (e.g., extra FAR and/or tax benefits) do not mandate consideration of life cycle carbon impacts. Hence, there are not strong market drivers for product manufacturers, developers, asset owners and other building sector stakeholders to design, operate and disclose from the perspective of life cycle embodied carbon.

1.4.5 Lack of Awareness and Expertise

LCA of buildings is a comparatively new topic, and a significant knowledge gap exists in the market regarding the calculation and reporting standards. The lack of awareness among building professionals regarding LCA stems from several factors. Firstly, many professionals in the building sector may not fully understand the concept of LCA or its importance in evaluating the environmental impacts of buildings throughout their life cycle. Secondly, there may be limited exposure to training or educational programs that cover LCA methodologies and applications. Thirdly, the complexity and technical nature of LCA tools and calculations may deter professionals from integrating them into their practices without adequate support or guidance. Lastly, without clear mandates or incentives from regulatory bodies or industry standards, there may be a perceived lack of urgency or necessity to incorporate LCA into building design and construction processes.

1.5 Efforts Taken to Mainstream LCA of Buildings in India

The reduction of life cycle carbon in the building sector has just begun to take shape in India as in the world. The following recent developments are beginning to engage building sector stakeholders on life cycle embodied carbon estimation and reduction:

- The inclusion of embodied carbon of construction materials and the utilization of an LCA framework to disclose life cycle carbon emissions in the Energy Conservation Sustainable Building Code (ECSBC), currently in draft stage, along with the Bureau of Indian Standards' (BIS) requirements and guidelines (in draft stage) for quantifying product carbon footprints using ISO 14044, represent significant steps toward adopting a national standard framework for LCA analysis in the Indian building sector.
- Efforts are also underway to estimate the embodied carbon of construction materials in the Indian context. Efforts by the Centre for Advanced Research in Building Science Energy (CARBSE) at CEPT University and Building Material and Technology Promotion Council (BMTPC) to develop a Indian-specific construction material embodied carbon dataset is a notable step in this direction.
- The reporting framework for LCA has also been included in some building rating systems, e.g., GRIHA, IGBC and LEED V4.

CHAPTER

02

Literature Review

2.1 Introduction

This chapter examines the Life Cycle Assessment (LCA) framework as outlined in various international standards and explores how these frameworks have been applied in different LCA studies, both nationally and internationally. It further investigates the gaps in the reviewed studies, particularly focusing on their system boundaries, the functional units used, and the impact indicators employed. Lastly, the chapter delves into how the insights gathered from the literature can be instrumental in developing a tailored framework for conducting LCA in the Indian context.

2.2 International Standards and Framework for LCA

International standards such as ISO 14040 and ISO 14044 provide a broad definition of LCA, and the general methodology that can be used for LCA of buildings. As defined in ISO 14040, there are four phases in a LCA study: a) the goal and scope definition phase, b) the inventory analysis phase, c) the impact assessment phase, and d) the interpretation phase. ISO 14044 gives us a detailed explanation of the methodology framework of LCA.

EN 15978 outlines the calculation methods and system boundaries specifically for the LCA of buildings, and is increasingly becoming the reference document for the nomenclature used to describe the different building life cycle stages. ISO 14040 and ISO 14044, being international standards, are referred to and used globally. In contrast, EN 15978, which is also based on the principles set out in ISO 14040 and ISO 14044, is more widely used in the European Union (EU) nations and underpins mandatory or voluntary standards in different countries.

Environmental Product Declarations (EPDs) transparently communicate the environmental performance or impact of any product or material over its lifetime. ISO 21930 and EN 15804 define the core rules for EPDs of construction products and services. ISO 21930 is mostly followed in the US, whereas EN 15804 is adopted in the EU.

2.2.1 Framework and Policies for Embodied Carbon

While the life cycle energy and emission analysis of buildings is still voluntary in different parts of the world, the policy landscape in some parts of the world is seeing a shift towards mandatory targets. This momentum has led to the development of public roadmaps, published guidance, standards, and national legislation aimed at reducing the carbon footprint of buildings.

In the U.S., efforts to reduce embodied carbon have included federal and state-level actions, such as the General Services Administration's (GSA) "Buy Clean Inflation Reduction Act Requirements" and state-led Buy Clean acts in California, Colorado, and Maryland [3], [7]. Financial incentives have also been introduced to support low-embodied-carbon projects. Notably, California has implemented a whole-building embodied carbon policy that will take effect from July 2024, marking a significant step in regulatory efforts.

Globally, cities like Toronto and Vancouver have implemented policies requiring limits on the embodied carbon for new buildings [8]. In Europe, France's RE2020 and London's Plan Policy SI 2 impose requirements for whole-life carbon assessments and compliance limits for new building projects [9], [10]. Denmark have set mandate that new buildings bigger than 1000 m2 constructed after 2023 should meet the threshold limit value of 12 $kgCO_{2eq.}/m^2/year$. Also, it sets out that new buildings smaller than 1000 m^2 are required to conduct LCA of buildings.

Various carbon accounting standards, frameworks, and labels support, compliment or inform regulations, such as the Canadian Green Building Council's Zero Carbon Building Design Standard and the UK's RICS Professional Statement on Whole Life Carbon Assessment [11]. Emerging labels like Europe's LCBI and Sweden's NollCO2 Certification set performance benchmarks, while initiatives like the *Building System Carbon Framework and the Built Environment Carbon Dataset* aim to standardize definitions and improve data collection. Green building rating systems such as LEED and others are increasingly including tighter embodied carbon compliance criteria and targets to enhance their impact.

Figure 2.1 below shows a timeline of selected global policies relating to building life cycle carbon and/or embodied carbon.

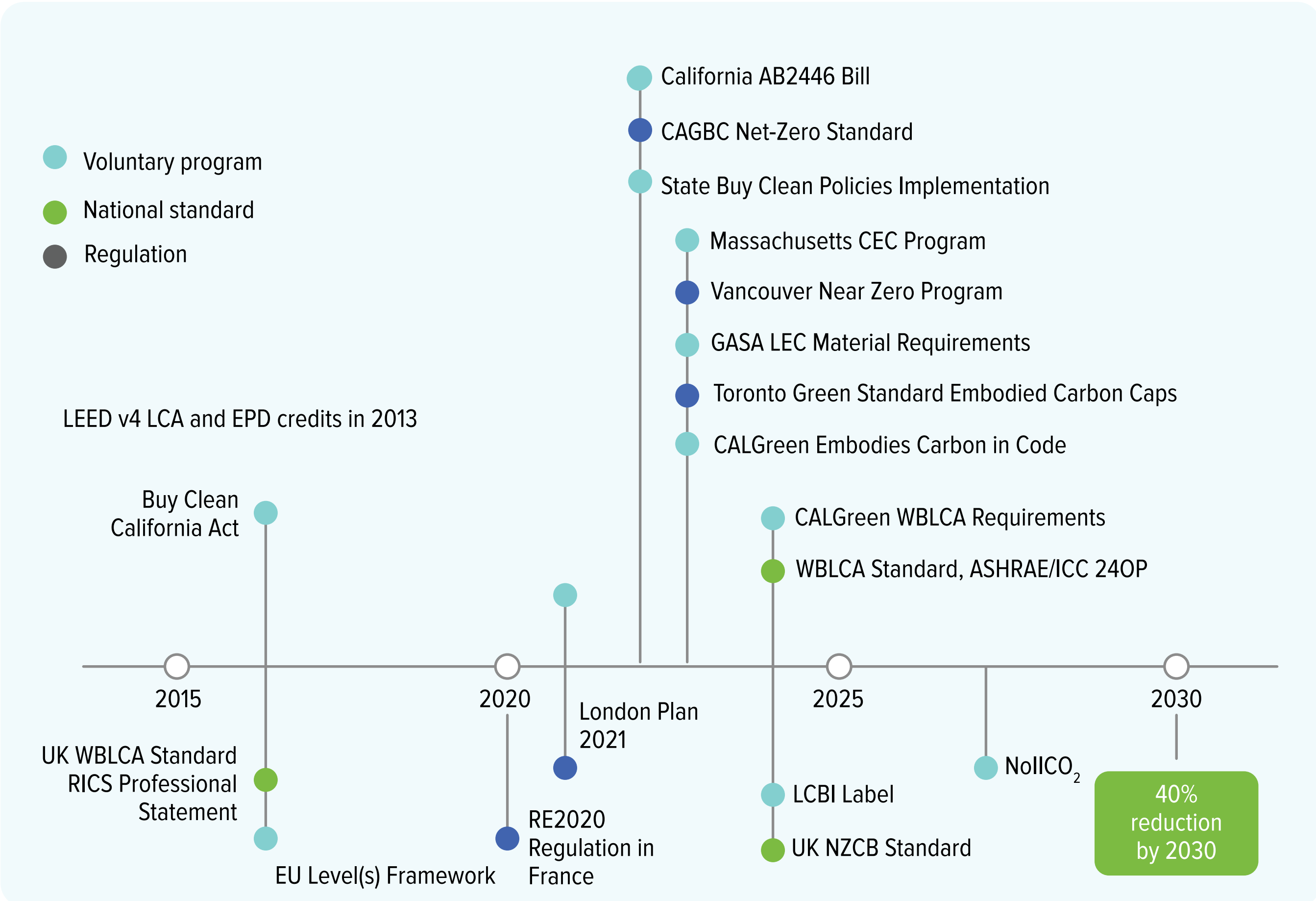


Figure 2.1 Timeline of selected global policies to address building sector embodied carbon in different parts of the world. [Source: The image has been repurposed from ref. 3]

2.3 Insights form the Literature Studies

Literature relating to LCA of buildings across different geographic regions have been reviewed to glean inferences on standards and framework followed for LCA, scope definition, and the methodology used for the material inventory analysis, impact assessment and interpretation of results. Tables 2.1 and 2.2 summarise the Indian and international LCA studies that were reviewed.

Table 2.1: Summary of literature review: India-specific LCA studies

Paper/ Report	Geographical location/Climatic condition	Building Type	Walling Material	System boundary	Reporting Variables	Key Findings	Relevance to Indian Context
Kiran et al. [12]	Kerala, India/ Hot & humid	Residential	Standard burnt clay, AAC brick, GFRG panel	A1-A5, B2-B6, and C1-C4	EE – GJ/m^2 floor area OE – kWh	Through comparative life cycle analysis of alternative walling materials, it was concluded that low EE materials result in lesser life cycle costing (LCC).	The structure with the GFRG walling system saves 8% of the plinth area and a reduction of 6.8% in the initial cost.
Bansal et al. [13]	New Delhi/ Composite	Residential	230 mm thick fired clay brick masonry in 1:6 (Cement: Coarse sand), mortar	A1 – B5	EE - GJ/m^2	Through analysis of initial and recurring EE, it has been reported that recurring EE is 86% of its initial EE.	The use phase embodied energy of Indian affordable houses is equal to 86% of its initial embodied energy. It can be minimised by using more durable construction materials for terracing, flooring and plastering/ rendering, which are major stakeholders in REE.
Maithel et al. [14]				A1 – A3	MJ/m^3	Different material compositions and different process methodologies of construction materials affect its EE significantly. Regional variations led to 3-84% variations in the upfront embodied carbon of brick	While calculating EE, regional variation in EE of different construction materials should be accounted for carefully to estimate the embodied carbon of buildings accurately.
Ramesh et al. [15]	Hyderabad (A.P.)/ warm & humid	Residential	Hollow concrete, soil cement, fly ash and aerated concrete with expanded polystyrene	A1 - A3 and B6	kWh/m^2 (usable floor area)-year	Different walling materials have been analysed from the LCA perspective in different climatic zones of India.	Insulation (EPS), though having high embodied carbon, results in savings from the life cycle perspective. It varies from 10% to 30% depending on the climatic conditions.
Sravani et al. [16]	Tirupati, India/Warm & humid	Residential	AAC blocks with PUF insulation	A1-C4	kgCO_{2eq}/m^2/year	LCA study shows that carbon emission contribution from the materials at the cradle-to-gate stage is highest, followed by the operational stage.	The initial carbon embodied in the building can be reduced through optimised design and reduced material intensity. The roofs and walls replaced with alternate materials showed a 2–6% reduction in terms of carbon dioxide emissions.

Paper/ Report	Geographical location/Climatic condition	Building Type	Walling Material	System boundary	Reporting Variables	Key Findings	Relevance to Indian Context
Satola et al. [17]	Bhubaneswar (warm and humid), Jodhpur (hot and dry), and New Delhi (composite)	Residential	Reinforced concrete, Clay brick, Autoclaved aerated concrete	A1-A5, B6	$kgCO_{2eq}$./capita/ year	Through parametric study-based LCA of buildings, it is reported that the apartment's floor area, equipment load, windows-to-floor ratio, mechanical ventilation airflow, and cooling temperature setpoint are the most influential design parameters in relation to the life cycle GHG emissions.	Based on the multi-objective optimisation, significant reductions in the range of 62–75% in terms of life cycle GHG emissions and 40–54% in terms of life cycle cost were achieved compared to the baseline 7-storey multifamily design scenario based on the minimum requirements of the Indian energy conservation code.
Devi et al. [18]	Chennai (Hot & humid)	Residential	Cement blocks, cement mortar	A1 – C4	$kWh/m^2/year$	LCA of residential buildings have been analysed for different life spans, and it is reported that a higher lifespan of buildings reduces the whole life embodied carbon of buildings, whereas it increases the operational carbon.	Buildings with good construction practices and materials having a higher life span would result in low life cycle embodied carbon. The operation energy would also be reduced by increasing the efficiency of the grid, but currently, the operational energy contributes to 50-70% of LCE.
Sharma et al. [19]	Hamirpur, Himachal Pradesh, India (Composite)	Educational	Kota stone (outer wall), Red brick masonry (inner wall)	A1 – A3, B1 – B4 and B6	Ton CO_2eq./m^2 (usable floor area)-year	RCC framework and steel were found to be the highest contributors in the construction phase of life cycle GHG emissions. It was also seen that most of the energy (59%) was consumed during the use (operation) phase of the building due to electrical appliances, viz. AC, heating devices, machinery and computers.	Alternative low EE materials and passive strategies must be explored for the building construction, operation and maintenance so that the problems of high energy consumption GHG emissions can be reduced significantly. Simple techniques such as an increase in the set-point temperature of AC to 26 °C and the practice of load shedding can show carbon savings of 10-12%.

Paper/ Report	Geographical location/Climatic condition	Building Type	Walling Material	System boundary	Reporting Variables	Key Findings	Relevance to Indian Context
Venkatraj et al. [20]			Assembly 1: Stucco and mineral wool insulation, Assembly 2: Precast concrete panel and mineral wool insulation, Assembly 3: Precast concrete panel and expanded polystyrene insulation, Assembly 4: Limestone and polyurethane insulation	A1-A5, B1-B5	MJ/m^2	The results of this study indicate that using different LCI techniques to calculate EE causes massive variations in EE factors. Further, it is reported that the disaggregated input-output-based hybrid (IOH) approach is more accurate compared to the process-based approach.	The process-based approach is more common and is being used in most of the commercial software. Also, the disaggregated input-output-based hybrid approach has not been reported in any of the Indian studies.
Praseeda et al. [21]	Composite, Warm & Humid, Moderate, Cold Climate	Residential	Monolithic RC, stone masonry, burnt clay brick masonry, stabilised soil block masonry and rammed earth	A1 – A3 and B6	GJ/m^2	Building structure, including the envelope, represents the major component, nearly 60%–70% of the EE of a building. OE has a major share (80%–90%) in LCE of buildings, followed by EE (10%–20%), whereas demolition and other process energy have a negligible share.	Considering the major share of building structures in EE, there is a need to decarbonise the building's materials and optimise building structures.
Devanand et al. [22]	Hassan, Karnataka, India (Hot & humid)	Residential	(i) Burnt brick, (ii) Solid concrete block, (iii) Fly ash brick, (iv) AAC block	A1 – A3	MJ/kg	Through comparison of different masonry walls, it is reported that a burnt brick wall has EE 2.8 times higher than an AAC block wall, 2.6 times higher than a Fly Ash wall and 3.9 times higher than a solid concrete wall.	Burnt bricks still dominate the Indian building sector, which results in large EE consumption. The production process of burnt bricks involving burning energy (fuel) has a major influence, contributing about 49 % to total EE. The AAC and Fly Ash should be mainstreamed as an alternative to burnt brick in an aggressive manner.

Paper/ Report	Geographical location/Climatic condition	Building Type	Walling Material	System boundary	Reporting Variables	Key Findings	Relevance to Indian Context
Praseeda et al. [23]	Composite, Warm & Humid, Moderate, Cold Climate	Residential	Monolithic RC, stone masonry, burnt clay brick masonry, stabilised soil block masonry and rammed earth	A1 - A3 and B6	GJ/m^2	RCC monolithic construction has EE 2.5 times higher than RCC structure with masonry infill wall, 3.6 times higher than burnt clay brick construction and five times higher than rammed earth construction.	In the case of dwellings with RC frame structure with masonry infill, the contribution of walls and supporting structure to the building's EE and total mass is 50% and 43%, respectively. Therefore, The use of alternative walling materials, such as stabilised soil blocks and rammed earth, results in low EE of buildings.
Basavaraj et al. [24]				A1 – A3	MJ/tonne	EE of cement manufactured at different geographic locations has been calculated. A 1% variation in EE has been observed.	The cement production process contributes to 8% of the anthropogenic CO_2 emissions. Therefore, it is important to understand its environmental impact.
Jain et al. [25]	Ahmedabad, Gujarat, India (Hot & dry)	Educational	Reinforced cement concrete, burnt clay bricks, extruded polystyrene insulation	A1-A5, B1-B6, C1-C3, and D	tCO_{2eq}	The results show that despite the annual net-zero operation status of a building, the building has a negative impact with 866 tCO_{2e} across a calculated lifespan of 60 years.	If no electricity was exported, operational Carbon emissions (B6) would reduce from 3294 to 10 tCO_{2e}.
Chel et al. [26]	New Delhi, India (Composite)	Residential	Stabilised mud brick blocks	A1-A3	MJ/m^2	A mud house is investigated, located in New Delhi, India. The embodied energy per unit floor is 2298.8 MJ/m^2 with a cooling energy saving of 1813 kWh/year and a carbon credit potential of € 52/year.	If 5% of the total households in India are made of adobe houses in rural areas or semi-urban areas, then the annual CO_2 emission mitigation into the atmosphere will be approximately 36.4 million metric tons/year which accounts for carbon credit of € 364 million/year. The passive house (or mud-house) was found to be an energy-efficient and eco-friendly habitat for achieving natural thermal comfort for the rural population of India since they cannot afford window air conditioners or air heaters in harsh summer and winter climatic conditions in India.

Paper/ Report	Geographical location/Climatic condition	Building Type	Walling Material	System boundary	Reporting Variables	Key Findings	Relevance to Indian Context
Bansal et al. [27]	New Delhi, India (Composite)	Residential	(i) Burnt clay bricks (ii) Hollow cement concrete blocks (iii) Aerated Autoclaved blocks (iv) Fly ash lime gypsum blocks (v) Solid cement concrete blocks	A1-A3	GJ/m^2	The calculation has been done for a total of 122 numbers of houses, having plinth areas varying between 20 m^2 and 60 m^2. The embodied energy is the least (2.092 GJ/m^2) for two-storied houses constructed with hollow cement concrete block-based masonry. However, the cost of building materials is found to be the lowest (US$ 62/m^2) for four-storied houses constructed with AAC block-based masonry.	Embodied energy is about 40% & cost is 20% less in houses constructed with alternative materials. But, there is no linear relation between the cost and embodied carbon of the houses.

Table 2.2: Summary of literature review: International LCA studies

Paper/Report	Geographical location/ Climatic condition	Building Type	Walling Material	System Boundaries	Reporting Variables	Key Findings	Relevance to Indian Context
Giordano et al. [28]	Turin, Italy (Hot & humid)	Residential	(i) masonry-based system with a cladding and insulated envelope (ii) wood stud wall, plastered wood siding and Rockwool insulation	A1 – A5 and B1- B5	OE & EE - kWh/m^2/year	Through analysis of EE and OE for two case study, the author tries to find the correlation between OE and EE and also relates it with WWR.	11- 13 % increase in the EE occurs with 14-20% in WWR. The choice of a proper balance metrics and weighting system should depend on the targets of the political agenda. A frequent constraint for various countries is the lack of national and agreed EE Datasets for building materials.
Gustavsson et al. [29]	Ostersund, Sweden (Cool & humid)	Residential	Plasterboard, lumber, Glulam, Rock wool insulation	A1 – A5 B5, C, and D	kWh/m^3	A detailed analysis has been provided, including the fossil fuel mix used for different materials and different technologies.	If coal-based fossil fuel is replaced with biofuel, it would decrease carbon emissions by 31 kgCO_2/m^2. It is important to adopt a life cycle perspective involving both material and energy supply when evaluating the primary energy and climatic impacts of buildings.
Adem Atmaca [30]	Gaziantep, Turkey (Warm & humid)	Residential	Double concrete blocks with XPS form board	A1 – A5, B1 – B6, C1 – C4 and D	kg Co_{2eq}	It is found that the operating phase is dominant in both urban and rural residential buildings and contributes 87–85 % of the primary energy requirements and 88–82 % of CO_2 emissions, respectively.	Insulation, though being the high embodied carbon in nature, results in savings from the life cycle perspective. It is calculated that the life-cycle energy consumption and CO_2 emissions of the residential buildings can be reduced by up to 22.8 and 23.4 %, respectively, by using a proper insulation material for the external walls.

Paper/Report	Geographical location/ Climatic condition	Building Type	Walling Material	System Boundaries	Reporting Variables	Key Findings	Relevance to Indian Context
Wralsen et al. [31]	Kristiansand, Norway (Cool & humid)	Residential	Bitumen, Gypsum, Fibre cement tile, XPS, Rockwool insulation	A1-A5, B1 -B6, C2-C4 and D4	MJ/m^2	A case study has been developed by renovating the building and including some passive measures. The author looked into the reduction in operational carbon after renovation.	The results of this study show that despite the low carbon intensity of the Norwegian energy mix, there was a considerable environmental benefit to renovation. The carbon payback period from the renovation is 1.09 years and 2.11 years for cumulative energy demand.
Tavares et al. [32]	Lisbon, Portugal (Warm & humid)	Residential	Plasterboard, PUF, PVC, Rockwool, Stainless steel	A1-A5	GJ	This study has assessed the embodied energy and GHG of a modular prefabricated house named Moby, addressing alternative structural materials (steel, concrete, timber, and LSF) and alternative house sizes (number of bedroom and inhabitants).	The impact of transport varies between 2% to around 26% of the total embodied impact. Transport-related impacts can be critical as may balance the potential benefits of prefabrication, particularly for modular prefabrication due to the high volume of the finished modules.
Takano et al. [33]	Helsinki, Finland (Cold & humid)	Residential	Wood plank, Reinforced concrete, Rock wool, Gypsum board	A1 – A3, B, C	MJ/m^2	This study has demonstrated the relationship between material selection and the life cycle energy balance of a building in Finland. The influence of the material selection appears differently in each life stage of the building.	The selection of the structural frame materials has a larger influence than the other component categories. Also, a combination of different structural frame (heavy-weight and light-weight) seems to be effective in some cases.
Rios et al. [34]	Arizona, United States (Dry)	Residential	(i) Wooden framing with fiberglass insulation (ii) Steel framed house with polyisocyanurate rigid form insulation	Material level A1 – A3, B1 – B5, C and D	kg CO_2eq	In the study presented in this paper, the authors used two different LCA methods to compare a single-use wood-framed wall against a reusable steel-framed wall in a tiny house in the U.S.	Reuse benefits depended on aggressive reuse rates (>70%) and multiple reuses of steel were needed to offset the embodied environmental impacts during steel production.

Paper/Report	Geographical location/ Climatic condition	Building Type	Walling Material	System Boundaries	Reporting Variables	Key Findings	Relevance to Indian Context
Petrovic et al. [35]	Dalarna, Sweden (Cool & humid)	Residential	Wood panel, Cellulose insulation, Cross-laminated timber	A1-A5 and B1 – B5	kg CO_2eq	The results of this study indicate that using different LCI techniques to calculate EE causes massive variations in EE factors. The results show that the highest impact was found to be in the in-use stage of the building.	The selection of wood-based materials has a significantly lower impact on carbon dioxide emissions in comparison with non-wood-based materials. Also, if the electricity mix has renewable energy sources, then the operational energy consumption can go down to 21% of CO_2 emissions.
Nolan et al. [36]	Ireland (Cool & humid)	Residential	(i) In-situ concrete frame building with reinforced concrete (RC) columns supporting a RC flat slab, (ii) Steel frame building using steel columns and beams to support the precast hollow core slab as the floor system, (iii) In-situ concrete frame building with RC walls supporting the RC floor slab, (iv) Steel frame building using a prefabricated modular system with lightweight steel sections.	Material level: A1 – A4 and B6	kWh/m^2	The analysis has indicated that the structural frame can affect the OE use over the lifetime of a building. This indicates that the selection of the type of structure can have an effect on the environmental performance of a building.	This EE to OE ratio calculated to current regulations is calculated at 0.21, switching to Nearly-ZEB construction, this ratio increases to 0.46

Paper/Report	Geographical location/ Climatic condition	Building Type	Walling Material	System Boundaries	Reporting Variables	Key Findings	Relevance to Indian Context
Nautiyal et al. [37]		Educational				The present chapter deals with LCA of an academic building located at hilly terrain to quantify energy consumption along with GHG emissions. The obtained results are also compared with another LCA study to see the effects of location and climate change on energy consumption and GHG emissions.	
Motuziene et al. [38]	Lithuania (Cool & humid)	Residential	(i) Cement plaster, silicate blocks, polystyrene foam, cement mortar (ii) Cement plaster, rock wool insulation, log walls (iii) Cement plaster, OSB plates, timber frame, rock wool, cement mortar	A1 – A3, B, C	MJ/m^2	The share of the embodied primary energy constitutes more than 1/3 of the life cycle primary energy.	Factors such as the lifetime of different construction materials and the whole building and other factors, that are important on the operational phase, should be considered more accurately
Hennequin et al. [39]	Lyngby, Denmark (Cool & humid)	Residential	Gypsum plasterboard, Stone wool, Wooden painted siding	Material level A1 – A3	MJ/tonne	Flood related repairs add between 4 and 18% of impact to the life cycle of the house.	The main element of the single-family residence impacting the environment is the structural frame, which makes up one-fifth of the total impact. 80% of the frame's impact is due to its cement-facing bricks. This could be mitigated using shale or clay bricks instead.

Paper/Report	Geographical location/ Climatic condition	Building Type	Walling Material	System Boundaries	Reporting Variables	Key Findings	Relevance to Indian Context
C. Thormark [40]	Gothenburg, Sweden (Cool & humid)	Residential	Glass wool, EPS wood studs	A1 – A3, B	MJ/m^2 floor area	Initially, the embodied energy was 40% of total energy needed for a lifetime expectancy of 50 years. Through material substitution, the embodied energy can be decreased by approximately 17% or increased by about 6%.	The results presented here indicate that embodied energy in conventional buildings can be reduced by approximately 10–15% through relatively simple means such as material recycling and combustion.
Tettey et al. [41]	Vaxjo, Sweden (Cool & humid)	Residential	Plaster-compatible mineral rock wool insulation, timber studs	A1 - A3	kWh/m^2	Reduction of about 6–7% in primary energy use and 6–8% in CO_2 emission when the insulation material in the reference buildings is changed from rock wool to cellulose fiber in the optimum versions. Also, the total fossil fuel use for only insulation material production was reduced by about 39%.	Enhancing material production technologies by reducing fossil fuel-use and increasing renewable energy sources, as well as careful material choice with renewable-based raw materials can contribute significantly in reducing primary energy use and GHG emission in the building sector. For instance, if natural gas is used instead of coal for material production, this can reduce the 7% of primary energy-use and 20% of the CO_2 emission.
Morel et al. [42]	France (Warm & humid)	Residential	(i) Stone masonry wall (ii) Rammed earth wall	A1 – A4	GJ	An adaption of local should be promoted for building construction. However, the adoption of local materials in developed countries can be hindered by the loss of traditional building crafts and a lack of appropriate building standards. When thermal insulation is used, building with local material reduces the embodied energy of the building materials by 215% for the stone masonry and by 285% for the rammed earth walls.	By adopting local materials, the amount of energy used in buildings decreased by up to 215% and the impact of transportation by 453%.

Paper/Report	Geographical location/ Climatic condition	Building Type	Walling Material	System Boundaries	Reporting Variables	Key Findings	Relevance to Indian Context
Monahan et al. [43]	Norfolk UK (Cool & humid)	Residential	Timber frame, PUF, cement particle board	A1 – A4	Ton CO_{2eq}	The house constructed using a panellised timber frame MMC construction, produced a building with a 34% reduction in embodied carbon when compared with traditional masonry construction for an equivalent house	Despite timber being the predominant structural and cladding material, concrete is the most significant material (by proportion) in embodied carbon terms, responsible for 36% of materials related embodied carbon.
Mithraratne et al. [44]	Auckland, New Zealand (Warm & humid)	Residential	Earth brick wall, Timber framed glass fibre insulated with fibre cement board	A1-A5, B1-B6 and C	MJ/m^2	For light, heavy and super insulated constructions the contribution due to construction alone is only 39%, 24%, and 55%, respectively.	The total environmental impact of the light construction type is 31% more than the super insulated construction type, and it is 9% less than that of the heavy construction type.
Cozar et al. [45]	Seville, Spain (mixed-Marine)	Heritage site	(i) Standard aluminium system (ii) Timber system (iii) Steel system	A1 – A5, and C1-C4	MJ/m^3	All three lightweight construction systems that use the most common materials (aluminium, wood and steel) are compared. The results indicate that the aluminium option, is the most efficient in terms of environmental impact.	The CED and GWP impact indicators of steel structure produce only 7.94% and 8.84% higher impact, respectively, than the aluminium system.
Huberman et al. [46]	Negev, Israel (Hot & dry)	Residential	Concrete with XPS	A1 – A5 and B6	MJ/m^3	It was found that the embodied energy of the building accounts for some 60% of the overall life-cycle energy consumption, which could be reduced significantly by using "alternative" wall infill materials.	While the studied wall systems (mass, insulation and finish materials) represent a significant portion of the initial EE of the building, the concrete structure (columns, beams, floor and ceiling slabs) on average constitutes about 50% of the building's pre-use phase energy.
Hafliger et al. [47]	Zurich, Switzerland (Cool & humid)	Residential	(i) Reinforced concrete (ii) Masonry (iii) Wood (iv) Insulation material	A1 – A3	m^2 of energy reference area per year	The impact of materials used during the building's life cycle has been assessed. Concrete has the main contribution to GWP but a low uncertainty in the calculation. A particular attention has been given to insulation and wooden materials.	This study shows that cement and concrete products, as well as masonry products, are mainly sensitive to the choice of the building Reference Study Period (RSP).

Paper/Report	Geographical location/ Climatic condition	Building Type	Walling Material	System Boundaries	Reporting Variables	Key Findings	Relevance to Indian Context
Wallhagen et al. [48]	Gavle, Sweden (Cool & humid)	Office	Plaster, wood, Rockwool, Gypsum	A1-A3, B6	kg CO_{2eq}/m^2 year	Various measures were estimated to reduce the total contribution to climate change by nearly 50% compared with the original building and the operational energy use by nearly 20% (from 100 to 81 kWh/m^2-yr)	The calculated yearly relative impact from building materials varies from 86% to 37% when the expected lifetime varies from 10 to 100 years for the original building.
Passer et al. [49]	Austria (Cool & humid)	Residential	(i) Gypsum & brick (ii) dry construction (gypsum) (iii) Timber/dry construction (iv) Brick	A1-A3, B1-B6 and C1-C2	EE: kg CO_{2eq}/m^2a OE: kWh/m^2a	A comparative study has been performed for two buildings. The high environmental indicator results for EP and AP, 12 % to 43 % and 10 % to 24 %, respectively, are mainly due to construction products used for technical building equipment.	Due to the important role of LCA in the criteria weighting in several building certification systems, a detailed consideration of the technical building equipment is therefore indispensable.
Milaj et al. [50]	Oregon, United States (Mixed-humid)	Commercial	Wood	A1-A3 and C1-C2	kg CO_{2eq}	Wood could be one of the alternatives for the structure of the building in place of reinforced concrete.	The average reduction in GWP due to wood substitution was about 60% across the six case studies. These findings reinforce the perception of wood as a green building material that has the potential for commercial construction.
Lasvaux et al. [51]	France	Residential	Masonry wall	A1-A5, B2, B4, B6, B7 and C1-C4	kWh/m^2 year	The results showed that the embodied impacts are more critical for the greenhouse gases emissions indicator with 70% of contribution than for the primary energy (non-renewable) indicator with 40% of contribution.	The embodied impacts represent between 40% and 72% for the following indicators: acidification, global warming, non-renewable primary energy, and radioactive waste. In order to optimize the environmental performance of buildings, there is not a single solution due to the multicriteria approach. A work indicator per indicator is needed to identify improvement actions.

Paper/Report	Geographical location/ Climatic condition	Building Type	Walling Material	System Boundaries	Reporting Variables	Key Findings	Relevance to Indian Context
Alwan et al. [52]	Lincolnshire, UK (Mixed-humid)	Observatory & Visitor Centre	Steel, timber, concrete and glass	A1-A3, B6	MJ	At present, the capital costs of carbon offsetting are circa £12/tCO2 and projected to rise to around £200/tCO2 by 2050.	Carbon analysis should be performed in the pre-design phase, where components with high carbon emissions can be identified and replaced with alternative materials. For instance, in this component accounted for a significant amount of embodied energy in the design. Instead, anchor piles are proposed; this approach has reduced the use of concrete by 40 %. The total embodied carbon through a redesign has been reduced by over 30 %.
Citherlet et al. [53]	Geneva, Switzerland (Hot & humid)	Residential	Mineral wool	A1-A5, B1-B2 and C1-C4	$MJ/m^2/year$	It is important to be concerned about the indirect impact when the final (total) energy demand is lower than about 150 $MJ/m^2/y$ for Swiss mix electricity production and lower than about 50 $MJ/m^2/y$ for UCTE mix.	The direct impact of electricity can be reduced by changing the energy mix. For instance, the direct impacts of electricity use are lower with the Swiss mix because approximately 60% is made of hydropower and 40% of nuclear.
Fay et al. [54]	Melbourne, Australia (Warm & humid)	Residential	Brick, timber, fibreglass insulation, plasterboard	A1-A3 and B6	GJ/m^2	The addition of higher levels of insulation in Australia paid back its initial embodied energy in life-cycle energy terms in around 12 years. However, the savings represented less than 6% of the total embodied energy and operational energy of the building over a 100-year life cycle.	In 25 years, the net benefit represents 105% of the initial embodied energy `cost' of the additional insulation. However, over 100 years, the likely physical life of the house, if well maintained, the net benefit represents 718% of the initial embodied energy cost of the additional insulation. Therefore. some other strategies can be adopted instead of increasing insulation.

Paper/Report	Geographical location/ Climatic condition	Building Type	Walling Material	System Boundaries	Reporting Variables	Key Findings	Relevance to Indian Context
Munoz et al. [55]	La Rioja, Spain (Dry)	Educational	Glass Panel, Sandwich panel with mineral wool	A1-A3, B6 and C1-C4	EE: MJ/kg OE: kWh/ m^2 yr	If numeric benchmarks for NRBs are assumed to be the same as for offices, then primary energy of nZEBs should range from 85 to 100 kWh m^{-2} y^{-1} and on-site renewable sources should contribute with 45 kWh m^{-2} y^{-1}. This is with the aim of limiting the net energy consumption, between 40 and 55 kWh m^{-2} y^{-1}.	Despite the building showing a low thermal transmittance of enclosures and also incorporating renewable energies, non-residential building cannot be considered as nZEB. In this case, despite the building was designed for a very low primary energy consumption, this consumption only represents 56% of the total demanded energy along the building life cycle.
Gong et al. [56]	Wuhan city, China (Warm & humid)			A1-A3, B6, C1-C4 and D	Ton CO_{2eq}	The findings showed that the proportion of carbon emissions in the construction operation phase was the largest, followed by the carbon emissions of the indirect energy consumption and the construction material preparation phase.	The increasing building area was the major driver of energy consumption and carbon emissions increase, followed by the behaviour factor. The influence coefficient of the building area and behaviour factor are 2.0 and 1.17 respectively. On the contrary, energy efficiency was the main inhibitory factor for reducing carbon emissions.
Achenbach et al. [57]	Germany (Cool & humid)		Particle board, gypsum plasterboard, wood Fiber insulation board	A1-A3, B2-B4, B6, C and D	m^2 average per component	The stage A3, A4 and A5 contribute to 41% of the total environmental impact.	The transport of the building elements (A4) has a high impact (up to 20%). This is reasoned by the bulkiness of the building elements and the fact that many lorries drive back empty from the construction site. Also, it is recommended to account for the prefabrication processes within the product stage.

Paper/Report	Geographical location/ Climatic condition	Building Type	Walling Material	System Boundaries	Reporting Variables	Key Findings	Relevance to Indian Context
Robertson et al. [58]	Burnaby, British Columbia, Canada (Mixed-marine)	Office	(i) Gypsum wallboard, steel stud framing, Spray foam insulation (ii) Gypsum wallboard, Wood stud framing, Anonymous R-13 insulation	A1-A4	TJ/m^2	The cradle-to-gate process energy was found to be nearly identical in both design scenarios (3.5 GJ/m^2), whereas the cumulative embodied energy (feedstock plus process) of construction materials was estimated to be 8.2 and 4.6 GJ/m^2 for the timber and concrete designs, respectively.	When considering GHG emissions, the heavy timber design alternative outperformed the concrete-framed counterpart by over 70% when taking into account carbon storage and by 17%, even when the carbon storage property of wood was not considered.
Guggemos et al. [59]	Fort Collins, Colorado, United States (Hot-humid)	Office	Aluminium-framed glass panel curtain walls	A1-A5, B2, B6 and C	kg CO_2	The concrete structural-frame construction has more associated energy use, CO_2, CO, NO_2, particulate matter, SO_2, and hydrocarbon emissions due to more formwork used, larger transportation impacts due to a larger mass of materials, and longer equipment use due to the longer installation process. In contrast, the steel-frame construction has more volatile organic compound (VOC) and heavy metal (Cr, Ni, Mn) emissions due to the painting, torch cutting, and welding of the steel members.	For the overall building life cycle, the construction phase impacts represent a relatively small part (0.4-11%) of the overall building life-cycle energy use and carbon emissions. The maintenance and end-of-life phases also tend to have a small contribution to total energy use and carbon emissions.
RH Crawford [60]	Melbourne, Australia (Warm & humid)	Office, residential, Velodrome	(i) Precast concrete, glazed panels, aluminium framed curtain walling and granite veneer panels (ii) Brick veneer construction	A1-A3	GJ/m^2	This paper evaluates the hybrid inventory analysis method, which aims to improve the limitations of previous methods. It was found that the truncation associated with process analysis can be up to 87%, reflecting the considerable shortcomings in the quantity of process data currently available. Capital inputs were found to account for up to 22% of the total inputs to a particular product.	Input-output analysis alone does not always provide an accurate model for replacing process data. Whilst previous LCI studies have neglected to account for capital energy inputs, even those based on comprehensive hybrid approaches, this study has shown the significance of these capital inputs. Excluding these capital inputs can result in underestimates in LCI values of up to 22%

Paper/Report	Geographical location/ Climatic condition	Building Type	Walling Material	System Boundaries	Reporting Variables	Key Findings	Relevance to Indian Context
Crawford et al. [61]	Melbourne, Australia (Warm & humid) Brisbane, Australia (Warm & humid)	Residential	(i) Brick veneer walls, 90 mm fibreglass insulation batts with single-sided reflective foil. (ii) Replace insulation with 200 mm fibreglass batts (iii) Replace insulation with 200 mm fibreglass batts	A1-A5 and B6	GJ	Scenarios combining design and material changes investigated in this study reveal that it might not be worthwhile pushing operational energy efficiency to an extreme level.	Simply adding insulation and high-performance glazing can paradoxically result in an increase in life cycle energy demand if no design changes are made.
Stephan et al. [62]	Brussels, Belgium (Mixed-humid)	Residential	Reinforced concrete structure with a brick facade	A1-A3 and B6	GJ	Space heating represents at most 23% of the total life cycle energy demand over 50 years and 47% if the rest of operational energies, i.e. domestic hot water and appliances, is considered. Transport consumes 34-51% of the total life cycle energy consumption while the embodied energy of buildings was found to be of the same order of magnitude as their operational energy.	On average, the embodied energy represented 77%, 60% and 43% of the life cycle operational energy for the passive house, low-energy house and normal construction respectively. Current energy assessment of buildings, therefore, often only analyses a small fraction of the total life cycle energy use. We should widen its scope to account for so-called indirect energy consumption.
Stephan et al. [63]	Brussels, Belgium (Mixed-humid)	Residential	Brick with PUF insulation	A1-A3, B2 and B6	GJ/m^2	The embodied energy of passive houses can represent up to 77% of the total embodied and operational energy over 100 years. Also, passive houses can have nearly the same energy consumption as a same standard new house.	A retrofitted apartment in the city has an energy consumption 15.2% lower than the best passive house scenario. An emphasis should be given to retrofitting the existing houses in India to reduce the operational carbon emission from these buildings and make them energy-efficient.

Paper/Report	Geographical location/ Climatic condition	Building Type	Walling Material	System Boundaries	Reporting Variables	Key Findings	Relevance to Indian Context
Stephan et al. [64]	Melbourne, Australia (Warm & humid)	Residential	Brick veneer wall – 100 mm of fibreglass insulation – double-glazed aluminium-framed windows	A1-A3 and B6	GJ	Embodied and transport energy consumptions represent, on average, 63% of the life-cycle energy and 60% of the life-cycle greenhouse gas emissions.	No single category dominates the life-cycle energy demand. Indeed, the largest contribution comes from the operation of appliances (17% of the total energy consumption and 22% of the total greenhouse gas emissions over 50 years), followed by transport requirements and heating. Therefore, the reduction of the total energy consumption requires reducing the energy requirements of multiple end-uses and not just the space heating and cooling demand, as is typically the focus.
Stephan et al. [65]	Beirut, Lebanon (Hot-humid)	Residential	Double concrete block wall – 100 mm air blade – Double glazed aluminium framed windows	A1-A3, B2 and B6	GJ/m^2	The life cycle energy demand is dominated by transport energy (49%) followed by operational (33%) and embodied (18%) requirements.	The main ways to reduce this life cycle energy demand comprise relocating jobs outside of the capital, putting in place an adequate public transport network, improving town planning to favour pedestrians and rely on gas or renewable energy sources instead of electricity when possible, notably for domestic hot water
Stephan et al. [66]	Melbourne, Australia (Warm & humid)	Residential	Brick veneer wall – 100 mm of fibreglass insulation – double-glazed aluminium-framed windows	A1-A3, B2 and B6	GJ/capita/m^2	This study quantifies the effect of house size on life cycle energy demand in order to inform future building energy efficiency regulations. The embodied energy represents 49-70% of the energy demand across all 360 variations.	The embodied and operational carbon is 58% and 42% for 100 m^2 houses and changes to 70% and 30% for 392 m^2 houses with 2 occupants. Results show that larger houses appear to be more energy efficient per m^2 than smaller houses while actually having a much higher life cycle energy demand.

2.3.1 Scope and System Boundaries

The delineation of system boundaries in the various studies, as depicted in Figure 2.2 and referenced in ISO 21930 and EN 15978, varies based on data availability and the specific objectives of each study, such as which life cycle stages are emphasized to impact decision-making processes in building life cycle management. The selection of system boundaries will influence which stages emerge as (or are perceived to be) contributing most prominently to the building's life cycle emissions. Studies limited to the manufacturing phase might focus on the 'A' stages (A1-A3), emphasizing the energy consumption and carbon emissions associated with the manufacturing processes of materials. Conversely, studies aiming to highlight both the upfront embodied energy and carbon emissions occurring during the use phase might extend their focus to include both 'A' and 'B' stages. Meanwhile, studies that consider life cycle carbon emissions and circularity aspects tend to encompass all stages of the building's life cycle. This variation in selected stages as system boundaries significantly affects the reported data on energy consumption and carbon emissions. For example, the reported life cycle energy and carbon emissions for buildings vary considerably when only the upfront ('A' stages) and operational ('B' stages) phases are considered, compared to analyses encompassing all life cycle stages.

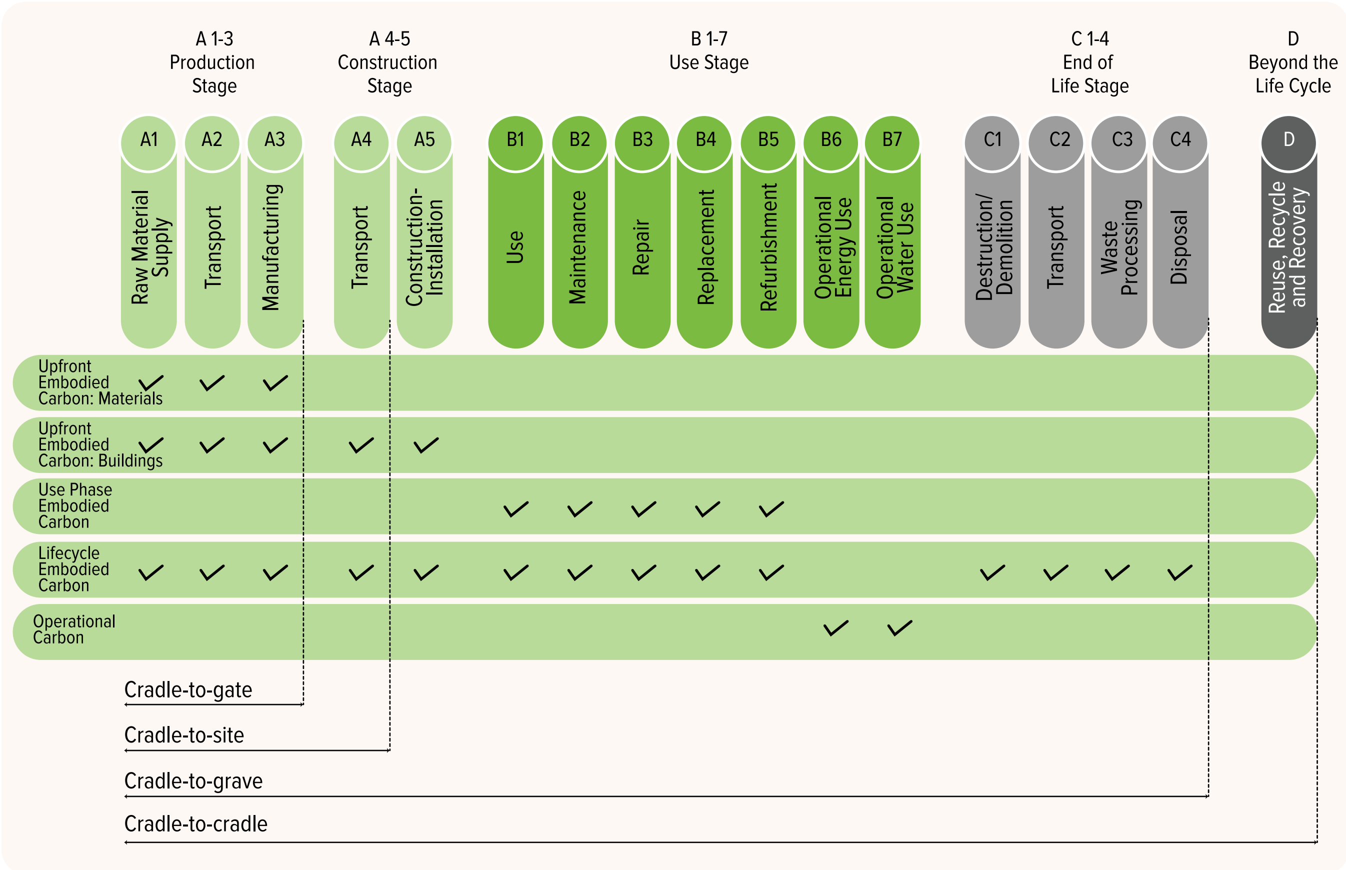


Figure 2.2 Representation of different system boundaries covered in the reviewed papers.

2.3.2 Interpretation of LCA results

The interpretation of the results reported in the reviewed literature can be broadly categorised as below.

Breakdown by building materials: These studies typically analysed the upfront embodied energy and carbon impact of materials used in construction. The analysis covered carbon emissions for extraction of raw materials (A1), transportation to the factory (A2) and manufacturing of the product (A3). EPDs play an important role in informing the carbon impact of the materials. However, many construction materials reported in the reviewed studies did not have EPDs, so values from different embodied carbon dataset (such as Gabi, Ecoinvent, One Click LCA, ICE and IFC datasets) were used. The focus of such studies was analysing which materials were the most carbon-intensive among all the materials used and whether they could be substituted with alternative low carbon materials.

Breakdown by building components: The building level results were broken down by different components or building elements such as foundation, structural elements (like beams, columns, struts), walls, floor, roof, finishing, installations, etc. The share of each building component in the total life cycle of building carbon emission was determined, and interventions were suggested for the specific building component to reduce the associated embodied carbon emission. These interventions could include material substitution, optimising the design of the building element (e.g. flat concrete slab versus hollow deck slab) or consideration of alternative construction systems.

Breakdown by life cycle stages: This kind of analysis has been used in most of the studies where carbon emissions related to each life cycle stage of the building were reported without necessarily breaking down the carbon emissions by materials, building elements, and other specifics. This kind of interpretation of results allows for a strategic overview, identifying key stages for efficiency improvements across the building's life cycle from the perspective of embodied and operational energy and/or emissions.

2.3.3 Functional Unit

Different functional units utilized for reporting LCA results pose a challenge in comparing outcomes across various studies. For life cycle carbon emissions, $kgCO_{2eq.}/m^2$ is predominantly used, whereas life cycle energy is commonly reported in MJ/m^2 or kWh/m^2. Typically, these metrics are normalized based on the internal floor area of the buildings, allowing for a standard basis of comparison.

However, some studies diverge by normalizing results against other metrics such as the volume of usable space, gross floor area, or the quantity of materials used. This variability complicates the direct comparison of LCA results across different studies. Additionally, it has been observed that authors might select different functional units at different stages of the LCA process, further adding to the complexity of inter-study comparisons. This variability underscores the need for standardization in reporting to enhance the comparability and consistency of LCA studies in the building sector. Additionally, different regions and regulatory bodies may have specific requirements for reporting LCA results, influencing the choice of functional units. Table 2.3 shows the different functional unit used across different studies.

Table 2.3: Functional units used in different building LCA studies

Functional Unit	Description
m^3	▸ Net volume of material
m^2	▸ Net living area ▸ Conditioned floor area ▸ Net floor area ▸ Usable floor area ▸ Gross floor area ▸ Gross internal floor area ▸ Gross external floor area

Functional Unit	Description
m^2/year	▸ Life cycle energy/emissions normalized by reference area for a year
m	The length of columns and beams in a building
kg	The quantity of the construction materials
kWh	Thermal energy depending on the heat source
kWh/m^2/year	kWh primary energy per year
TJ	Energy consumption
$tCO_{2\text{-eq}}$/capita	Greenhouse gas emissions per occupant

2.3.4 Methodology Used for Embodied and Operational Energy and Carbon Emissions

2.3.4.1 Methodology for Embodied Energy and Carbon Emissions

Amongst the reviewed studies the process-based material inventory analysis (refer next section) remains the primary method of embodied energy and carbon emissions estimation across the building life cycle compared to input-output and hybrid-based analysis which were less commonly reported. Many of the studies use readily available datasets such as Inventory of Carbon and Energy (ICE), Eco-invent, Gabi, IFC Indian construction material dataset, U.S. Life cycle inventory (U.S. LCI). Additionally, most studies have used various software tools such as One Click LCA, SimaPro, SimStadt and Eco-Indicator with their embedded life cycle inventory dataset.

Process based analysis

Process based analysis of embodied carbon relies on the physical flows of materials, energy and emissions along the life cycle stages of a product or process, from raw material extraction to end-of-life treatment, and has been considered more reliable than other methods discussed below. Process-based analysis requires identifying and modelling each unit process involved in the system boundary and collecting data on the inputs and outputs of each unit process from primary or secondary sources. Process-based analysis can provide detailed and specific information on the environmental performance of a product or process, but it can also be time-consuming, data-intensive, and prone to truncation errors or system boundary uncertainties.

Input-output based analysis

The input/output-based analysis transforms economic transactions into energy and carbon flows through the utilization of product costs and average energy tariffs [67]. However, it encounters challenges such as assuming uniformity and proportionality, inaccuracies and uncertainties in economic data, and the grouping and aggregation of sectors.

Hybrid analysis

Hybrid life cycle inventory analysis combines the strengths of process based and input-output based analysis. For example, hybrid-based analysis can use process-based analysis data of the construction materials and input-output based analysis can be used for the background system, i.e., the upstream activities that support the manufacturing of the construction materials.

2.3.4.2 Methods for Operational Energy and Carbon Emission Analysis

In the examined studies, operational energy estimation has been conducted through various methods, including physics-based Energy Simulation Tools/Software, LCA/LCCA/LCEA tools (such as SimaPro, One Click LCA, Ecotect), mathematical calculations, proprietary software/models, and national standards or other published references. The computation of building operational energy demand in these studies primarily employs three alternative approaches:

a) Using energy consumption data from utility bills (suitable for existing buildings).

b) Using pre-existing datasets, national standards, or published literature containing reference building information.

c) Energy modelling integrating building physics, data analytics, and hybrid techniques.

Physics-based energy simulation tools and software have garnered the highest acceptance among researchers. Notably, energy simulation engines like EnergyPlus, DOE-2.2, and eQuest, coupled with Building Information Modeling (BIM) software such as Revit, ArchiCAD, and Archsim (integrated with Grasshopper or SketchUp), along with graphical user interfaces like Green Building Studio, OpenStudio, and Design Builder, have been extensively utilized.

The carbon emissions associated with operational energy consumption are converted to carbon emissions by using the emission factor of the electricity grid and the emission factors of fuels used to meet the operational energy demand of buildings.

2.3.4.3 Methods for Onsite Construction Related Energy and Carbon Emission Analysis

For the analysis of energy consumption and carbon emissions associated with onsite construction activities, studies mainly used data on machinery and equipment from two sources:

1. **Real-Time Project Data:** Researchers gathered detailed information from ongoing construction projects, including the types, quantities, and operational hours of machinery and equipment. This real-time data ensures an accurate representation of energy consumption and carbon emissions, reflecting the specific conditions and practices of the construction site.

2. **Published Literature:** In the absence of real-time data, studies referred to existing literature documenting similar construction activities. This included case studies, industry reports, and research articles providing standardized data on the energy use and carbon emissions of construction machinery.

2.3.4.4 Methods for Transport, Use-Stage (Embodied) and Demolition Stage Energy Carbon Emission Analysis

Most studies have found it challenging to estimate energy and carbon emissions for the use stage, transport, and demolition stage. This is primarily due to lack of detailed information on maintenance, replacement, and refurbishment schedules, as well as inadequate data on carbon emissions from transportation during construction, demolition waste quantities and energy consumed by demolition machinery. Two main factors contribute to this issue: firstly, there is a prevailing belief among stakeholders that energy and carbon emissions from these stages contribute very little (less than 5%) to the total life cycle carbon of a building, leading to their frequent exclusion from calculations. Secondly, there is significant uncertainty related to the technologies and methods used during these life cycle stages.

2.4 Findings from Indian and International Studies

It has been observed that studies conducted globally and in India have significant variations in system boundaries used for the LCA analysis. Also, it has been noted that many studies have not done analysis for each life cycle stage of the buildings and yet presented the findings in terms of life cycle energy and emission irrespective of the system boundaries used. This indicates a major gap in the comprehensive LCA of buildings, highlighting the need for more robust and comprehensive across all phases of a building's life cycle. Additionally, most studies have reported results in terms of energy and not embodied carbon. Therefore, in the following sections, the results have been compared in terms of energy for different life cycle stages of the buildings.

The analysis presented in the following subsections uses the definitions used in individual papers for life cycle embodied and operational energy.

2.4.1 Findings of Indian Studies

Figure 2.3 illustrates the life cycle embodied and operational energy as defined and reported by various India-specific studies as a percentage of total life cycle energy. The figure shows that life cycle embodied energy ranges between 5-89%, with an average of approximately 39%, while operational energy ranges between 11-95%, with an average of approximately 59%. The significant variations in reported life cycle embodied and operational energy can also be attributed to the Datasets used for embodied carbon calculations, varying building typologies, materials, construction systems, usage patterns and climatic conditions.

Figures 2.4, 2.5, and 2.6 illustrate the percentage share of transport, demolition, and use-phase embodied energy in relation to the total life cycle energy consumption of buildings. The data shows that transport-related energy consumption ranges from 0.7% to 4%, with an average of 2.5%. Demolition-related energy consumption varies between 1% and 3.2%, averaging 2.3%. Use-phase energy consumption ranges from 13% to 53.9%, with an average of 22.5%.

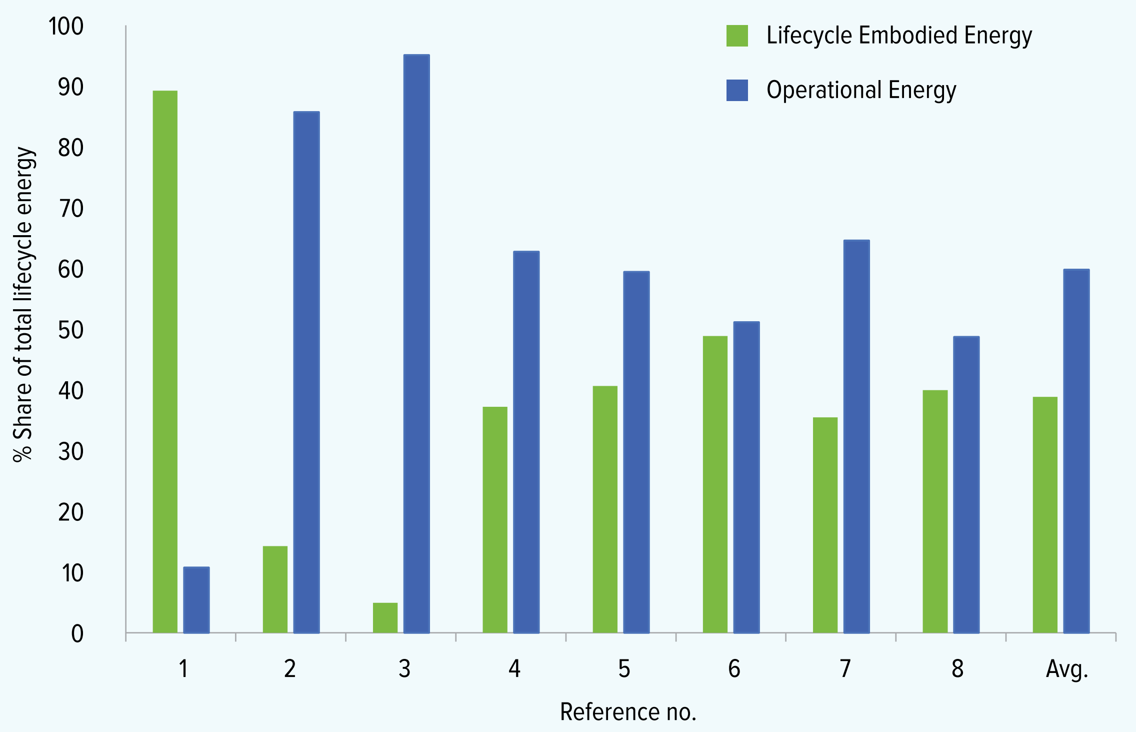


Figure 2.3: Life cycle embodied and operational energy consumption as a percentage of life cycle energy (LCE) consumption. The above graph is prepared using the definitions used and reported for life cycle embodied and operational energy in the references [12], [15], [17], [18], [19], [21], [23], [25]

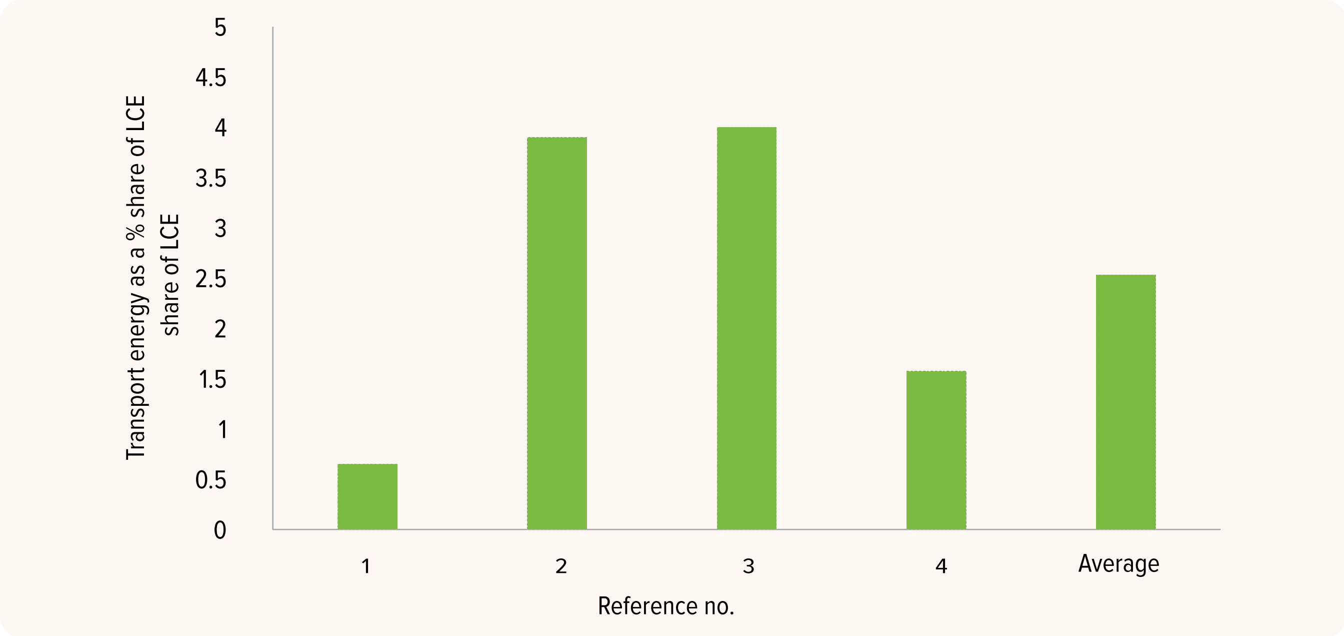


Figure 2.4: Transport-related energy consumption as a percentage of life cycle energy (LCE) consumption. The above graph is prepared using the definitions used and reported for life cycle embodied and transport energy in the references: [16], [18], [23], [25]

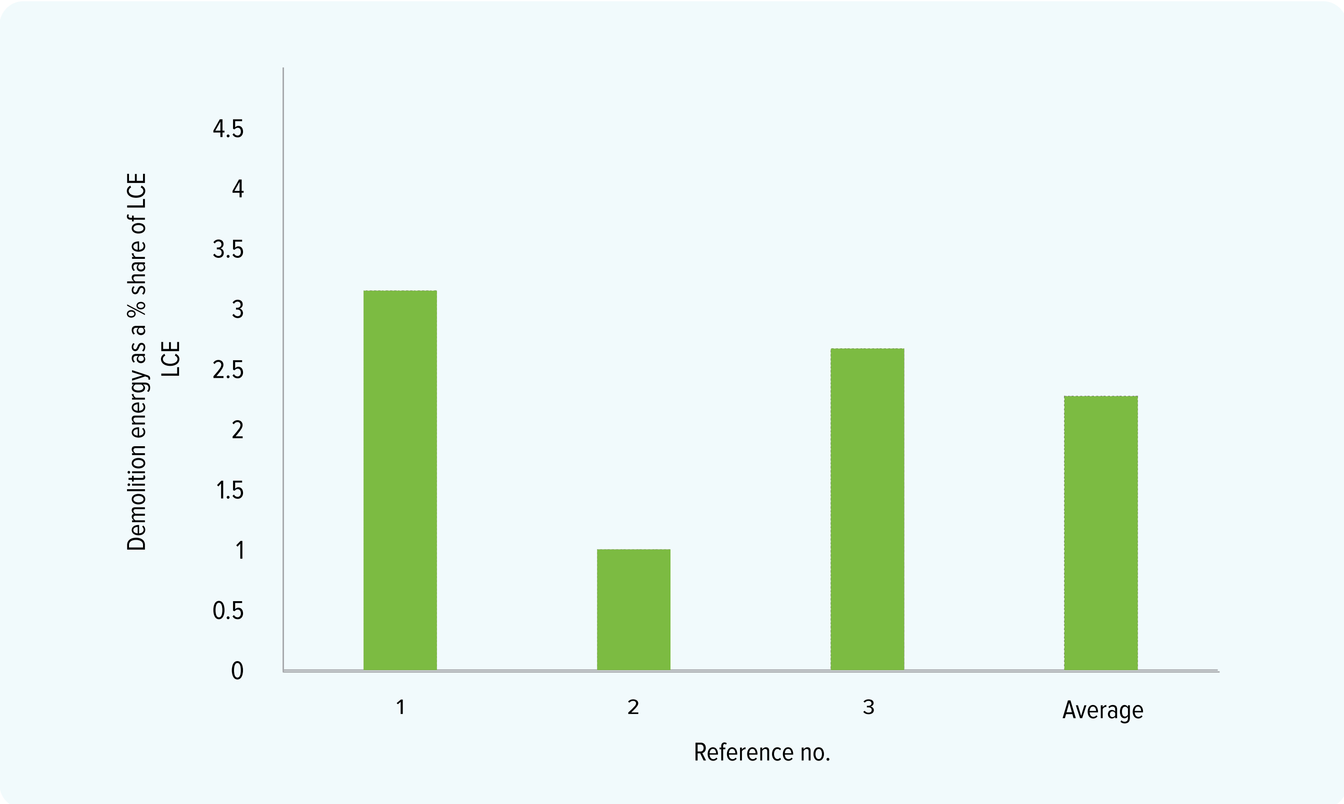


Figure 2.5: Demolition related energy consumption as a percentage of life cycle energy (LCE) consumption. The above graph is prepared using the definitions used and reported for life cycle embodied and demolition energy in the references: [16], [18], [25]

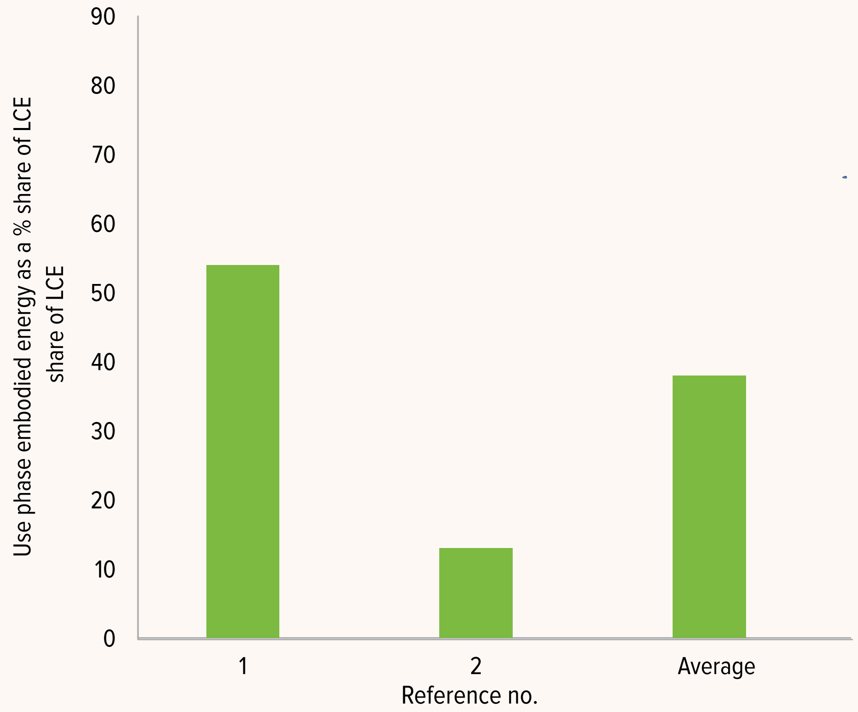


Figure 2.6: Use phase energy consumption as a percentage of life cycle energy (LCE) consumption. The above graph is prepared using the definitions used and reported for life cycle embodied and use phase energy in the references: [16], [25]

2.4.2 Findings of International Studies

Figure 2.7 shows the life cycle embodied and operational energy consumption reported by various studies as a percentage share of buildings' life cycle energy consumption. These values vary within a range of 4.9-75% for life cycle embodied energy consumption and 24.5-95.1% for operational energy consumption. The estimated average value for life cycle embodied and operational energy consumptions are 39% and 62%, respectively.

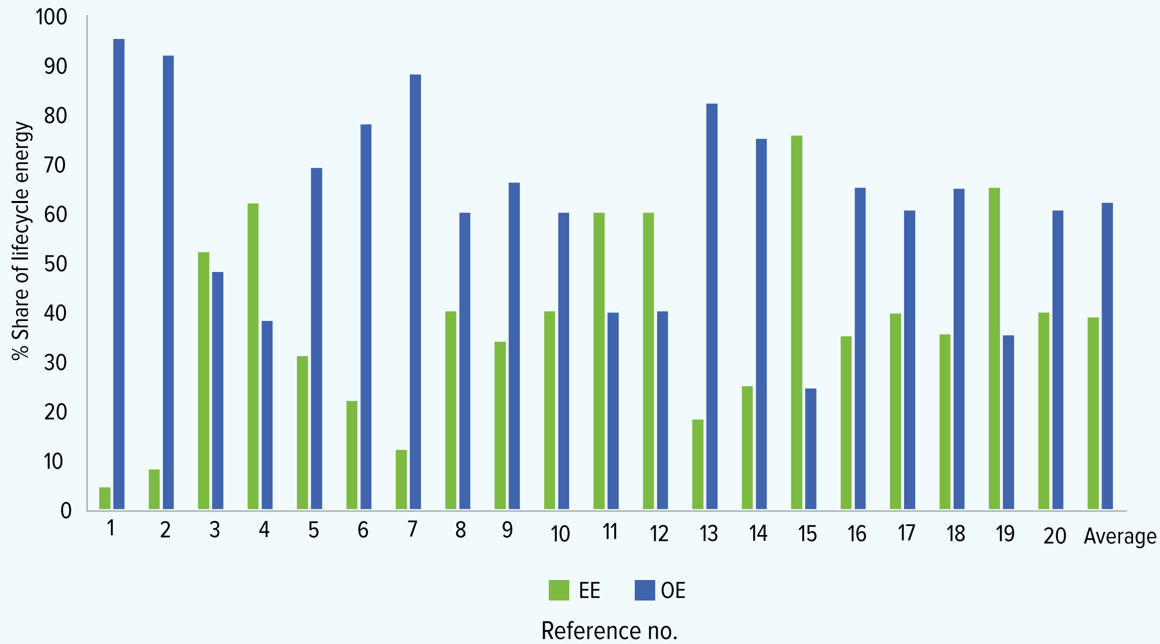


Figure 2.7: Life cycle embodied energy (EE) and operational energy (OE) as a percentage of life cycle energy (LCE) consumption. The above graph is prepared using the definitions used and reported for life cycle embodied and operational energy in the references: [68], [69], [70], [71], [72], [73], [74], [75], [60], [76], [28], [34], [35], [36], [37], [38], [40], [44], [46], [19]

Figure 2.8 depicts the percentage of the life cycle embodied energy in total life cycle energy in the world's four regions. There is a significant variation in the reported values for the life cycle embodied energy consumption throughout the four regions, the average reported values for Asia and Europe do not differ that much (34.7% and 36.2%, respectively). The use of different embodied energy Datasets, building material types, building typologies and construction systems are some of the reasons for variations in the reported life cycle embodied carbon energy consumption across the regions.

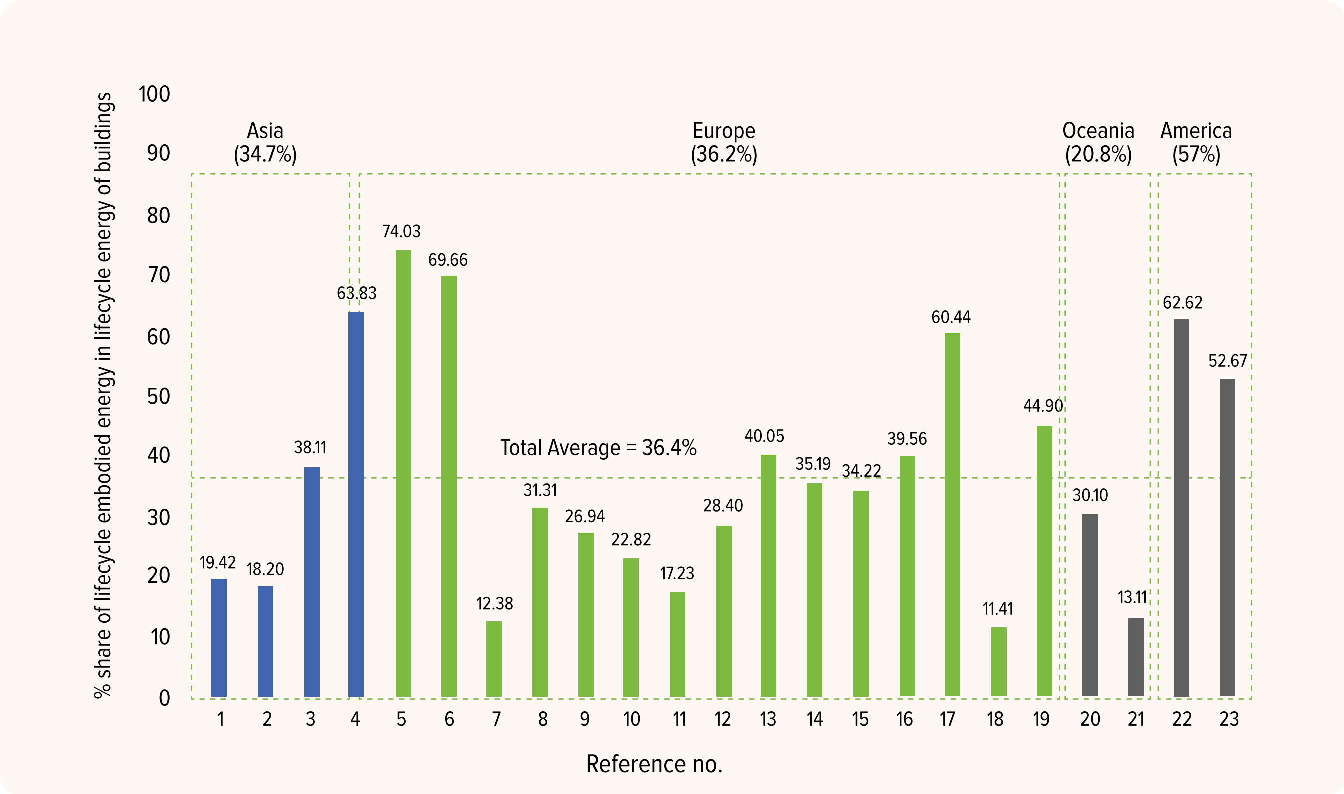


Figure 2.8: Percentage share of life cycle embodied energy consumption in total life cycle energy consumption observed in reviewed studies by geographic location of the world. (Asian studies, European studies, Asia, Europe, Oceania and America studies [69] [70] [71] [72], [73], [74], [75], [76] [28] [34] [35], [36], [37], [38][19], [40], [44], [46] [60], [77], [68], [78])

The following section shows the share of transport-related energy consumption, demolition-related energy consumption and use phase embodied energy consumption in the total life cycle embodied energy consumption. Figure 2.9 shows that across the studies reviewed, transport-related energy consumption varies in the range of 2 - 23% with an average of 6%, and demolition-related energy consumption varies in the range of 0.1 – 13% with an average of 3%.

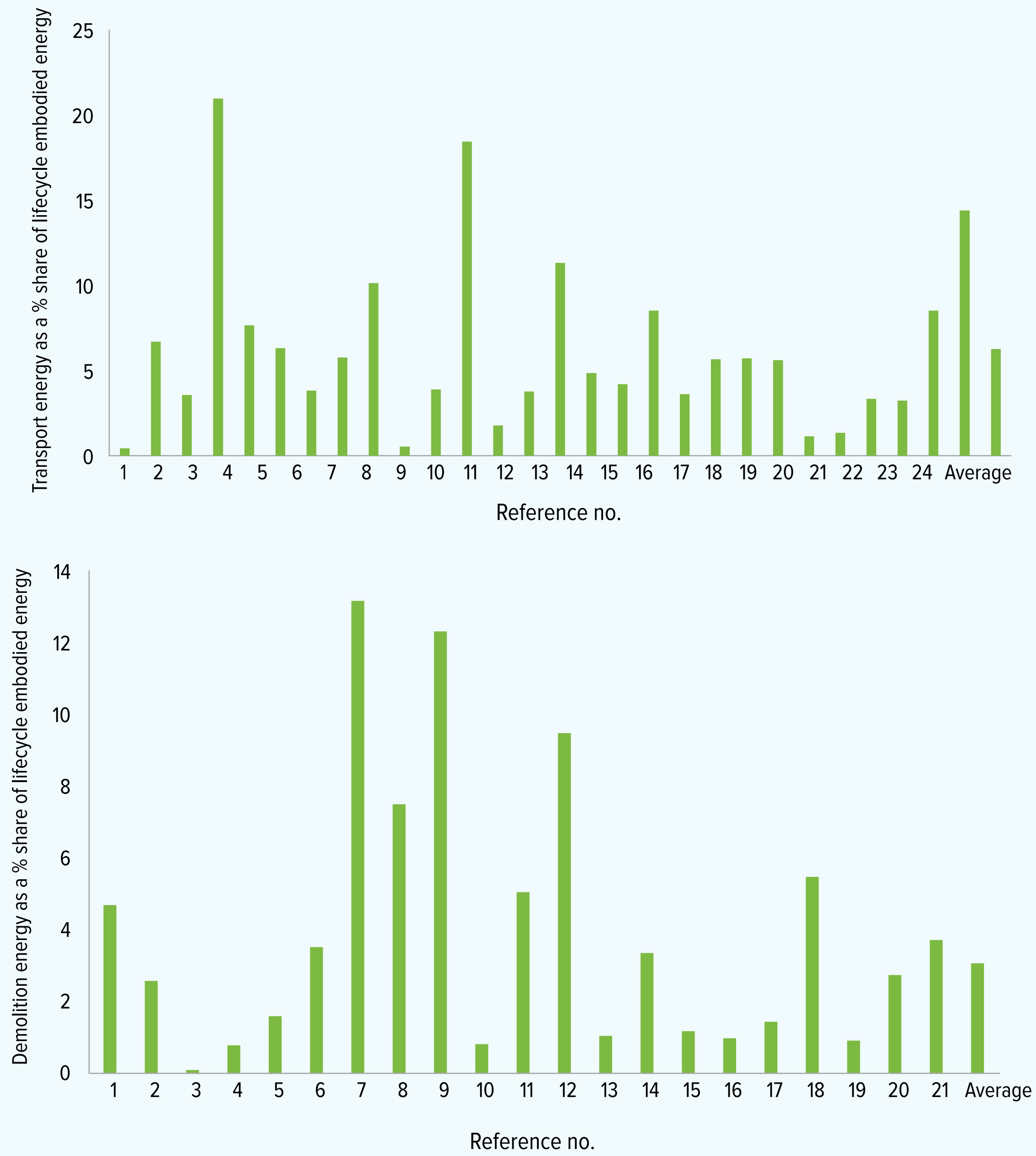


Figure 2.9: Percentage share of transport and demolition-related energy consumption in the total life cycle embodied energy consumption. The graph for the percentage share of transport energy is prepared using the definitions used and reported for life cycle embodied and demolition energy in the references: [79], [80], [81] [82], [83], [84], [85], [86], [87] [88], [89], [90], [75], [91], [92], [93], [94], [95], [96], [97], [72], [98], [99], [100]. Similarly, the graph for the share of demolition energy is prepared using the definitions used and reported for life cycle embodied and demolition energy in the references: [82], [101] [29], [89], [102], [92], [103], [104], [53], [105], [106], [94], [107], [108], [109], [110], [111], [112], [113], [114], [115]

Use phase embodied energy consumption is a major component often excluded from life cycle embodied energy calculations, which in some cases was found equal to or greater than a building's upfront embodied carbon emissions (A1-A3). Figure 2.10 shows the annual use phase embodied carbon emission as a percentage of the life cycle embodied carbon emission (excluding demolition energy) as reported in the studies reviewed. Considering an average 50-year life cycle of buildings, the values vary within a range of 5–60%, with an average value of 25%.

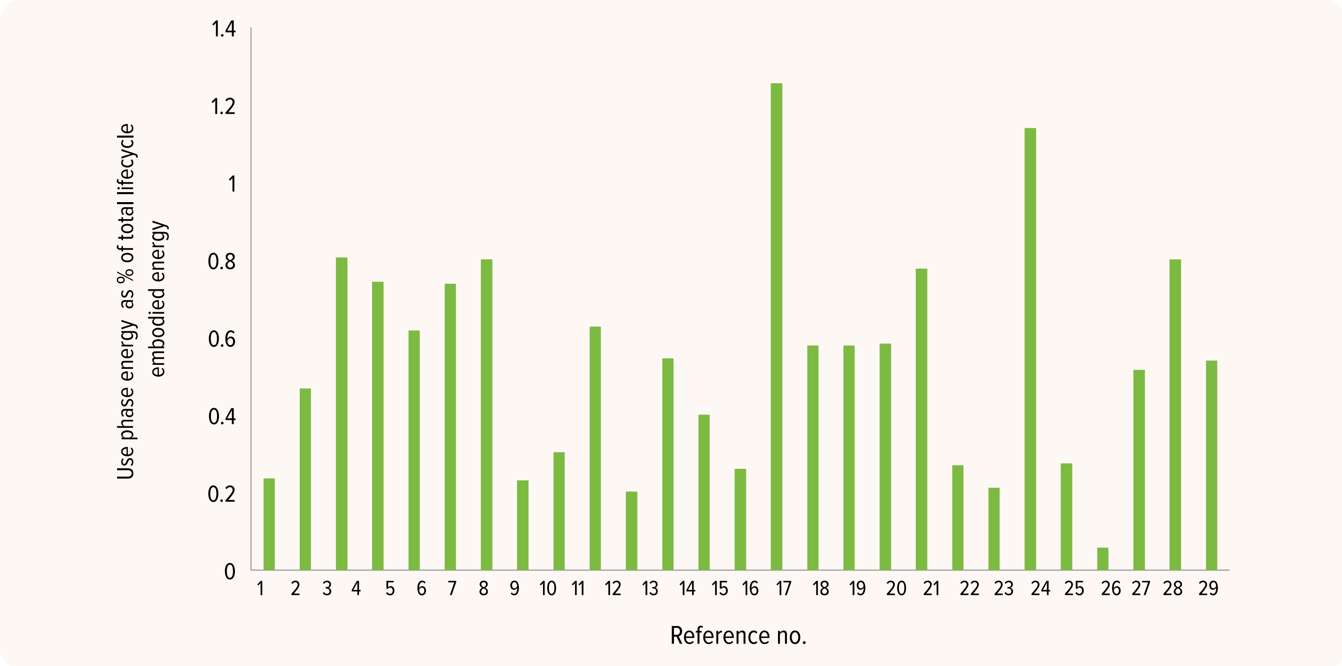


Figure 2.10 Use phase embodied energy as a percentage share of total life cycle embodied energy. The above graph is prepared using the definitions used and reported for life cycle embodied and use phase energy in the references: [116], [80], [117], [118], [65], [83], [54], [84], [40], [89], [119], [120], [102], [92], [62], [121], [122], [123], [106], [124], [109], [110], [125], [113], [126], [72], [98], [127], [63]

2.5 Reporting of LCA Results

Reporting the LCA results is necessary to understand how well the buildings perform in terms of their life cycle energy and/or carbon impacts. However, it is often challenging to do so given the variations in building materials, construction techniques, life span, usage patterns, geographic locations and system boundaries. The metrics used or referred to in the studies varied significantly.

It is observed that most of the performance metrics use area per year (m2/year) as the normalising parameter for operational energy/carbon analysis and floor area (m2) for life cycle energy/carbon analysis. The bottom-up approach (starting from the materials level to the building level as a final stage) was the most frequently used methodology for reporting the LCA results. This means that results have been reported for materials for A1-A3 stages (upfront carbon emission), then building component-wise, e.g., walling system, beam, column, etc. and finally at the building level for different life cycle stages. Seven recommendations were provided after review of the literature: (i) clear definition of the assessment method; (ii) clear definition of the functional equivalent; (iii) combining the top-down and bottom-up approaches; (iv) including different performance levels (from limit to target values); (v) standardized system boundaries; (vi) the metrics should cover the most widespread building types; and (vii) metrics should be logical and technically defensible.

2.6 Summary of the Chapter

The chapter provides an overview of international standards such as ISO 14040, ISO 14044, and EN 15978, which define the broad framework for LCA. It delves into the methodology and application of LCA of buildings used for studies globally drawing relevant insights for the Indian context.

The review assessed standards, methodologies, and frameworks used in LCA in different studies, particularly looking at how they define the scope or system boundary, methodologies for inventory analysis, and how they report and interpret results. The insights gathered from national and international literature are synthesized to propose a tailored framework for conducting LCA in India, which would aid in making informed decisions to reduce the environmental impact of buildings effectively.

Key conclusions from this chapter are as follows:

Using LCA results at different levels to inform energy/carbon emission reduction interventions: Life cycle energy/carbon of a building is a function of energy and carbon emissions associated with the manufacturing of materials and/or construction products, variation in type and amount of materials used in different building components as well as energy and carbon emissions that occur during construction, use and end of life stages (for instance material durability or disposal technologies for specific materials). Therefore, it becomes important that LCA results are broken down by materials, building component and life cycle stages to help arrive at the most relevant interventions. These may include, for instance, opting for alternative low-carbon materials, optimising the design to reduce material quantities used in building elements, and other interventions that impact the durability and recyclability of materials or building elements.

Methodology of inventory analysis: Datasets prepared using process-based analysis are preferred, considering the non-homogeneity and uncertainties related to the construction materials manufacturing process.

Methodology of operational energy and associated carbon analysis: Considering the wide acceptability of dynamic simulation tools such as EnergyPlus, Design Builder, Open Studio etc., to estimate operational energy and associated carbon emissions is a good choice for early design stage of buildings. For existing buildings electricity bills should be considered.

Methodology for construction, transport, use phase and demolition stage analysis: The literature review shows that inadequate data related to these stages remains a challenge. Data gaps can be addressed by collecting onsite data from real-time projects or can be referred from the existing literature.

System boundaries for LCA analysis: The literature review highlights significant variations in the system boundaries considered across different studies. Many studies focus primarily on stages A1-A5 and B6, often excluding other stages of a building's life cycle. This selective focus may be attributed to the perceived lower impact of the excluded stages on the building's life cycle energy and carbon emissions. This observation raises an important question: Has that been conclusively proved? It seems not, and if that is the case should research concentrate first on establishing the life cycle stages with a more pronounced impact on life cycle energy and carbon emissions? This approach to system boundary selection is crucial for developing targeted and effective sustainability strategies in building design and construction.

Need for standardization of LCA: There is a pressing need for standardization in the reporting structure to ensure consistency and comparability across studies., support more effective decision-making in building design and construction practices, plus inform documentation and reporting of life cycle impacts for different building uses, construction types and climatic zones.

Data variability and quality: Wide variations in reported energy across different life cycle stages of buildings highlight the need for rigorous data quality checks. These checks are essential to verify the accuracy of energy and carbon emission estimates at each life cycle stage. Utilizing both generic data and product-specific data, such as Environmental Product Declarations (EPDs), can address some of these variations effectively. Generic data provides a broad, industry-wide perspective, useful for preliminary assessments, but it may lack the precision needed for specific projects. Conversely, EPDs offer detailed, product-specific insights, ensuring a higher accuracy of impact assessments. Therefore, incorporating stringent data quality checks for both types of data ensures that energy and carbon emission estimates are reliable, supporting more sustainable and informed decision-making throughout the building life cycle.

Reporting: Lastly, the chapter outlines the reporting process for comparing life cycle energy and carbon emissions of buildings across various studies. It recommends that results be benchmarked using a combined top-down and bottom-up approach and normalized by m^2 (floor area) to ensure comparability. This suggests that, for data reporting purposes, the highest acceptable values should be established first. Subsequently, a bottom-up approach should be employed, beginning with the reporting of upfront embodied carbon for materials, followed by embodied carbon at the building component level, and finally progressing to the reporting of embodied carbon for the entire building at each life cycle stage. For the use stage specifically, it suggests that results should be further normalized by the unit of per year per m^2 (floor area). This methodological consistency will facilitate more accurate comparisons and enhance the utility of life cycle assessments to inform sustainable building practices.

CHAPTER

03

Factors Affecting Life Cycle Embodied Carbon in Indian Context

3.1 Introduction

It is observed from the literature review that multiple factors such as functional units, system boundaries and materials' embodied carbon dataset affect the life cycle embodied energy and carbon emission of buildings. In India, the only study covering all the life cycle stages of buildings has been conducted for a net zero educational building [25]. The carbon emission associated with different life cycle stages as a percentage of life cycle embodied carbon has been shown in Figure 3.1. It is important to note that the numbers presented are specific to a particular building. To gain a comprehensive understanding of life cycle carbon emissions across different building typologies, similar studies need to be conducted for various types of buildings to have more accurate picture of life cycle carbon emissions across the building typologies.

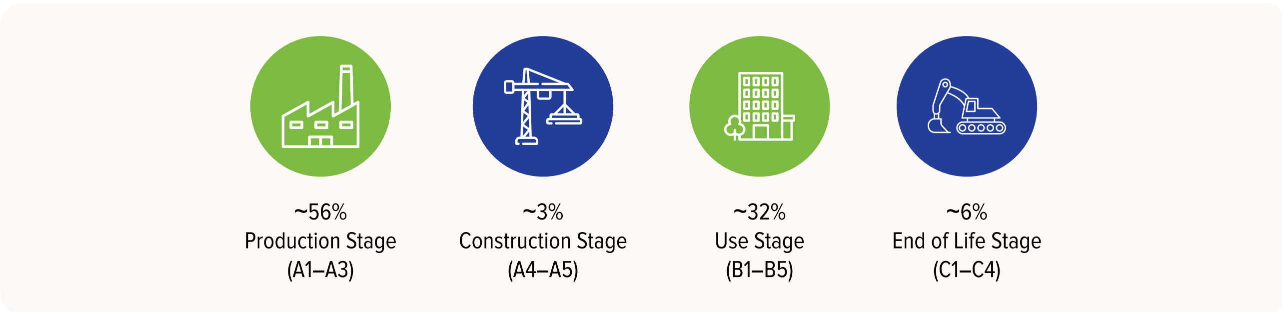


Figure 3.1 Breakdown of total life cycle embodied energy of a building by life cycle stages.

To accurately estimate the life cycle embodied energy and carbon emission of buildings, a conceptual framework has been presented (Figure 3.2) where energy and carbon emission data for each stage need to be captured through generic construction material embodied energy and carbon dataset, product-specific EPDs, onsite surveys for machinery used, region-specific building bye-laws, public work departments, etc.

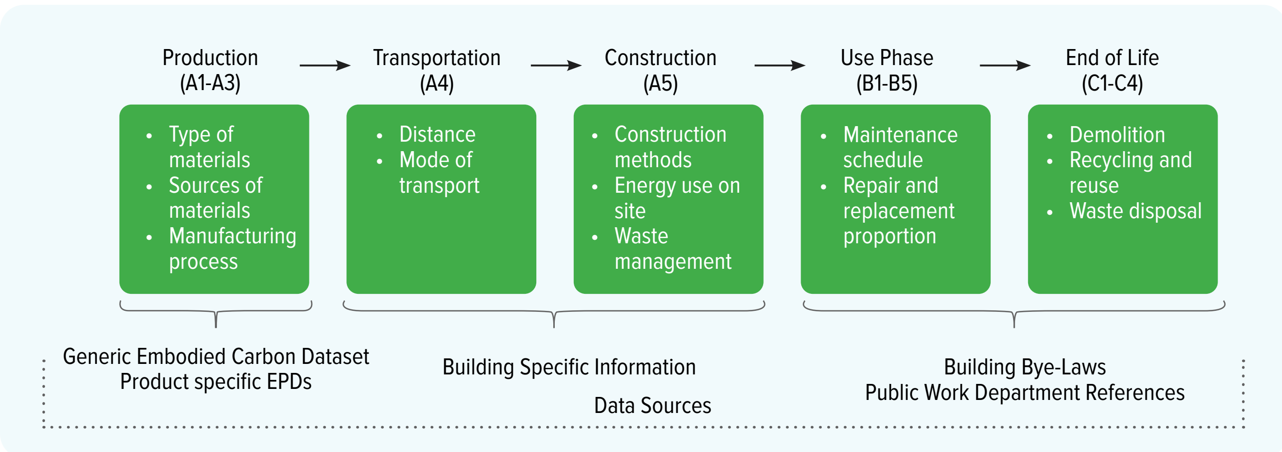


Figure 3.2: Stages and data sources for life cycle embodied carbon estimation of buildings

3.2 Analysis of Different Factors Affecting Embodied Carbon Emission from Different Life Cycle Stages

This section presents the impact of using different embodied carbon datasets, differences in transportation distances, building lifespan and manufacturing process-related energy consumption by geographic location on the upfront embodied, transport-related and use phase carbon emissions. To illustrate the impact of these variables, a case study of small-scale commercial buildings with a floor area of 288 m^2 has been considered. The operational energy and associated emissions (for B6 stage) have not been included in this analysis. The onsite construction (A5), Use stage (B1), and end-of-life stages (C1-C4) have also been excluded due to data gaps and their relatively low contribution to the total life cycle embodied energy consumption of the building. The layout of the selected building and its bill of quantities (BOQ) are presented in Appendix 1. The following sections discuss the impact of the different factors mentioned above on the different life cycle stages' (A1-A3, A4, B2-B5) carbon emissions of the selected building.

3.2.1 Impact of Emission Intensity Data on Upfront Carbon Emission for the Case Study Building

To analyse the impact of emission intensity data on upfront carbon, a comparative analysis using two datasets, namely One Click LCA's inbuilt construction materials' embodied carbon dataset and IFC's Indian construction material dataset, has been conducted. The calculation of upfront embodied carbon for the materials used in the selected building is presented in Table 3.1. The system boundary for the analysis is A1 – A3, i.e., cradle to gate. As observed from the table, there is approximately a 17% variation in the upfront embodied carbon of materials used in building construction, as estimated using the two different datasets.

The likely reason for this difference is that One Click LCA utilizes some of the material embodied carbon data from the IFC dataset for Indian construction materials. For some construction materials, it adopts the emission factor from other countries and converts it to India construction materials using the grid emission factor of India. This highlights the necessity for standardizing a generic embodied carbon dataset for construction materials, which should be used consistently, especially in cases where Environmental Product Declarations (EPDs) for specific construction materials are unavailable.

Table 3.1: Case study: Impact of emissions intensity data on upfront embodied carbon

Building Material	Units	Qty	Weight of the material (kg)	One Click LCA Dataset ($kgCO2_{eq.}/kg$)	IFC Dataset ($kgCO_{2eq.}/kg$)	Embodied One Click LCA ($kgCO2_{eq.}$)	Embodied IFC ($kgCO_{2eq.}$)
Bricks	Nos.	26404.5	66011.3	0.24	0.39	15842.7	25744.4
Coarse sand	Cum	74.2	118661.6	0.0023	0.009	272.9	1068.0
Fine Sand	Cum	5.4	9064.1	0.0023	0.009	20.8	81.6
Cement	Cum	45.8	65930.5	0.94	0.91	61974.7	59996.7
Aggregates	Cum	121.9	192647.8	0.0025	0.009	481.6	1733.8
Steel	kg	16767.2	16767.2	2.29	2.6	38396.8	43594.6
Water	Ltr	32186.4	32186.4	0.0003	0.0003	9.7	9.7
Framing	Rmt	195.1	195.1	16.52	26	3223.6	5073.4
Double layer glass	Sqm	63.4	63.4	52.7	52.7	3341.2	3341.2
Paint	Sqm	209.7	179.9	3.99	2.91	717.7	523.4
Putty	Sqm	209.7	161.3	0.32	0.27	51.6	43.5
Admixture	kg	585.4	585.4	1.67	1.67	977.6	977.6
Vitrified Tiles (10mm)	kg	2789.8	2789.8	0.5	0.68	1394.9	1897.0
Ceiling Tiles (2x2)	kg	421.5	421.5	0.3364	2.7	141.8	1138.1
Adhesive	kg	981.3	981.3	0.84	0.47	824.3	461.2
Foam Concrete	kg	1468.5	1468.5	0.34	0.322	499.3	472.8
Waterproofing chem	kg	17.1	17.1	2.88	2.88	49.3	49.3
Wooden Flooring	kg	1303.4	1303.4	0.28	2	365.0	2606.9
Aluminium Skirting	kg	148.9	148.9	16.65	35	2479.8	5212.9
POP	kg	3092.1	3092.1	0.18	0.13	556.6	402.0
Gypsum Plaster	kg	109.7	109.7	0.18	0.099	19.7	10.9
Gypsum Board	kg	3507.6	3507.6	0.29	0.26	1017.2	912.0
GI Matel Section for Frame	kg	945.4	945.4	3.225	3	3048.9	2836.2
50mm Glasswool Insulation	kg	487.8	487.8	3.3857	2.5	1651.4	1219.4
Gypsum Compound	kg	621.2	621.2	0.0949	0.0037	59.0	2.3
Aluminim Doors & Glazing Frame	kg	516.8	516.8	1.996	1.2	1031.5	620.2
Aluminium Frames in doors & Glazing	kg	182.9	182.9	16.52	26	3021.2	4754.9
12mm Laminated Modular Partitions In toilets	kg	99.2	99.2	0.2925	0.43	29.0	42.7
32mm Flush doors on toilets entry	kg	24.9	24.9	0.8226	0.43	20.5	10.7
					Total	**141520.2**	**164837.3**

3.2.2 Regional Variations in Embodied Carbon of Building Materials for the Case Study Building

To illustrate the impact of variations in manufacturing process-related energy consumption by geographic location on upfront embodied carbon, the variance due to bricks manufactured in different regions of India has been analysed. Data on other building materials has not been forthcoming, and hence, this analysis has been limited to bricks. Upfront embodied carbon of materials, such as bricks or other construction products, depends on several factors, including manufacturing processes used, the distance from where the raw materials are transported, and the mode of transport to the factory. The embodied carbon data of bricks manufactured in eastern, northern, western, and southern parts of India was taken from Sameer et al. [14]. Figure 3.3 shows region-wise variations of the upfront embodied carbon for brick manufactured in the eastern, western and northern regions. The percentage variation has been calculated relative to upfront embodied carbon calculated using the IFC Indian construction material dataset presented in Table 3.1. It can be observed from the figure that upfront embodied carbon varies from 0.04 to 5%.

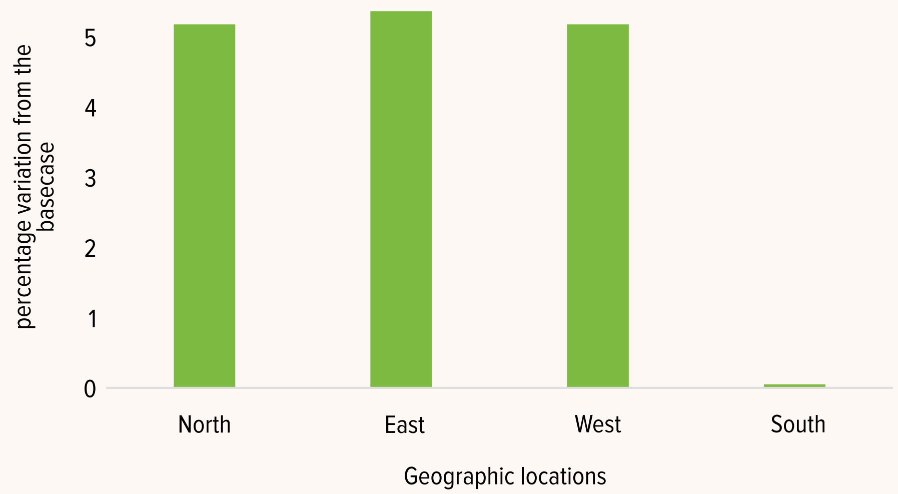


Figure 3.3: Variation in the embodied carbon of bricks by geographic location

3.2.3 Effect of Variations in Transportation Distance on Transport-Related Carbon Emission

A parametric analysis was conducted to examine the impact of varying transportation distances on carbon emissions for stages A1-A3 (upfront embodied carbon) and A4 (transport-related carbon emission) combined. For this analysis, a standard diesel fuel truck with a 10-tonne capacity and a fuel efficiency of 3.5 km per litre was used to transport construction materials to the site. Figure 3.4 illustrates the variations in emissions due to different transportation distances on upfront embodied carbon (A1-A3) and transportation-related emissions stage (A4) combined.

It was observed that while transportation emissions increase proportionally with the distance travelled, the combined carbon emissions of stages A1 to A4 do not increase at the same rate. For instance, a 100% increase in travel distance results in only a 2% increase in the total carbon emissions of stages A1 to A4. This demonstrates that the contribution of transportation-related emissions to the total carbon emission (of stages A1-A4) is relatively small. This analysis highlights that while transportation emissions are important, their overall impact on the life cycle embodied carbon of buildings is limited when compared to other stages.

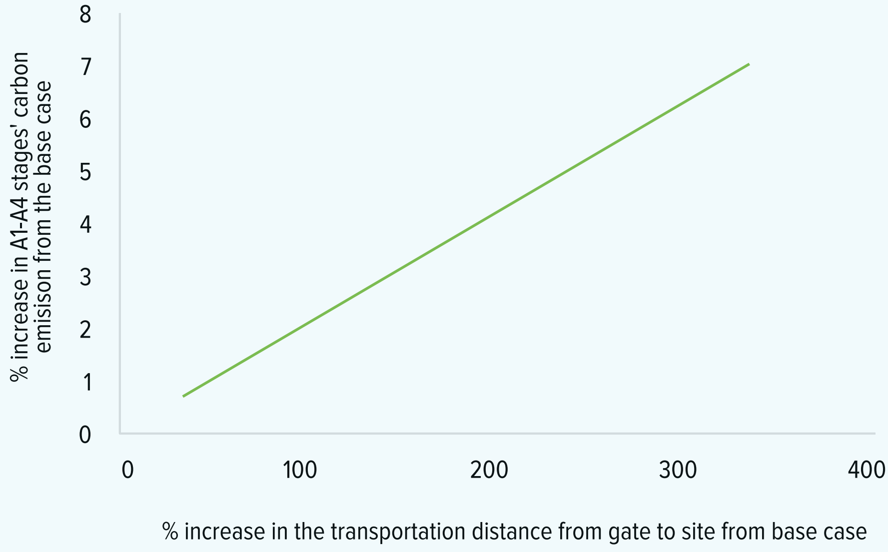


Figure 3.4: Variation in the carbon emission of transport (A4) and upfront carbon emission (A1-A3) combined with respect to distance travelled from gate to site

3.2.4 Effect of Different Building Design Life on the Use Phase Embodied Carbon Emission of Case Study Building

The design life of buildings significantly impacts their life cycle embodied carbon emissions. A longer lifespan reduces the need for new construction, thus lowering the associated carbon emissions from construction activities. However, it also increases the use phase embodied carbon emissions corresponding to stages B1 – B5. To assess the impact of different building design lifespans on use-phase embodied carbon emissions, the embodied carbon associated with stages such as replacement, refurbishment, repair, and maintenance has been estimated. This estimation is based on changes in the proportion of construction materials used over a specific building design life, as identified in various studies. The table showing the proportion of materials changed over certain periods and the associated change in use phase embodied carbon emissions is presented in Appendix 1 (Table A.2).

Figure 3.5 illustrates that when the building lifespan is extended by 10 and 20 years from the base case of 50 years, use phase embodied carbon emissions increase by approximately 2.5% and 5%, respectively. However, instead of extending the building design life from the baseline, the building gets demolished and a new building is constructed, then the embodied carbon emission would approximately double compared to extending the building design life. For example, for the case study building if it gets demolished after 50 years and considering the similar construction with same upfront embodied carbon of materials, the total life cycle embodied carbon after 70 years will be two times more compared to extending the design life of building by 20 years from the base design life of 50 years (analysis has been presented as Table A.3 in appendix section). This indicates that extending the lifespan of buildings reduces the need for new construction and consequently allows for the deferment of carbon emissions associated with new construction.

To reduce the use phase embodied carbon emissions, construction materials with a longer lifespan should be considered during the design stages. By selecting durable materials, the frequency of replacements and maintenance can be reduced, ultimately lowering the use phase embodied carbon emission of the building.

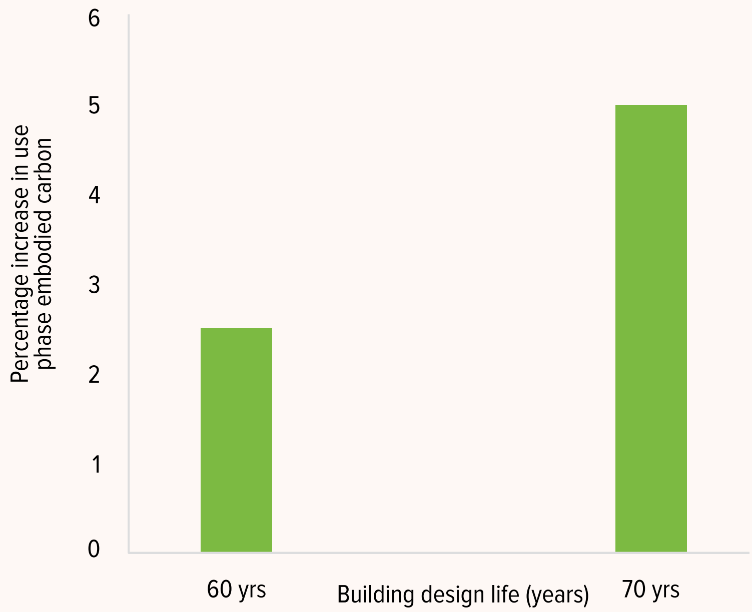


Figure 3.5 Variation in use phase embodied carbon of the case study building with increasing life span

3.3 Summary of the Chapter

- The chapter evaluates how various factors, such as material/product emissions intensity datasets, transportation distances, building design life, and geopgrahic varations in manufacturing process-related emissions influence the upfront embodied carbon emission, transport-related carbon emission and use phase embodied carbon emission.
- A comparative analysis between embodied carbon calculations from One Click LCA and IFC's Indian construction material dataset shows an approximate 17% variation in upfront embodied carbon emissions. This variation is due to the use of emission factors from other countries, adjusted with Indian grid emission factors. This underscores the need for a standardized embodied carbon dataset for construction materials, rigorous data quality checks and periodic updates to capture the improvements happening on the manufacturing side. The analysis of variation in transportation distance and its impact on A1-A4 stages' emission shows that the impact of transport-related emission with respect to A1-A4 stages is comparatively small.
- Geographic variation in manufacturing-related emissions for bricks leads to a maximum 5% variation in the upfront embodied carbon of materials from the base case which was calculated using IFC dataset. This indicates that the brick manufacturing process corresponding to different geographic locations led to relatively minor variations from the values calculated using the IFC dataset, and hence, it can be used for different geographic locations.
- The analysis of varying building design life and its relation to use phase embodied carbon emissions suggests that as the building design life increases by 10 and 20 years, the use phase embodied emissions increase by 2.5% and 5%, respectively. However, extending building design life help in deferment of carbon emission due to new construction after demolishing the building. This underscores the need for durable construction materials during the design phase to mitigate the recurring embodied carbon emissions over the building's lifespan and also avoid the need for new construction.

CHAPTER

04

Conclusion and Way Forward

The report provides a detailed analysis of the current state of LCA practices, standards and frameworks followed globally as well as in India for buildings' life cycle energy and emission analysis.

The report begins by presenting the status quo of LCA in Indian contexts, identifying key challenges hindering its adoption. These challenges include the lack of a standardized LCA framework, the unavailability of India-specific datasets for embodied carbon in construction materials, absence of LCA based compliance with existing codes and standards, and the absence of financial incentives for disclosing building life cycle carbon emissions. However, the report also highlights ongoing efforts to address these issues, such as the incorporation of an ISO-based LCA framework in the ECSBC (currently in draft stage), BIS guidelines for calculating product carbon footprints based on ISO standards, and initiatives by CEPT University to develop an India-specific construction material embodied carbon dataset.

The literature review in the report highlights the variability in system boundaries across different studies carried out globally as well as in India, driven by varying objectives related to emissions at different life cycle stages of buildings and influencing design decisions. This variability is compounded by the absence of a standardized LCA framework mandated by codes and standards across countries. The review also underscores significant differences in embodied carbon datasets for construction materials used in various studies. The lack of standardized datasets across the countries leads to discrepancies in reported upfront embodied and life cycle carbon emissions. Additionally, the report points out that differing system boundaries and functional units pose significant challenges for bconsistent reporting of CA results and conducting comparative analyses of different studies.

The report quantifies various factors affecting embodied carbon emissions at different life cycle stages of buildings using a case study from India. It highlights that the use of One Click LCA and IFC datasets, frequently cited in Indian studies, results in a 17% variation in upfront embodied carbon emissions of materials, underscoring the need for a standardized India-specific embodied carbon dataset. Additionally, it quantifies the impact of variations in manufacturing process-related emissions by geographic location, building design lifespan, and transportation distances. Geographical differences in manufacturing process for bricks results in up to 5% variation. The impact of transportation-related emissions is minor when combined with upfront embodied carbon. The analysis reveals that an increase of 10 and 20 years from the base case of 50 years in building design lifespan results in a 2.5% and 5% change in use-phase embodied carbon emissions, respectively, emphasizing the need for durable construction materials to reduce use-phase embodied carbon emissions.

The report highlights several key challenges hindering the mainstreaming of LCA in the Indian building sector:

- Lack of a standardized LCA framework
- Absence of an India-specific embodied carbon dataset
- Limited awareness among practitioners, policymakers, and implementing authorities
- Insufficient incentives

To address the challenges, the report provides the following recommendations.

Delineation of Standard LCA Framework

The Bureau of Indian Standards (BIS) should establish a national LCA framework for calculating and disclosing the life cycle embodied carbon data of construction materials and buildings. Having this framework from BIS would facilitate its incorporation into the Indian building code for implementation. BIS can either adopt an internationally established standard or develop an India-specific tailored LCA framework. Additionally, BIS should set rules for reporting standards of upfront and life cycle embodied carbon emissions to enable benchmarking of results across the country.

Development of India-specific embodied carbon dataset

The draft National Resource Efficiency Policy (NREP) aims to reduce embodied carbon through resource efficiency and circularity, highlighting the need for urgent attention and action in this critical area. In the absence of the NREP, the government can encourage the voluntary disclosure of embodied carbon data using LCA methodology for products listed on the Government e-Marketplace and the national public procurement platform. This is especially important for building materials with high embodied carbon, such as concrete, steel, glass, and various walling materials. Establishing a national embodied carbon dataset using standardized testing methods to disclose data for common and energy-intensive materials, such as cement, steel, and bricks, would be a promising first step. Additionally, the manufactures of these energy intensive materials should be encouraged to publish EPDs of their products which can be included in the national dataset.

Develop reporting standards for different building typologies and construction systems

A comprehensive life cycle carbon emission reporting standards for various building typologies should be established by developing reference buildings, similar to the benchmarks already created for operational carbon emissions and energy consumption in different types of commercial buildings in India. These benchmarks will serve as a crucial criterion for incentivizing asset owners and developers to disclose the life cycle emissions of their buildings.

References

[1] RMI, “Whole System Approach to Decarbonize India's Building.” Accessed: Apr. 03, 2024. [Online]. Available: https://rmi.org/insight/wholesystem-approach-to-decarbonize-indias-buildings

[2] IEA, “Global buildings sector CO2 emissions and floor area in the Net Zero Scenario, 2020-2050, IEA, Paris.” Accessed: Apr. 03, 2024. [Online]. Available: https://www.iea.org/data-and-statistics/charts/global-buildings-sector-co2-emissions-and-floor-area-in-the-net-zero-scenario-2020-2050

[3] “U.S. General Services Administration Interim IRA Low Embodied Carbon Material Requirements,” 2023. [Online]. Available: https://www.gsa.gov/system/fies/Interim

[4] D. Davis *et al.*, “Pathways to Steer India's Buildings Sector Towards a Net Zero Future,” 2024. [Online]. Available: https://cstep.in/drupal/sites/default/files/2024-03/Pathways to Steer India's Buildings Sector Towards a Net-Zero Future.pdf

[5] NIUA and RMI, “From the ground up: A whole-system approach to decarbonising India's buildings sector,” 2022. [Online]. Available: https://rmi.org/insight/whole-system-approach-to-decarbonize-indias-buildings/

[6] KPMG, “Embodied carbon management for global infrastructure.” [Online]. Available: https://assets.kpmg.com/content/dam/kpmg/in/pdf/2023/03/embodied-carbon-management-for-global-infrastructure.pdf

[7] “Embodied carbon reduction challenge,” Massachusetts Clean Energy Center. Accessed: Aug. 09, 2023. [Online]. Available: https://builtenvironmentplus.org/embodied-carbon-reduction-challenge-competition/

[8] “Toronto Becomes First Jurisdiction in North America to Enact Whole-building Embodied Carbon Caps on New City-owned Buildings,” Mantle Developments. Accessed: May 05, 2023. [Online]. Available: https://mantledev.com/insights/toronto-becomes-first-jurisdiction-in-north-america-to-enact-whole-building-embodied-carbon-caps-on-new-city-owned-buildings/

[9] C. Nicolas and C. Mediterranee, “Guide RE 2020: REGLEMENTATION ENVIRONNEMENTALE,” 2021. [Online]. Available: https://www.cerema.fr/system/files/documents/2021/12/guide_re2020_dhup-cerema1.pdf

[10] “Policy: Green Buildings Policy for Rezonings,” 2023. [Online]. Available: https://guidelines.vancouver.ca/policy-green-buildings-for-rezonings.pdf

[11] K. Buckley, “ASHRAE AND THE INTERNATIONAL CODE COUNCIL SEEKING COMMENTS ON GREENHOUSE GAS EMISSIONS EVALUATION STANDARD.” Accessed: Aug. 09, 2023. [Online]. Available: https://www.ashrae.org/about/news/2023/ashrae-and-the-international-code-council-seeking-comments-on-greenhouse-gas-emissions-evaluation-standard

[12] K. Kiran and K. B. Anand, “Comparison of life cycle cost and embodied energy for buildings with alternative walling materials,” *Mater Today Proc*, 2023, doi: https://doi.org/10.1016/j.matpr.2023.05.286.

[13] B. Deepak, M. Vijay K, and K. Arvinder, “Initial or recurring embodied energy: Importance in Indian affordable housing,” *Journal of Building Engineering*, vol. 49, p. 104072, 2022, doi: https://doi.org/10.1016/j.jobe.2022.104072.

[14] S. Maithel and A. Ravi, "Embodied energy dataset for bricks & blocks in india using process analysis methodology," *Int Symp Promot Innov Res Energy Effic*, pp. 150–158, 2017.

[15] T. Ramesh, R. Prakash, and K. K. Shukla, "Life cycle energy analysis of a residential building with different envelopes and climates in Indian context," *Appl Energy*, vol. 89, no. 1, pp. 193–202, 2012, doi: https://doi.org/10.1016/j.apenergy.2011.05.054.

[16] T. Sravani, R. Prasanna Venkatesan, and A. Madhumathi, "A comparative LCA study of passive cooling roof materials for a residential building: An Indian Case study," *Mater Today Proc*, vol. 64, pp. 1014–1022, 2022, doi: https://doi.org/10.1016/j.matpr.2022.05.089.

[17] D. Satola, A. Houlihan-Wiberg, and A. Gustavsen, "Global sensitivity analysis and optimisation of design parameters for low GHG emission lifecycle of multifamily buildings in India," *Energy Build*, vol. 277, p. 112596, 2022, doi: https://doi.org/10.1016/j.enbuild.2022.112596.

[18] P. D. L. and S. Palaniappan, "A case study on life cycle energy use of residential building in Southern India," *Energy Build*, vol. 80, pp. 247–259, 2014, doi: https://doi.org/10.1016/j.enbuild.2014.05.034.

[19] Varun, A. Sharma, V. Shree, and H. Nautiyal, "Life cycle environmental assessment of an educational building in Northern India: A case study," *Sustain Cities Soc*, vol. 4, pp. 22–28, 2012, doi: https://doi.org/10.1016/j.scs.2012.03.002.

[20] V. Venkatraj and M. K. Dixit, "Life cycle embodied energy analysis of higher education buildings: A comparison between different LCI methodologies," *Renewable and Sustainable Energy Reviews*, vol. 144, p. 110957, 2021, doi: https://doi.org/10.1016/j.rser.2021.110957.

[21] P. Kl, B. V. Venkatarama Reddy, and M. Mani, "Life cycle energy assessment in buildings: framework, approaches, and case studies," in *Elsevier*, 2017, pp. 113–136.

[22] R. Devanand, S. Prashanth, P. L. Devi, B. A. Chethan, R. Amar, and H. N. Harsha, "Assessment of embodied energy of masonry building materials in Hassan, India," *Mater Today Proc*, vol. 80, pp. 685–694, 2023, doi: https://doi.org/10.1016/j.matpr.2022.11.069.

[23] K. I. Praseeda, B. V. V. Reddy, and M. Mani, "Embodied and operational energy of urban residential buildings in India," *Energy Build*, vol. 110, pp. 211–219, 2016, doi: https://doi.org/10.1016/j.enbuild.2015.09.072.

[24] A. S. Basavaraj and R. Gettu, "Primary life cycle inventory data for cement production, with relevance to sustainability assessment–Indian cases," *Data Brief*, vol. 54, p. 110258, 2024, doi: https://doi.org/10.1016/j.dib.2024.110258.

[25] M. Jain and R. Rawal, "Emissions from a net zero building in India: life cycle assessment," *Building & Cities*, vol. 3, no. 1, pp. 398–416, 2022.

[26] A. Chel and G. N. Tiwari, "Thermal performance and embodied energy analysis of a passive house – Case study of vault roof mud-house in India," *Appl Energy*, vol. 86, no. 10, pp. 1956–1969, 2009, doi: https://doi.org/10.1016/j.apenergy.2008.12.033.

[27] D. Bansal, R. Singh, and R. L. Sawhney, "Effect of construction materials on embodied energy and cost of buildings—A case study of residential houses in India up to 60m2 of plinth area," *Energy Build*, vol. 69, pp. 260–266, 2014, doi: https://doi.org/10.1016/j.enbuild.2013.11.006.

[28] R. Giordano, V. Serra, E. Tortalla, V. Valentini, and C. Aghemo, "Embodied Energy and Operational Energy Assessment in the Framework of Nearly Zero Energy Building and Building Energy Rating," *Energy Procedia*, vol. 78, pp. 3204–3209, 2015, doi: https://doi.org/10.1016/j.egypro.2015.11.781.

[29] L. Gustavsson, A. Joelsson, and R. Sathre, "Life cycle primary energy use and carbon emission of an eight-storey wood-framed apartment building," *Energy Build*, vol. 42, no. 2, pp. 230–242, 2010, doi: https://doi.org/10.1016/j.enbuild.2009.08.018.

[30] A. Atmaca, "Life-cycle assessment and cost analysis of residential buildings in South East of Turkey: part 2 — a case study," *Int J Life Cycle Assess*, vol. 21, pp. 925–942, 2016.

[31] B. Wrålsen, R. O'Born, and C. Skaar, "Life cycle assessment of an ambitious renovation of a Norwegian apartment building to nZEB standard," *Energy Build*, vol. 177, pp. 197–206, 2018, doi: https://doi.org/10.1016/j.enbuild.2018.07.036.

[32] V. Tavares, N. Lacerda, and F. Freire, "Embodied energy and greenhouse gas emissions analysis of a prefabricated modular house: The 'Moby' case study," *J Clean Prod*, vol. 212, pp. 1044–1053, 2019, doi: https://doi.org/10.1016/j.jclepro.2018.12.028.

[33] A. Takano, S. K. Pal, M. Kuittinen, K. Alanne, M. Hughes, and S. Winter, "The effect of material selection on life cycle energy balance: A case study on a hypothetical building model in Finland," *Build Environ*, vol. 89, pp. 192–202, 2015, doi: https://doi.org/10.1016/j.buildenv.2015.03.001.

[34] F. Cruz Rios, D. Grau, and W. K. Chong, "Reusing exterior wall framing systems: A cradle-to-cradle comparative life cycle assessment," *Waste Management*, vol. 94, pp. 120–135, 2019, doi: https://doi.org/10.1016/j.wasman.2019.05.040.

[35] B. Petrovic, J. A. Myhren, X. Zhang, M. Wallhagen, and O. Eriksson, "Life cycle assessment of a wooden single-family house in Sweden," *Appl Energy*, vol. 251, p. 113253, 2019, doi: https://doi.org/10.1016/j.apenergy.2019.05.056.

[36] T. Nolan and M. Doyle-Kent, "An Investigation into the Role of the Building Structure on Energy Use & CO2 Emissions over the Life Cycle of a Medium-Rise Residential Building," *IFAC-PapersOnLine*, vol. 51, no. 30, pp. 60–65, 2018, doi: https://doi.org/10.1016/j.ifacol.2018.11.246.

[37] H. Nautiyal, V. Shree, P. Singh, S. Khurana, and V. Goel, "Chapter 11 - Life Cycle Assessment of an Academic Building: A Case Study," in *Environmental Carbon Footprints*, S. S. Muthu, Ed., Butterworth-Heinemann, 2018, pp. 295–315. doi: https://doi.org/10.1016/B978-0-12-812849-7.00011-8.

[38] V. Motuzienė, A. Rogoža, V. Lapinskienė, and T. Vilutienė, "Construction solutions for energy efficient single-family house based on its life cycle multi-criteria analysis: a case study," *J Clean Prod*, vol. 112, pp. 532–541, 2016, doi: https://doi.org/10.1016/j.jclepro.2015.08.103.

[39] T. Hennequin, Y. Dong, K. Arnbjerg-Nielsen, and H. J. D. Sørup, "Life cycle assessment of a typical European single-family residence and its flood related repairs," *J Clean Prod*, vol. 228, pp. 1334–1344, 2019, doi: https://doi.org/10.1016/j.jclepro.2019.04.125.

[40] C. Thormark, "The effect of material choice on the total energy need and recycling potential of a building," *Build Environ*, vol. 41, no. 8, pp. 1019–1026, 2006, doi: https://doi.org/10.1016/j.buildenv.2005.04.026.

[41] U. Y. A. Tettey, A. Dodoo, and L. Gustavsson, "Effects of different insulation materials on primary energy and CO2 emission of a multi-storey residential building," *Energy Build*, vol. 82, pp. 369–377, 2014, doi: https://doi.org/10.1016/j.enbuild.2014.07.009.

[42] J. C. Morel, A. Mesbah, M. Oggero, and P. Walker, "Building houses with local materials: means to drastically reduce the environmental impact of construction," *Build Environ*, vol. 36, no. 10, pp. 1119–1126, 2001, doi: https://doi.org/10.1016/S0360-1323(00)00054-8.

[43] J. Monahan and J. C. Powell, "An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework," *Energy Build*, vol. 43, no. 1, pp. 179–188, 2011, doi: https://doi.org/10.1016/j.enbuild.2010.09.005.

[44] N. Mithraratne and B. Vale, "Life cycle analysis model for New Zealand houses," *Build Environ*, vol. 39, no. 4, pp. 483–492, 2004, doi: https://doi.org/10.1016/j.buildenv.2003.09.008.

[45] J. C. Gómez de Cózar, A. G. Martínez, Í. A. López, and M. R. Alfonsea, "Life cycle assessment as a decision-making tool for selecting building systems in heritage intervention: Case study of Roman Theatre in Itálica, Spain," *J Clean Prod*, vol. 206, pp. 27–39, 2019, doi: https://doi.org/10.1016/j.jclepro.2018.09.169.

[46] N. Huberman and D. Pearlmutter, "A life-cycle energy analysis of building materials in the Negev desert," *Energy Build*, vol. 40, no. 5, pp. 837–848, 2008, doi: https://doi.org/10.1016/j.enbuild.2007.06.002.

[47] I.-F. Häfliger *et al.*, "Buildings environmental impacts' sensitivity related to LCA modelling choices of construction materials," *J Clean Prod*, vol. 156, pp. 805–816, 2017, doi: https://doi.org/10.1016/j.jclepro.2017.04.052.

[48] M. Wallhagen, M. Glaumann, and T. Malmqvist, "Basic building life cycle calculations to decrease contribution to climate change – Case study on an office building in Sweden," *Build Environ*, vol. 46, no. 10, pp. 1863–1871, 2011, doi: https://doi.org/10.1016/j.buildenv.2011.02.003.

[49] A. Passer, H. Kreiner, and P. Maydl, "Assessment of the environmental performance of buildings: A critical evaluation of the influence of technical building equipment on residential buildings," *Int J Life Cycle Assess*, vol. 17, pp. 1116–1130, 2012.

[50] K. Milaj, A. Sinha, T. Miller, and J. Tokarczyk, "Environmental utility of wood substitution in commercial buildings using life-cycle analysis," *Wood and fiber science*, vol. 49, no. 3, pp. 338–358, 2017.

[51] S. Lasvaus *et al.*, "Towards guidance values for the environmental performance of buildings: application to the statistical analysis of 40 low-energy single family houses LCA in France," *Int J Life Cycle Assess*, vol. 22, pp. 657–674, 2017.

[52] Z. Alwan and P. Jones, "The importance of embodied energy in carbon footprint assessment," *Structural Survey*, vol. 32, no. 1, pp. 49–60, 2014.

[53] S. Citherlet and T. Defaux, "Energy and environmental comparison of three variants of a family house during its whole life span," *Build Environ*, vol. 42, no. 2, pp. 591–598, 2007, doi: https://doi.org/10.1016/j.buildenv.2005.09.025.

[54] G. T. Roger Fay and U. Iyer-Raniga, "Life-cycle energy analysis of buildings: a case study," *Building Research \& Information*, vol. 28, no. 1, pp. 31–41, 2000, doi: 10.1080/096132100369073.

[55] P. Muñoz, P. Morales, V. Letelier, L. Muñoz, and D. Mora, "Implications of Life Cycle Energy Assessment of a new school building, regarding the nearly Zero Energy Buildings targets in EU: A case of Study," *Sustain Cities Soc*, vol. 32, pp. 142–152, 2017, doi: https://doi.org/10.1016/j.scs.2017.03.016.

[56] Y. Gong and D. Song, "Life Cycle Building Carbon Emissions Assessment and Driving Factors Decomposition Analysis Based on LMDI—A Case Study of Wuhan City in China," *Sustainability*, vol. 7, no. 12, pp. 16670–16686, 2015, doi: 10.3390/su71215838.

[57] H. Achenbach, J. L. Wenker, and S. Rüter, "Life cycle assessment of product- and construction stage of prefabricated timber houses: a sector representative approach for Germany according to EN 15804, EN 15978 and EN 16485," *European Journal of Wood and Wood Products*, vol. 76, no. 2, pp. 711–729, 2018, doi: 10.1007/s00107-017-1236-1.

[58] A. B. Robertson, F. C. F. Lam, and R. J. Cole, "A Comparative Cradle-to-Gate Life Cycle Assessment of Mid-Rise Office Building Construction Alternatives: Laminated Timber or Reinforced Concrete," *Buildings*, vol. 2, no. 3, pp. 245–270, 2012, doi: 10.3390/buildings2030245.

[59] A. A. Guggemos and A. Horvath, "Comparison of Environmental Effects of Steel- and Concrete-Framed Buildings," *Journal of Infrastructure Systems*, vol. 11, no. 2, pp. 93–101, 2005.

[60] R. H. Crawford, "Validation of a hybrid life-cycle inventory analysis method," *J Environ Manage*, vol. 88, no. 3, pp. 496–506, 2008, doi: https://doi.org/10.1016/j.jenvman.2007.03.024.

[61] R. H. Crawford, E. L. Bartak, A. Stephan, and C. A. Jensen, "Evaluating the life cycle energy benefits of energy efficiency regulations for buildings," *Renewable and Sustainable Energy Reviews*, vol. 63, pp. 435–451, 2016, doi: https://doi.org/10.1016/j.rser.2016.05.061.

[62] A. Stephan, R. H. Crawford, and K. de Myttenaere, "Towards a more holistic approach to reducing the energy demand of dwellings," *Procedia Eng*, vol. 21, pp. 1033–1041, 2011, doi: https://doi.org/10.1016/j.proeng.2011.11.2109.

[63] A. Stephan, R. H. Crawford, and K. de Myttenaere, "A comprehensive assessment of the life cycle energy demand of passive houses," *Appl Energy*, vol. 112, pp. 23–34, 2013, doi: https://doi.org/10.1016/j.apenergy.2013.05.076.

[64] A. Stephan and R. H. Crawford, "A multi-scale life-cycle energy and greenhouse-gas emissions analysis model for residential buildings," *Archit Sci Rev*, vol. 57, no. 1, pp. 39–48, 2014, doi: 10.1080/00038628.2013.837814.

[65] A. Stephan and L. Stephan, "Reducing the total life cycle energy demand of recent residential buildings in Lebanon," *Energy*, vol. 74, pp. 618–637, 2014, doi: https://doi.org/10.1016/j.energy.2014.07.028.

[66] A. Stephan and R. H. Crawford, "House size and future building energy efficiency regulations in Australia," *Living and Learning: Research for a Better Built Environment: 49th International Conference of the Architectural Science Association*, pp. 342–351, 2015.

[67] B. Muller and L. Schebek, "Input-Output-based Life Cycle Inventory: Development and Validation of a Dataset for the German Building Sector," *J Ind Ecol*, vol. 17, no. 4, pp. 504–516, 2013, doi: https://doi.org/10.1111/jiec.12018.

[68] P. Du, A. Wood, B. Stephens, and X. Song, "Life-Cycle Energy Implications of Downtown High-Rise vs. Suburban Low-Rise Living: An Overview and Quantitative Case Study for Chicago," *Buildings*, vol. 5, no. 3, pp. 1003–1024, 2015, doi: 10.3390/buildings5031003.

[69] J. Xiao, C. Wang, T. Ding, and A. Akbarnezhad, "A recycled aggregate concrete high-rise building: Structural performance and embodied carbon footprint," *J Clean Prod*, vol. 199, pp. 868–881, 2018, doi: https://doi.org/10.1016/j.jclepro.2018.07.210.

[70] J. Li, B. Rismanchi, and T. Ngo, "Feasibility study to estimate the environmental benefits of utilising timber to construct high-rise buildings in Australia," *Build Environ*, vol. 147, pp. 108–120, 2019, doi: https://doi.org/10.1016/j.buildenv.2018.09.052.

[71] X. Su and X. Zhang, "A detailed analysis of the embodied energy and carbon emissions of steel-construction residential buildings in China," *Energy Build*, vol. 119, pp. 323–330, 2016, doi: https://doi.org/10.1016/j.enbuild.2016.03.070.

[72] A. Utama and S. H. Gheewala, "Indonesian residential high rise buildings: A life cycle energy assessment," *Energy Build*, vol. 41, no. 11, pp. 1263–1268, 2009, doi: https://doi.org/10.1016/j.enbuild.2009.07.025.

[73] J. Wang, C. Yu, and W. Pan, "Life cycle energy of high-rise office buildings in Hong Kong," *Energy Build*, vol. 167, pp. 152–164, 2018, doi: https://doi.org/10.1016/j.enbuild.2018.02.038.

[74] A. Koezjakov, D. Urge-Vorsatz, W. Crijns-Graus, and M. van den Broek, "The relationship between operational energy demand and embodied energy in Dutch residential buildings," *Energy Build*, vol. 165, pp. 233–245, 2018, doi: https://doi.org/10.1016/j.enbuild.2018.01.036.

[75] T. Y. Chen, J. Burnett, and C. K. Chau, "Analysis of embodied energy use in the residential building of Hong Kong," *Energy*, vol. 26, no. 4, pp. 323–340, 2001, doi: https://doi.org/10.1016/S0360-5442(01)00006-8.

[76] L. Aye, T. Ngo, R. H. Crawford, R. Gammampila, and P. Mendis, "Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules," *Energy Build*, vol. 47, pp. 159–168, 2012, doi: https://doi.org/10.1016/j.enbuild.2011.11.049.

[77] H. Skates, M. Donn, and A. Alcorn, "Embodied energy significance in the energy performance of New Zealand housing," *International Solar Energy Society UK SEction - Conference - C*, pp. 254–261, 2001.

[78] M. K. Dixit, J. L. Fernández-Solís, S. Lavy, and C. H. Culp, "Identification of parameters for embodied energy measurement: A literature review," *Energy Build*, vol. 42, no. 8, pp. 1238–1247, 2010, doi: https://doi.org/10.1016/j.enbuild.2010.02.016.

[79] S. E. Philip J. Davies and S. K. Firth, "Challenges for capturing and assessing initial embodied energy: a contractor's perspective," *Construction Management and Economics*, vol. 32, no. 3, pp. 290–308, 2014, doi: 10.1080/01446193.2014.884280.

[80] C. Thormark, "Energy and resources, material choice and recycling potential in low energy buildings," *International CIB Conference*, vol. 7, p. 26, 2007.

[81] J. Nässén, J. Holmberg, A. Wadeskog, and M. Nyman, "Direct and indirect energy use and carbon emissions in the production phase of buildings: An input–output analysis," *Energy*, vol. 32, no. 9, pp. 1593–1602, 2007, doi: https://doi.org/10.1016/j.energy.2007.01.002.

[82] L. Vukotic, R. A. Fenner, and K. Symons, "Assessing embodied energy of building structural elements," *Proceedings of the Institution of Civil Engineers - Engineering Sustainability*, vol. 163, no. 3, pp. 147–158, 2010, doi: 10.1680/ensu.2010.163.3.147.

[83] M. Cellura, F. Guarino, S. Longo, and M. Mistretta, "Energy life-cycle approach in Net zero energy buildings balance: Operation and embodied energy of an Italian case study," *Energy Build*, vol. 72, pp. 371–381, 2014, doi: https://doi.org/10.1016/j.enbuild.2013.12.046.

[84] C. Thormark, "A low energy building in a life cycle—its embodied energy, energy need for operation and recycling potential," *Build Environ*, vol. 37, no. 4, pp. 429–435, 2002, doi: https://doi.org/10.1016/S0360-1323(01)00033-6.

[85] L. Gustavsson and A. Joelsson, "Life cycle primary energy analysis of residential buildings," *Energy Build*, vol. 42, no. 2, pp. 210–220, 2010, doi: https://doi.org/10.1016/j.enbuild.2009.08.017.

[86] D. G. Fridley, N. Zheng, and N. Zhou, "Estimating total energy consumption and emissions of China's commercial and office buildings," *Lawrence Berkeley Mational Laboratory*, 2008.

[87] T. Ramesh, R. Prakash, and K. K. Shukla, "Life cycle energy analysis of buildings: An overview," *Energy Build*, vol. 42, no. 10, pp. 1592–1600, 2010, doi: https://doi.org/10.1016/j.enbuild.2010.05.007.

[88] A. M. Moncaster and K. E. Symons, "A method and tool for 'cradle to grave' embodied carbon and energy impacts of UK buildings in compliance with the new TC350 standards," *Energy Build*, vol. 66, pp. 514–523, 2013, doi: https://doi.org/10.1016/j.enbuild.2013.07.046.

[89] M. Leckner and R. Zmeureanu, "Life cycle cost and energy analysis of a Net Zero Energy House with solar combisystem," *Appl Energy*, vol. 88, no. 1, pp. 232–241, 2011, doi: https://doi.org/10.1016/j.apenergy.2010.07.031.

[90] L. Shiu, "Life Cycle Assessment of Vanier Residence in University of British Columbia." 2009. [Online]. Available: https://open.library.ubc.ca/collections/18861/items/1.0077961

[91] K. Doyoon, "Preliminary life cycle analysis of modular and conventional housing in Benton Harbor, Michigan," *PhD Dissertation*, 2008.

[92] K. Adalberth, "Energy use during the life cycle of single-unit dwellings: Examples," *Build Environ*, vol. 32, no. 4, pp. 321–329, 1997, doi: https://doi.org/10.1016/S0360-1323(96)00069-8.

[93] M. Almeida, L. Braganca, and P. Mendonca, "Potentialities of lightweight construction solutions for sustainability," *International Conference of Passive and Low Energy Cooling for the Built Environment*, 2005.

[94] S. John, B. Nebel, N. Perez, and A. Bushanan, "Environmental impacts of multi-storey buildings using different construction materials," 2008.

[95] C. Scheuer, G. A. Keoleian, and P. Reppe, "Life cycle energy and environmental performance of a new university building: modeling challenges and design implications," *Energy Build*, vol. 35, no. 10, pp. 1049–1064, 2003, doi: https://doi.org/10.1016/S0378-7788(03)00066-5.

[96] M. A. Sattler and M. R. Sperb, "Environmental impact analysis of low cost housing in Brazil," *In Proceedings of PLEA*, pp. 176–181, 2000.

[97] P. Chulsukon, J. S. Haberl, L. O. Degelman, and K. E. Sylvester, "Development and analysis of a sustainable low energy house in a hot and humid climate," *Energy systems laboratory, Texas A&M University*, 2002.

[98] W. Deng, D. Prasad, P. Osmond, and F. T. Li, "QUANTIFYING LIFE CYCLE ENERGY AND CARBON FOOTPRINTS OF CHINA'S RESIDENTIAL SMALL DISTRICT," *Journal of Green Building*, vol. 6, no. 4, pp. 96–111, 2011, doi: 10.3992/jgb.6.4.96.

[99] Y. Chang, R. J. Ries, and S. Lei, "The embodied energy and emissions of a high-rise education building: A quantification using process-based hybrid life cycle inventory model," *Energy Build*, vol. 55, pp. 790–798, 2012, doi: https://doi.org/10.1016/j.enbuild.2012.10.019.

[100] N. Yokoo, T. Oka, K. Yokoyama, T. Sawachi, and M. Yamamoto, "Comparison of embodied energy/CO2 of office buildings in China and Japan," *Journal of Civil Engineering and Architecture*, vol. 9, no. 3, pp. 300–307, 2015.

[101] "A life cycle assessment study of embodied effects for existing historic buildings," *Athena Sustainable Material Institute*, 2009.

[102] N. Kohler, M. Klingele, and S. Heitz, "Simulation of energy and massflows of buildings during their life cycle," *Centre Scientifique et Technique du Batiment, proceedings of the Second International Conference on Buildings and the Environment*, vol. 1, pp. 41–48, 1997.

[103] S. Citherlet and J. Hand, "Assessing energy, lighting, room acoustics, occupant comfort and environmental impacts performance of building with a single simulation program," *Build Environ*, vol. 37, no. 8, pp. 845–856, 2002, doi: https://doi.org/10.1016/S0360-1323(02)00044-6.

[104] S. Junnila, A. Horvath, and A. A. Guggemos, "Life-cycle assessment of office buildings in Europe and the United States," *Journal of Infrastructure Systems*, vol. 12, no. 1, pp. 10–17, 2006.

[105] A. Dodoo, L. Gustavsson, and R. Sathre, "Building energy-efficiency standards in a life cycle primary energy perspective," *Energy Build*, vol. 43, no. 7, pp. 1589–1597, 2011, doi: https://doi.org/10.1016/j.enbuild.2011.03.002.

[106] I. M. Johnstone, "Energy and mass flows of housing: a model and example," *Build Environ*, vol. 36, no. 1, pp. 27–41, 2001, doi: https://doi.org/10.1016/S0360-1323(99)00065-7.

[107] P. C. Kernan, "Life-cycle energy analysis of an office building." 1996. [Online]. Available: https://open.library.ubc.ca/collections/831/items/1.0087061

[108] S. Blanchard and P. Reppe, "Life cycle analysis of a residential home in Michigan," *Center of Sustainable Systems, University of Michigan*, 1998.

[109] B. Lippke, J. Wilson, J. Perez-Garcia, J. Bowyer, and J. Meil, "CORRIM: life-cycle environmental performance of renewable building materials," *Journal of Forest Product*, vol. 54, no. 6, pp. 8–19, 2004.

[110] P. Winistorfer, Z. Chen, B. Lippke, and N. Stevens, "Energy consumption and greenhouse gas emissions related to the use, maintenance, and disposal of a residential structure," *Wood and fiber science*, pp. 128–139, 2005.

[111] G. Haines, M. Org, A. Barkan, and K. Pressnail, "An economic and environmental comparison of standard versus energy efficient homes in Toronto, Canada," *Sustainable Urban Areas*, 2007.

[112] M. Suzuki and T. Oka, "Estimation of life cycle energy consumption and CO2 emission of office buildings in Japan," *Energy Build*, vol. 28, no. 1, pp. 33–41, 1998, doi: https://doi.org/10.1016/S0378-7788(98)00010-3.

[113] S. Humphrey, A. Amato, and R. Frewer, "Whole life comparison of high rise residential blocks in Hong Kong," *Hong Kong Housing Authority*, 2004.

[114] A. Atmaca and N. Atmaca, "Life cycle energy (LCEA) and carbon dioxide emissions (LCCO2A) assessment of two residential buildings in Gaziantep, Turkey," *Energy Build*, vol. 102, pp. 417–431, 2015, doi: https://doi.org/10.1016/j.enbuild.2015.06.008.

[115] L. Shu-hua, C. Yuan, and Z. Xue, "Life-Cycle Energy Assessment of Urban Residential Buildings in China," *IEEE International Conference on Advanced Management Science (ICAMS)*, 2010.

[116] J. Bastos, S. A. Batterman, and F. Freire, "Life-cycle energy and greenhouse gas analysis of three building types in a residential area in Lisbon," *Energy Build*, vol. 69, pp. 344–353, 2014, doi: https://doi.org/10.1016/j.enbuild.2013.11.010.

[117] R. Fay and G. Treloar, "LIFE CYCLE ENERGY ANALYSIS—: A measure of the environmental impact of buildings," *Environment Design Guide*, pp. 1–7, 2003, Accessed: Apr. 03, 2024. [Online]. Available: http://www.jstor.org/stable/26148428

[118] A. Rauf and R. H. Crawford, "The effect of material service life on the life cycle energy of residential buildings," *The 46th Annual Conference of the Architectural Science Association (ANZAScS) - Building on Knowledge: Theory and Practice*, 2012.

[119] A. Utama and S. H. Gheewala, "Life cycle energy of single landed houses in Indonesia," *Energy Build*, vol. 40, no. 10, pp. 1911–1916, 2008, doi: https://doi.org/10.1016/j.enbuild.2008.04.017.

[120] D. Barnes and L. Rankin, "The energy economics of building construction," *Building Internation*, vol. 8, pp. 31–42, 1975.

[121] M. PALEARI, "Life cycle assessment and zero energy residential buildings: environmental assessment, economics and social remarks," *PhD Dissertation*, 2013.

[122] S. F. Pullen, "Energy used in the Construction and Operation of Houses," *Archit Sci Rev*, vol. 43, no. 2, pp. 87–94, 2000, doi: 10.1080/00038628.2000.9697439.

[123] P. Newton, S. Tucker, and M. Ambrose, "Housing form, energy use and greenhouse gas emission," in *Achieving Sustainable Urban Form*, K. Williams, E. Burton, and M. Jenks, Eds., SPON Press, 2000, pp. 74–84.

[124] B. Randolph, D. Holloway, S. Pullen, and P. Troy, "The environmental impacts of residential development: case studies of 12 estates in Sydney," *[Final Report of ARC Linkage Project LP 0348770]. Kensington, Australia: City Futures Research Centre, University of New South Wales*, 2007.

[125] W. O. Collinge, A. Landis, A. Jones, L. Schaefer, and M. Bilec, "Dynamic life cycle assessment: framework and application to an institutional building," *Int J Life Cycle Assess*, vol. 18, pp. 538–552, 2013.

[126] A. Shukla, G. N. Tiwari, and M. S. Sodha, "Embodied energy analysis of adobe house," *Renew Energy*, vol. 34, no. 3, pp. 755–761, 2009, doi: https://doi.org/10.1016/j.renene.2008.04.002.

[127] P. E. D. L. G. Treloar R. Fay and U. Iyer-Raniga, "Analysing the life-cycle energy of an Australian residential building and its householders," *Building Research \& Information*, vol. 28, no. 3, pp. 184–195, 2000, doi: 10.1080/096132100368957.

Appendix

Floorplan of the case study building

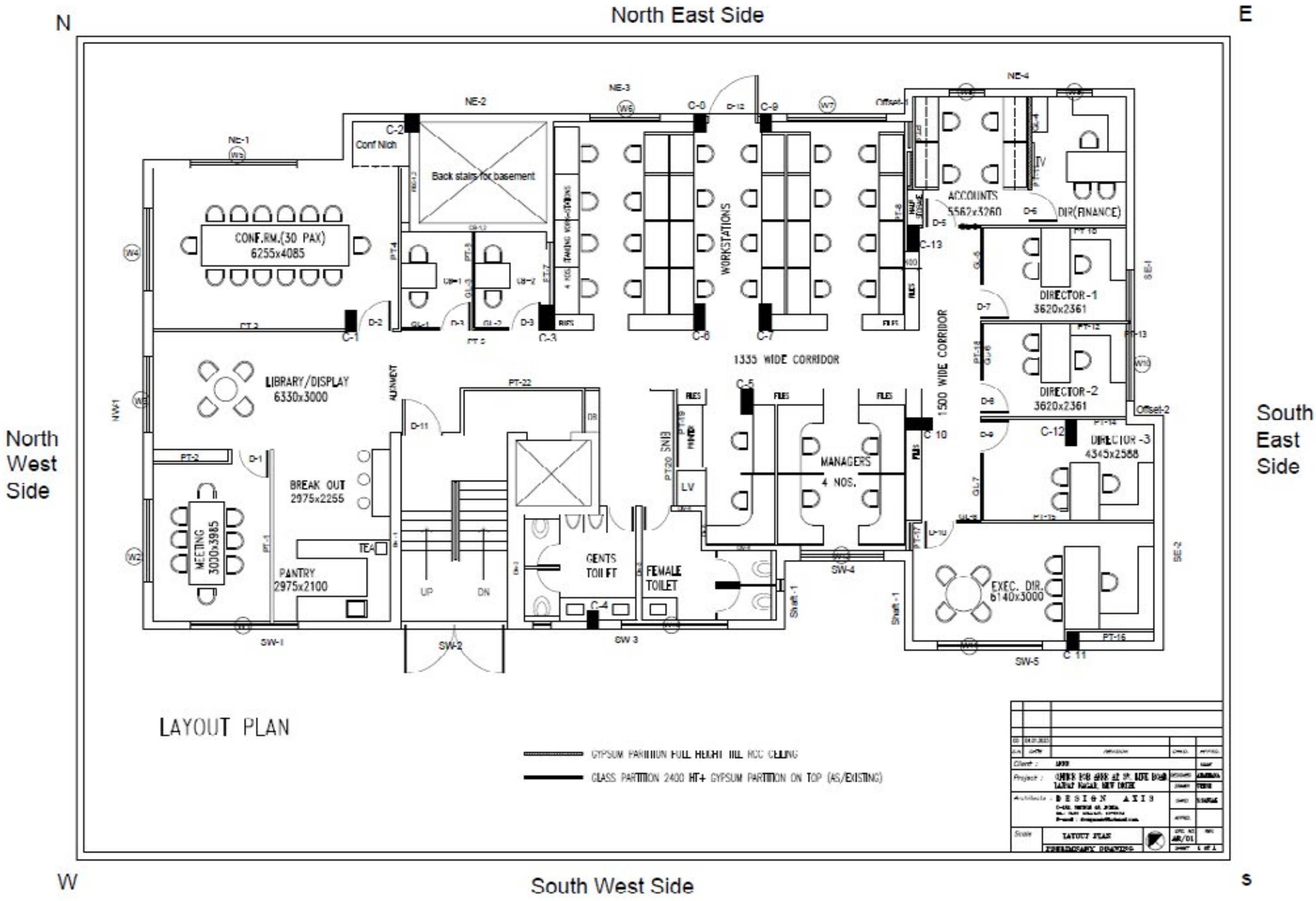


Figure A.1: Floorplan of the case study building

Table A.1 shows the BOQ information of the case study building

Table A.1: Materials' BOQ of case study building

Component	Units	Qty	Weight of the material (kg)
Burnt clay Bricks	Nos.	26404.5	66011.3
coarse sand	Cum	74.2	118661.6
Fine river sand	Cum	5.4	9064.1
OPC Cement	Cum	45.8	65930.5
Aggregate	Cum	121.9	192647.8
Steel	kg	16767.2	16767.2
Water	Ltr	32186.4	32186.4
80X50mm Powder coated Aluminium Section	Rmt	195.1	195.1
Double layer glass	Sqm	63.4	NA
Paint	Sqm	209.7	179.9
Putty	Sqm	209.7	161.3
Admixture	kg	585.4	585.4
Vitrified Tiles (10mm)	kg	2789.8	2789.8
Ceiling Tiles (2x2)	kg	421.5	421.5

Component	Units	Qty	Weight of the material (kg)
Adhesive	kg	981.3	981.3
Foam Concrete	kg	1468.5	1468.5
Waterproofing chem	kg	17.1	17.1
Wooden Flooring	kg	1303.4	1303.4
Aluminium Skirting	kg	148.9	148.9
POP	kg	3092.1	3092.1
Gypsum Plaster	kg	109.7	109.7
Gypsum Board	kg	3507.6	3507.6
GI Matel Section for Frame	kg	945.4	945.4
50mm Glasswool Insulation	kg	487.8	487.8
Gypsum Compound	kg	621.2	621.2
Aluminim Doors & Glazing Frame	kg	516.8	516.8
Aluminium Frames in doors & Glazing	kg	182.9	182.9
12mm Laminated Modular Partitions In toilets	kg	99.2	99.2
32mm Flush doors on toilets entry	kg	24.9	24.9

Table A.2 shows the calculation of use phase embodied carbon emission of case study building

Table A.2: Use phase embodied carbon calculation for the case study building

						life of building = 50 years					life of building = 60 years					life of building = 70 years				
Component	Units	Qty	Weight of the material (kg)	IFC Database ($kgCO_{2eq.}$/kg)	Embodied IFC (kgCO2eq.)	% change	After years	No of changes	Quantity (kg)	Total emission (kgCO2eq.)	% change	After years	No of changes	Quantity (kg)	Total emission (kgCO2eq.)	% change	After years	No of changes	Quantity (kg)	Total emission (kgCO2eq.)
Bricks	Nos.	26404.50	66011.26	0.39	25744.39	0	100				0	100				0	100			
Coarse sand	Cum	74.16	118661.62	0.009	1067.95	40	15	3.33	26453.33	238.08	40	15	4	31744.00	285.70	40	15	4.67	37034.67	333.31
Fine Sand	Cum	5.40	9064.11	0.009	81.58	40	15	3.33	12085.33	108.77	40	15	4	14502.40	130.52	40	15	4.67	16919.47	152.28
Cement	Cum	45.79	65930.48	0.91	59996.74	40	15	3.33	8352.00	7600.32	40	15	4	10022.40	9120.38	40	15	4.67	11692.80	10640.45
Aggregates	Cum	121.93	192647.82	0.009	1733.83															
Steel	kg	16767.17	16767.17	2.6	43594.64	0	0				0	0				0	0			
Water	Ltr	32186.44	32186.44	0.0003	9.66	0	0				0	0				0	0			
Framing	Rmt	195.13	195.13	26	5073.43	0	75				0	75				0	75			
Double layer glass	Sqm	63.36	NA	52.7	3341.18	0	100				0	100				0	100			
Paint	Sqm	209.71	179.87	2.91	523.44	100	10	5.00	899.37	2617.18	100	10	6	1079.25	3140.61	100	10	7.00	1259.12	3664.05
Putty	Sqm	209.71	161.27	0.27	43.54	100	10	5.00	806.35	217.71	100	10	6	967.62	261.26	100	10	7.00	1128.89	304.80
Admixture	kg	585.37	585.37	1.67	977.57	0	0				0	0				0	0			
Vitrified Tiles (10mm)	kg	2789.78	2789.78	0.68	1897.05	100	20	2.50	6974.44	4742.62	100	20	3	8369.33	5691.15	100	20	3.50	9764.22	6639.67
Ceiling Tiles (2x2)	kg	421.52	421.52	2.7	1138.10	100	20	2.50	1053.79	2845.24	100	20	3	1264.55	3414.29	100	20	3.50	1475.31	3983.34
Adhesive	kg	981.25	981.25	0.47	461.19	100	20	2.50	2453.14	1152.97	100	20	3	2943.76	1383.57	100	20	3.50	3434.39	1614.16
Foam Concrete	kg	1468.47	1468.47	0.322	472.85	100	30	1.67	2447.45	788.08	100	30	2	2936.93	945.69	100	30	2.33	3426.42	1103.31
Waterproofing chem	kg	17.12	17.12	2.88	49.31	100	15	3.33	57.07	164.35	100	15	4	68.48	197.22	100	15	4.67	79.89	230.09
Wooden Flooring	kg	1303.43	1303.43	2	2606.87	0	100				0	100				0	100			
Aluminium Skirting	kg	148.94	148.94	35	5212.86	0	75				0	75				0	75			
POP	kg	3092.07	3092.07	0.13	401.97	100	20	2.50	7730.18	1004.92	100	20	3	9276.21	1205.91	100	20	3.50	10822.25	1406.89
Gypsum Plaster	kg	109.71	109.71	0.099	10.86	0	50				0	50				0	50			
Gypsum Board	kg	3507.61	3507.61	0.26	911.98	0	50				0	50				0	50			
GI Matel Section for Frame	kg	945.40	945.40	3	2836.21	0	70				0	70				0	70			
50mm Glasswool Insulation	kg	487.76	487.76	2.5	1219.41	100	30	1.67	812.94	2032.35	100	30	2	975.53	2438.82	100	30	2.33	1138.12	2845.29
Gypsum Compound	kg	621.19	621.19	0.0037	2.30	0	50				0	50				0	50			
10mm Glass in Aluminim Doors & Glazing	kg	516.80	516.80	1.2	620.16	0	75				0	75				0	75			
Aluminium Frames in doors & Glazing	kg	182.88	182.88	26	4754.85	0	75				0	75				0	75			
12mm Laminated Modular Partitions in toilets	kg	99.19	99.19	0.43	42.65	0	60				0	60				0	60			
32mm Flush doors on toilets entry	kg	24.95	24.95	0.43	10.73	0	60				0	60				0	60			
Total					164837.28					23512.60					28215.12					32917.65

Table A.3 presents a comparative analysis of embodied carbon emissions for two scenarios: constructing a new building after the original design life ends, versus extending the building's design life by 10 and 20 years beyond the baseline of 50 years.

Table A.3 comparative analysis of emissions for the cases: constructing a new building versus extending the building design life

Life cycle embodied carbon till 50 years (upfront embodied + Use phase embodied carbon) ($kgCO_{2eq.}$)	Life cycle embodied carbon till 60 years for the case of extending building design life (upfront embodied + Use phase embodied carbon) ($kgCO_{2eq.}$)	Life cycle embodied carbon till 60 years for the case of extending building design life (upfront embodied + Use phase embodied carbon) ($kgCO_{2eq.}$)
167190.3	193052.4 (10 years extension)	357889.7
	197754.9 (20 years extension)	362592.2
	Percentage increase from the base case	
	15.5 (10 years extension)	114.1
	18.3 (20 years extension)	116.9

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