SED FUND

Confederation of Indian Industry

IGBC

# EMBODIED CARBON EMISSIONS BASELINE ESTIMATION FOR BUILDINGS IN INDIA

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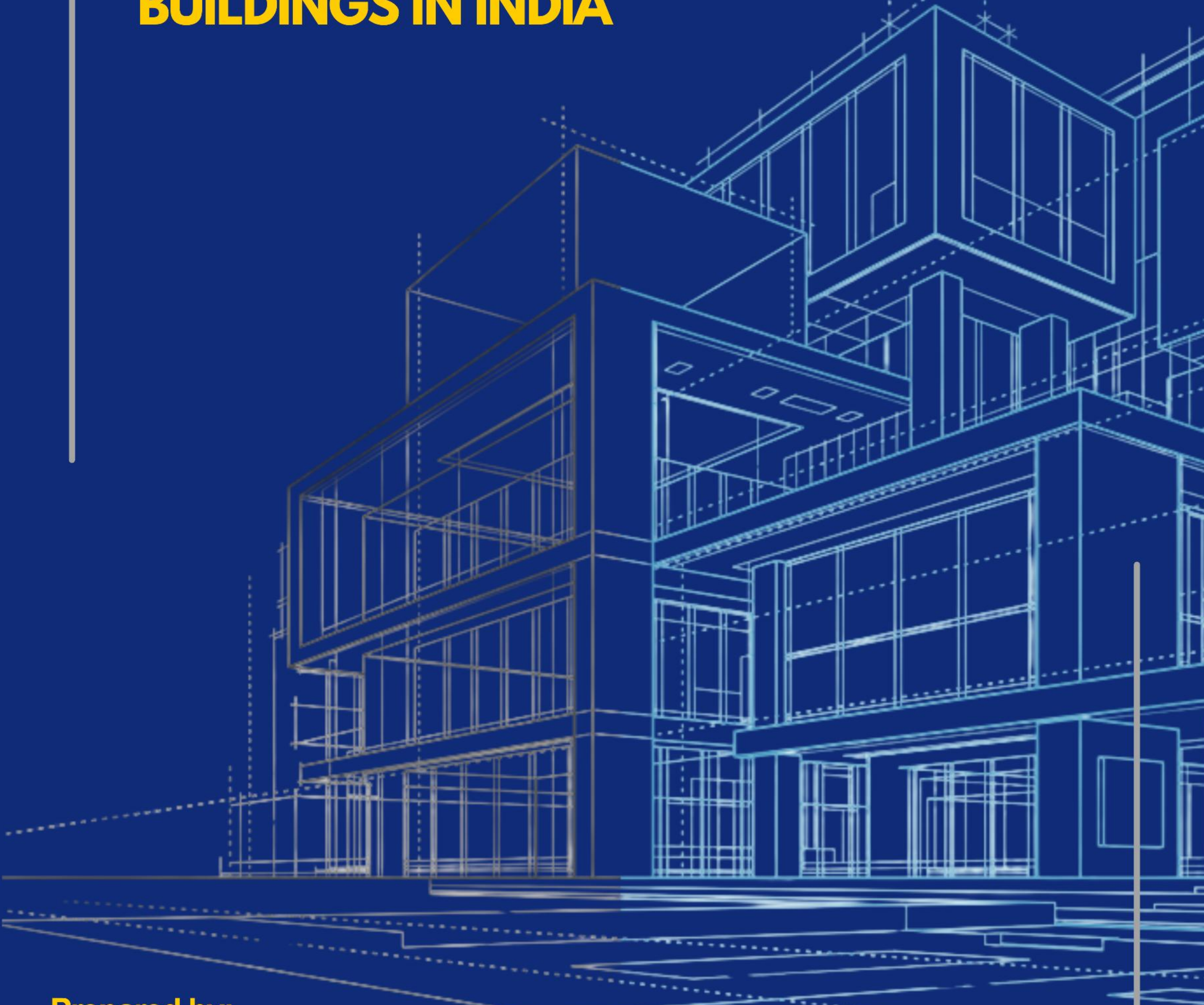

**Prepared by:**
CII – Indian Green Building Council
Survey # 64, Kothaguda Post,
RR District, Hyderabad – 500 084, India
www.igbc.in

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# Foreword

India's unprecedented urban expansion, set to more than triple the nation's building sector by 2050, presents one of the most significant climate challenges as well as opportunity. Whilst past efforts on buildings environment focused more on operational aspects, the sheer scale of material consumption has now put the focus that we urgently prioritise embodied carbon—the emissions locked into a building via construction materials used, before a building is even occupied. As a first step, this study, "Embodied Carbon Emissions Baseline Estimation for Buildings in India," is a direct response towards addressing this critical national gap. Recognizing the reality that there is limited embodied carbon data and related benchmarks specific to India, the Indian Green Building Council (IGBC), under the Confederation of Indian Industry (CII), is looking to intervene to develop this essential data and contribute to baseline estimations.

The Sustainability, Equity and Diversity Fund (SED) is happy to partner with and support IGBC in this endeavour. This project relies on Life Cycle Assessment Methodologies and creates the first comprehensive set of national baselines on embodied carbon in building by meticulously dissecting the elements of embodied carbon footprint across India's four major climatic zones (Hot & Dry, Warm & Humid, Composite, and Temperate) and across four five-impact building typologies (Commercial, Residential, Institutional, Government Offices and Industrial). We are confident that the study which looks at green buildings through the lens of embodied emissions, would establish baseline figures which are both regional and context specific. We are also confident that going forward IGBC would collectively raise the ambition of all stakeholders and ensure that green buildings are truly green and net-zero across their entire life cycle.

The findings presented here are intended to be a foundational catalyst to bring in systemic ecosystem level change. By providing granular data and a clear Embodied Carbon Intensity benchmark and baseline, this report offers the critical evidence necessary to inform policy —specifically on the integration of embodied carbon into national building codes, green rating systems, local regulations and procurement mandates. A higher adoption of embodied carbon benchmarks would drive market transformation by encouraging innovation in low-carbon materials and their adoption, incorporation of low carbon taxonomies like the Green Steel Taxonomy proposed by Ministry of Steel, Government of India, fostering circular economy practices, and bringing in a common and shared understanding across the entire building sector's value chain.

All stakeholders in the construction sector—policymakers, building material manufacturers, structural engineers & consultants, architects, engineers, EPC firms, real estate developers, ESG service providers and financial institutions should take note and appropriately incorporate the same in their respective domains. Prioritizing the systematic reduction of embodied carbon is not merely an environmental imperative; it is essential to ensure that India's vast urban expansion is synonymous with the energy transition, resilience and sustainability, thereby advancing India's building sector toward its net-zero goals.

**With best regards,**

**Vikas Mehta**
**Executive Director**
**Sustainability, Equity and Diversity Fund (SED Fund)**

# Foreword

India's construction sector is witnessing unprecedented growth, offering immense opportunities to build sustainably and responsibly. India has committed to achieve Net Zero by 2070, and therefore, it becomes important to address not only the operational carbon, also the embodied carbon in buildings in India. The Indian Green Building Council (IGBC), taking cognisance of this imperative, has taken a pioneering step to establish national baseline for embodied carbon in buildings.

This study - Embodied Carbon Emissions Baseline Estimation for the Buildings in India - represents a crucial stride in India's journey towards a truly Net Zero future. By mapping the embodied carbon across diverse building typologies and climatic zones, the report provides vital data and insights that will guide policy frameworks, design aspects, and innovations in material. These findings will also serve as a foundation for integrating embodied carbon considerations into codes, rating systems, and procurement practices across the country.

With its strong network, technical expertise, and commitment to continuous advancement, IGBC remains at the forefront of driving India's sustainable construction movement. Through initiatives like this, the Council is equipping stakeholders with the knowledge and tools required to transition towards low-carbon mission.

As you will appreciate, this effort reinforces our collective responsibility to ensure that building and construction sector in India grows in harmony with our planet.

**With best regards,**

**B Thiagarajan**
**National Chairman**
**Indian Green Building Council**


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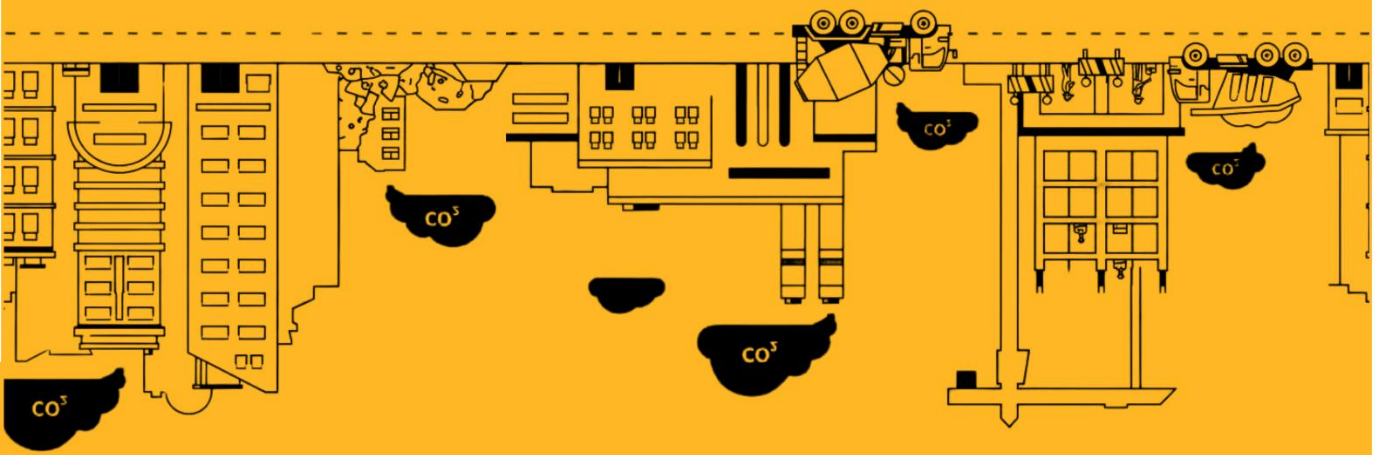

# Acknowledgement

We extend our sincere gratitude to SED Fund for their generous support, which made this project possible. We would like to especially acknowledge and thank Mr. Sivaram Krishnamoorthy (Director, SED Fund) for his encouragement and continued support throughout the project.

We are also extremely grateful to our case study partners for their collaboration, and for sharing their valuable insights, experiences, and data, which greatly enriched the quality of this report.

Finally, we would like to thank the CII-GBC team, particularly Mr. K.S. Venkatagiri (Executive Director) and Mr. S. Karthikeyan (Deputy Executive Director), for their visionary leadership, regular feedback, and valuable guidance that steered the project to completion.

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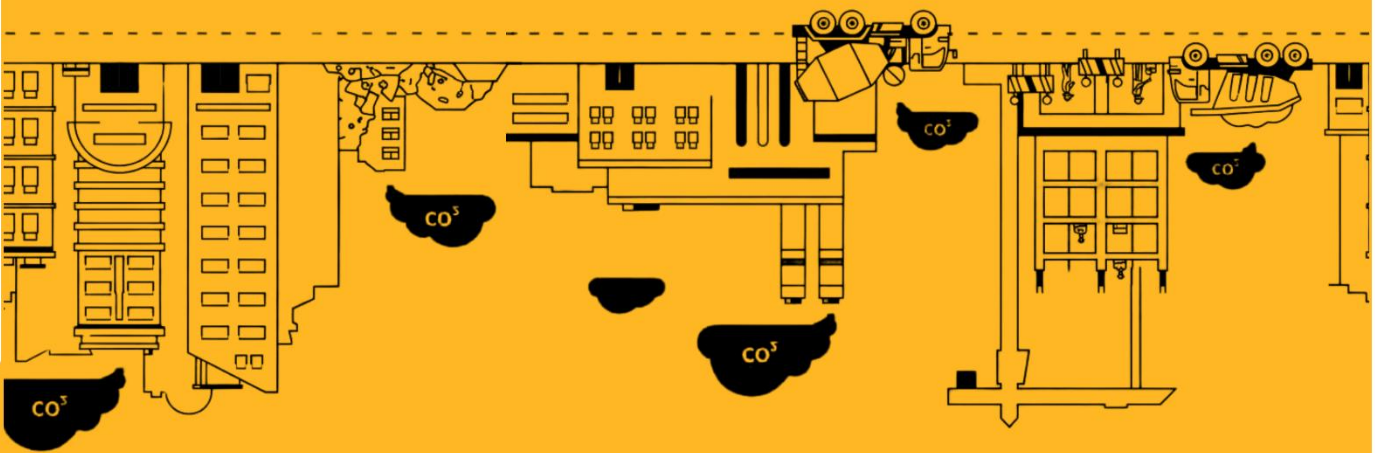
## List of Abbreviations

| Abbreviation | Full Form |
|---|---|
| AAC | Autoclaved Aerated Concrete |
| A1–A3 | Product Stage (Raw material supply, transport, and manufacturing) |
| A4 | Transport Stage (Delivery to site) |
| A5 | Construction Stage (On-site processes and assembly) |
| B1–B7 | Use Stage (Including energy use, maintenance, and refurbishment) |
| B4–B5 | Replacement and End-of-Life Stages |
| $CO_2e$ | Carbon Dioxide Equivalent |
| D | Beyond Building Life Cycle Stage (e.g., reuse, recycling) |
| EIA | Environmental Impact Assessment |
| EPI | Energy Performance Index |
| EPD | Environmental Product Declaration |
| GHG | Greenhouse Gases |
| GWP | Global Warming Potential |
| HVAC | Heating, Ventilation, and Air Conditioning |
| IPCC | Intergovernmental Panel on Climate Change |
| LCA | Life Cycle Assessment |
| MEP | Mechanical, Electrical, and Plumbing |
| MIVAN | Monolithic Industrialized Voided Aluminium Formwork |
| MRF | Materials Recovery Facility |
| NZCB | Net Zero Carbon Building |
| PEB | Pre-Engineered Building |
| PPC | Portland Pozzolana Cement |
| SDG | Sustainable Development Goals |
| WLCA | Whole Life Carbon Assessment |

## Glossary

| Term | Detailed Definition |
|---|---|
| Whole Life Carbon (WLC) | The total amount of greenhouse gas emissions generated throughout a building's entire lifecycle, including both embodied and operational emissions, measured in $KgCO_2e$ /m² per square meter. |
| Embodied Carbon | Greenhouse gas emissions resulting from the extraction, manufacturing, transportation, construction, maintenance, repair, replacement, and disposal of building materials and products. |
| Carbon Intensity | A performance metric that expresses the total $CO_2e$ emissions per square meter of built-up area, helping compare the environmental efficiency of different buildings or systems. |
| Carbon Footprint | The total amount of greenhouse gases emitted directly or indirectly by a specific activity, product, or entity, often measured in terms of $CO_2$ equivalent ($CO_2e$). |
| Life Cycle Assessment (LCA) | A scientific method used to evaluate the environmental impacts of a product or building across all stages of its life—from raw material extraction to disposal or reuse. |
| A1–A3 (Product Stage) | The initial stages of a building product's life cycle: extraction of raw materials (A1), transportation to the manufacturer (A2), and product manufacturing (A3). |
| A4 (Transport Stage) | The emissions associated with transporting construction materials from the factory or supplier to the construction site. |
| A5 (Construction Stage) | Emissions produced during the actual construction phase, including the use of machinery, energy consumption, and on-site waste generation. |
| B4–B5 (Use/Replacement/End-of-Life) | Emissions arising during the operational life of the building from maintenance, repair, and replacement (B4), as well as during its demolition and material disposal (B5). |
| Cradle-to-Gate | An approach to LCA that includes emissions from material extraction (cradle) up to the point the product leaves the factory (gate), excluding use and end-of-life stages. |
| Environmental Product Declaration (EPD) | A third-party verified document that provides transparent, comparable data about a product's environmental impact based on LCA principles. |
| Curtain Wall System | A lightweight, non-load-bearing outer wall, often made of glass and aluminium, primarily used in commercial buildings; generally high in embodied carbon. |
| PEB (Pre-Engineered Building) | Factory-made steel building components assembled on site, commonly used in industrial structures; known for their high structural efficiency but high embodied carbon. |
| Circular Economy in Buildings | A design and construction approach aimed at reducing waste, extending the lifespan of materials, and promoting reuse and recycling. |
| Transportation Emissions | Emissions generated from transporting materials, equipment, and labour to and from the construction site; influenced by distance and logistics. |


# EMBODIED CARBON EMISSIONS BASELINE ESTIMATION FOR BUILDINGS IN INDIA



# Executive Summary

India's construction sector is undergoing an unprecedented expansion, with the building sector expected to more than triple in floor area by 2050. This rapid urban growth, while vital for economic development and societal well-being, presents a serious climate challenge. Historically, efforts to decarbonize the sector have focused on operational emissions—those arising from energy use in lighting, heating, and cooling. However, as buildings become more energy-efficient, embodied carbon emissions—those associated with raw material extraction, manufacturing, transport, and construction—are projected to constitute a significant, and increasingly dominant, share of total life cycle emissions.

This project aims to address this emerging priority by establishing a comprehensive baseline for embodied carbon emissions across key building typologies and climate zones in India. The goal is to inform the development of actionable pathways toward net-zero carbon buildings that account for both operational and embodied emissions.

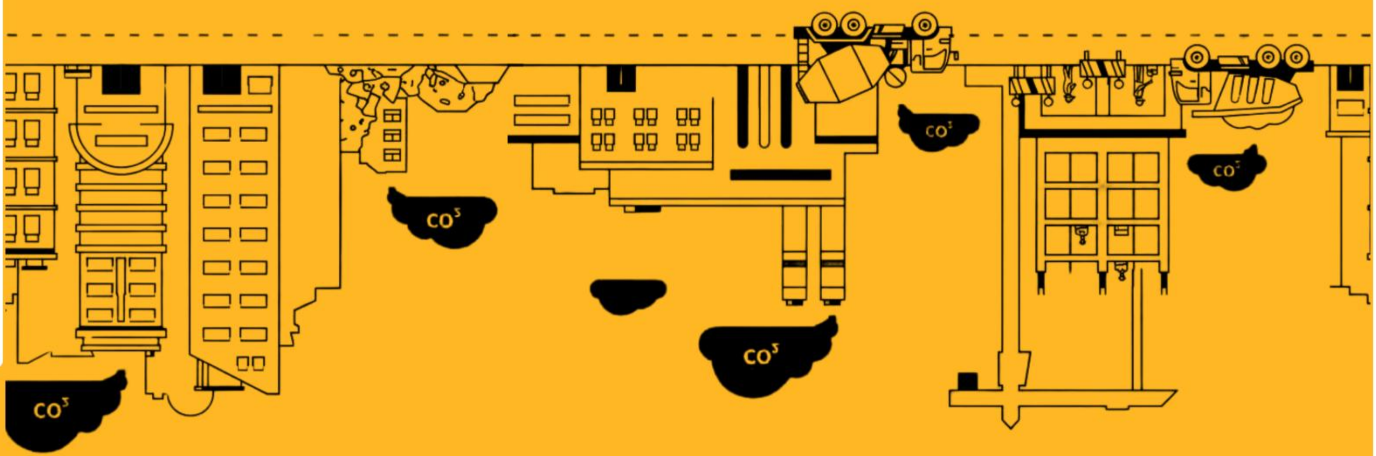
The study examines four major climate zones—Hot & Dry, Warm & Humid, Composite, and Temperate—as defined by the Bureau of Energy Efficiency. Each zone reflects distinct climatic conditions and building practices that influence material choices, construction techniques, and embodied carbon footprints. Simultaneously, the study focuses on four high-impact building typologies: Commercial (Office), Residential (Multi-storeyed Apartments), Institutional (Schools and Government Offices), and Industrial (Factories). These categories encompass the majority of India's current and future building stock and offer substantial opportunities for carbon mitigation.

Utilizing Life Cycle Assessment (LCA) methodologies aligned with international standards (ISO 14040/44, EN 15978), the study quantifies upfront embodied emissions—those occurring before building occupancy—covering material extraction, production, transportation, and on-site construction. Where feasible, end-of-life emissions from demolition and material recovery are also examined to provide a cradle-to-grave perspective. The analysis prioritizes high-emission materials such as cement, steel, bricks, aluminium, and glass, with emissions data derived from local databases, Environmental Product Declarations (EPDs), and industry-standard references.

Finally, the project will deliver evidence-based recommendations to inform and catalyse policy interventions and market transformation in India's building sector. These recommendations will support the integration of embodied carbon considerations into regulatory frameworks, green certification systems, building codes, and public procurement policies. In addition, the project seeks to empower developers, architects, engineers, and policymakers by providing insights into existing scenarios, Climatic, Seismic and Typological influence on embodied carbon along with baseline numbers, helping them build a clearer understanding of current performance levels and make more informed design and project decisions. This effort will be instrumental in advancing low-carbon approaches and supporting India's transition toward a climate-resilient, resource-efficient, and net-zero buildings in India.

By establishing a robust national baseline, this study aims to position India's building sector on a credible, data-driven path to net-zero carbon, ensuring climate resilience, resource efficiency, and long-term sustainability across the construction value chain.


# EMBODIED CARBON EMISSIONS BASELINE ESTIMATION FOR BUILDINGS IN INDIA



# 1 BACKGROUND

- Introduction
- Context
- Relevance Across India's Climatic Zones
- Addressing Variability Across Building Typologies
- Objective and Scope of the Study

# 1. Background

## 1.1 Introduction

India is witnessing rapid urbanization and economic growth, with its building and construction sector playing a central role in the nation's development. As India continues to expand its infrastructure to accommodate the growing population and urban migration, the building sector is emerging as one of the largest contributors to national energy demand and greenhouse gas (GHG) emissions. According to the Global Alliance for Buildings and Construction, India's building floor area is expected to increase from 15.8 billion $m^2$ in 2015 to 57.6 billion $m^2$ by 2050—indicating that nearly 70% of the buildings required by 2050 are yet to be built. This projected growth makes it imperative to embed sustainability into the construction process, especially in the early phases when material selection and design decisions are made.

Traditionally, sustainability efforts in the buildings have focused on operational carbon—emissions resulting from energy use during building operation, such as for heating, cooling, lighting, and appliances. While reducing operational carbon remains essential, there is a growing recognition of the importance of embodied carbon—the emissions generated from the extraction, manufacture, transport, and installation of construction materials, as well as emissions from repair, renovation, and end-of-life demolition. As operational emissions reduce due to improved efficiency and renewable energy integration, embodied carbon will account for a larger share of total building-related emissions, making it a critical frontier for climate action.

## 1.2 Context

Embodied carbon is particularly significant in India due to the construction sector's heavy reliance on energy- and emission-intensive materials such as cement, steel, aluminium, glass, and fired clay bricks. Cement and steel alone are expected to rise sharply in demand—from 328 million tonnes and 99 million tonnes in 2019 to 1,360 million tonnes and 755 million tonnes respectively by 2050. These materials are deeply embedded in India's construction ecosystem, and their production contributes heavily to $CO_2$ emissions due to fossil fuel use and process emissions. Moreover, the construction industry is highly fragmented, involving a multitude of stakeholders—architects, engineers, material suppliers, contractors, and informal labour—which makes standardization, monitoring, and intervention more complex.

Another challenge is the lack of India-specific life cycle inventory (LCI) data for construction materials, making it difficult to assess the embodied emissions with accuracy. International tools and databases are not well-suited to the Indian construction context, given differences in material compositions, energy sources, manufacturing technologies, and supply chains. Thus, there is an urgent need for localized LCA tools, emission factors, and construction databases that account for regional construction practices, building types, and climatic conditions.

## 1.3 Relevance Across India's Climatic Zones

India's vast geographic expanse brings with it a diverse range of climatic conditions, which significantly influence how buildings are designed, constructed, and operated. The Bureau of Energy Efficiency (BEE) categorizes India into four primary climate zones: Hot & Dry, Warm & Humid, Composite, and Temperate. Each of these zones has distinct environmental characteristics—temperature ranges, humidity levels, solar radiation patterns, and rainfall intensities—that shape regional building practices, choice of materials, architectural responses, and ultimately the embodied carbon footprint of buildings. Understanding the nuances of these climate zones is critical for developing region-specific strategies to assess and reduce embodied carbon emissions.

### I. Hot & Dry Zone (e.g., Rajasthan, Gujarat)

Characterized by low humidity, intense solar radiation, and wide temperature fluctuations between day and night, the Hot & Dry zone requires buildings to minimize heat gain and enhance thermal mass. Traditionally, construction in this zone utilizes thick walls made of stone, adobe, or fired clay bricks that help stabilize indoor temperatures. While these high-mass materials can provide passive thermal comfort, they often carry high embodied energy, especially when sourced from distant locations or manufactured using energy-intensive processes like kiln-firing. Additionally, as modern construction shifts toward concrete and steel for structural efficiency and aesthetics, the embodied carbon in buildings has increased, moving away from climate-adapted vernacular solutions. Promoting locally sourced, low-carbon alternatives such as compressed stabilized earth blocks (CSEBs), fly ash bricks, or lime-based materials could reduce the embodied emissions without compromising thermal comfort.

### II. Warm & Humid Zone (e.g., Kerala, Coastal Maharashtra, Odisha)

This zone experiences high temperatures, high humidity, and heavy rainfall for most of the year. In response, buildings are often designed with elevated plinths, sloped roofs, shaded verandas, and large openings for ventilation. The construction materials in these regions must be durable against moisture, termites, and fungal decay. As a result, concrete, treated wood, and galvanized steel are commonly used, particularly for structural components, roofing, and finishes. However, these materials typically have high embodied carbon, particularly when they are imported or heavily processed. The humid climate also restricts the use of certain low-carbon, natural materials due to durability concerns. Consequently, the embodied emissions in this zone can be high unless alternative moisture-resistant materials—such as bamboo-based panels, polymer composites, or hybrid natural-synthetic systems—are integrated. Additionally, transportation plays a major role in embodied carbon here, as many high-performance materials are not locally manufactured and must be brought in from other parts of the country.

### III. Composite Zone (e.g., Delhi, Nagpur, Lucknow, Jaipur, Punjab)

The Composite zone represents a complex mix of climatic conditions, including hot summers, cold winters, and a monsoon season. This variability requires buildings to be adaptive and multifunctional, leading to intricate designs and increased reliance on mechanical systems for heating, ventilation, and air conditioning (HVAC). Material choices in these regions are often driven by structural needs and aesthetic preferences, resulting in a combination of reinforced concrete frames, brick infill walls, stone cladding, aluminium window systems, and glass facades. These material systems, while popular, significantly raise the embodied carbon footprint of buildings. Moreover, to achieve thermal comfort across seasons, designers often incorporate insulation materials and multi-glazed windows, which are carbon-intensive in their production. Given the diverse climate challenges, this zone is ideal for piloting climate-resilient, low-carbon material technologies and hybrid construction systems that balance embodied and operational carbon. Emphasis must also be placed on passive design elements, reuse of materials, and regional sourcing to mitigate the overall life-cycle impact.

### IV. Temperate Zone (e.g., Bengaluru)

Temperate zones in India, while relatively moderate in climatic extremes, experience comfortable temperatures throughout the year with seasonal rainfall. This climate provides an opportunity to design buildings with lower reliance on active HVAC systems, which shifts the carbon footprint focus more heavily on embodied emissions. Urban areas like Bengaluru, however, are witnessing a surge in high-rise commercial and residential developments using concrete, steel, aluminium, and glass, materials known for their high embodied energy and carbon intensity. These choices are often driven by market aesthetics, rapid construction demands, and a lack of regulatory emphasis on low-carbon materials. In temperate zones, where operational energy use is comparatively lower, embodied carbon can constitute the majority share of a building's total life-cycle emissions. Therefore, these regions offer high potential for intervention through material substitution, adaptive reuse, modular construction, and circular economy practices. Leveraging the benign climate, design strategies can prioritize natural ventilation, daylighting, and local materials, drastically reducing both embodied and operational emissions.

## 1.4 Addressing Variability Across Building Typologies

Embodied carbon emissions are intricately linked to a building's design, construction method, functional use, materials used, and life cycle patterns. In India, the construction ecosystem is marked by wide typological diversity, each with different emissions profiles, decision-making frameworks, and opportunities for low-carbon intervention. The four typologies covered in this project—Commercial (Office), Residential (Multi-storeyed Apartments), Institutional (Schools and Government Offices), and Industrial (Factories)—represent a significant share of India's buildings sector. Understanding the embodied carbon characteristics and material demands across these categories is essential for developing effective, targeted decarbonization strategies tailored to Indian conditions.

### I. Institutional Buildings (Schools and Government Offices)

Institutional buildings serve public functions and are typically constructed and managed by government departments, public sector undertakings (PSUs), or educational institutions. These buildings are usually low- to mid-rise structures and follow standardized design templates for classrooms, corridors, offices, and utility spaces. Commonly used materials include RCC, brick masonry, stone flooring, and aluminium windows, with construction guided by public works department (PWD) norms or CPWD schedules of rates (SOR).

While institutional buildings are less prone to interior refurbishments than commercial buildings, their design and material choices are often outdated, lacking integration of climate-responsive or low-carbon materials. For example, many government office buildings still use high cement content concrete, burnt clay bricks, and non-insulated fenestration, which increase both embodied and operational emissions.

However, institutional buildings offer high potential for systemic intervention, particularly because they are built at scale through centralized procurement mechanisms. By introducing embodied carbon benchmarks into government construction guidelines and promoting green public procurement, the state can create a market signal for sustainable materials. Pilot projects in green campuses, net-zero energy schools, or climate-resilient health centres can demonstrate the feasibility of low-carbon alternatives, including lime-stabilized plasters, low-carbon cement blends, recycled aggregates, and vernacular materials adapted to regional climates.

## II. Commercial Buildings (Office Spaces)

Commercial office buildings in India, particularly in urban business districts and IT parks, are among the most material- and service-intensive typologies. These buildings are generally multi-storeyed or high-rise, with reinforced concrete frames, extensive glass façades, false ceilings, partitions, flooring systems, and elevators. Interior fitouts, including HVAC systems, lighting, flooring, and furnishings, are often customized to tenant requirements and frequently renovated—leading to high recurring embodied emissions over the building's lifespan.

High-performance façades—such as double-glazed units, aluminium composite panels, and structural glazing—have high embodied carbon due to the energy-intensive manufacturing of aluminium, glass, and sealants. Likewise, centralized HVAC systems, raised flooring, and acoustic partitions add substantial embodied carbon. With commercial buildings often seeking certifications such as IGBC, there is increasing awareness of operational efficiency; however, embodied carbon is still under-addressed in these ratings.

Given their visibility and replicability in real estate portfolios, commercial office buildings are ideal candidates for early adoption of low-carbon materials, modular construction, and circular design practices. Strategies such as material reuse, designing for disassembly, and life cycle-based procurement can significantly reduce the embodied footprint without compromising occupant comfort or building performance.

## III. Residential Buildings (Multi-storeyed Apartments)

Multi-storeyed residential buildings are the most common form of urban housing in India, especially under government and private housing schemes such as PMAY (Urban), state housing boards, and private real estate developers. These buildings typically use RCC frame structures with brick or concrete block infill, plaster finishes, standardized plumbing and electrical fittings, and relatively basic interior finishes. The material composition includes cement, steel, aggregates, bricks/blocks, tiles, and paints—resulting in embodied carbon concentrated in structural and envelope elements.

These buildings are usually designed for a long operational life (40–60 years) and are often constructed at scale. Hence, small improvements in material efficiency or substitution can lead to significant carbon reductions across portfolios. However, cost pressures and tight construction timelines often lead to the use of conventional materials and construction methods, with little attention to environmental performance.

Emerging trends such as precast construction, autoclaved aerated concrete (AAC) blocks, fly ash bricks, and green cement alternatives offer pathways to reduce embodied emissions in this typology. Additionally, incorporating passive design principles—like optimal orientation, shading, and natural ventilation—can lower operational loads, allowing for lighter structural designs and further material savings.

## IV. Industrial Buildings (Factories)

Industrial buildings—including factories, processing plants, logistics warehouses, and assembly units—are among the most material- and structure-intensive types of construction. Unlike commercial or residential buildings, which balance functional and aesthetic concerns, industrial buildings are designed primarily for utility, with an emphasis on large, unobstructed spans, structural durability, and the efficient movement of equipment and goods. Their architectural design is often minimal, driven by operational requirements such as workflow efficiency, loading and unloading areas, and space for heavy machinery.

The structural systems of industrial buildings are typically composed of steel portal frames, pre-engineered building (PEB) systems, and metal decking for roofs. Floors are generally constructed using reinforced concrete slabs, engineered to support substantial live loads. Walls and roofing often incorporate metal sheeting or precast concrete panels, chosen for their ease of assembly, durability, and resistance to environmental factors. These buildings tend to have minimal interior finishes, with a focus instead on mechanical and electrical installations such as HVAC systems, exhaust units, overhead cranes, and lighting systems—all necessary to support industrial operations.

From an embodied carbon perspective, industrial buildings are highly intensive, with emissions primarily driven using cement and steel in structural elements. The widespread use of galvanized steel, roof insulation materials, and cool roof systems—intended to enhance thermal performance—adds further to the overall carbon footprint. Additionally, many factories are in special economic zones (SEZs) or industrial corridors, often situated in peri-urban or rural areas. This location factor contributes to higher emissions from the transportation of construction materials, especially for heavy and prefabricated components brought in from distant suppliers.

Efforts to decarbonize industrial building construction must begin with optimizing material selection and design. Using high-strength or recycled-content steel can reduce the total volume of material required and minimize emissions from virgin steel production. Similarly, incorporating lightweight concrete, recycled aggregates, and industrial by-products such as ground granulated blast-furnace slag (GGBS) or fly ash into the concrete mix can significantly reduce the embodied carbon of flooring and foundations. The adoption of modular construction techniques—such as prefabricated wall panels or steel frames designed for disassembly—not only improves construction efficiency but also facilitates future expansions, reuse, or material recovery at end-of-life.

As industries increasingly align with Environmental, Social, and Governance (ESG) principles, global supply chain compliance, and green manufacturing certifications, the need for embodied carbon transparency is growing. Green factory rating systems, like IGBC's Green Factory Building certification for industrial buildings, are beginning to incorporate embodied carbon indicators, encouraging manufacturers and developers to measure and manage the full life cycle emissions of their infrastructure. In this context, embodied carbon assessment and mitigation are poised to become not only environmental imperatives but also key drivers of market competitiveness, risk reduction, and brand value in the industrial sector.

## 1.5 Objective and Scope of the Study

### I. Objective

The objective of this project is to create a baseline scenario on embodied emissions for buildings across different climatic zones in India and to create a roadmap to achieving net zero buildings incorporating GHG emissions across building sector value chain

### II. Scope of the Study

#### A. Geographic and Climatic Coverage

The study spans India's four major climate zones, as defined by the Bureau of Energy Efficiency (BEE), to reflect regional construction practices, material choices, and environmental performance variations:

- Hot & Dry Zone
- Warm & Humid Zone

- Composite Zone
- Temperate/ Cold Zone

This zonal approach ensures that climate-specific building responses, material sourcing patterns, and embodied emissions are appropriately captured and addressed.

**B. Building Typologies**

The study focuses on four major building types that represent a significant portion of India's building sectors:

- Institutional Buildings (Schools and Government Offices)
- Commercial Buildings (Office Spaces)
- Residential Buildings (Multi-storeyed Apartments)
- Industrial Buildings (Factories)

Each typology will be analysed for its material composition, construction methods, and design characteristics, to evaluate how function and usage influence embodied carbon emissions.

**C. Life Cycle Stages Considered**

This study primarily focuses on assessing upfront embodied carbon emissions—that is, the greenhouse gas (GHG) emissions released before the building becomes operational. These emissions occur during the early stages of the building life cycle and are typically non-recoverable, making them critical for early intervention in climate strategies.

The key life cycle stages included in this assessment are:

- Raw Material Extraction: Emissions generated during the mining or harvesting of natural resources such as limestone, iron ore, bauxite, clay, and timber that are used in producing building materials.
- Manufacturing and Processing of Building Materials: This includes energy-intensive industrial processes like cement production, steel smelting, aluminium extrusion, brick kilning, and chemical treatments, which contribute significantly to a building's total embodied carbon.
- Transportation to the Construction Site: Emissions associated with moving raw and finished materials—often over long distances—from manufacturing facilities to building sites, using diesel-powered trucks, rail, or other freight modes.
- On-Site Construction Activities: These include the use of construction equipment, on-site mixing, welding, assembly, and energy consumption during the construction phase, along with temporary structures and formwork materials.

Together, these phases make up what is known as "upfront embodied carbon", as defined by international frameworks like the World Green Building Council and EN 15978. These emissions occur before the building is occupied and typically account for a significant proportion of total life cycle emissions, especially in low-energy or net-zero energy buildings.

While the primary focus is on upfront emissions, where data is available and relevant, the study will also extend to end-of-life considerations—including building demolition, material disposal, and potential recycling or reuse. This additional assessment aims to provide a more complete cradle-to-grave perspective, which can support circular economy thinking and inform long-term sustainability strategies in building design and regulation.

## D. Material Focus

The study will prioritize high-impact construction materials, including:

- Cement and concrete
- Steel (structural and reinforcement)
- Bricks and blocks (clay, fly ash, AAC, etc.)
- Aluminium and glass (especially in facades)
- Flooring, roofing, and insulation materials

Material emission factors (kg $CO_2$e per unit) will be compiled using national databases, manufacturer-specific Environmental Product Declarations (EPDs), and relevant international datasets where Indian data is unavailable.

## E. Quantification Approach

The study will employ Life Cycle Assessment (LCA) methodologies following international standards (e.g., ISO 14040/44, EN 15978) to quantify embodied carbon in terms of:

- Embodied Carbon Intensity (kg $CO_2e/m^2$)
- Material-wise contribution to total embodied emissions
- Comparative analysis across climate zones and typologies

Baseline data will be collected from actual construction projects, including Bills of Quantities (BoQs), architectural drawings, specifications, and interviews with developers and contractors. In the absence of full data, standard references (e.g., CPWD SoR, INDC toolkits) will be used.

## F. Policy and Market Implications

The findings will feed into:

- Recommendations for policy reforms
- Inputs for IGBC green building rating systems
- Awareness-building among developers, architects, and policymakers

# 2 MATERIALS AND METHODS

- Scope of Assessment
- Typology Selection and Case Studies
- LCA Tool and Standards
- Methodological Framework

# 2. Materials and Methods

This study is centred on the quantification and evaluation of upfront embodied carbon emissions in the Indian building sector, focusing specifically on five representative building typologies: commercial (offices), residential (multi-storeyed apartments), institutional (schools and government offices), and industrial (factories).

The environmental assessment is conducted by analysing the building structure, with an emphasis on material-related emissions generated during the product stage (A1–A3) and construction stage (A4–A5) of the life cycle. These stages represent upfront emissions, which occur prior to building occupation and are critical for early-stage decarbonization strategies.

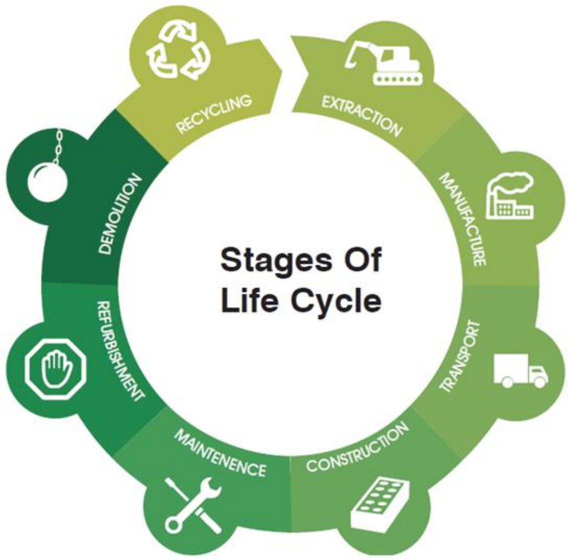



*Figure 1: Building Life Cycle*

## 2.1 Scope of Assessment

The study includes the following stages of the building life cycle as defined by the EN 15978 framework:

- **A1 (Raw Material Supply)**: Extraction and processing of raw materials (e.g., limestone for cement, iron ore for steel).
- **A2 (Transport to Manufacturing)**: Emissions from transporting raw materials to manufacturing plants.
- **A3 (Manufacturing)**: Energy and process emissions during the production of building materials.
- **A4 (Transport to Site)**: Emissions from delivering finished construction materials to the project site.
- **A5 (Construction and Installation Processes)**: On-site emissions due to equipment use, temporary works, and installation processes.

The focus remains on upfront embodied carbon, which can be directly influenced through design and procurement decisions during early project phases.

This study is centred on the quantification and evaluation of upfront embodied carbon emissions in the Indian building sector, focusing specifically on five representative building typologies: commercial (offices), residential (multi-storeyed apartments), institutional (schools and government offices), and industrial (factories). The environmental assessment is conducted by analysing the building structure, with an emphasis on material-related emissions generated during the product stage (A1–A3) and construction stage (A4–A5) of the life cycle. These stages represent upfront emissions, which occur prior to building occupation and critical for early-stage decarbonization strategies.

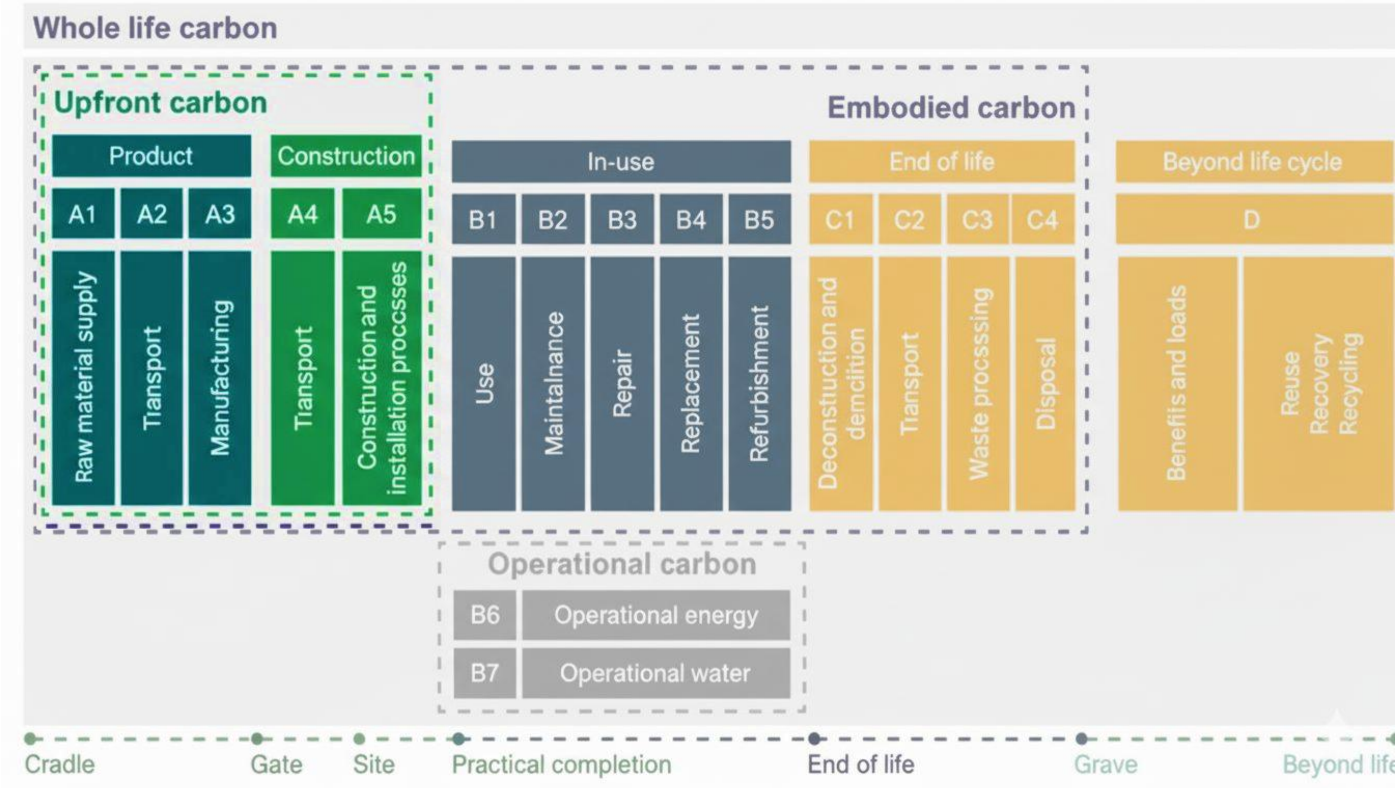



*Figure 2: Whole Life Cycle Stages*

## 2.2 Typology Selection and Case Studies

To reflect the diversity of India's building sectors, five building typologies were selected for detailed embodied carbon assessment:

- Institutional Buildings (Government Office)
- Commercial Buildings (Office Spaces)
- Residential (Multi-storeyed Apartments)
- Institutional Buildings (Schools)
- Industrial (Factory Buildings)

Case study buildings for each typology were selected across India's four major climate zones—Hot & Dry, Warm & Humid, Composite, and Temperate—to capture the regional variations in construction practices, material selection, and transportation impacts. Buildings were chosen based on data availability, representativeness, and ongoing or recently completed construction status.

## 2.3 LCA Tool and Standards

The embodied carbon assessment was conducted using One Click LCA, a globally recognized software platform for life cycle assessment in the buildings. The tool enables integration of material quantity data (BoQs) with regional and international Environmental Product Declarations (EPDs) and LCA databases to determine Global Warming Potential (GWP) values in kg $CO_2$-equivalent. data (BoQs) with regional and international Environmental Product Declarations (EPDs) and LCA databases to determine Global Warming Potential (GWP) values in kg $CO_2$-equivalent.

While One Click LCA provides a comprehensive framework for embodied carbon estimation, it presents certain limitations in isolating results specifically for life cycle stages A1–A5. As a result, the material-wise split of embodied carbon has been represented using the whole life carbon values based on generic assumptions applied by One Click LCA for stages B and C. This approach ensures consistency and completeness in interpreting material-level impacts while acknowledging the tool's stage-specific data extraction constraints.

The study methodology complies with the following internationally accepted **LCA standards and frameworks**:

- ISO 14040 and ISO 14044: Life Cycle Assessment – Principles, Framework, and Requirements
- ISO 21930:2017: Environmental Declaration of Building Products
- ISO 21931:2010: Environmental Performance of Buildings – Framework for Methods of Assessment
- EN 15804:2012: Core Rules for the Product Category of Construction Products
- EN 15978:2011: Assessment of Environmental Performance of Buildings – Calculation Method

These standards ensure methodological consistency, transparency, and comparability of the results across different building projects and regions.

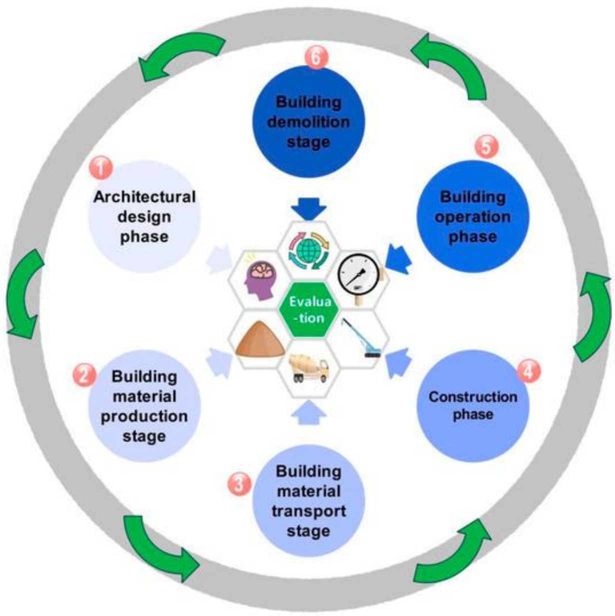



*Figure 3: Life Cycle Assessment Process*

## 2.4 Methodological Framework

The overall methodology consists of three main steps:

### I. Data Collection

Data was collected from architectural and structural drawings, detailed Bills of Quantities (BoQs), construction specifications, and stakeholder interviews (architects, contractors, and developers). The data focused on structural elements—such as foundations, columns, beams, slabs, and load-bearing walls—which are responsible for the majority of upfront embodied emissions. Data related to site-specific transportation modes and distances for key materials (cement, steel, aggregates, blocks, etc.) was also recorded.

Building information collected which included:

- Area
- Occupancy
- No. of floors
- Use and location
- Primary structural system

## II. Data Mapping

All collected material quantities were mapped to corresponding materials and components in the One Click LCA database. Where possible, Indian EPDs and region-specific datasets were used. In the absence of local data, internationally accepted generic datasets were adopted, ensuring transparency in assumptions and emission factors. Construction processes (A5) were modelled using One Click LCA's built-in construction phase modules and adjusted where local practices deviated from global averages.

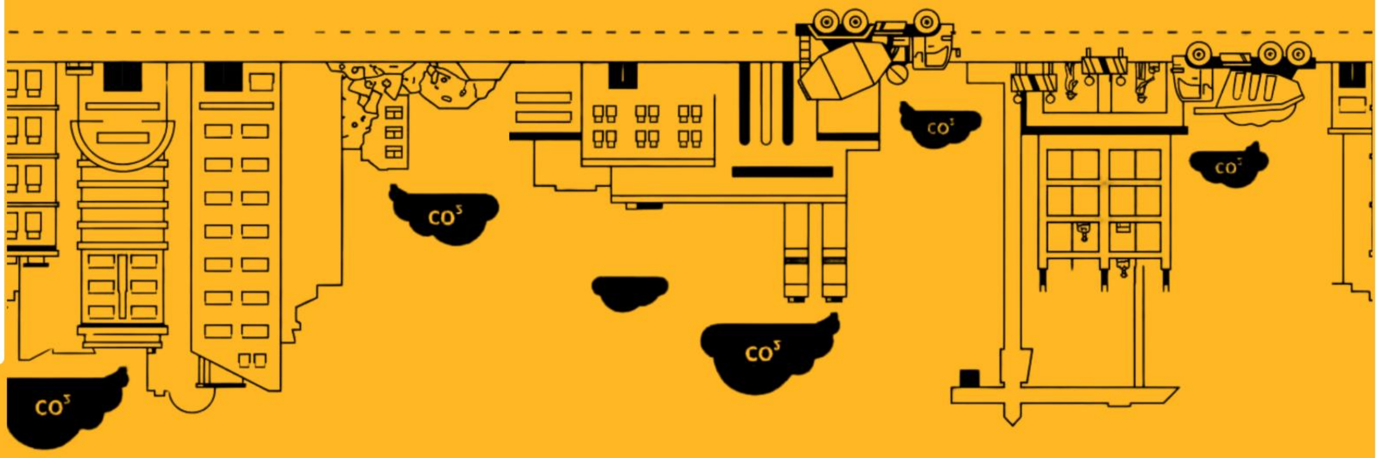
## III. Data Analysis

Each building typology was assessed separately to determine the upfront embodied carbon intensity, expressed as:

- Total kg $CO_2$e per building
- kg $CO_2$e per square meter of gross floor area (GFA)

Comparative analysis was conducted across typologies and climate zones to identify material hotspots, typology-specific emission trends, and regional differences in embodied carbon performance. The findings also helped identify low-carbon alternatives and potential policy interventions based on lifecycle emissions data.


# EMBODIED CARBON EMISSIONS BASELINE ESTIMATION FOR BUILDINGS IN INDIA



# 3 BASELINING EMBODIED CARBON EMISSIONS

- Introduction to Baselining
- Embodied Carbon Baselining
- Challenges in Baselining
- Applications

# 3. Baselining Embodied Carbon Emissions

## 3.1 Introduction to Baselining

Establishing a baseline for embodied carbon emissions is the foundational step in enabling data-driven decision-making and climate action in the building sector. A carbon baseline refers to a quantitative estimate of the current level of greenhouse gas (GHG) emissions, expressed in terms of $CO_2$-equivalents, associated with a defined set of construction activities, materials, or building typologies. It acts as a reference point against which future reduction efforts can be measured, monitored, and verified. In the context of embodied carbon, the baseline includes emissions generated during the production, transportation, and construction of building materials and components—often referred to as upfront emissions (A1–A5 stages).

Given the diversity of building practices, materials, and climatic conditions in India, developing a robust baseline is essential for establishing national and regional decarbonization targets, updating building codes, informing policy frameworks, and enabling carbon benchmarking across building types.

The primary objectives of embodied carbon baselining in this study are:

- To quantify the current levels of embodied carbon emissions across major building typologies.
- To identify material-level and process-level hotspots responsible for the majority of emissions.
- To enable comparability between buildings across typologies and climate zones.
- To support the development of emission benchmarks and thresholds for green building standards and public procurement.

## 3.2 Embodied Carbon Baselining

The accurate baselining of carbon emissions, particularly embodied carbon, is critical for understanding the environmental impact of buildings and identifying high-impact intervention points across their life cycle.

This section presents a structured approach to baselining through two key components:

(1) material selection and construction techniques,

(2) life cycle carbon footprint assessment.

Each component plays a distinct yet interconnected role in quantifying and understanding upfront embodied emissions and informing low-carbon strategies for the Indian building sector.

### I. Material Selection and Construction Techniques

The type, quantity, and source of materials used in construction form the core of any embodied carbon baseline. In the Indian context, the construction sector is heavily reliant on high-carbon, resource-intensive materials, such as ordinary Portland cement (OPC), reinforcement steel, burnt clay bricks, and concrete blocks. The embodied emissions from these materials are driven by both the energy consumed in production and the chemical processes involved, particularly in cement and steel manufacturing.

## II. Key Emission-Intensive Materials:

- Cement and Concrete: Cement production, especially clinker formation, is highly carbon intensive. Cement contributes to nearly 50–60% of the total embodied carbon in most Indian buildings.
- Steel: Reinforcement steel and structural steel are widely used in multi-storey buildings and industrial sheds. Emissions are associated with smelting, rolling, and transportation.
- Bricks and Blocks: Burnt clay bricks, still widely used across India, are produced in inefficient kilns using coal and biomass fuels. Alternatives like AAC blocks and fly ash bricks can offer lower embodied carbon.
- Glass and Aluminium: Common in commercial buildings, these materials have high embodied energy due to complex processing and often long transportation routes.
- Finishing Materials: While finishes contributing a smaller share per unit, the cumulative impact from paints, false ceilings, tiles, and woodwork is significant, particularly in commercial and institutional buildings.

## III. Construction Techniques and Carbon Impact:

- Cast-in-situ RCC vs. Precast Systems: In-situ casting consumes more materials and generates higher wastage, while precast systems offer better quality control and reduced material overuse.
- Load-Bearing vs. Framed Structures: Load-bearing masonry (common in low-rise buildings) often uses more bricks but less steel, while framed structures increase steel and concrete use.
- Manual vs. Mechanized Construction: Mechanization can reduce time and labour but may increase equipment-related emissions unless sourced from low-carbon energy.

Understanding these material choices and techniques is essential for establishing emission baselines, as they directly influence material quantities, construction efficiency, and waste generation on-site.

## IV. Life Cycle Carbon Footprint Assessment

Once material data and supply chain inputs are compiled, the final stage of baselining involves calculating the life cycle carbon footprint, focusing on upfront embodied carbon—i.e., emissions that occur before the building is occupied. This is done by mapping material quantities and activities to their corresponding Global Warming Potential (GWP) values using Life Cycle Assessment (LCA) tools such as One Click LCA.

## V. Life Cycle Stages Considered (A1–A5)

- **A1**: Raw material extraction and processing (e.g., mining limestone, smelting iron).
- **A2**: Transport of raw materials to manufacturers.
- **A3**: Manufacturing of construction materials (e.g., cement grinding, brick firing).
- **A4**: Transport of finished products to construction sites.

- **A5**: On-site construction activities including energy use, temporary works, formwork, and waste management.

Together, these stages represent the upfront embodied carbon, typically expressed in:

- Total kg $CO_2e$ per building
- kg $CO_2e/m^2$ of Gross Floor Area (GFA)

## 3.3 Challenges in Baselining

Several challenges were encountered during the baselining process:

- Data Availability: Difficulty in obtaining complete BoQs and consistent documentation across projects.
- Lack of Indian EPDs: Reliance on generic or international emission factors due to limited India-specific EPDs.
- Uncertainties in A4 and A5: Transportation distances and on-site energy use vary significantly and are often underreported.
- Material Variability: Regional differences in cement types, steel grades, and brick varieties create inconsistencies in carbon calculations.
- Limited India-Specific EPDs: Heavy reliance on global or generic emission factors due to lack of localized Environmental Product Declarations.
- Lack of Standardized Methodology: Absence of national LCA databases and harmonized assessment frameworks reduces comparability across projects.
- Limited Technical Capacity: Insufficient expertise and training among practitioners in LCA tools and embodied carbon assessment methods.
- Low Industry Transparency: Manufacturers' reluctance to disclose process-level emission data restricts accurate baseline development.

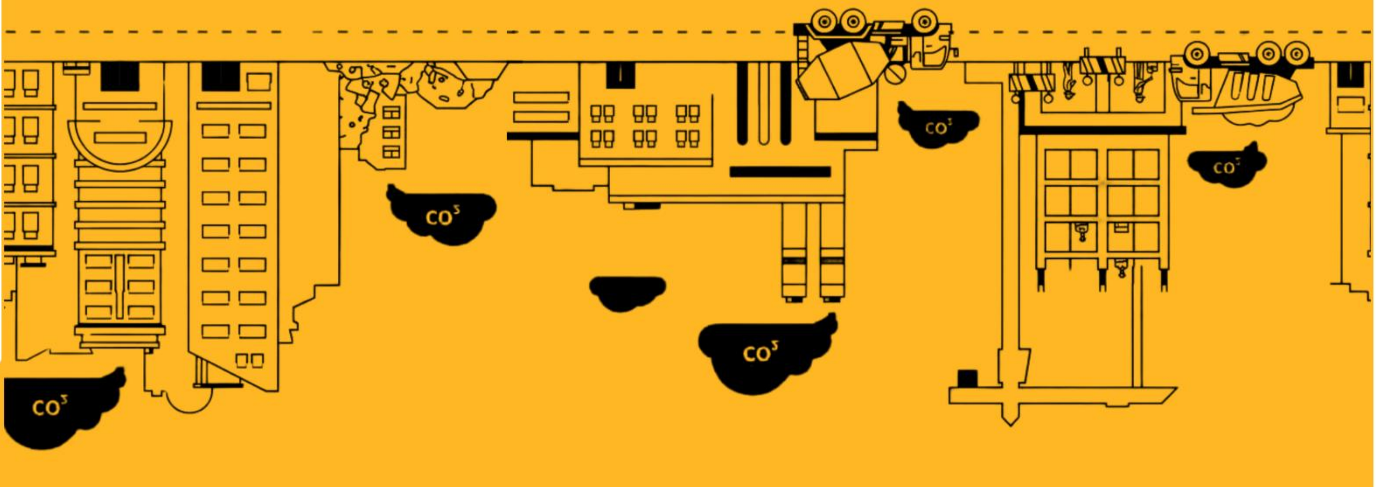
## 3.4 Applications

The established embodied carbon baselines can be used to:

- Benchmark new building projects for green certification, performance improvement, or regulatory compliance.
- Set carbon intensity thresholds within national and sub-national building codes and standards.
- Guide procurement policies by promoting low-carbon materials, technologies, and suppliers.
- Support embodied carbon disclosure requirements in ESG reporting, green finance, and climate risk assessments.
- Track progress toward national decarbonization goals, providing measurable indicators for policy implementation.

- Enable comparative analysis across building typologies, regions, or construction systems to identify best practices.
- Facilitate carbon pricing and offset mechanisms, providing credible baselines for carbon accounting and credit generation.
- Enhance supply chain transparency, allowing material manufacturers to benchmark and reduce their own embodied impacts.
- Support research and development, by creating datasets that drive innovation in low-carbon materials and construction methods.


# EMBODIED CARBON EMISSIONS BASELINE ESTIMATION FOR BUILDINGS IN INDIA



# 4 CASE STUDY : SELECTED BUILDINGS

## Building Typologies Across India's Climate Zones

- Temperate /Cold Climate
- Composite Climate
- Warm and Humid Climate
- Hot and Dry Climate

## Comparative Analysis of Baseline Emissions

- Climate zone-wise
- Seismic zone-wise
- Typology-wise

# 4. Case Study- Selected buildings

India's vast geographical spread encompasses diverse climatic conditions, which significantly influence building design, construction techniques, and material selection. Consequently, the embodied carbon emissions of buildings are not uniform across the country—they vary by both climate zone and building typology. Understanding this dual variability is essential for accurately assessing carbon footprints and designing targeted mitigation strategies.

This chapter presents an analysis of carbon intensity trends across 20 buildings situated in four distinct climatic zones of India: Composite, Hot & Dry, Temperate, and Warm & Humid. Each zone is represented by five buildings, offering a balanced cross-section for comparison. The buildings span seven states and one union territory, with notable representation from Maharashtra and Karnataka in the Warm & Humid and Temperate zones, respectively. Composite climate buildings are primarily located in Punjab, Madhya Pradesh, and Chandigarh, while Hot & Dry zones include projects from Gujarat and Rajasthan. This geographic and climatic spread provides valuable insights into how regional climate and construction practices influence whole life carbon emissions.

The figure below depicts the map of all climatic zones in India and highlights the number of buildings considered from each state in the sample.

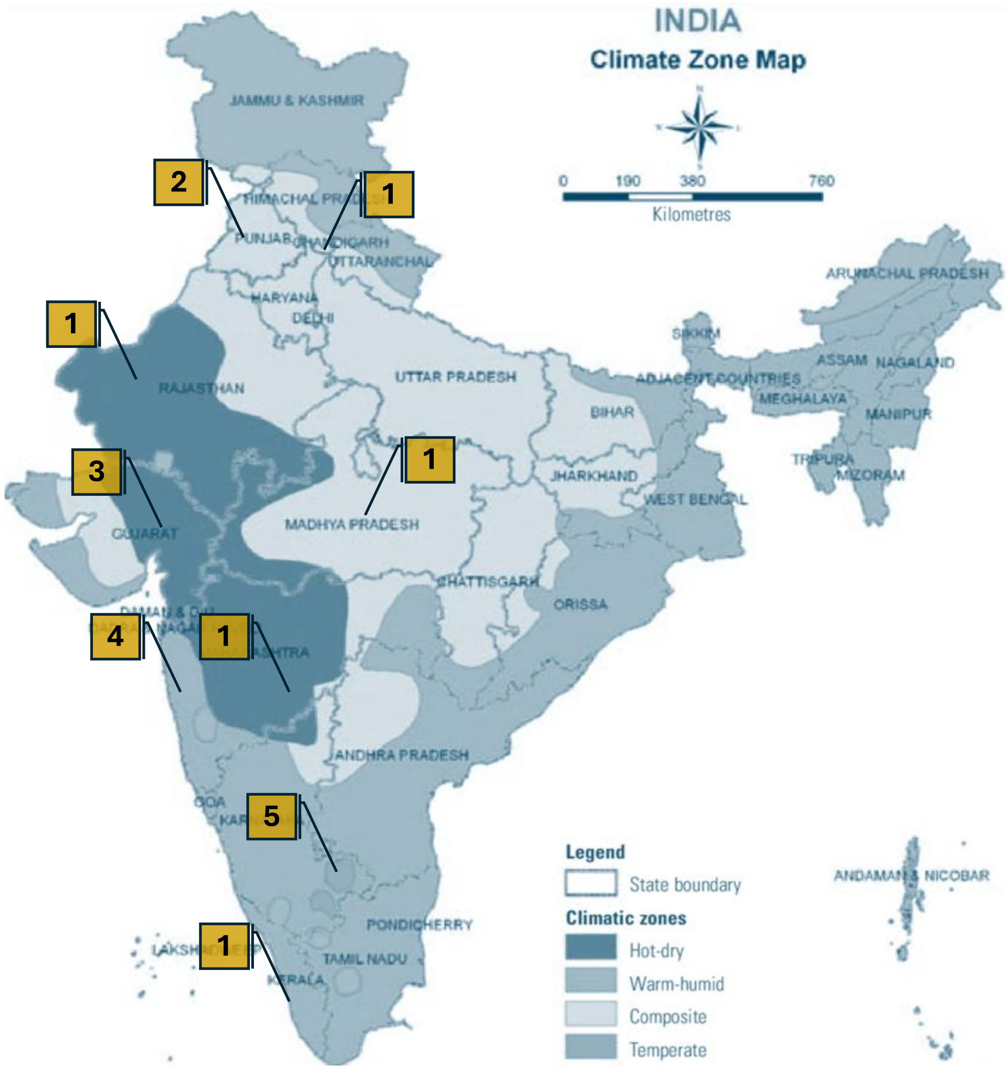



*Figure 4:Climate Zone Map*

## Selected Building Typologies Across India's Climate Zones

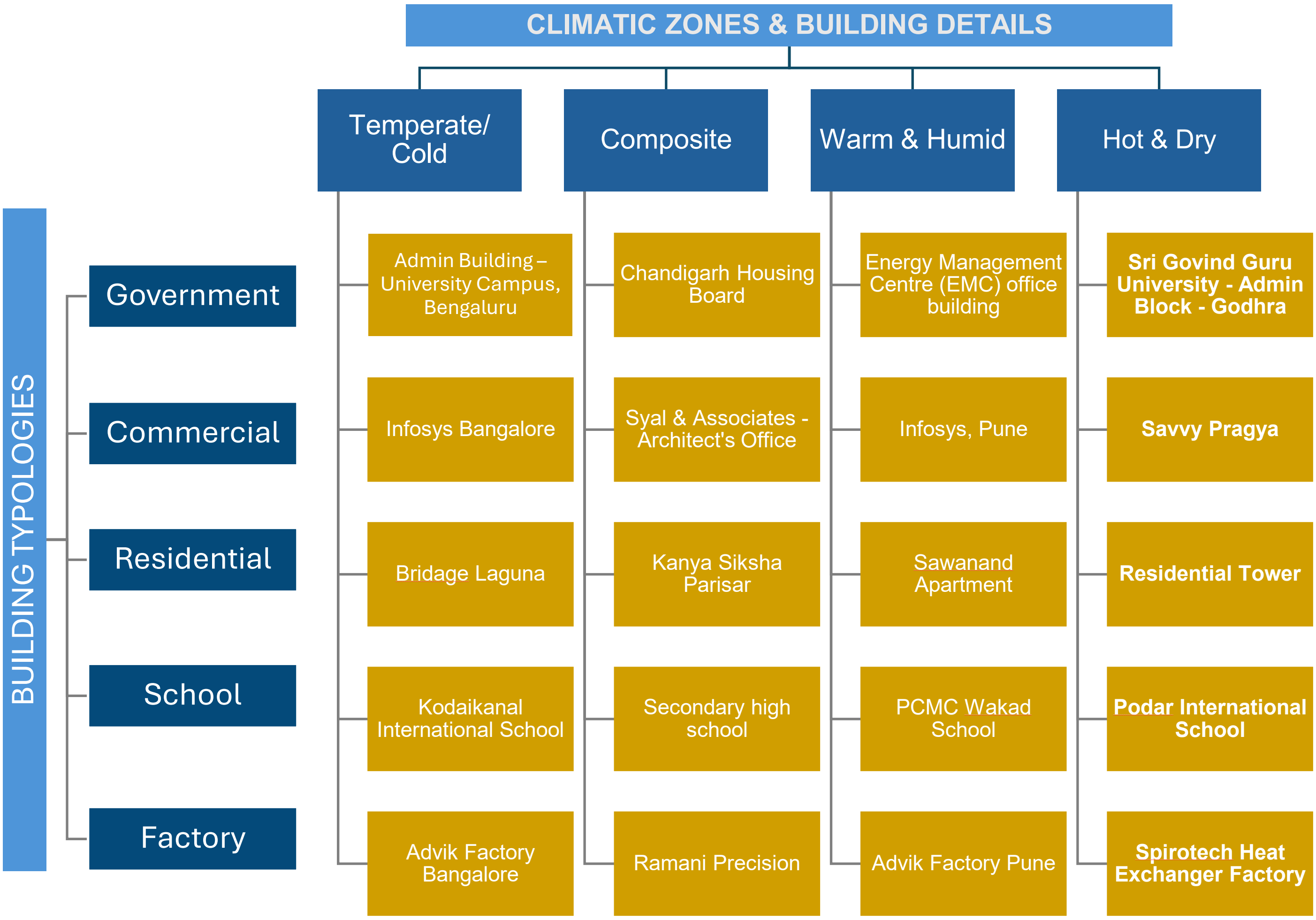



*Figure 5:Climate Zone and Building Details flowchart*

## 4.1 Embodied carbon in Selected Buildings

### I. Temperate/Cold Climate

#### A. Institutional Building (Government Office) – Admin building, University campus

##### Overview

The Admin Office Building is a G+1 government facility located in Bengaluru, Karnataka. Situated in a temperate climate and Seismic Zone II, the building follows conventional RCC construction practices with a mix of masonry infill and façade glazing. The structure spans a modest built-up area of 1,690 m², and the scope of the upfront life carbon assessment covers A1–A3 (product stage), A4 (transport), and A5 (construction) stages.

| Parameter | Details |
|---|---|
| **Name of the project** | Admin Building – University Campus |
| **Building Typology** | Institutional Building- Government office |
| **Total Number of Floors** | G+1 |
| **Built-up Area (m²)** | 1,690.00 |
| **LCA Stages Included** | A1–A3, A4, A5 |
| **Climate** | Temperate |
| **Seismic Zone** | II |

## Results

The total upfront embodied carbon for the Admin Office Building is 967,965 kg$CO_2$e, corresponding to 573 kg$CO_2$e/m². The manufacturing and extraction stages (A1–A3) dominate the emissions profile at 841,709 kg$CO_2$e or 499 kg$CO_2$e/m² (87%), while transportation of materials (A4) and construction processes (A5) contribute 21 kg$CO_2$e/m² (4%) and 54 kg$CO_2$e/m² (9%), respectively. This distribution reflects a front-loaded carbon profile typical of concrete-intensive government office buildings.

At the material level, the top five contributors are ready-mix concrete for foundations and internal walls (183 kg$CO_2$e/m², 15%), common clay bricks (159 kg$CO_2$e/m², 13%), concrete admixtures (157 kg$CO_2$e/m², 13%), glass façades and glazing (157 kg$CO_2$e/m², 13%), and reinforcement steel (rebar) (154 kg$CO_2$e/m², 12%). These materials together account for the majority of emissions, while other materials, including timber (96 kg$CO_2$e/m²), cement (79 kg$CO_2$e/m²), paints and coatings (69 kg$CO_2$e/m²), and aluminium (44 kg$CO_2$e/m²), contribute meaningfully to the overall footprint.

From a structural element perspective, foundations are the largest contributor at 368 kg$CO_2$e/m² (30%), followed by the load-bearing frame (329 kg$CO_2$e/m², 27%), external walls (257 kg$CO_2$e/m², 21%), and floor coverings and finishes (196 kg$CO_2$e/m², 16%). Façade openings, internal partitions, ground floor slab, and fittings contribute smaller shares, collectively reflecting the combined impact of substructure, structural frame, and conventional finishes.

## Inferences

The lifecycle stage distribution confirms that A1–A3 manufacturing stages dominate, contributing 87% of total embodied carbon. Transportation and construction processes have limited impact, underscoring the importance of low-carbon material selection and efficient design in early project stages.

**Distribution of Embodied Carbon in A1 to A5 Life cycle stages**

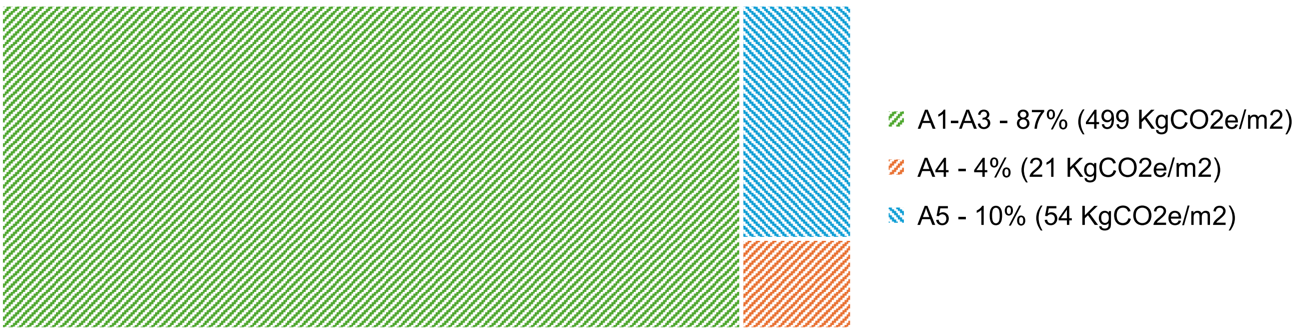



*Figure 6: Distribution of Embodied Carbon in A1 to A5 Life cycle stages, Admin Building, Bengaluru*

Structurally, the foundations and load-bearing frame together account for 697 kg$CO_2$e/m² (57%), highlighting the influence of substructure and primary structural systems on the building's carbon footprint. External walls and floor finishes further contribute 453 $kgCO_2e/m^2$ (37%), indicating the significance of enclosure and interior finishes in medium-rise government office buildings.

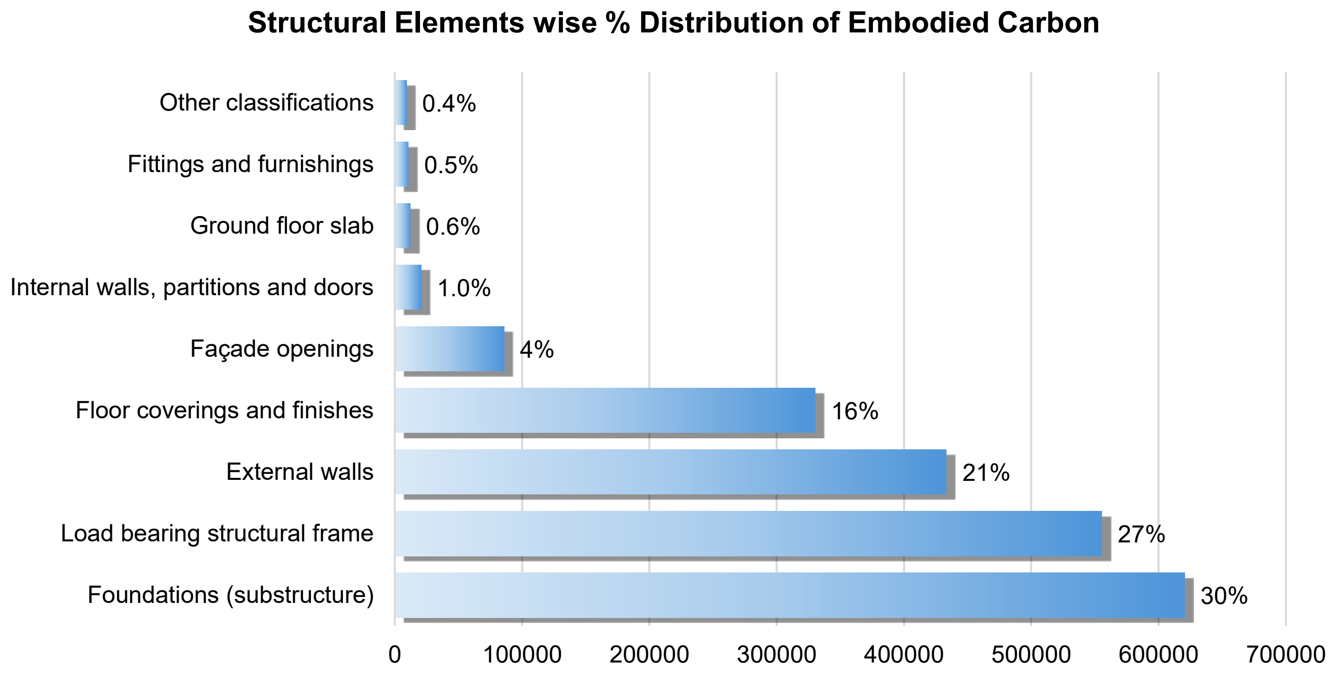



*Figure 7 Structural Elements wise % distribution of total Embodied Carbon, Admin Building, Bengaluru*

At the material level, the five highest contributors—ready-mix concrete, clay bricks, admixtures, glazing, and rebar—collectively form the bulk of embodied carbon (770 $kgCO_2e/m^2$, 67%). Opportunities for carbon reduction include low-carbon concrete formulations, alternative masonry units (e.g., AAC blocks), high-recycled content steel, and optimisation of façade and finish materials, particularly in foundational and substructural elements.

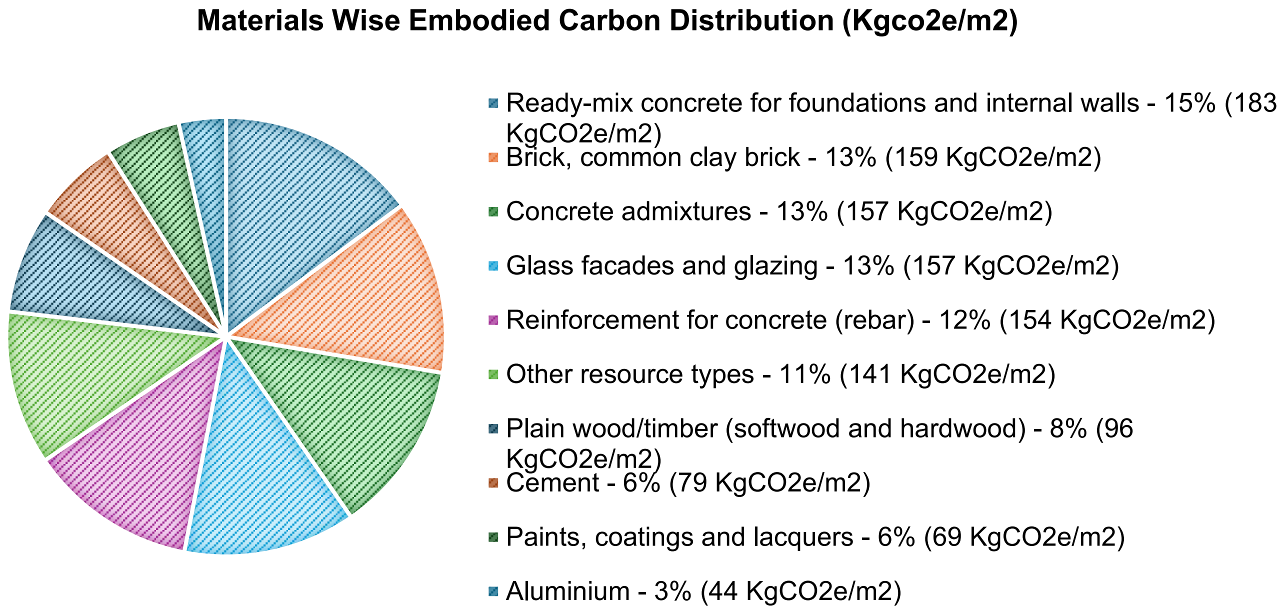



*Figure 8: Materials Wise Embodied Carbon Distribution (Kgco2e/m2), Admin Building, Bengaluru*

## B. Commercial Building (Office) – Infosys, Bengaluru

### Overview

Infosys Bengaluru is a large commercial office building located in Seismic Zone II with a temperate climate profile. The structure comprises a basement and five floors, with a total built-up area of 357,784 m². The assessment includes lifecycle stages A1–A3 (product stage), A4 (transport), and A5 (construction-installation). Given its typology, scale, and design features, the building represents a high-intensity commercial facility with extensive façade treatments and specialized structural requirements.

| Parameter | Details |
|---|---|
| **Name of the project** | Infosys Bengaluru |
| **Building Typology** | Commercial Office |
| **Total Number of Floors** | Basement + 5 |
| **Built-up Area (m²)** | 357,784 |
| **LCA Stages Included** | A1–A3, A4, A5 |
| **Climate** | Temperate |
| **Seismic Zone** | II |

### Results

The total whole life upfront carbon emissions for the Infosys Bengaluru project are 150,192,674.6 kg $CO_2e$, equating to 420 kg $CO_2e/m^2$. The embodied emissions are heavily dominated by the product stage (A1–A3), contributing 93% (392 kg $CO_2e/m^2$) kgc2of total emissions. Construction-stage emissions (A5) account for 6% (26 kg $CO_2e/m^2$), while transport (A4) contributes only 1% (4 kg $CO_2e/m^2$). The building's material profile is primarily characterized by a high use of aluminium and coated glass, with aluminium alone contributing 43% (266 kg $CO_2e/m^2$) and coated glass 39% (241 kg $CO_2e/m^2$) of the total emissions. Structural concrete and reinforcement contribute more modestly, at 4% (25 kg $CO_2e/m^2$) and 3% (22 kg $CO_2e/m^2$) respectively. In terms of building elements, façade openings—comprising glazed and aluminium components—contribute a disproportionate 85% (522 kg $CO_2e/m^2$) of total impact, underscoring the significant embodied emissions associated with the façade design.

### Inferences

The embodied carbon emissions are overwhelmingly concentrated in the product stage (A1–A3), which contributes 93% of total emissions. This suggests that emissions are front-loaded into the building's material sourcing and manufacturing phase, a typical trend for high-specification commercial buildings with specialized materials. Site transport (A4) and construction installation (A5) have marginal contributions in comparison.

**Distribution of Embodied Carbon in A1 to A5 Life cycle stages**

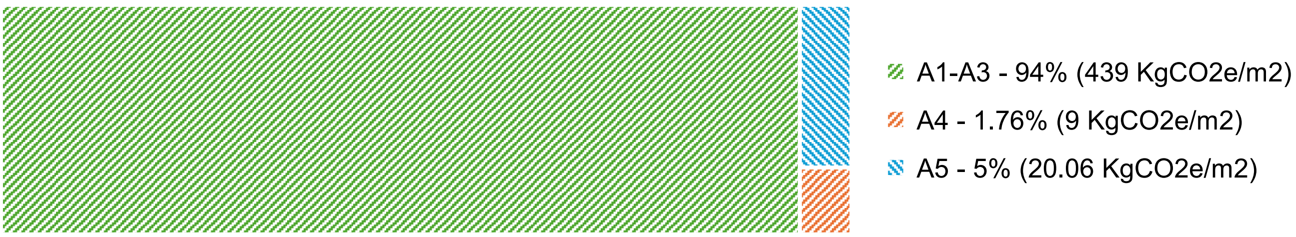



*Figure 9 Distribution of Embodied Carbon in A1 to A5 Life cycle stages, Infosys Bengaluru*

From a structural perspective, the façade openings are the single largest contributors to overall carbon impact, accounting for 85% of emissions due to the extensive use of aluminium and coated glass. In contrast, traditional structural elements such as the frame (4%) and foundations (3%) have relatively low contributions, likely owing to material optimization and the design emphasis on vertical rather than horizontal expansion.

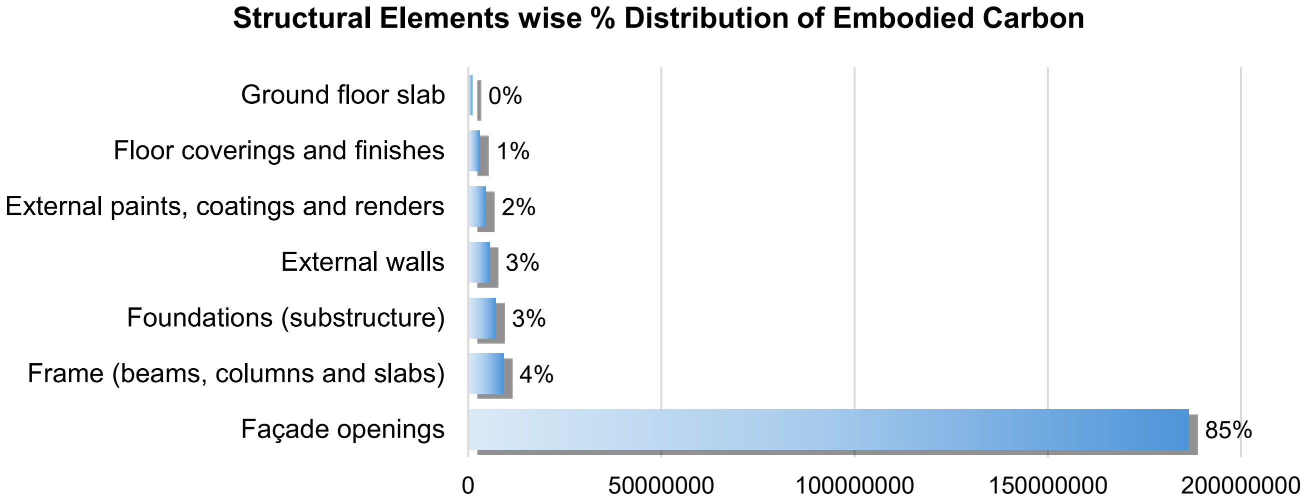



*Figure 10 Structural Elements wise % distribution of total Embodied Carbon, Infosys Bengaluru*

The five most impactful material categories are: aluminium (43%), coated glass panes (39%), ready-mix concrete for structures (4%), reinforcement (3%), and paints and coatings (2%). These materials alone account for over 90% of total material emissions, highlighting the importance of façade material selection in future low-carbon design strategies for commercial buildings.

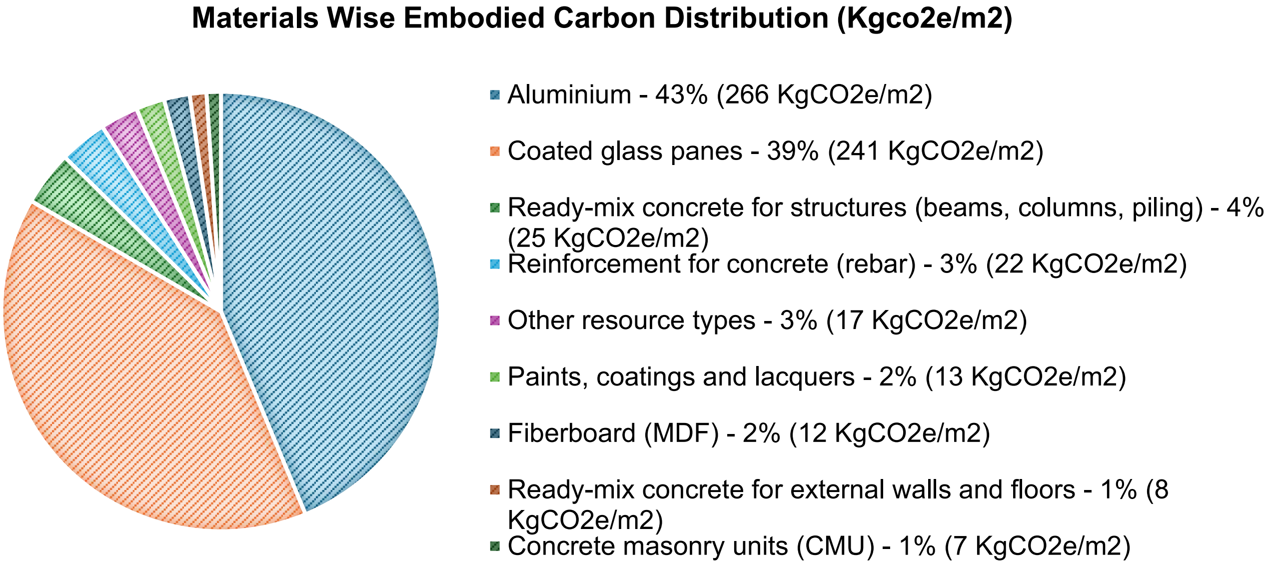



*Figure 11 Materials Wise Embodied Carbon Distribution (Kgco2e/m2) , Infosys Bengaluru*

## C. Residential Building – Brigade Laguna, Bengaluru

### Overview

Brigade Laguna is a multi-tower residential complex situated in the temperate climate zone of Bengaluru. Comprising four towers, each with 14 floors above ground and two basement levels, the project spans a total built-up area of 32,470 m². The building follows a conventional RCC construction system and accommodates a mix of apartment units designed for urban living. The project's location in Seismic Zone II implies relatively low structural demand from seismic events, enabling a standard structural design.

| Parameter | Details |
|---|---|
| **Name of the project** | Brigade Laguna |
| **Building Typology** | Residential |
| **Total Number of Floors** | 2B+G+14 (4 towers) |
| **Built-up Area (m²)** | 32,470.00 |
| **LCA Stages Included** | A1–A3, A4, A5 |
| **Climate** | Temperate |
| **Seismic Zone** | II |

### Results

The upfront embodied carbon for Brigade Laguna is 16,842,296 $kgCO_2e$, corresponding to an intensity of 519 $kgCO_2e/m^2$. The majority of emissions occur in the manufacturing stages (A1–A3), which contribute 91% or 475 $kgCO_2e/m^2$. Transportation to site (A4) adds 4% or 20 $kgCO_2e/m^2$, while construction activities (A5) contribute 5% or 25 $kgCO_2e/m^2$. This stage-wise distribution demonstrates that material production overwhelmingly dominates the project's embodied carbon footprint, with transport and onsite activities playing relatively minor roles.

At the material level, the largest contributor is reinforcement steel, responsible for 29% (173 $kgCO_2e/m^2$) of total emissions. This is followed by ready-mix concrete for external walls and floors at 26% (151 $kgCO_2e/m^2$), cement at 15% (87 $kgCO_2e/m^2$), wall and floor tiles at 7% (44 $kgCO_2e/m^2$), and ready-mix concrete for foundations and internal walls at 7% (39 $kgCO_2e/m^2$). Secondary contributors include CMU (6%), plastic membranes (3%), and sand, soil, and gravel (3%). Together, the top five materials account for over 80% of the project's embodied carbon, underlining the concentrated impact of concrete and steel.

From a structural perspective, the load-bearing structural frame is the single largest contributor, with 33% (194 $kgCO_2e/m^2$) of emissions. This is followed by the foundations at 26% (152 $kgCO_2e/m^2$) and floor coverings and finishes at 22% (129 $kgCO_2e/m^2$). External walls contribute 15% (91 $kgCO_2e/m^2$), while other categories such as external coatings (3%), façade openings (2 $kgCO_2e/m^2$), and stairs, ramps, and weatherproofing (<1%) provide only marginal additions.

### Inferences

The lifecycle stage distribution highlights that A1–A3 manufacturing alone accounts for 91% of upfront carbon, consistent with the emission profile of high-rise RCC residential buildings in temperate climates. Transport and construction activities together represent just 9% (45 $kgCO_2e/m^2$), confirming that decarbonisation opportunities lie predominantly in material production rather than logistics or site-level interventions.

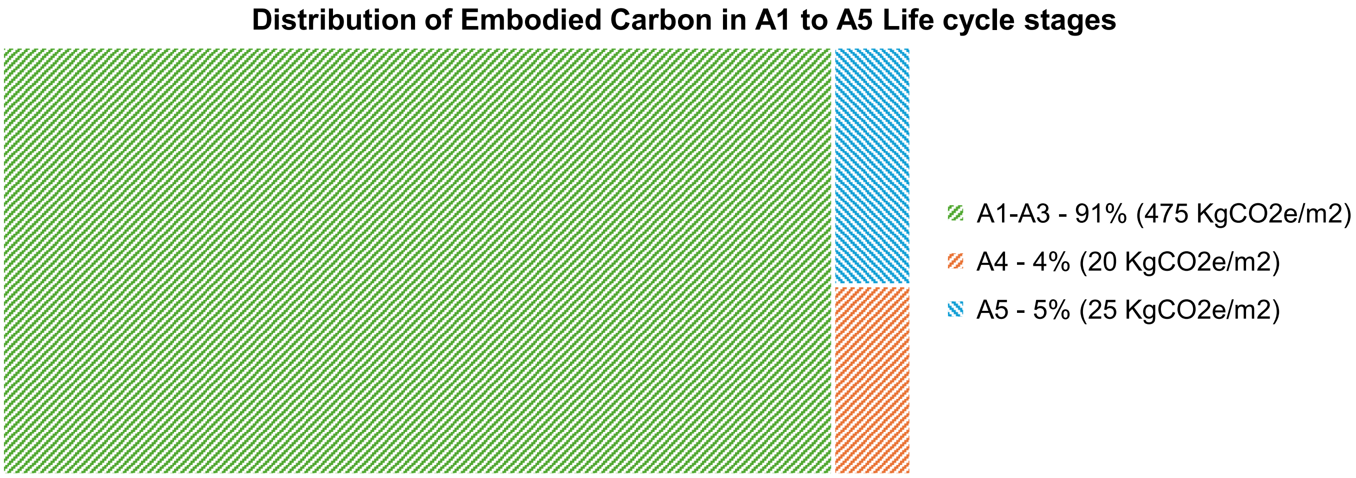



*Figure 12 Materials Wise Embodied Carbon Distribution (Kgco2e/m2), Brigade Laguna*

Structurally, the frame and foundations together account for 346 kg$CO_2$e/m² (59%), forming the bulk of the project's carbon footprint. The floor coverings and finishes (129 kg$CO_2$e/m², 22%) and external walls (91 kg$CO_2$e/m², 15%) add further substantial contributions, driven by extensive surface areas across the multi-tower development. Smaller structural categories contribute less than 5% in total, underscoring the dominance of the core RCC systems in shaping emissions.

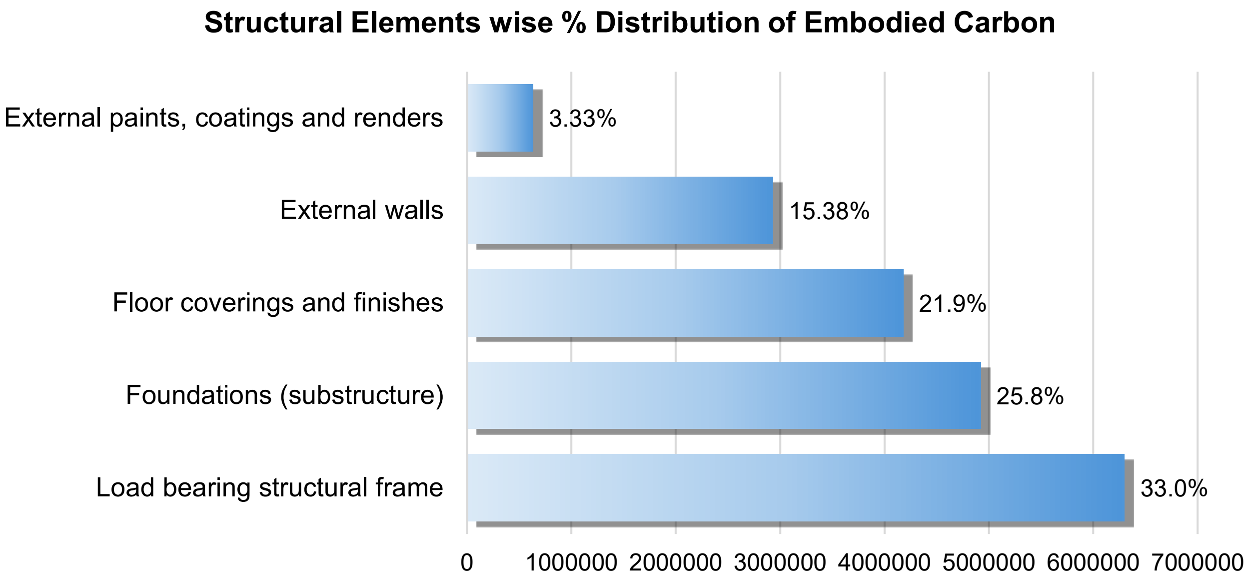



*Figure 13 Structural Elements wise % distribution of total Embodied Carbon, Brigade Laguna*

At the material level, the results show a steel–concrete dominance, with reinforcement steel, ready-mix concrete, and cement together contributing nearly 70% of the total embodied carbon. Tiles and CMU add further weight but remain secondary in impact. Notably, the reliance on conventional RCC and masonry systems drives high intensities. Future mitigation strategies should focus on optimising concrete mix designs, reducing clinker in cement, and increasing recycled content in reinforcement steel to achieve meaningful reductions in embodied carbon for similar high-rise residential projects.

Materials Wise Embodied Carbon Distribution (Kgco2e/m2)

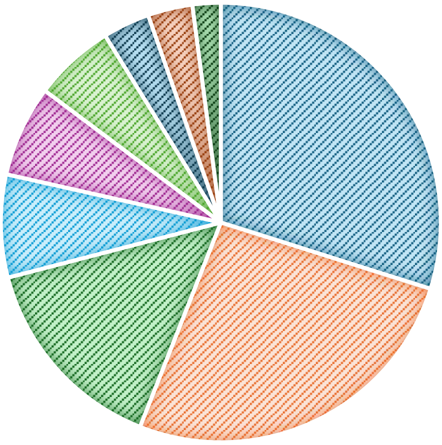



*Figure 14 Materials Wise Embodied Carbon Distribution (Kgco2e/m2), Brigade Laguna*

## D. Institutional Building (School) – Kodaikanal International School, Kodaikanal, Tamil Nadu

### Overview

The project is a G+1 educational facility located in Tamil Nadu, designed to accommodate school functions within a compact footprint of 3,234 m². Located in a Cold climate and a low seismic zone, the building adheres to standard construction practices without the need for significant seismic reinforcements. The LCA covers all pre-operational stages—product, transport to site, and construction—providing a complete picture of the embodied carbon profile at handover.

This structure features typical school building components, such as reinforced concrete framing and extensive floor finishes, likely tailored to heavy foot traffic and institutional durability. The material choices reflect both performance and aesthetic requirements associated with educational spaces.

| Parameter | Details |
|---|---|
| **Name of the project** | Kodaikanal International School |
| **Building Typology** | School |
| **Total Number of Floors** | G+1 |
| **Built-up Area (m²)** | 3,234 |
| **LCA Stages Included** | A1–A3, A4, A5 |
| **Climate** | Cold |
| **Seismic Zone** | III |

### Results

The total Whole Life upfront Carbon Assessment for the school project stands at 1,511,136.68 $KgCO_2e$ /m², translating to 468 $KgCO_2e$ /m². The dominant contributor is the product stage (A1–A3), accounting for 94% of total emissions. Construction stage (A5) adds a further 4%, while transportation (A4) contributes a marginal 2%. This distribution pattern suggests that material production processes overwhelmingly shape the project's carbon footprint, consistent with trends observed in institutional projects of this scale.

Among material categories, cement and structural steel are the largest contributors, jointly responsible for over 80% of emissions—cement at 287 $KgCO_2e$ /m² and structural steel at 223 $KgCO_2e$ /m². These values suggest heavy use of reinforced concrete, possibly due to slab-intensive design. Floor and wall tiles, coatings, and rebar also contribute moderately, highlighting the layered nature of interior finishes common in educational facilities. Finishing materials such as paints and tiles together add nearly 81 $KgCO_2e$ /m², a non-trivial fraction considering the scale.

In terms of structural breakdown, the ground floor slab is the single highest emitter at 223 $KgCO_2e$ /m², reflecting a dense material volume at the base level. Floor finishes follow closely, suggesting extensive use of tiling or protective surface treatments across circulation areas. Foundations, coatings, and the load-bearing frame each contribute incrementally, reinforcing that both structural mass and interior specifications play key roles in defining the total embodied impact.

## Inferences

The life cycle stage analysis reveals a highly product-driven carbon profile, with 94% of emissions arising from the manufacturing and procurement of materials. This highlights the importance of early-stage design choices, especially those related to concrete and steel use, in managing carbon impacts. Limited influence from transportation and construction phases indicates relatively localized sourcing or efficient logistics in the supply chain.

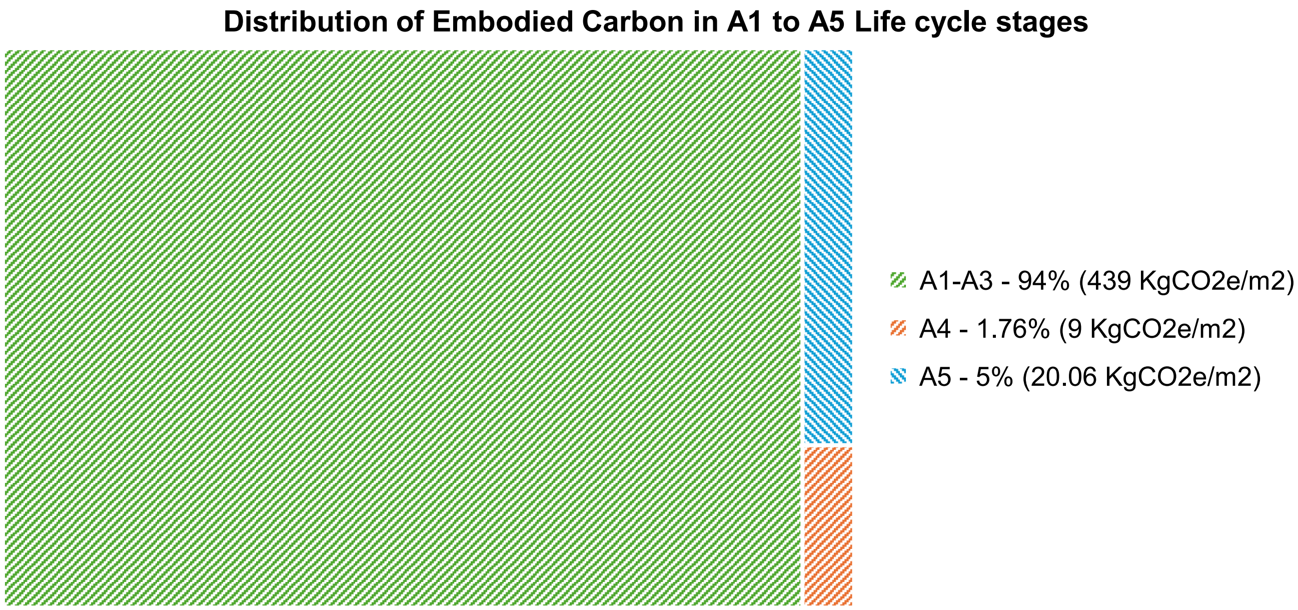



*Figure 15 Distribution of Embodied Carbon in A1 to A5 Life cycle stages, International School.*

From a structural perspective, the dominance of emissions from the ground floor slab and floor finishes points to a material-intensive approach at the horizontal plane. These areas likely required high durability and finish standards suited for school use. Foundations also contribute significantly, suggesting moderate excavation and substructure depth, potentially influenced by soil conditions or service integration requirements.

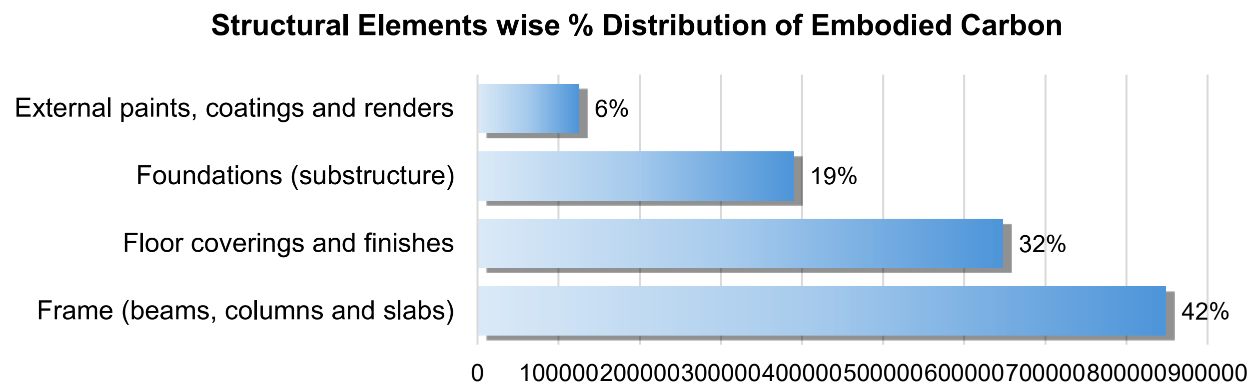



*Figure 16 Structural Elements wise % distribution of total Embodied Carbon, International School.*

Material-wise, the significant share of cement and steel aligns with typical reinforced concrete systems, yet their combined share exceeding 500 Kg$CO_2$e /m² flags potential for improvement. Interior elements like paints and tiling, though secondary, add meaningful cumulative impacts. These findings suggest opportunities for reducing embodied carbon via design-level substitution (e.g., low-carbon concrete, alternative finishes) and tighter specification control, particularly in large-span slab and finish layers.

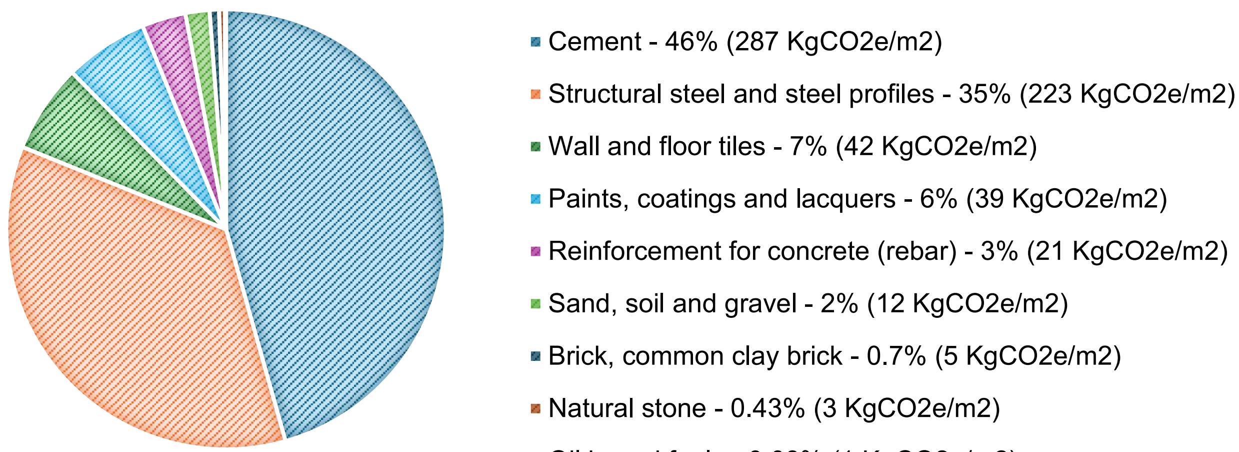



*Figure 17 Materials Wise Embodied Carbon Distribution (Kgco2e/m2), International School.*

## E. Industrial Building (Factory) – Advik Factory, Bengaluru

### Overview

Advik Factory is a ground plus one industrial facility located in the temperate climate zone of Bengaluru, classified under Seismic Zone II. The structure is typical of a pre-engineered building (PEB) system, characterized by its steel frame, functional layout, and optimized use of land. Designed to accommodate medium-scale manufacturing operations, the building reflects industrial efficiency while maintaining structural simplicity. Its typology necessitates durability and quick construction, which is supported by prefabricated components and minimal on-site activities.

The structure has a total built-up area of 5,861.34 square metres and follows a streamlined material palette common to factory buildings: steel profiles for the main structure, concrete for foundations and slabs, and a mix of basic finishes. The LCA included embodied carbon emissions from product manufacturing (A1–A3), transportation (A4), and construction installation processes (A5), providing a cradle-to-site perspective on environmental impact. However, it is important to note that only a portion of the building was considered in the embodied carbon assessment. The areas demanding heavy structural design, typical in factory settings, were not part of the zone studied for this LCA; hence, the results may reflect comparatively lower embodied carbon values than the entire facility would.

| Parameter | Details |
|---|---|
| **Name of the project** | Advik Factory |
| **Building Typology** | Factory |
| **Total Number of Floors** | G+1 |
| **Built-up Area ($m^2$)** | 5,861.34 |
| **LCA Stages Included** | A1–A3, A4, A5 |
| **Climate** | Temperate |
| **Seismic Zone** | II |

## Results

The upfront embodied carbon footprint of Advik Factory stands at 341 $KgCO_2e$ /$m^2$, which is modest for an industrial facility of this scale and function. The project's location in Seismic Zone II means structural reinforcement requirements are not excessive, contributing to its relatively lean use of concrete and steel.

The use of a prefabricated steel frame system appears to have played a role in reducing material wastage and optimizing transportation logistics. While the emissions from transport and construction processes remain minor, the production stage dominates with 94% of the total emissions, reflecting the impact of industrial-scale steel use. Interpreting these results in the broader context of factory buildings, Advik Factory performs efficiently in terms of embodied emissions. The steel-intensive frame contributes heavily to upfront carbon, but it also enables faster construction and flexibility in design. The use of conventional concrete and minimal insulation materials further supports the lean carbon profile. Overall, the data suggests that while high steel content drives emissions in such typologies, careful structural design and location-specific efficiencies can moderate the overall impact.

## Inferences

The distribution of emissions across life cycle stages is significantly skewed toward A1–A3, which alone contributes 321 $KgCO_2e$ /$m^2$ out of the total 341 $KgCO_2e$ /$m^2$. This concentration reflects the dominance of material manufacturing in shaping the project's carbon footprint, with only marginal additions from transportation and site construction. Such a profile is characteristic of prefabricated buildings, where site-related impacts are minimized due to off-site assembly and efficient logistics. The relatively low values in A4 and A5 suggest both sourcing and execution strategies were streamlined, further reducing ancillary emissions.

**Distribution of Embodied Carbon in A1 to A5 Life cycle stages**

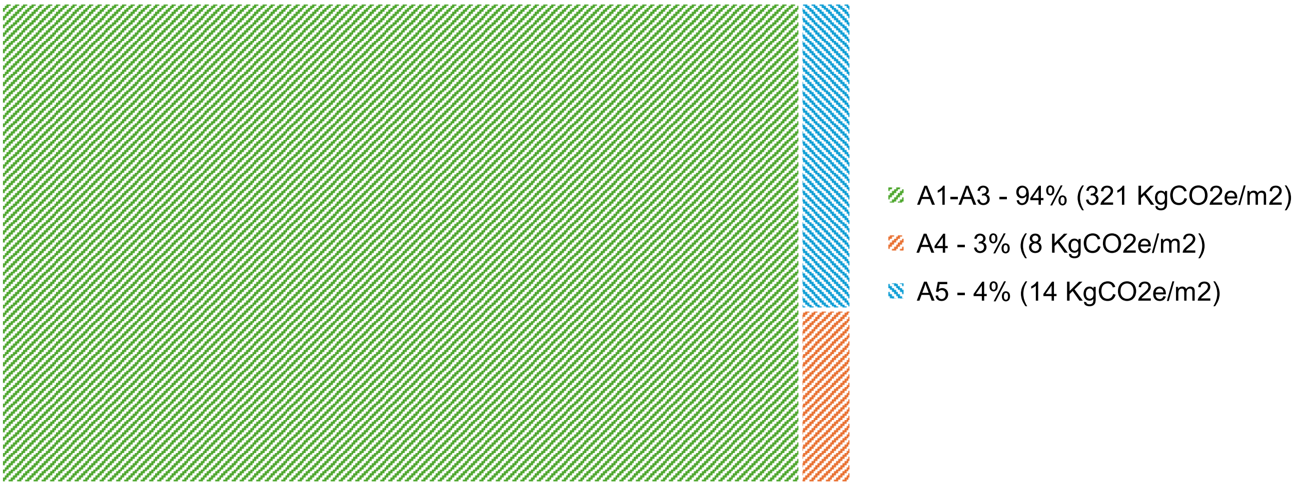



*Figure 18 Distribution of Embodied Carbon in A1 to A5 Life cycle stages, Advik Factory (Bengaluru)*

When examining emissions across structural elements, the frame—comprising beams, columns, and slabs—emerges as the most carbon-intensive, responsible for 66% of the total. This is followed by the foundations, which contribute nearly a quarter of the emissions. The dominance of these two elements highlights the role of the building's structural system in determining its environmental footprint. The remaining elements, including external walls and finishes, account for a much smaller fraction, pointing to limited diversity in materials and a functional design approach.

**Structural Elements wise % Distribution of Embodied Carbon**

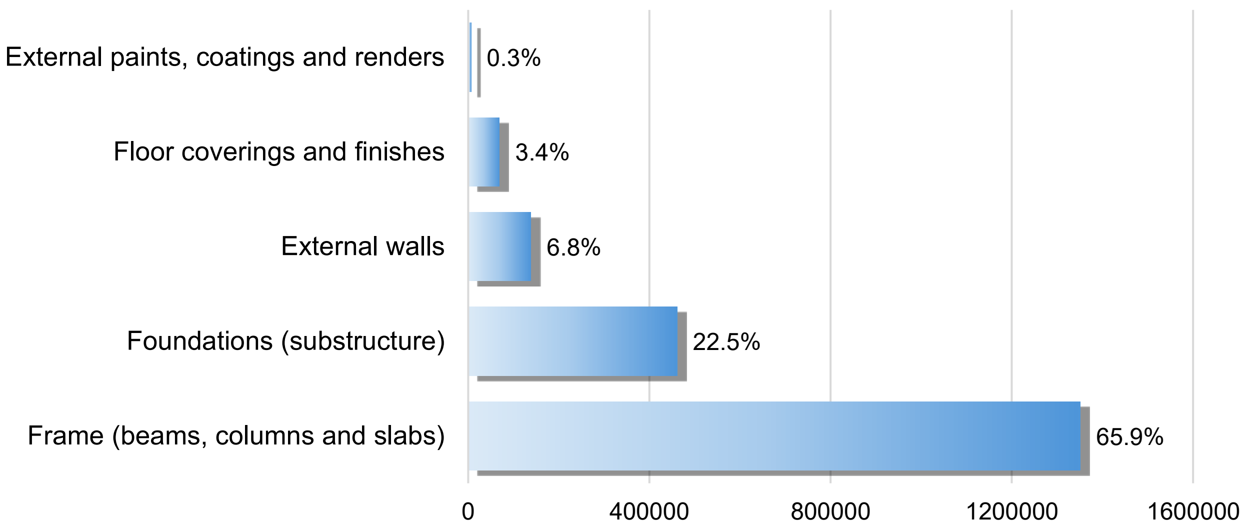



*Figure 19 Structural Elements wise % distribution of total Embodied Carbon , Advik Factory (Bengaluru)*

From a material perspective, structural steel alone contributes 229 $KgCO_2e$ /m², which is two-thirds of the total embodied carbon. Cement follows at 81 $KgCO_2e$ /m², primarily used in foundations and floor slabs. Other materials such as bricks, aggregates, and surface finishes contribute only marginally, underscoring the impact of primary loadbearing and structural materials. The limited use of high-impact finishes or synthetic materials reinforces the efficiency-first philosophy evident in the project's execution. These patterns reinforce that for industrial buildings, material selection—particularly in framing—remains the most significant lever for reducing embodied carbon.

Materials Wise Embodied Carbon Distribution (Kgco2e/m2)

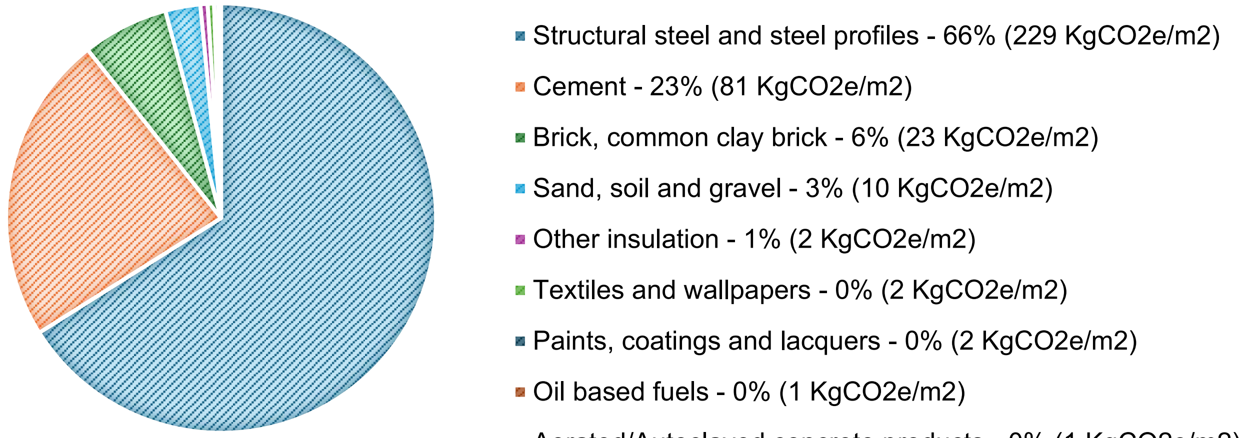



*Figure 20 Materials Wise Embodied Carbon Distribution (Kgco2e/m2) , Advik Factory (Bengaluru)*

## II. Composite Climate

### A. Institutional Building (Government Office) – Chandigarh Housing Board, Chandigarh

#### Overview

Chandigarh Housing Board Office Building Block B is a G+5 government office building located in a composite climate zone and Seismic Zone IV. The building has a total built-up area of 16,175 m² and follows typical RCC construction systems suited for public administrative use. The whole life carbon assessment covers A1–A3 (product stage), A4 (transport), and A5 (construction stage), offering a comprehensive estimate of embodied carbon emissions across the project's life cycle.

| Parameter | Details |
|---|---|
| **Name of the project** | Chandigarh Housing Board Office Building |
| **Building Typology** | Institutional Building- Government office |
| **Total Number of Floors** | G+5 |
| **Built-up Area (m²)** | 16,175 |
| **LCA Stages Included** | A1–A3, A4, A5 |
| **Climate** | Composite |
| **Seismic Zone** | IV |

#### Results

The total upfront embodied carbon emissions of the building were estimated at 12,153,602.47 $KgCO_2e$ /m² , which corresponds to **752 $KgCO_2e$ /m².** The majority of emissions (94%) were attributed to the A1–A3 stage, contributing 705 $KgCO_2e$ /m². Construction (A5) accounted for 5% (41 $KgCO_2e$ /m²), while transport (A4) contributed just 1% (7 $KgCO_2e$ /m²). The dominance of the product stage indicates a material-intensive construction approach typical for institutional RCC buildings in high seismic zones.

In terms of materials, ready-mix concrete for foundations and internal walls was the highest contributor at 40% (313 $KgCO_2e$ /m²), followed by reinforcement steel at 32% (251 $KgCO_2e$ /m²). Additional emissions came from ready-mix concrete used in external walls and floors (12%), cement (10%), and clay bricks (3%). Minor contributions were observed from AAC blocks, machinery, natural stone, and aggregates. These findings point to a high dependency on traditional high-emission structural materials with limited use of alternatives.

When classified by structural elements, substructure foundations alone accounted for 50% (387 $KgCO_2e$ /m²) of total emissions, reflecting substantial below-ground structural work likely necessitated by soil or seismic requirements. External walls contributed 49% (378 $KgCO_2e$ /m²), underscoring their extensive material use and surface area. Construction site scenarios (A5) contributed just 1%, and basement-related emissions were negligible. The emission profile is heavily concentrated in core structural elements, especially concrete-intensive ones.

## Inferences

The lifecycle stage analysis indicates that the A1–A3 stage overwhelmingly dominates the building's embodied carbon, consistent with its dependence on high-emission materials such as cement, concrete, and steel. The minor contributions from A4 and A5 (totalling just 6%) suggest efficient logistics and standard on-site construction activities. However, the high base values at A1–A3 emphasize the importance of upstream interventions in material selection and manufacturing processes to reduce the project's carbon footprint.

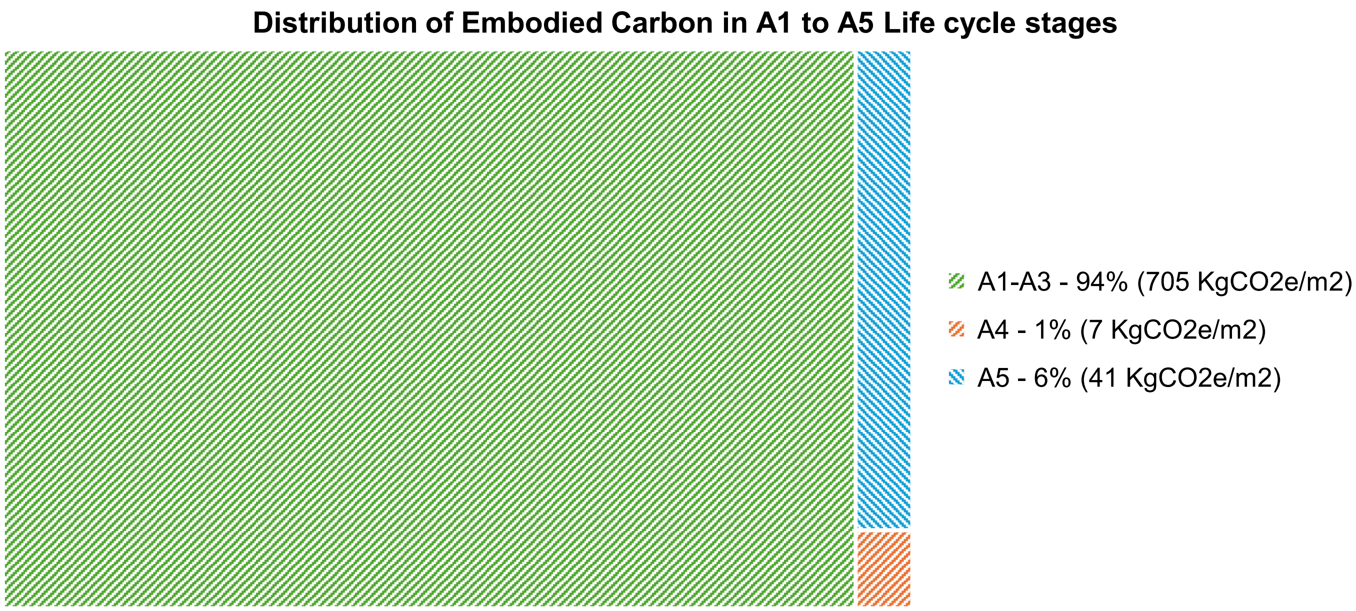



*Figure 21 Distribution of Embodied Carbon in A1 to A5 Life cycle stages, Chandigarh Housing Board*

The structural breakdown shows that substructure and external walls are the major contributors, jointly accounting for 99% of the total emissions. This is indicative of a design with heavy foundations and extensive envelope construction—possibly to meet both seismic safety standards and institutional aesthetics. The near-equal split between substructure and envelope highlights the dual impact of structural stability and spatial enclosure on the building's embodied emissions.

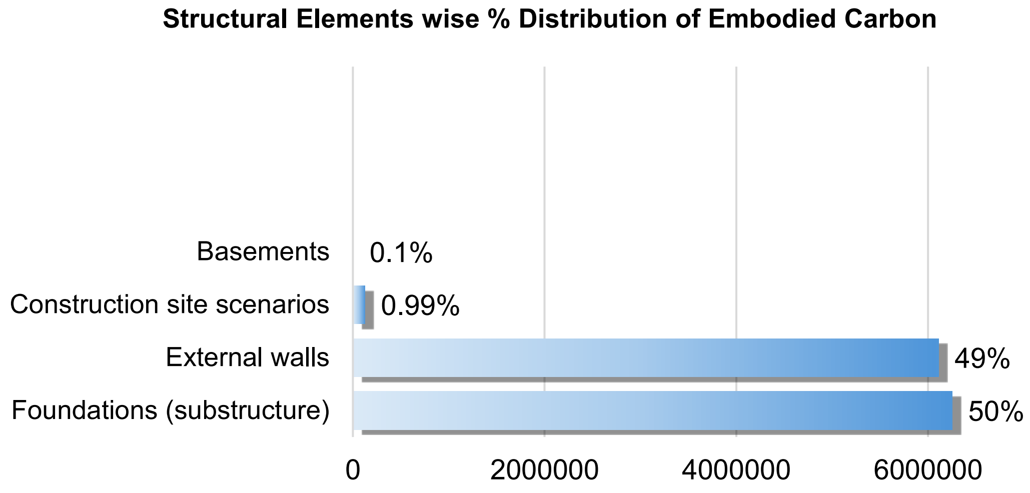



*Figure 22 Structural Elements wise % distribution of total Embodied Carbon, Chandigarh Housing Board*

The five largest material contributors were:

- Ready-mix concrete for foundations and internal walls (40%)
- Reinforcement steel (32%)
- Ready-mix concrete for external walls and floors (12%)
- Cement (10%)
- Clay bricks (3%)

Together, these materials account for 97% of the total material-related emissions. This underlines the building's strong reliance on RCC systems, with limited use of low-carbon alternatives or hybrid systems. Reducing cement content through supplementary cementitious materials, optimizing rebar design, and incorporating lower-emission envelope solutions could help in reducing future impacts in similar government office developments.

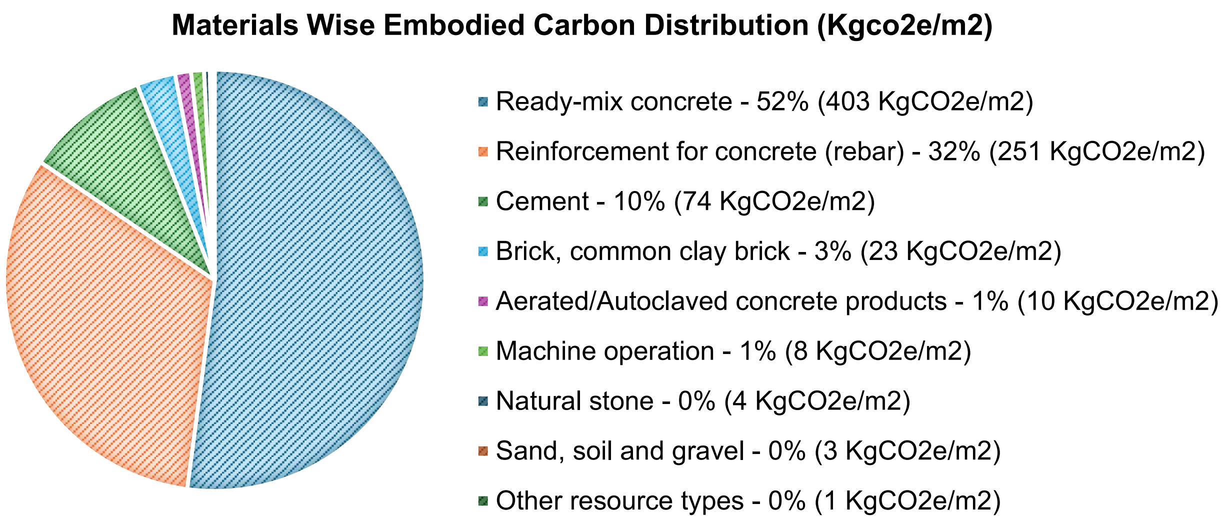



*Figure 23 Materials Wise Embodied Carbon Distribution (Kgco2e/m2) , Chandigarh Housing Board*

## B. Commercial Building (Office) – Syal Associates Architect Office, Mohali, Punjab

### Overview

The Syal Associates Architects Office in Chandigarh is a G+3 commercial office space located in a composite climate and designated under Seismic Zone IV. The building has a substantial built-up area of 11,424 m² and incorporates conventional construction systems for commercial use. The Whole Life Carbon Assessment has been conducted for the initial life cycle stages – product (A1–A3), transport (A4), and construction (A5).

| Parameter | Details |
|---|---|
| **Name of the project** | Syal Associates Architects Office |
| **Building Typology** | Commercial Office |
| **Total Number of Floors** | G+3 |
| **Built-up Area (m²)** | 11,424 |
| **LCA Stages Included** | A1–A3, A4, A5 |
| **Climate** | Composite |
| **Seismic Zone** | IV |

### Results

The total upfront embodied carbon for Syal Associates Architects Office is 7,306,513 kg$CO_2$e, corresponding to 640 kg$CO_2$e/m². The manufacturing stages (A1–A3) dominate the emissions profile at 5,696,994 kg$CO_2$e or 587 kg$CO_2$e/m² (92%), while transportation of materials (A4) and construction processes (A5) contribute 22 kg$CO_2$e/m² (3%) and 32 kg$CO_2$e/m² (5%), respectively. This distribution confirms the front-loaded nature of embodied carbon in commercial office buildings with conventional RCC and masonry construction.

At the material level, the five highest contributors are common clay bricks (203 kg$CO_2$e/m², 28%), reinforcement steel (178 kg$CO_2$e/m², 24%), ready-mix concrete for foundations and internal walls (102 kg$CO_2$e/m², 14%), cement (72 kg$CO_2$e/m², 10%), and paints, coatings, and lacquers (57 kg$CO_2$e/m², 8%). Aluminium products, including aluminium-framed glass doors (54 kg$CO_2$e/m², 7%) and general aluminium components (34 kg$CO_2$e/m², 5%), further contribute to the embodied carbon, reflecting the material palette used for façade elements and fenestrations.

From a structural element perspective, external walls are the largest contributor at 219 kg$CO_2$e/m² (30%), followed by the load-bearing structural frame (232 kg$CO_2$e/m², 32%), and façade openings (97 kg$CO_2$e/m², 13%). Foundations account for 67 kg$CO_2$e/m² (9%), while floor coverings and finishes contribute 58 kg$CO_2$e/m² (8%), and external paints, coatings, and renders add 57 kg$CO_2$e/m² (8%). Minor contributions arise from stairs and ramps (4 kg$CO_2$e/m²), site fuel (1 kg$CO_2$e/m²), and water consumption (1 kg$CO_2$e/m²).

### Inferences

The lifecycle stage distribution confirms that A1–A3 manufacturing stages dominate, accounting for 92% of the total embodied carbon, consistent with commercial office buildings in seismic Zone IV using RCC and masonry systems. The comparatively smaller contributions from A4 and A5 indicate that material transport and on-site construction activities have a limited impact relative to production emissions.

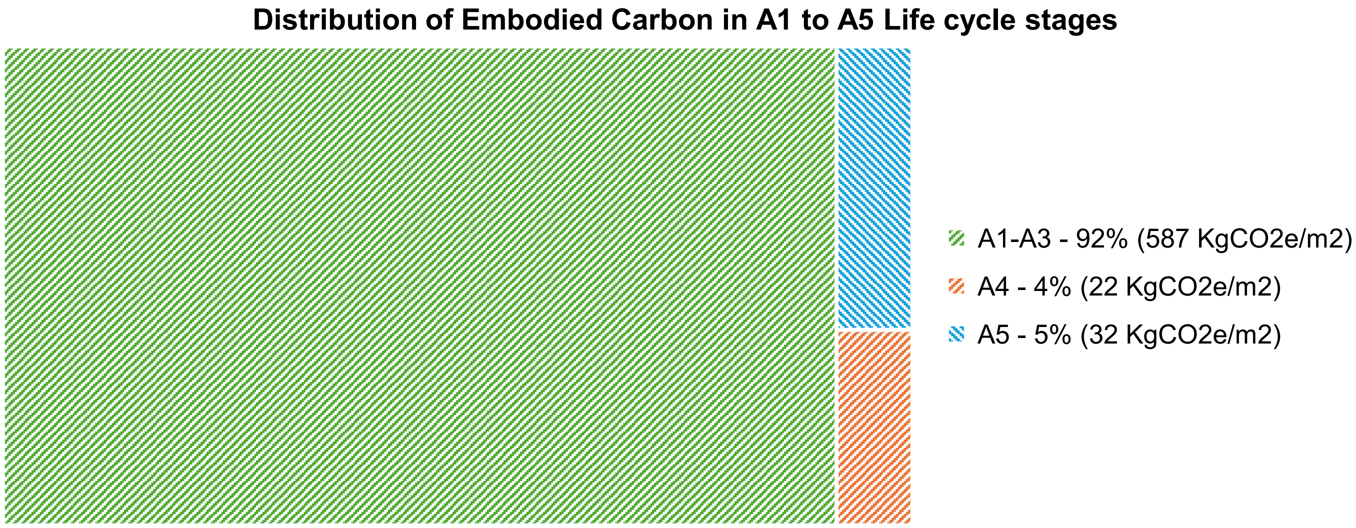



*Figure 24 Distribution of Embodied Carbon in A1 to A5 Life cycle stages, Syal Architects Office*

Structurally, the combined impact of the load-bearing frame and external walls (551 $kgCO_2e/m^2$, 62%) underscores the influence of primary structural and façade systems in determining the building's carbon footprint. Façade openings, floor finishes, and surface coatings add further contributions but remain secondary in the overall emissions profile.

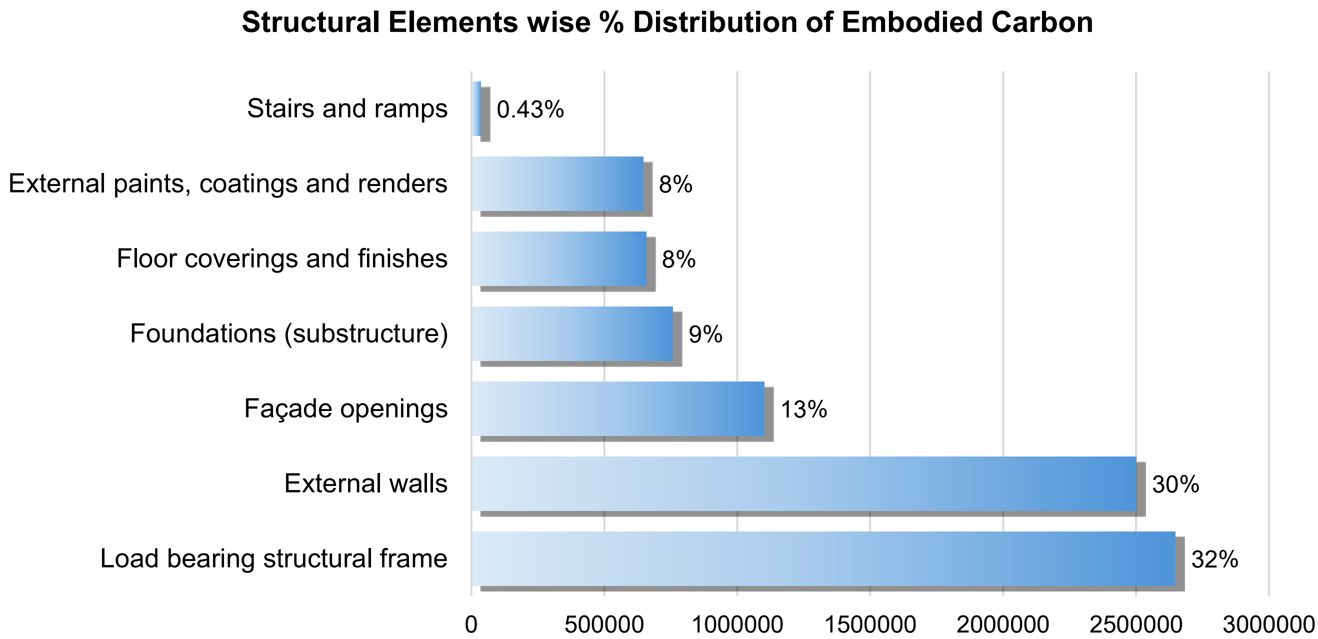



*Figure 25 Structural Elements wise % distribution of total Embodied Carbon , Syal Architects Office*

At the material level, common clay bricks, reinforcement steel, and ready-mix concrete together contribute 503 $kgCO_2e/m^2$ (66%), defining most of the building's embodied carbon. The results suggest targeted decarbonisation strategies could focus on low-carbon masonry alternatives (e.g., AAC blocks), recycled-content reinforcement, and optimised concrete mixes, as well as efficient façade systems, to achieve meaningful reductions in upfront carbon emissions without compromising structural integrity or architectural performance.

**Materials Wise Embodied Carbon Distribution (Kgco2e/m2)**

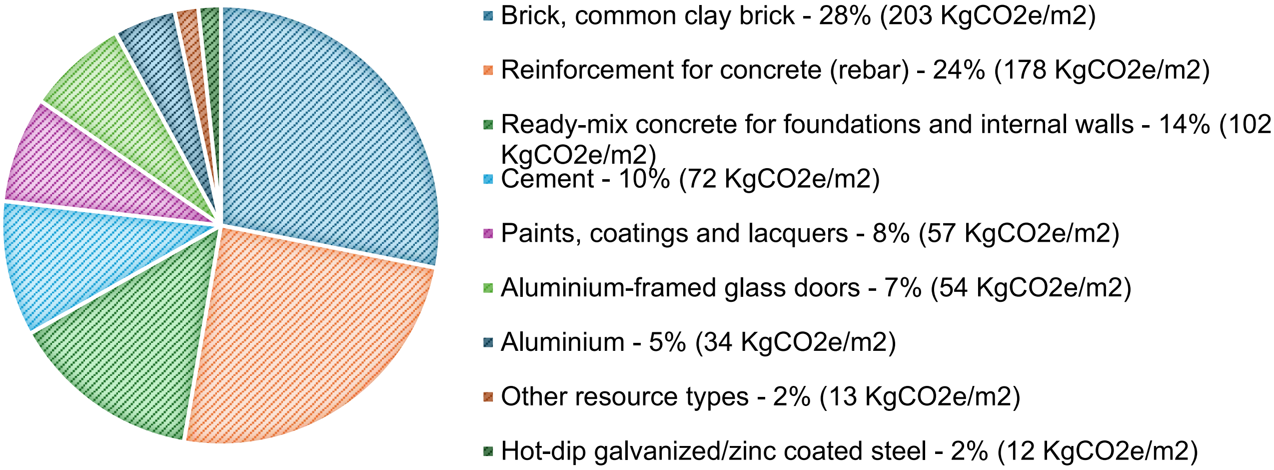



*Figure 26 Materials Wise Embodied Carbon Distribution (Kgco2e/m2) , Syal Architects Office*

## C. Residential Building – Kanya Siksha Residency, Bhopal, Madhya Pradesh

### Overview

Kanya Siksha Residency is a G+6 residential building with a built-up area of 900 m² located in a composite climate and Seismic Zone II. The whole life carbon assessment includes lifecycle stages A1–A3, A4, and A5, covering product, transport, and construction emissions. The project caters to institutional residential requirements and follows conventional RCC construction methods typical for mid-rise structures.

| Parameter | Details |
|---|---|
| **Name of the project** | Kanya Siksha Parisar |
| **Building Typology** | Residential |
| **Total Number of Floors** | G+6 |
| **Built-up Area (m²)** | 900 |
| **LCA Stages Included** | A1–A3, A4, A5 |
| **Climate** | Composite |
| **Seismic Zone** | II |

### Results

The upfront embodied carbon for Kanya Siksha Parisar is 415,293 $kgCO_2e$, translating to an intensity of 462 $kgCO_2e/m^2$. The manufacturing stages (A1–A3) are the dominant source, contributing 381,247 $kgCO_2e$ (92%), equal to 424 $kgCO_2e/m^2$. Transportation (A4) adds 12,767 $kgCO_2e$ (3%), or 15 $kgCO_2e/m^2$, while construction processes (A5) contribute 21,279 $kgCO_2e$ (5%), equal to 24 $kgCO_2e/m^2$.

At the material level, the highest contributor is ready-mix concrete for foundations and internal walls at 142,549 $kgCO_2e$ (29%), or 159 $kgCO_2e/m^2$. This is followed by reinforcement steel at 131,883 $kgCO_2e$ (27%), or 147 $kgCO_2e/m^2$, and cement at 90,903 $kgCO_2e$ (18%), or 102 $kgCO_2e/m^2$. Other significant contributors include aluminium frame windows (36 $kgCO_2e/m^2$, 6%), paints, coatings and lacquers (31 $kgCO_2e/m^2$, 6%), and masonry mortar (16 $kgCO_2e/m^2$, 3%). Smaller inputs such as EPS insulation, lightweight ready-mix concrete, and aggregates provide measurable but secondary impacts.

From the perspective of structural elements, the load-bearing frame is the largest contributor at 216,561 $kgCO_2e$ (44%), equal to 241 $kgCO_2e/m^2$. This is followed by foundations at 89,343 $kgCO_2e$ (18%), or 100 $kgCO_2e/m^2$, and external walls at 50,819 $kgCO_2e$ (10%), or 57 $kgCO_2e/m^2$. Other notable shares come from façade openings (44 $kgCO_2e/m^2$, 8%), floor coverings and finishes (40 $kgCO_2e/m^2$, 7%), and wall and ceiling finishes (35 $kgCO_2e/m^2$, 6%). Minor but visible contributions arise from external coatings (31 $kgCO_2e/m^2$, 6%) and construction site activities (3 $kgCO_2e/m^2$).

## Inferences

The lifecycle stage distribution confirms that **A1–A3 manufacturing accounts for 92%** of total emissions, underscoring the dominance of material production in this mid-rise RCC residential project. Transportation and site construction together contribute only **39 $kgCO_2e/m^2$ (8%)**, reflecting moderate logistical and site impacts relative to materials.

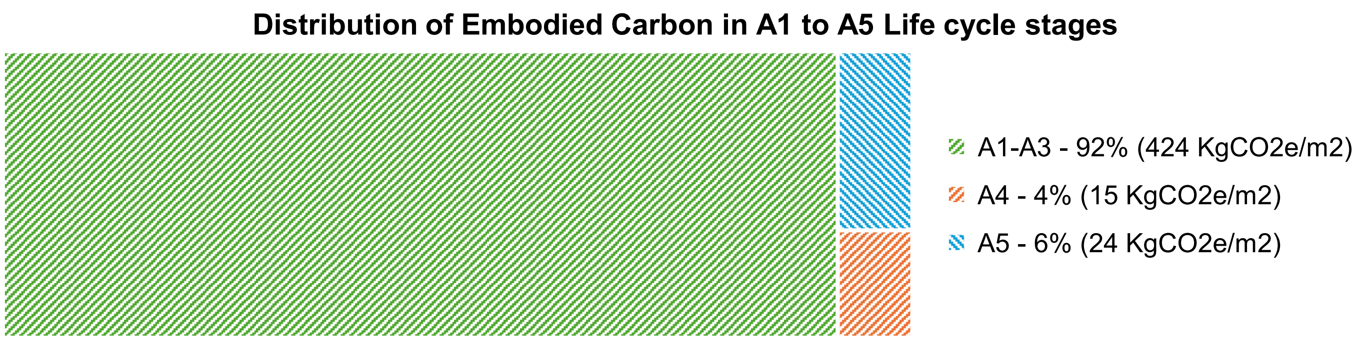



*Figure 27 Distribution of Embodied Carbon in A1 to A5 Life cycle stages, Kanya Siksha Parisar*

From a structural perspective, the load-bearing frame and foundations together contribute 341 $kgCO_2e/m^2$ (62%), highlighting the concentration of embodied carbon in the structural system. External walls, façade openings, and finishes together account for another 21%, demonstrating the significant but secondary role of enclosure and surface treatments.

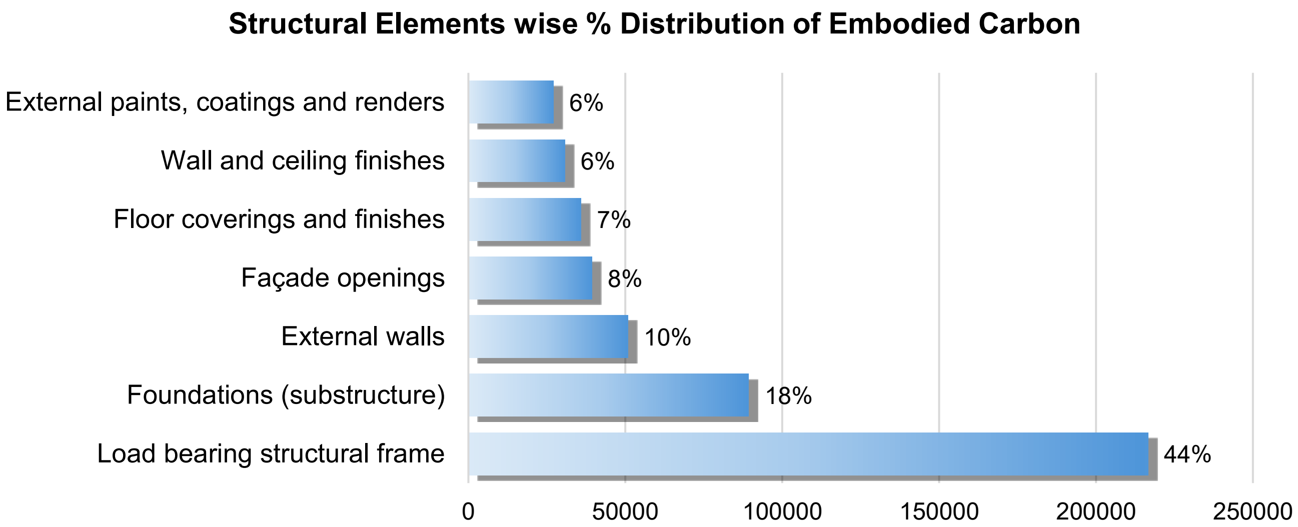



*Figure 28 Structural Elements wise % distribution of total Embodied Carbon, Kanya Siksha Parisar*

At the material level, the top five contributors — ready-mix concrete for foundations and internal walls (29%), reinforcement steel (27%), cement (18%), aluminium frame windows (6%), and paints and coatings (6%) — together represent over 85% of total emissions. This profile suggests that decarbonisation strategies should prioritise concrete mix optimisation, reinforcement with recycled content, and supplementary cementitious materials, while also addressing emissions from finishes and fenestration.

**Materials Wise Embodied Carbon Distribution (Kgco2e/m2)**

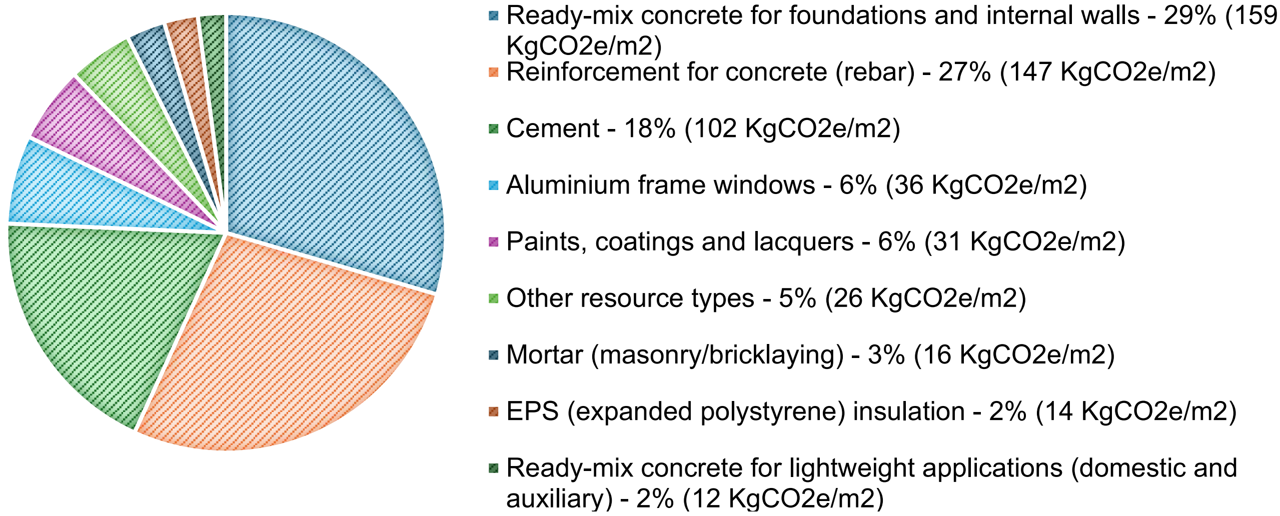



*Figure 29 Materials Wise Embodied Carbon Distribution (Kgco2e/m2) , Kanya Siksha Parisar*

## D. Institutional Building (School) – Secondary School, Bandakpur, Madhya Pradesh

### Overview

The Secondary School located in Bandakpur, Madhya Pradesh is a G+2 educational building designed to serve institutional functions. With a built-up area of 5,934 m², it is situated in a composite climate zone and falls under Seismic Zone II. The whole life carbon (WLC) assessment covers modules A1–A3 (product stage), A4 (transport), and A5 (construction installation).

| Parameter | Details |
|---|---|
| **Name of the project** | Secondary School, Bandakpur. |
| **Building Typology** | School |
| **Total Number of Floors** | G+2 |
| **Built-up Area (m²)** | 5934 |
| **LCA Stages Included** | A1-A3, A4, A5 |
| **Climate** | Composite |
| **Seismic Zone** | II |

### Results

The total upfront embodied carbon for Secondary School – Bandakpur is 2,594,656 $kgCO_2e$, corresponding to 438 $kgCO_2e/m^2$. The manufacturing stages (A1–A3) dominate the emissions profile at 2,097,672 $kgCO_2e$

or 354 $kgCO_2e/m^2$ (81%), while transportation of materials (A4) and construction processes (A5) contribute 62 $kgCO_2e/m^2$ (14%) and 23 $kgCO_2e/m^2$ (5%), respectively. This distribution confirms the front-loaded nature of embodied carbon in low-rise institutional buildings using conventional RCC and concrete-intensive construction.

At the material level, the five highest contributors are reinforcement steel (153 $kgCO_2e/m^2$, 27%), ready-mix concrete for foundations and internal walls (145 $kgCO_2e/m^2$, 26%), autoclaved aerated concrete products (54 $kgCO_2e/m^2$, 10%), cement (50 $kgCO_2e/m^2$, 9%), and wall and floor tiles (41 $kgCO_2e/m^2$, 7%). Other contributors include structural steel and profiles (39 $kgCO_2e/m^2$, 7%), aluminium frame windows (23 $kgCO_2e/m^2$, 4%), and paints and coatings (13 $kgCO_2e/m^2$, 2%), reflecting the material palette used for structural and finishing elements.

From a structural element perspective, the load-bearing structural frame is the largest contributor at 251 $kgCO_2e/m^2$ (45%), followed by foundations (92 $kgCO_2e/m^2$, 16%) and internal walls, partitions, and doors (60 $kgCO_2e/m^2$, 11%). External walls contribute 55 $kgCO_2e/m^2$ (10%), while floor coverings and finishes add 52 $kgCO_2e/m^2$ (9%). Minor contributions arise from façade openings (30 $kgCO_2e/m^2$, 5%), external paints and coatings (17 $kgCO_2e/m^2$, 3%), stairs and ramps (4 $kgCO_2e/m^2$), and site fuel/water use (2 $kgCO_2e/m^2$).

## Inferences

The lifecycle stage distribution confirms that A1–A3 manufacturing stages dominate, accounting for 81% of the total embodied carbon, consistent with concrete-intensive low-rise school buildings in Seismic Zone II. The contributions from A4 and A5 are smaller, indicating moderate transport impacts and efficient on-site construction practices.

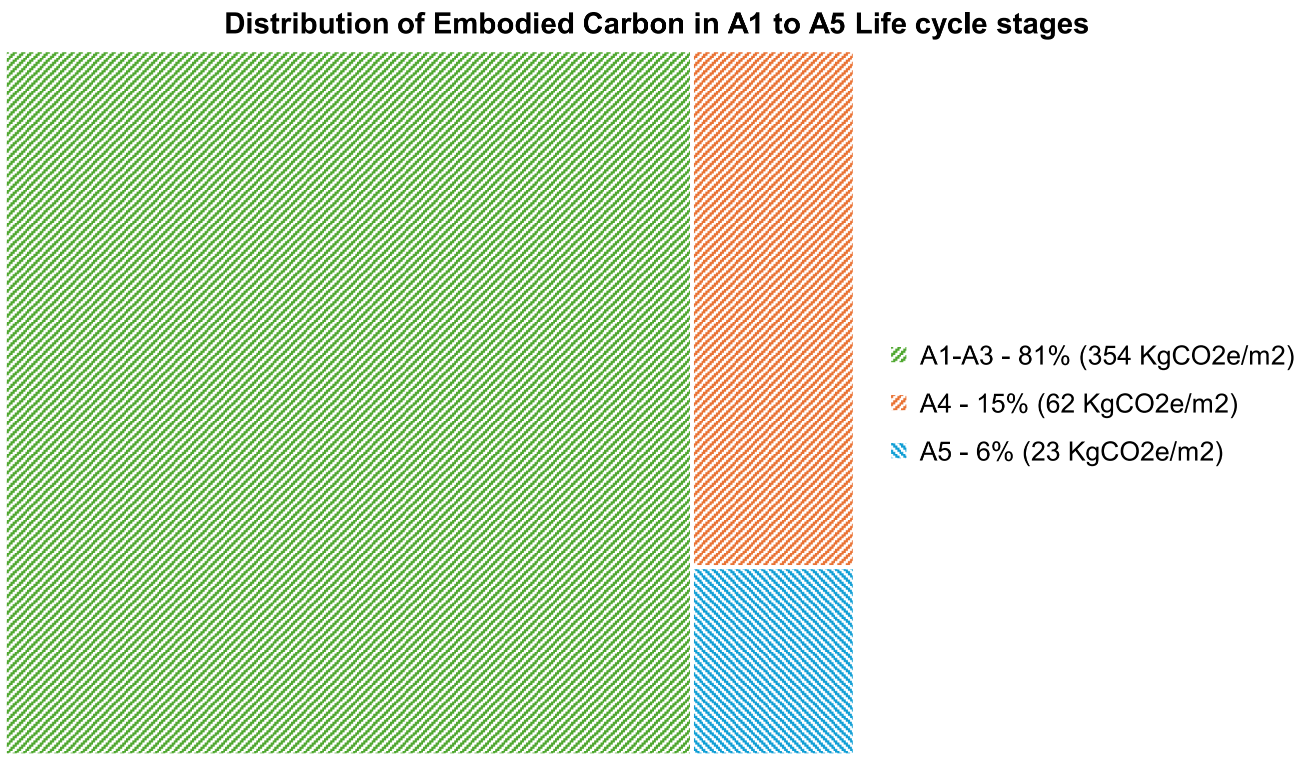



*Figure 30 Distribution of Embodied Carbon in A1 to A5 Life cycle stages, School – MP*

Structurally, the combined impact of the load-bearing frame and foundations (343 $kgCO_2e/m^2$, 61%) underscores the influence of primary structural systems on the building's overall carbon footprint. Internal walls, external walls, and finishes add secondary contributions, while façade openings and surface coatings remain minor contributors.

## Structural Elements wise % Distribution of Embodied Carbon

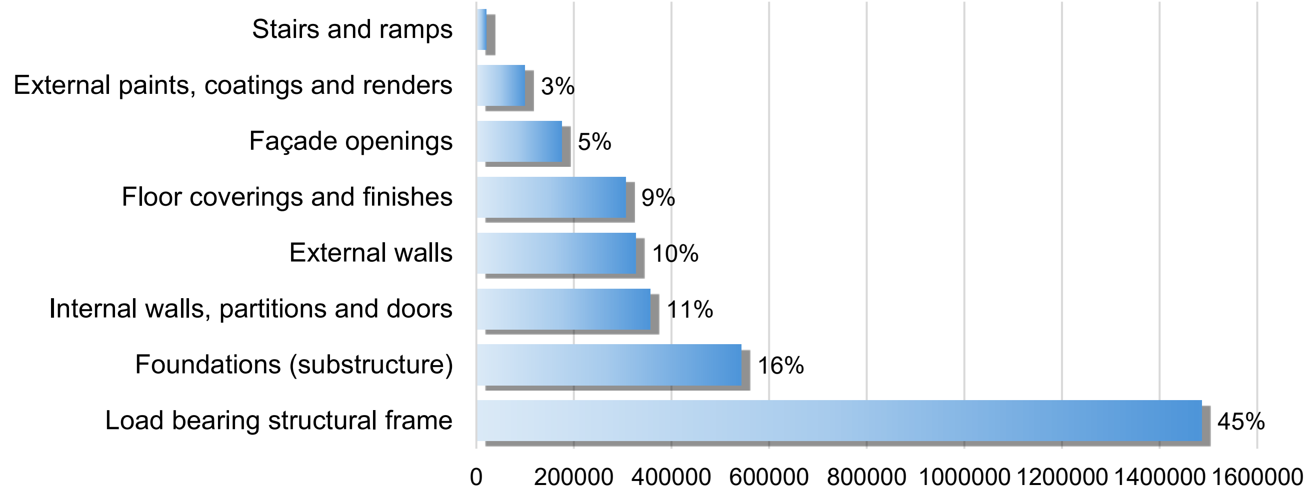



*Figure 31 Structural Elements wise % distribution of total Embodied Carbon, School – MP*

At the material level, reinforcement steel, ready-mix concrete, autoclaved aerated concrete products, cement, and wall/floor tiles define the majority of the embodied carbon, representing over 70% of the total footprint. The results suggest targeted decarbonisation strategies could focus on low-carbon concrete mixes, recycled steel content, alternative masonry products (AAC blocks), and optimized finishes to reduce upfront carbon without compromising structural performance or functional requirements.

## Materials Wise Embodied Carbon Distribution (Kgco2e/m2)

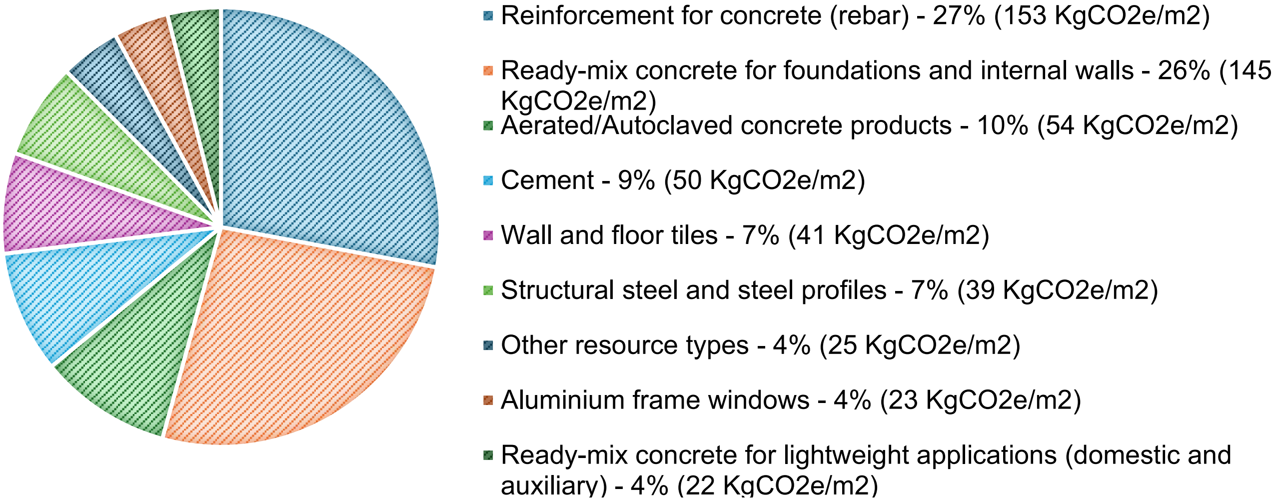



*Figure 32 Materials Wise Embodied Carbon Distribution (Kgco2e/m2), School – MP*

## E. Industrial Building (Factory) – Ramani Precision Machines, Mohali, Punjab

### Overview

Ramani Precision Machines is a factory building located in Mohali, comprising G+3 floors with a built-up area of 4,077 m². The project is situated in a composite climate and falls within Seismic Zone IV. The upfront embodied carbon analysis was conducted for the life cycle stages A1–A3 (product stage), A4 (transportation), and A5 (construction stage). The structural system predominantly incorporates reinforced concrete and steel, with significant use of bricks and industrial finishes.

| Parameter | Details |
|---|---|
| **Name of the project** | Ramani Precision Machines |
| **Building Typology** | Factory |
| **Total Number of Floors** | G+3 |
| **Built-up Area (m²)** | 4,077 |
| **LCA Stages Included** | A1–A3, A4, A5 |
| **Climate** | Composite |
| **Seismic Zone** | IV |

## Results

Among all the typologies assessed in the LCA, Ramani Precision Machines, Mohali recorded the highest total upfront embodied carbon emissions, estimated at 5,497,773 $kgCO_2e$, translating to a carbon intensity of 1,349 $kgCO_2e/m^2$. This elevated value is primarily due to its construction typology as a factory building built with in-situ cast RCC frames, structural steel profiles, and common burnt clay bricks—a combination of materials with inherently high embodied carbon, not observed in any other buildings studied. The product stage (A1–A3) was the dominant contributor, accounting for 94% of total emissions at 1,274 $KgCO_2e$ /m². Construction activities (A5) contributed 58 $KgCO_2e$ /m² (4%), and transportation of materials to site (A4) added another 18 $KgCO_2e$ /m² (1%). The results clearly indicate that the bulk of emissions stem from the extraction, processing, and manufacturing of building materials.

The most carbon-intensive building elements were the ground floor slab and external walls, each contributing approximately 33% of total emissions, or around 500 $KgCO_2e$ /m². The foundations accounted for a further 20% (302 $KgCO_2e$ /m²), highlighting the carbon burden associated with substructure components in an industrial building. Coatings, renders, and finishes together added 142 $KgCO_2e$ /m², suggesting high-emission external treatments. Other elements such as floor finishes, façade openings, and site fuel consumption made minimal contributions.

From a materials perspective, ready-mix concrete, structural steel, brick, and reinforcement steel were the largest contributors, together making up 80% of the total material emissions. Ready-mix concrete and structural steel each contributed around 21%, followed closely by brick and rebar at 19% each. Paints, coatings, and lacquers added another 9%, while cement contributed 8%, reinforcing the high embodied carbon footprint of conventional industrial construction materials.

## Inferences

The embodied emissions profile is dominated by the product stage (A1–A3), which contributed 1,274 $KgCO_2e$ /m² (94%). This aligns with the use of emissions-intensive structural materials like concrete, steel, and bricks. Construction (A5) and transport (A4) together accounted for 76 $KgCO_2e$ /m² (6%), reflecting a relatively standard logistics and site execution process with no unusual fuel or installation burdens.

## Distribution of Embodied Carbon in A1 to A5 Life cycle stages

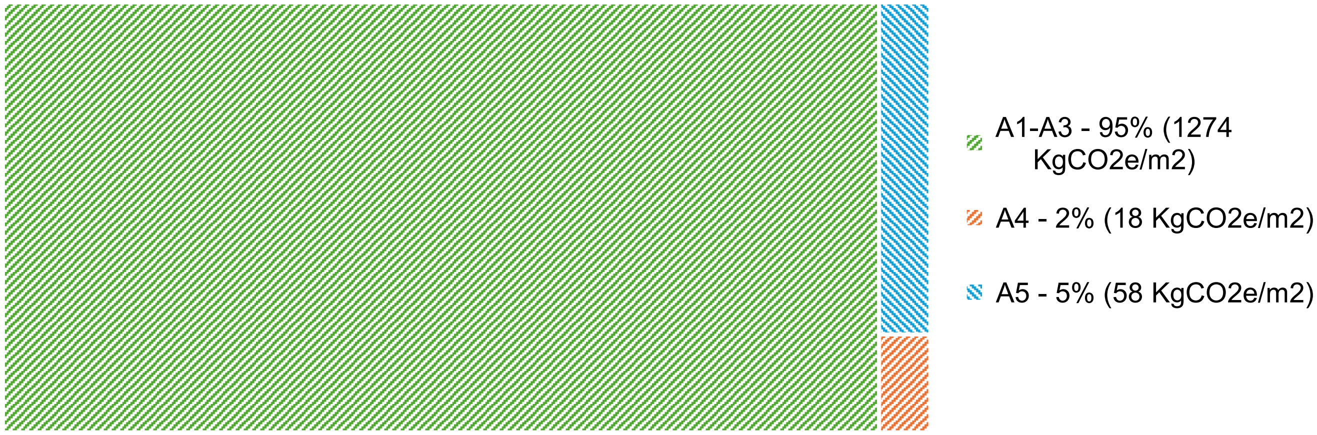



*Figure 33 Distribution of Embodied Carbon in A1 to A5 Life cycle stages, Ramani Precision Machines, Mohali*

Structural Element Contributions: The ground floor slab and external walls each contributed approximately one-third of the total emissions, together accounting for over 1,000 $KgCO_2e$ /m². This is consistent with the operational demands of a factory building where slab thickness, finish durability, and wall robustness are critical. Foundations contributed 302 $KgCO_2e$ /m² (20%), typical for industrial facilities designed to support heavy machinery and structural loads.

## Structural Elements wise % Distribution of Embodied Carbon

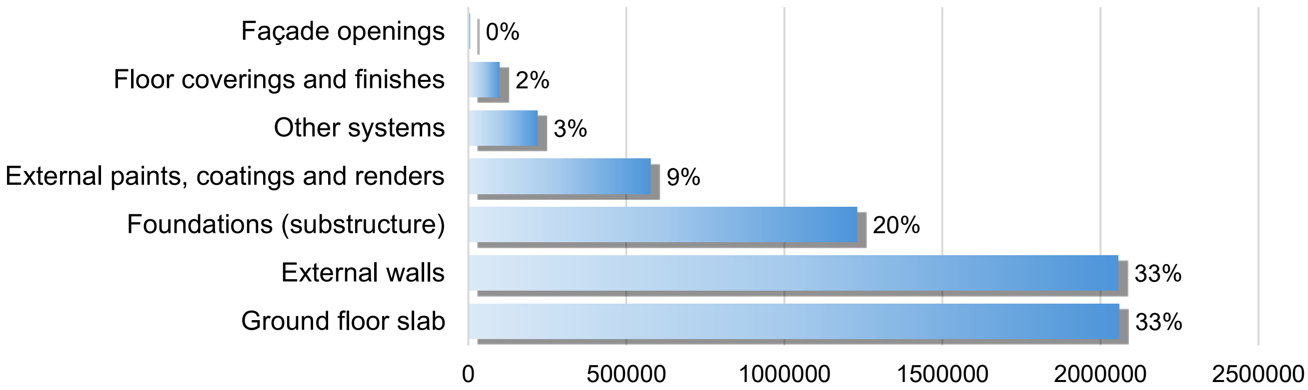



*Figure 34 Structural Elements wise % distribution of total Embodied Carbon, Ramani Precision Machines, Mohali*

The top five materials contributing to the embodied carbon of the Ramani Precision Machines project are dominated by conventional structural and finishing elements. Ready-mix concrete, primarily used for foundations and internal walls, is the highest contributor at 321 $KgCO_2e$ /m², accounting for 21% of total material emissions. This is closely followed by structural steel and profiles, which also contribute 21% (317 $KgCO_2e$ /m²), reflecting the material intensity typical of industrial buildings.

Clay bricks are the third largest contributor at 289 $KgCO_2e$ /m², representing 19% of the material footprint. Reinforcement steel, essential for structural integrity, follows closely with 284 $KgCO_2e$ /m² (19%). These two materials are widely used in both load-bearing and non-load-bearing components of the building. Finishing elements like paints and coatings also make a significant impact, contributing 142 $KgCO_2e$ /m², or 9% of the total.

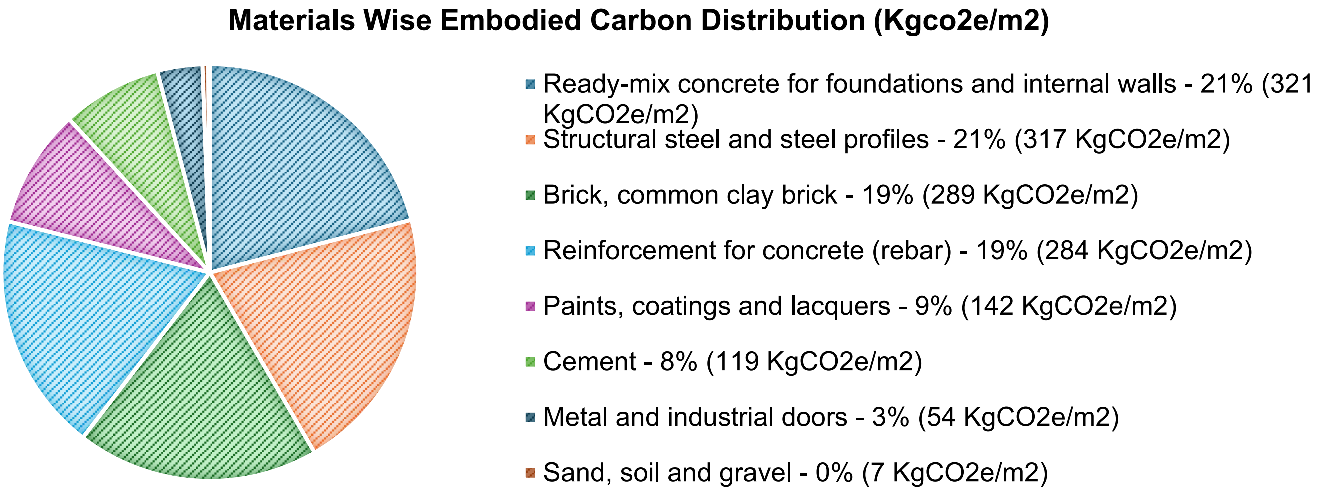



*Figure 35 Materials Wise Embodied Carbon Distribution (Kgco2e/m2) , Ramani Precision Machines, Mohali*

## III. Warm and Humid Climate

### A. Institutional Building (Government Office) – Energy Management Centre (EMC), Trivandrum

#### Overview

The Energy Management Centre (EMC) office building is a G+1 government facility located in Trivandrum, Kerala, within a warm-humid climatic zone and Seismic Zone III. The building has a total built-up area of 4,796 m² and was assessed for its whole life carbon performance, covering life cycle stages A1–A3 (product stage), A4 (transportation), and A5 (construction). Designed as a state-run energy-efficiency demonstration project, EMC relies heavily on passive design strategies, with minimal mechanical cooling restricted to specific zones like the auditorium and enclosed offices. The structure is predominantly RCC, reflecting conventional low-rise public sector construction practices in the region.

| Parameter | Details |
|---|---|
| **Name of the project** | Energy Management Centre (EMC) |
| **Building Typology** | Institutional Building- Government office |
| **Total Number of Floors** | G+1 |
| **Built-up Area (m²)** | 4796 |
| **LCA Stages Included** | A1–A3, A4, A5 |
| **Climate** | Warm and Humid |
| **Seismic Zone** | III |

## Results

The upfront embodied carbon emissions for the EMC building were estimated at 476 $KgCO_2e$ /m², with most emissions concentrated in the product stage. Stage A1–A3 contributed 447 $KgCO_2e$ /m² (94%), indicating the heavy influence of material manufacturing and processing. Stage A5 (construction) accounted for 23 $KgCO_2e$ /m² (5%), while transportation to site (A4) contributed only 7 $KgCO_2e$ /m² (1%), reflecting localized sourcing and typical low-rise transport logistics.

From a structural perspective, foundations (substructure) were the dominant element, contributing 214 $KgCO_2e$ /m² (38%), followed by the load-bearing structural frame at 123 $KgCO_2e$ /m² (22%). These values highlight the embodied carbon intensity of reinforced concrete used extensively in the structural system. Internal walls, floor finishes, and facade openings also contributed significantly, together accounting for approximately 32% of total emissions.

Material-wise, the top contributors were ready-mix concrete for walls and floors (157 $KgCO_2e$ /m², 28%), reinforcement steel (144 $KgCO_2e$ /m², 26%), and cement (104 $KgCO_2e$ /m², 18%). These were followed by CMU blocks (60 $KgCO_2e$ /m², 11%) and tiles (34 $KgCO_2e$ /m², 6%), collectively indicating reliance on conventional, high-carbon construction materials without major use of low-carbon substitutes such as blended cement or alternative aggregates.

## Inferences

The distribution of emissions across life cycle stages shows a clear dominance of the A1–A3 stage, which accounted for 94% of total emissions. This aligns with patterns observed in other low-rise RCC buildings in the region, where material manufacturing is the single largest driver of carbon impact. Emissions from the transportation and construction stages were limited, together forming just 6%, due to short transport distances and conventional construction methods without extensive energy use onsite.

**Distribution of Embodied Carbon in A1 to A5 Life cycle stages**

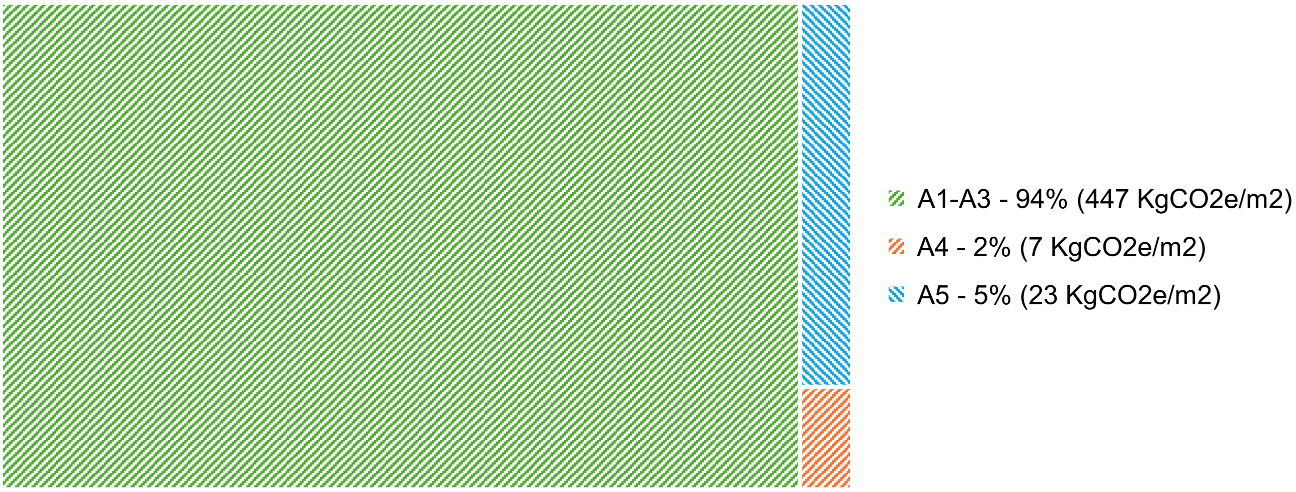



*Figure 36 Distribution of Embodied Carbon in A1 to A5 Life cycle stages, (EMC) office building*

The substructure and structural frame emerged as the most carbon-intensive building elements. Foundations alone contributed 214 $KgCO_2e$ /m², primarily due to the high volume of reinforced concrete used below ground. The structural frame contributed a further 123 $KgCO_2e$ /m², which included slabs, columns, and beams. Internal partitions, finishes, and facade systems had moderate contributions, reflecting typical material application in a G+1 office building with limited envelope complexity.

## Structural Elements wise % Distribution of Embodied Carbon

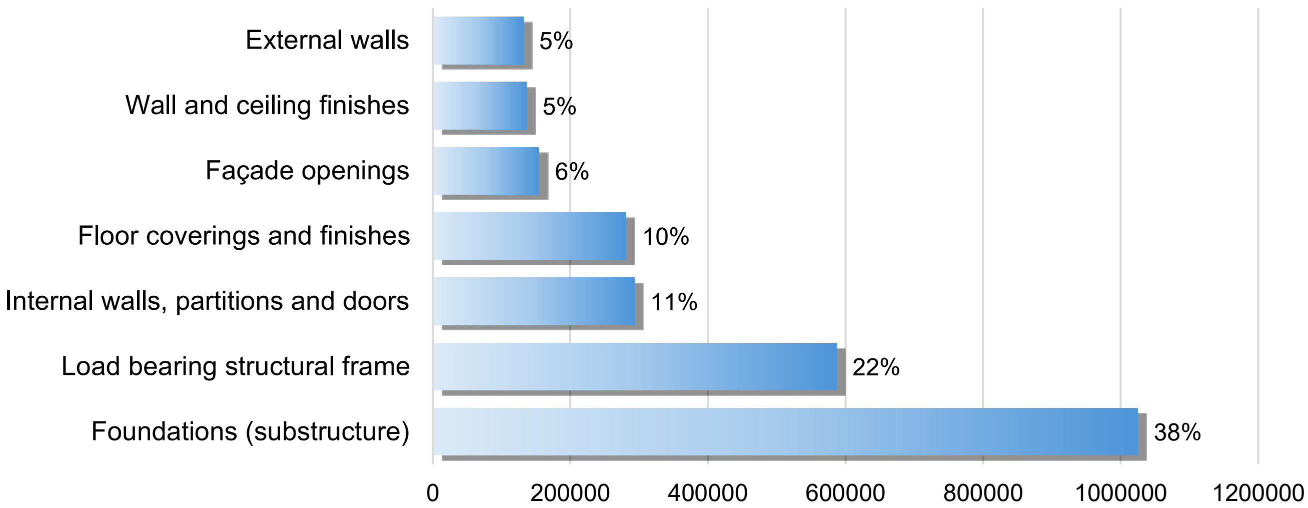



*Figure 37 Structural Elements wise % distribution of total Embodied Carbon (EMC) office building*

The top five materials by embodied carbon were ready-mix concrete for walls and floors (157 $KgCO_2e/m^2$), reinforcement steel (144 $KgCO_2e/m^2$), cement (104 $KgCO_2e/m^2$), CMU blocks (60 $KgCO_2e/m^2$), and tiles (34 $KgCO_2e/m^2$). Together, these accounted for over 90% of the total material-related emissions. The absence of significant low-carbon material substitutions or optimizations suggests an opportunity to reduce emissions in future phases or similar projects by exploring blended cements, recycled aggregates, or material efficiency in structural design.

## Materials Wise Embodied Carbon Distribution (Kgco2e/m2)

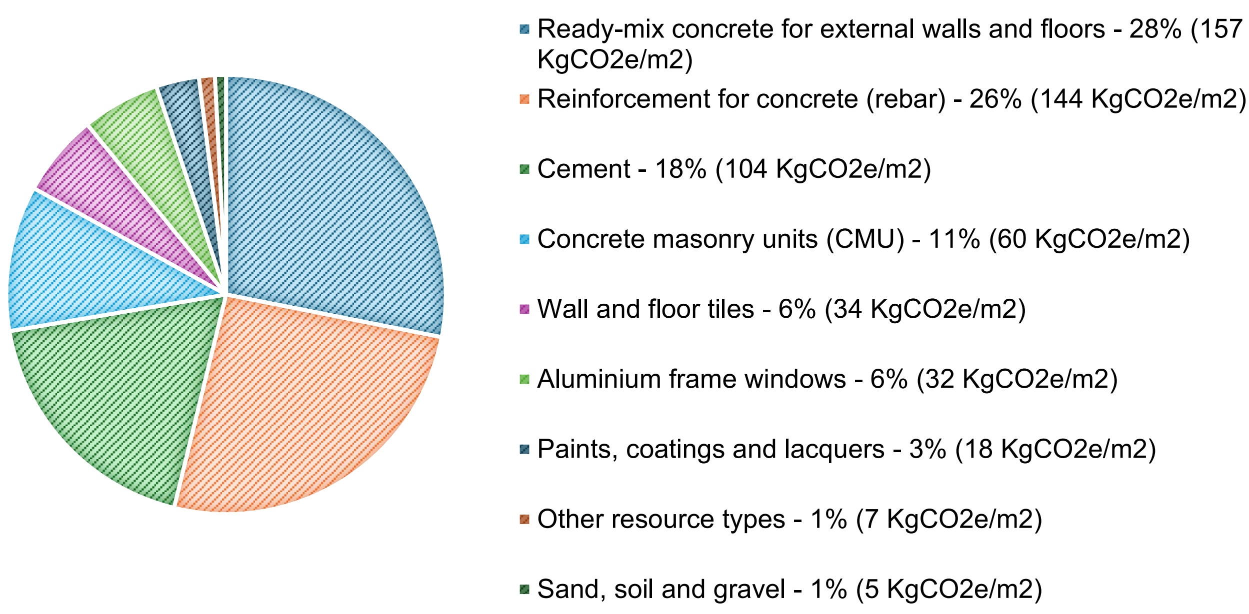



*Figure 38 Materials Wise Embodied Carbon Distribution (Kgco2e/m2) (EMC) office building*

## B. Commercial Building (Office) – Infosys, Pune, Maharashtra

### Overview

Infosys, Pune is a G+5 commercial office facility located in Maharashtra, with a built-up area of 28,111 m². The building is situated in a warm and humid climatic zone and falls under Seismic Zone II. The WLCA covers life cycle stages A1–A3 (product stage), A4 (transportation), and A5 (construction). As a large-scale office development, it provides a representative case for carbon performance in institutional commercial campuses in this regional and climatic context.

| Parameter | Details |
|---|---|
| **Name of the project** | Infosys Pune |
| **Building Typology** | Commercial Office |
| **Total Number of Floors** | G+5 |
| **Built-up Area (m²)** | 28,111 |
| **LCA Stages Included** | A1–A3, A4, A5 |
| **Climate** | Warm & Humid |
| **Seismic Zone** | III |

### Results

The total upfront embodied carbon for Infosys, Pune is estimated at 16,527,581 $KgCO_2e$ /m², corresponding to **588 $KgCO_2e$ /m².** The emissions are largely concentrated in the product stage (A1–A3), which contributes 95% of the total impact (560 $KgCO_2e$ /m²). Construction (A5) and transportation (A4) contribute 3% (17 $KgCO_2e$ /m²) and 2% (12 $KgCO_2e$ /m²), respectively. These figures are typical for a commercial RCC structure with significant material intensity.

Material-wise, the largest contributor is reinforcement and structural steel, responsible for 31% (182 $KgCO_2e$ /m²), followed closely by concrete (M10 and others) at 30% (176 $KgCO_2e$ /m²). Aluminium frames and AAC blocks contribute 12% (129 $KgCO_2e$ /m²) and 5% (53 $KgCO_2e$ /m²), respectively, while glass (DGU) contributes 1% (53 $KgCO_2e$ /m²).

From a building element perspective, the frame (beams, columns, slabs) is the most emission-intensive component, contributing 51% (300 $KgCO_2e$ /m²), followed by vertical structures and façade at 34% (200 $KgCO_2e$ /m²) and foundations at 9% (53 $KgCO_2e$ /m²). Other systems and external site elements contribute modestly.

### Inferences

The majority of the building's embodied carbon—95%—is concentrated in the product stage (A1–A3), highlighting the significant emissions from material extraction and manufacturing. Construction (A5) and transport (A4) play a relatively minor role, collectively contributing just 5% of the total emissions.

Distribution of Embodied Carbon in A1 to A5 Life cycle stages

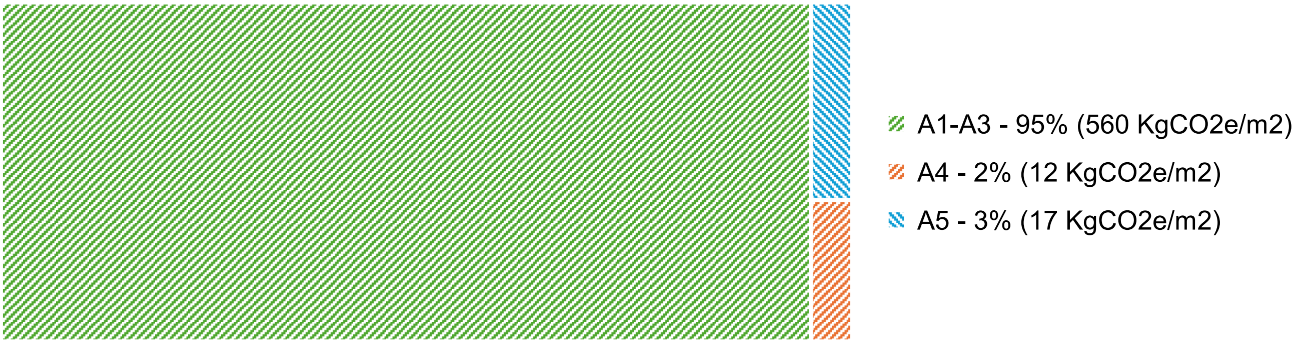



*Figure 39 Distribution of Embodied Carbon in A1 to A5 Life cycle stages*

Structural Element Insights: Structural elements dominate the carbon profile, with the frame contributing more than half the total emissions (300 Kg$CO_2$e /m², 51%) due to its extensive use of reinforced concrete. The vertical structures and façade add another 200 Kg$CO_2$e /m² (34%), while foundations contribute 53 Kg$CO_2$e /m² (9%). These findings align with the building's scale and structural requirements for commercial occupancy.

Structural Elements wise % Distribution of Embodied Carbon

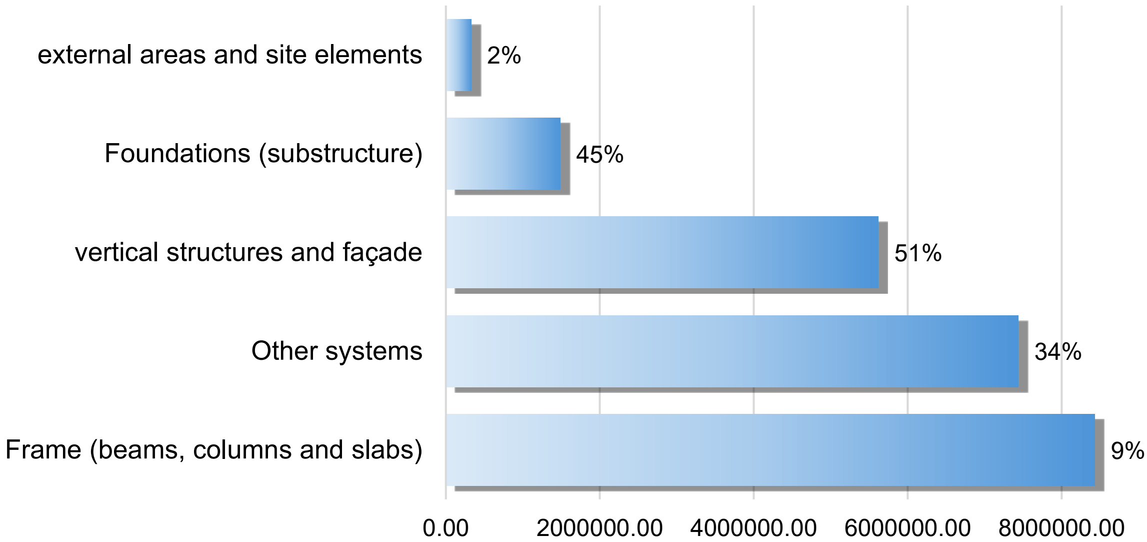



*Figure 40 Structural Elements wise % distribution of total Embodied Carbon*

Material-Level Insights: Five materials account for over 80% of total emissions:

- Steel (rebars + structural) – 182 Kg$CO_2$e /m² (31%)
- Concrete (M10) – 176 Kg$CO_2$e /m² (30%)
- Aluminium frames – 129 Kg$CO_2$e /m² (12%)
- AAC blocks – 53 Kg$CO_2$e /m² (5%)
- Glass DGU – 53 Kg$CO_2$e /m² (1%

These materials, particularly steel and concrete, are consistent high-impact contributors across large RCC commercial buildings. Design-level interventions aimed at reducing their intensity or substituting with lower-carbon alternatives can yield significant carbon savings

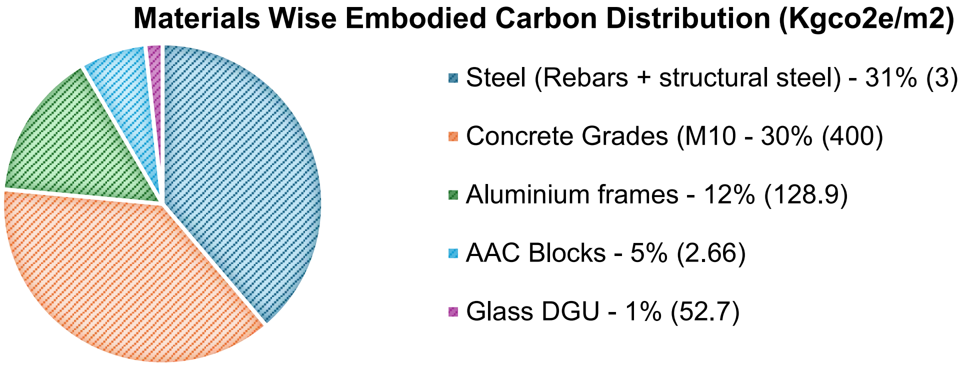



*Figure 41 Materials Wise Embodied Carbon Distribution (Kgco2e/m2)*

## C. Residential Building – Sawanand Apartments, Pune, Maharashtra

### Overview

Sawanand Apartments is a stilt plus six-storey residential complex located in Pune, Maharashtra, situated in Seismic Zone II and a warm-humid climatic region. The project has a total built-up area of 1,858 m² and was evaluated across life cycle stages A1–A3 (product stage), A4 (transport), and A5 (construction). As a typical mid-rise residential development, the building features an RCC frame structure with AAC block masonry, standard floor finishes, and PVC-framed windows. The assessment aimed to quantify embodied carbon impacts during early construction stages and identify major contributing elements and materials for potential design optimization.

| Parameter | Details |
|---|---|
| **Name of the project** | Sawanand Apartments |
| **Building Typology** | Residential |
| **Total Number of Floors** | S+6 |
| **Built-up Area (m²)** | 1,858 |
| **LCA Stages Included** | A1–A3, A4, A5 |
| **Climate** | Warm and Humid |
| **Seismic Zone** | III |

### Results

The upfront embodied carbon emissions of the Sawanand Apartments project were estimated at 456 Kg$CO_2$e /m², with the largest share of emissions concentrated in the product stage (A1–A3), which contributed 421 Kg$CO_2$e /m² (93%). Construction-related emissions (A5) accounted for 25 Kg$CO_2$e /m² (6%), while transportation (A4) contributed 11 $KgCO_2e$ /m² (3%), reflecting typical patterns observed in small-scale urban residential developments.

The most carbon-intensive structural element was the RCC frame (beams, columns, and slabs), responsible for 188 $KgCO_2e$ /m² (36%), closely followed by external walls at 187 $KgCO_2e$ /m² (36%), which included AAC blocks and concrete layers. Other significant contributors included floor coverings and finishes (46 $KgCO_2e$ /m²) and foundations (35 $KgCO_2e$ /m²), while roofs, façade openings, and internal walls collectively contributed around 8% of the total footprint.

At the material level, the highest contributor was ready-mix concrete used in external walls and floors, accounting for 128 $KgCO_2e$ /m² (25%), followed closely by AAC blocks (125 $KgCO_2e$ /m², 24%) and reinforcement steel (119 $KgCO_2e$ /m², 23%). Other materials with notable contributions included cement (72 $KgCO_2e$ /m², 14%), tiles (21 $KgCO_2e$ /m², 4%), and PVC frame windows (13 $KgCO_2e$ /m², 2%). Collectively, the top five materials contributed more than 90% of total embodied emissions.

## Inferences

The life cycle stage analysis shows that A1–A3 dominated with 93% of total emissions, confirming that embodied carbon is largely driven by material manufacturing and processing in residential buildings of this typology. The construction stage (A5) and transport (A4) contributed a combined 9%, aligning with industry patterns for mid-rise concrete structures located in urban environments with short material sourcing distances.

**Distribution of Embodied Carbon in A1 to A5 Life cycle stages**

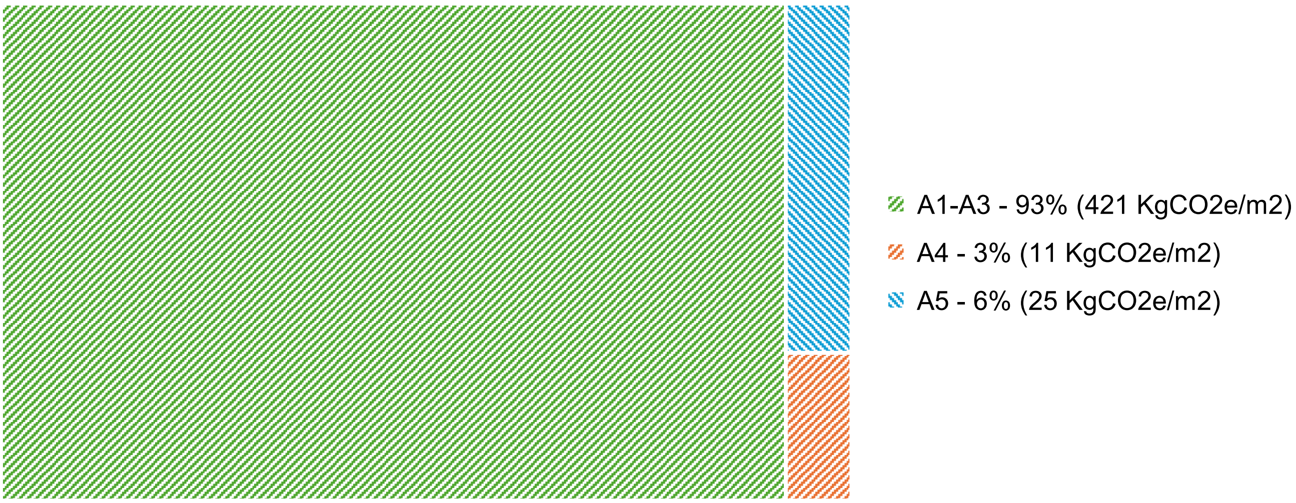



*Figure 42* ***Distribution of Embodied Carbon in A1 to A5 Life cycle stages****, Sawanand Apartments, Pune, Maharashtra*

In terms of structural composition, the RCC frame and external walls emerged as the two most carbon-intensive elements, each contributing 36% of the total footprint. The RCC frame's high impact was due to the large volume of concrete and reinforcement required for slabs and vertical supports, while the walls' contribution reflects extensive use of AAC blocks and cement-based finishes. Substructure elements and interior finishes were secondary contributors, with the roof, partitions, and facade openings contributing modestly.

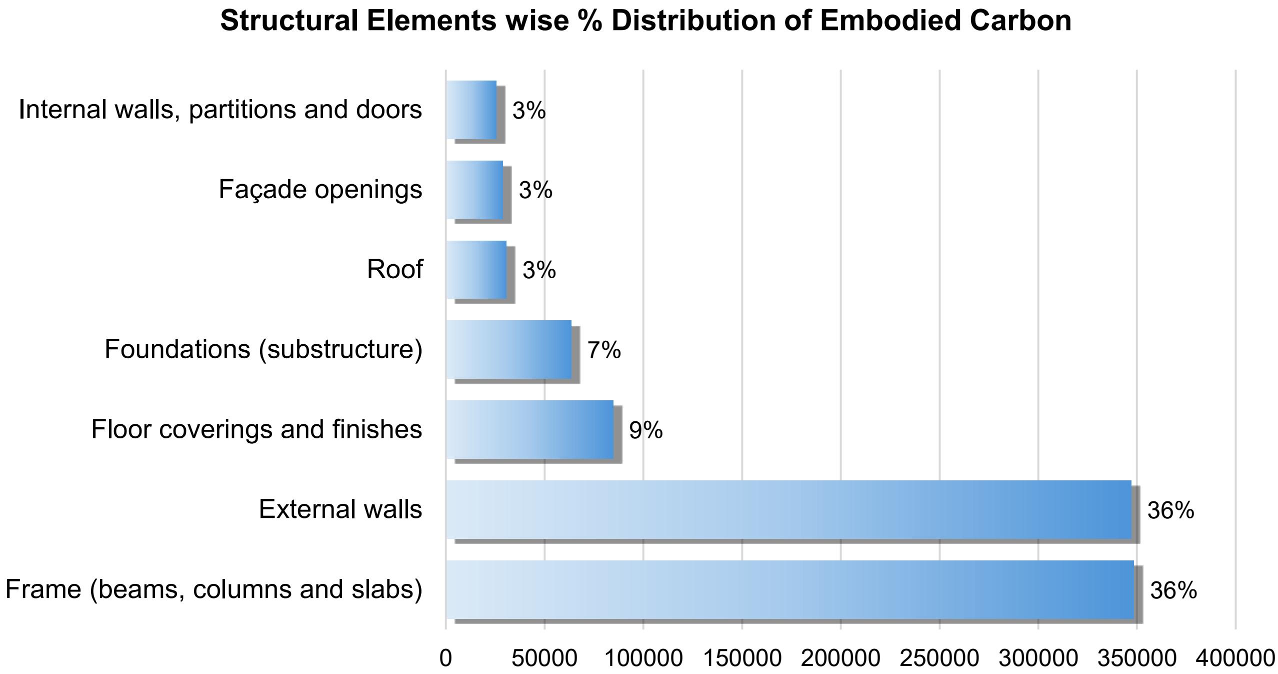



*Figure 43 Structural Elements wise % distribution of total Embodied Carbon, Sawanand Apartments, Pune, Maharashtra*

The five highest emitting materials were ready-mix concrete (128 Kg$CO_2$e /m²), AAC blocks (125 Kg$CO_2$e /m²), reinforcement steel (119 Kg$CO_2$e /m²), cement (72 Kg$CO_2$e /m²), and tiles (21 Kg$CO_2$e /m²). These materials alone accounted for more than 85% of the building's total embodied emissions. Despite the use of AAC blocks—often perceived as a low-carbon alternative—the overall carbon footprint remained high due to the combined mass and embedded emissions of cement-based materials and reinforcement. Future design strategies may benefit from material substitution, quantity optimization, or the integration of supplementary cementitious materials.

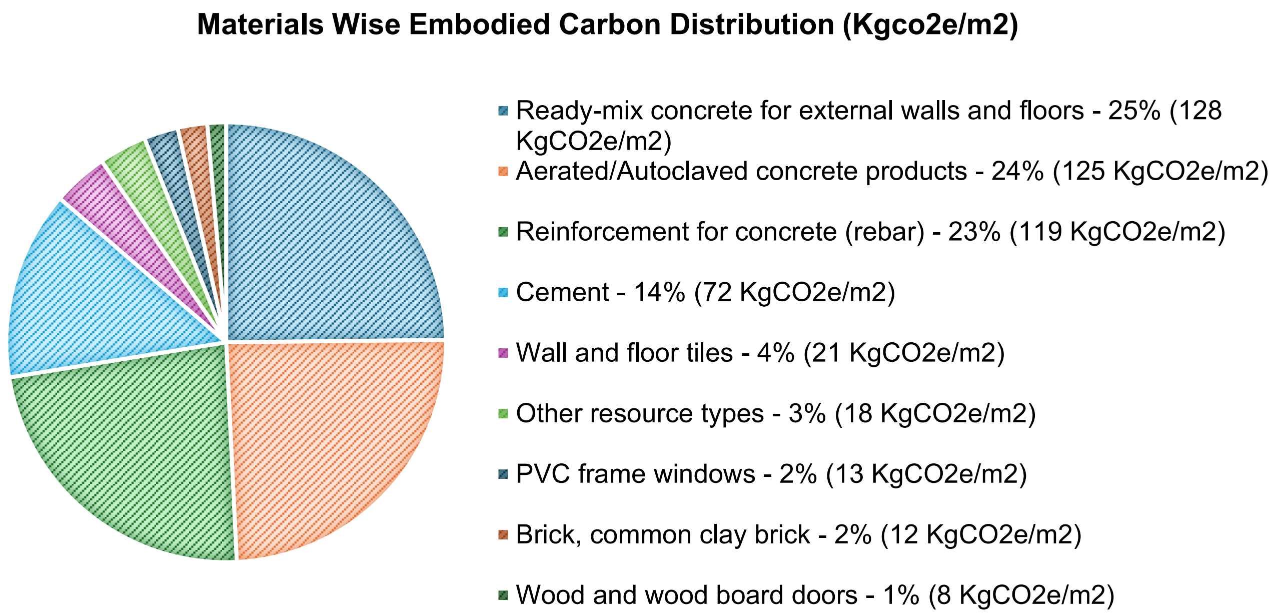



*Figure 44 Materials Wise Embodied Carbon Distribution (Kgco2e/m2), Sawanand Apartments, Pune, Maharashtra*

## D. Institutional Building (School) – PCMC Wakad School, Pune, Maharashtra

### Overview

PCMC Wakad School is a government educational facility located in Pune, Maharashtra, situated in Seismic Zone II and a warm-humid climatic region. This G+5 institutional building spans a built-up area of 14,824 m² and was analysed across life cycle stages A1–A3 (product stage), A4 (transport), and A5 (construction). Designed to accommodate large student populations, the structure follows a reinforced concrete frame system with concrete masonry walls, internal and external finishes, and PVC-framed fenestrations. The embodied carbon assessment provides insights into stage-wise emissions and the relative impact of building components and material systems.

| Parameter | Details |
|---|---|
| **Name of the project** | PCMC Wakad School |
| **Building Typology** | School |
| **Total Number of Floors** | G+5 |
| **Built-up Area (m²)** | 14,824 |
| **LCA Stages Included** | A1–A3, A4, A5 |
| **Climate** | Warm and Humid |
| **Seismic Zone** | III |

### Results

The total upfront embodied carbon for PCMC Wakad School is 5,143,647 $kgCO_2e$, corresponding to 347 $kgCO_2e/m^2$. The manufacturing and extraction stages (A1–A3) dominate the emissions profile at 4,721,225 $kgCO_2e$ or 319 $kgCO_2e/m^2$ (92%), while transportation of materials (A4) and construction processes (A5) contribute 12 $kgCO_2e/m^2$ (3%) and 17 $kgCO_2e/m^2$ (5%), respectively. This distribution aligns with expectations for a medium-rise, concrete-intensive institutional building.

At the material level, the five highest contributors are reinforcement steel (155 $kgCO_2e/m^2$, 35%), cement (65 $kgCO_2e/m^2$, 15%), ready-mix concrete for foundations and internal walls (59 $kgCO_2e/m^2$, 13%), concrete masonry units (CMU) (55 $kgCO_2e/m^2$, 12%), and paints, coatings, and lacquers (42 $kgCO_2e/m^2$, 9%). Other materials, including natural stone (20 $kgCO_2e/m^2$) and PVC frame windows (16 $kgCO_2e/m^2$), also contribute meaningfully to the overall footprint.

From a structural element perspective, the load-bearing structural frame is the largest contributor at 182 $kgCO_2e/m^2$ (41%), followed by external walls (74 $kgCO_2e/m^2$, 17%) and floor coverings and finishes (56 $kgCO_2e/m^2$, 13%). External paints and coatings contribute 36 $kgCO_2e/m^2$ (8%), while foundations account for 31 $kgCO_2e/m^2$ (7%). Wall and ceiling finishes, façade openings, and internal partitions contribute smaller shares, with minor contributions from the ground floor slab and other systems.

### Inferences

The lifecycle stage distribution confirms that A1–A3 manufacturing stages dominate, contributing 92% of the total embodied carbon, which is consistent with medium-rise school buildings in seismic Zone II constructed with conventional concrete and masonry systems. The relatively smaller contributions from A4 and A5 indicate limited emissions from material transport and on-site construction activities.

## Distribution of Embodied Carbon in A1 to A5 Life cycle stages

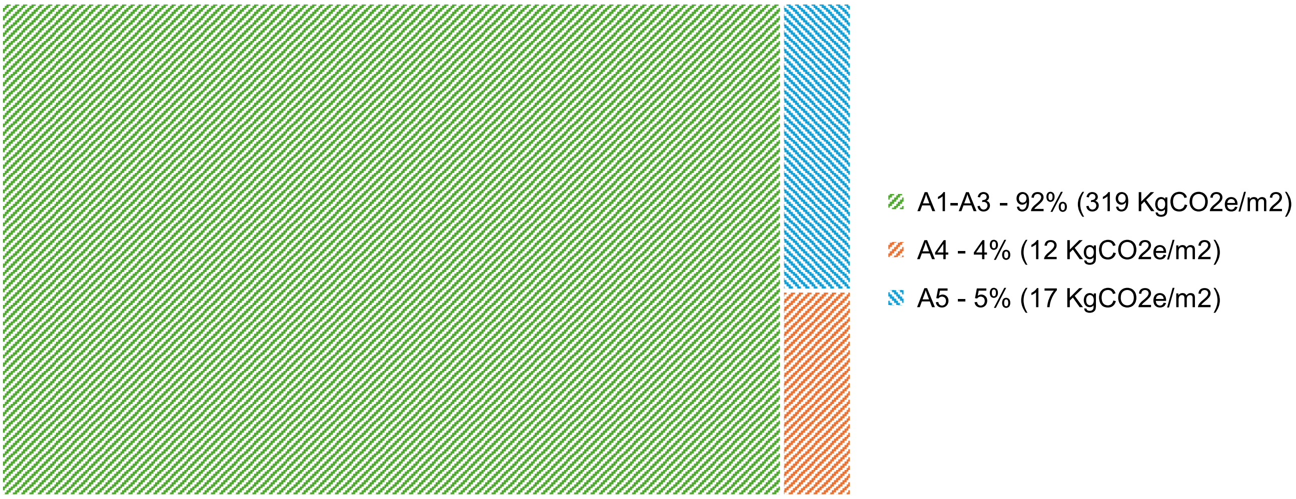



*Figure 45 Distribution of Embodied Carbon in A1 to A5 Life cycle stages, PCMC Wakad School,*

Structurally, the load-bearing frame and external walls together account for 256 $kgCO_2e/m^2$ (58%), highlighting the influence of primary structural and enclosure systems on the building's carbon footprint. Floor finishes, surface coatings, and wall/ceiling finishes add further contributions but remain secondary in the overall profile.

## Structural Elements wise % Distribution of Embodied Carbon

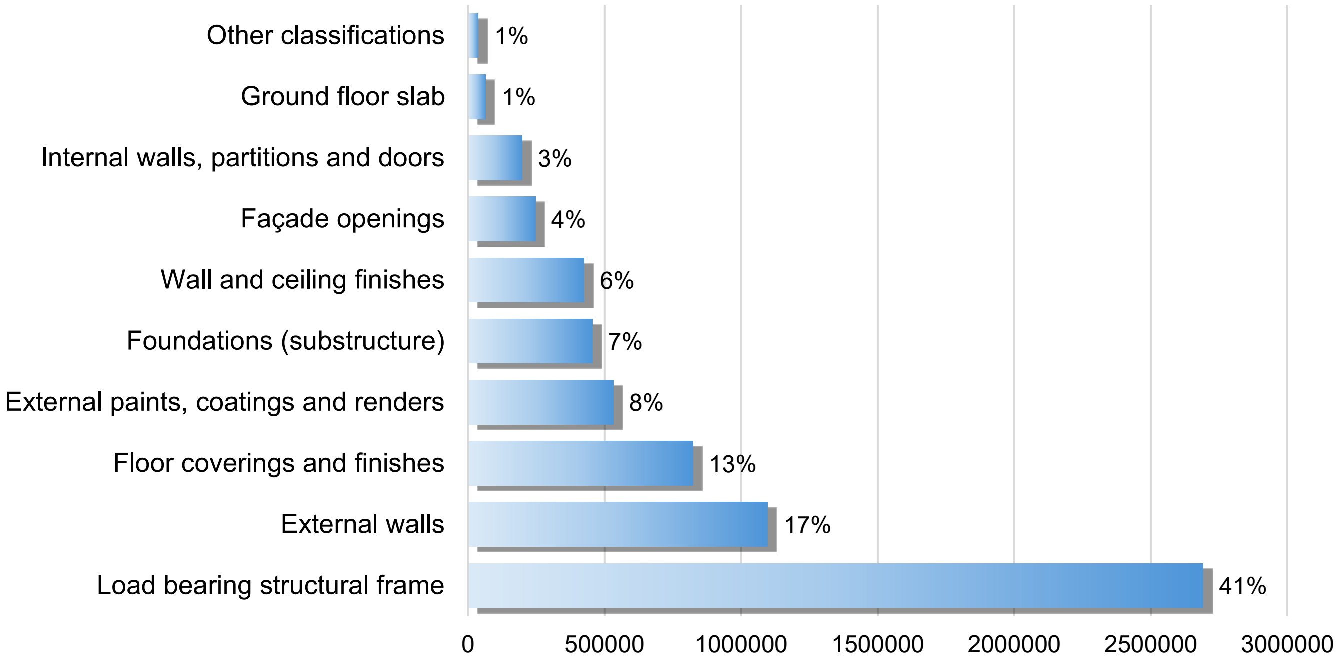



*Figure 46 Structural Elements wise % distribution of total Embodied Carbon , PCMC Wakad School.*

At the material level, reinforcement steel, cement, and concrete (including CMU and ready-mix concrete) collectively contribute 334 $kgCO_2e/m^2$ (96 $kgCO_2e/m^2$ more than secondary contributors), forming the majority of embodied carbon. This emphasizes the potential for carbon reductions through the use of low-carbon binders, blended cements, structural efficiency measures, and optimisation of wall and finish materials in similar institutional projects.

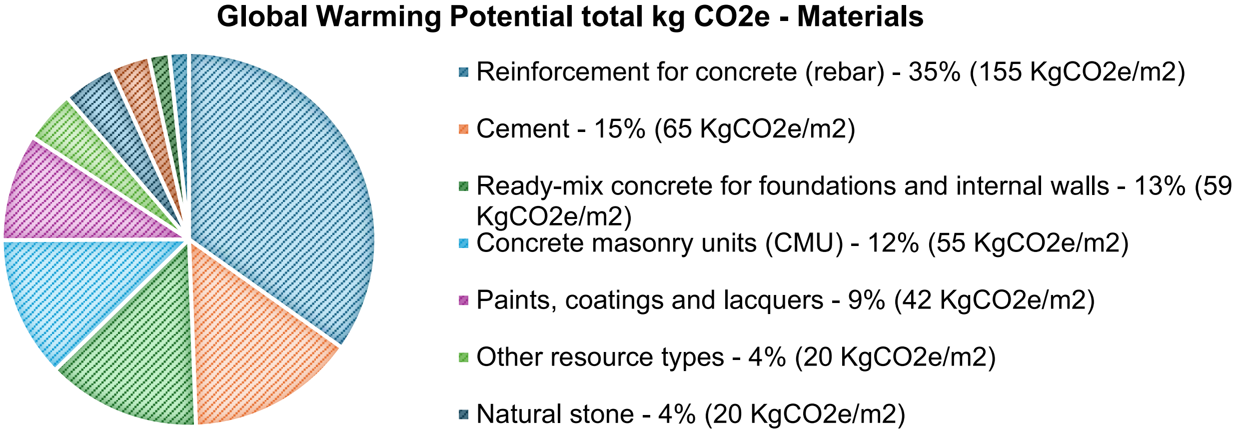



*Figure 47 Materials Wise Embodied Carbon Distribution (Kgco2e/m2) , PCMC Wakad School.*

## E. Industrial Building (Factory) – Advik Factory, Pune, Maharashtra

### Overview

Advik Factory is an industrial facility located in Pune, Maharashtra, falling under Seismic Zone II and situated in a warm-humid climate. This G+1 manufacturing building spans a built-up area of 6,832 m² and was evaluated for embodied carbon across life cycle stages A1–A3 (product), A4 (transport), and A5 (construction). The structure primarily comprises a steel frame system with extensive substructure works and minimal interior partitioning. Designed for heavy-duty industrial operations, the project integrates durable materials and robust finishes suited for factory functionality.

| Parameter | Details |
|---|---|
| **Name of the project** | Advik Factory |
| **Building Typology** | Factory |
| **Total Number of Floors** | G+1 |
| **Built-up Area (m²)** | 6,832 |
| **LCA Stages Included** | A1–A3, A4, A5 |
| **Climate** | Warm and Humid |
| **Seismic Zone** | III |

### Results

The upfront embodied carbon emissions for Advik Factory were estimated at 428 $KgCO_2e$ /m², with total emissions amounting to 2,920,365.51 $KgCO_2e$ /m² . The majority of emissions were concentrated in the product stage (A1–A3), contributing 397 $KgCO_2e$ /m² (93%), followed by construction activities (A5) at 17 $KgCO_2e$ /m² (4%), and transport (A4) at 15 $KgCO_2e$ /m² (3%). This distribution reflects the emissions-intensive material palette used in industrial buildings with extensive foundation and steel systems.

The substructure and foundation systems dominated element-wise emissions, contributing 389 $KgCO_2e$ /m² (78%), attributable to heavy-duty structural steel and reinforced concrete footings. Floor finishes (68 $KgCO_2e$ /m², 13%) and internal walls and doors (24 $KgCO_2e$ /m², 5%) followed, while façade openings and coatings made marginal contributions. Other components like stairs, site fuel, and the ground floor slab together accounted for less than 2%.

Material-wise, the building's carbon profile was heavily influenced by structural steel and steel profiles, which contributed 290 $KgCO_2e$ /m² (58%), highlighting their dominant role in both superstructure and foundation systems. This was followed by cement (99 $KgCO_2e$ /m², 20%) and natural stone (42 $KgCO_2e$ /m², 8%), both commonly used in industrial flooring and structural components. Metal doors (21 $KgCO_2e$ /m²), tiles (15 $KgCO_2e$ /m²), and sand/gravel (10 $KgCO_2e$ /m²) added incremental impacts, while lightweight components like paints, aluminium, and glass made up the remainder.

## Inferences

The emissions were highly concentrated in the product stage (A1–A3), accounting for 93% of the total embodied carbon. Transport and construction stages contributed only 3% and 4% respectively, consistent with the logistics and material handling processes of an urban factory site. The high A1–A3 impact confirms the emissions are driven primarily by the structural materials and foundational systems rather than site-related activities.

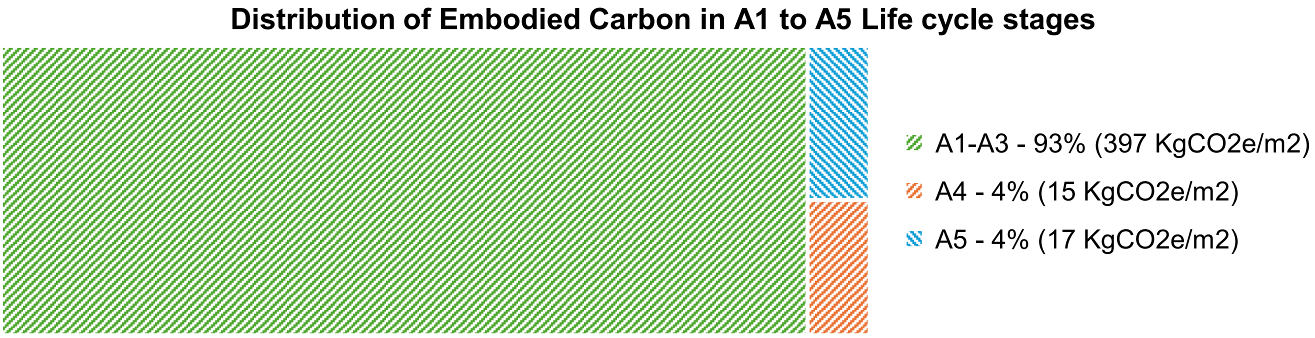



*Figure 48 Distribution of Embodied Carbon in A1 to A5 Life cycle stages, Advik Factory, Pune, Maharashtra*

Among the structural elements, foundations accounted for 78% of total emissions, due to the extensive use of steel and reinforced concrete to support heavy machinery and loading requirements. Finishes, internal partitions, and façade openings were responsible for only a small fraction of the overall footprint, as is typical for utilitarian industrial spaces with minimal interior demarcations.

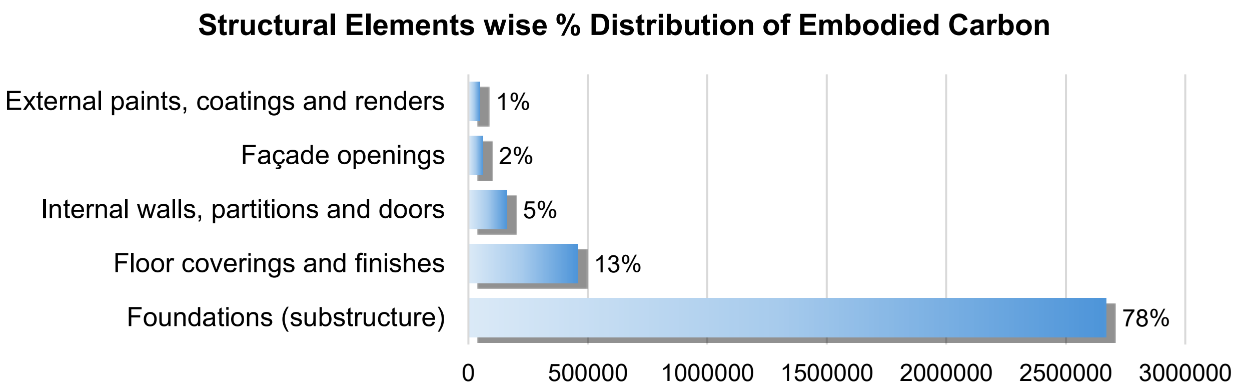



*Figure 49 Structural Elements wise % distribution of total Embodied Carbon, Advik Factory, Pune, Maharashtra*

Structural steel and steel profiles account for the largest share of embodied carbon at 58%, with an intensity of 290 $KgCO_2e$ /m². Cement follows at 20%, contributing significantly to the overall footprint due to its high usage and emission factor. Other materials like natural stone, metal doors, and tiles contribute smaller portions but still add up to the total environmental impact.

**Materials Wise Embodied Carbon Distribution (Kgco2e/m2)**

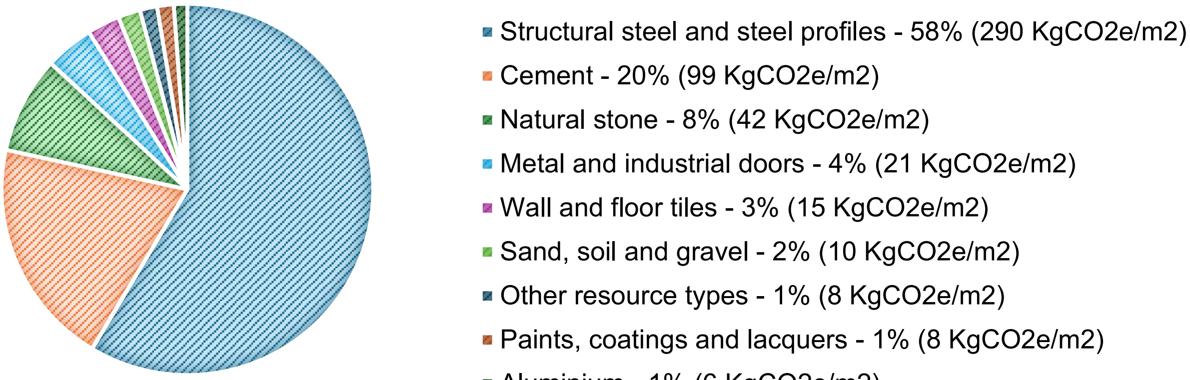



*Figure 50 Materials Wise Embodied Carbon Distribution (Kgco2e/m2) , Advik Factory, Pune, Maharashtra*

## IV. Hot and Dry Climate

### A. Institutional Building (Government Office) – Admin Building, Shri Govind Guru University, Godhra, Gujarat

#### Overview

Sri Govind Guru University – Admin Block, located in Godhra, is a government institutional facility comprising three floors (G+2) with a built-up area of 10,431 m². Situated in a hot and dry climate zone and seismic zone II, the building has been assessed for its whole life carbon performance across life cycle stages A1–A3 (product stage), A4 (transportation), and A5 (construction installation). The structure primarily employs reinforced concrete with common clay bricks and multiple ready-mix concrete mixes for various applications.

| Parameter | Details |
|---|---|
| **Name of the project** | Sri Govind Guru University – Admin Block |
| **Building Typology** | Institutional Building- Government office |
| **Total Number of Floors** | G+2 |
| **Built-up Area (m²)** | 10,431 |
| **LCA Stages Included** | Hot and Dry |
| **Climate** | A1–A3, A4, A5 |
| **Seismic Zone** | III |

#### Results

The upfront embodied carbon emissions for the project total 9,513,381 kg $CO_2e$, with an intensity of 913 kg $CO_2e$/m². The product stage (A1–A3) is the largest contributor at 92%, emitting 8,778,263 kg $CO_2e$ (842 kg

$CO_2e/m^2$). Transportation (A4) and construction (A5) stages contributed 3% and 5% respectively, amounting to 30 and 41 kg $CO_2e/m^2$. Among resource types, reinforcement steel emerged as the top contributor, responsible for 42% of total emissions (389 kg $CO_2e/m^2$), followed by ready-mix concrete for foundations (27%), clay bricks (15%), and additional concrete mixes for external and auxiliary elements. Structural classification data shows that foundations alone account for nearly half the building's emissions (49%, 464 kg $CO_2e/m^2$), highlighting their carbon intensity due to volume and material choices. The frame (beams, columns, slabs) contributed 35%, and external walls 12%, indicating a strong influence of core structure on embodied emissions.

## Inferences

Lifecycle Stages: The product stage (A1–A3) dominates the emission profile at 92%, which is typical for a building of this scale and typology, where the embodied impacts of raw material extraction and manufacturing are significant. Stages A4 and A5 collectively add just under 10%, reflecting average transport and construction practices for institutional projects in similar contexts.

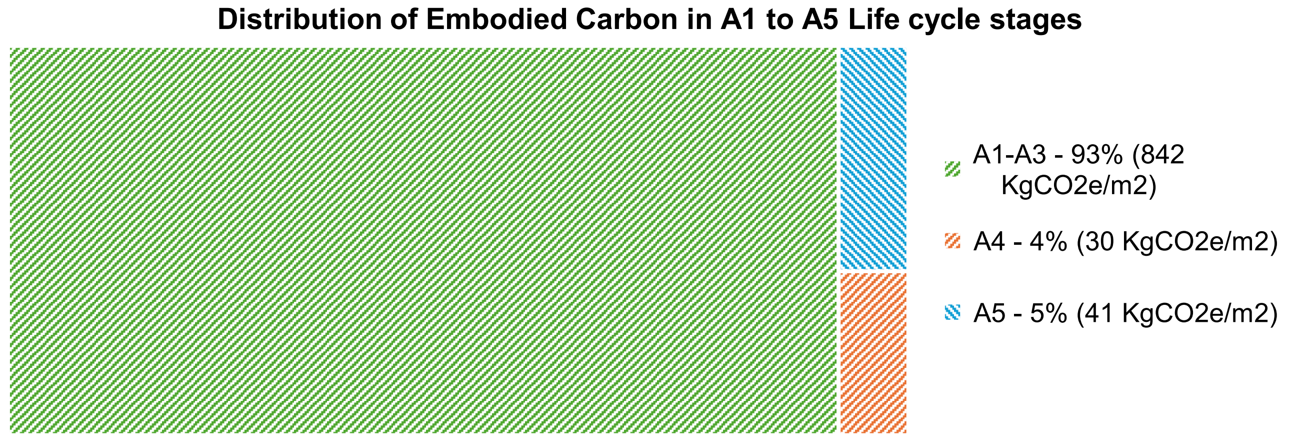



*Figure 51 Distribution of Embodied Carbon in A1 to A5 Life cycle stages, Sri Govind Guru University – Admin Block*

Structural Elements**:** The foundations were the most carbon-intensive structural element, contributing 49% of total emissions. This is attributed to extensive use of reinforced concrete and possibly deeper substructures needed for site-specific geotechnical stability. The load-bearing frame (beams, columns, slabs) was the second-highest contributor at 35%, reaffirming the impact of RCC systems in government infrastructure. External walls and facade systems, while contributing less in mass, still added 12% and 4% respectively due to the brick masonry and finishes.

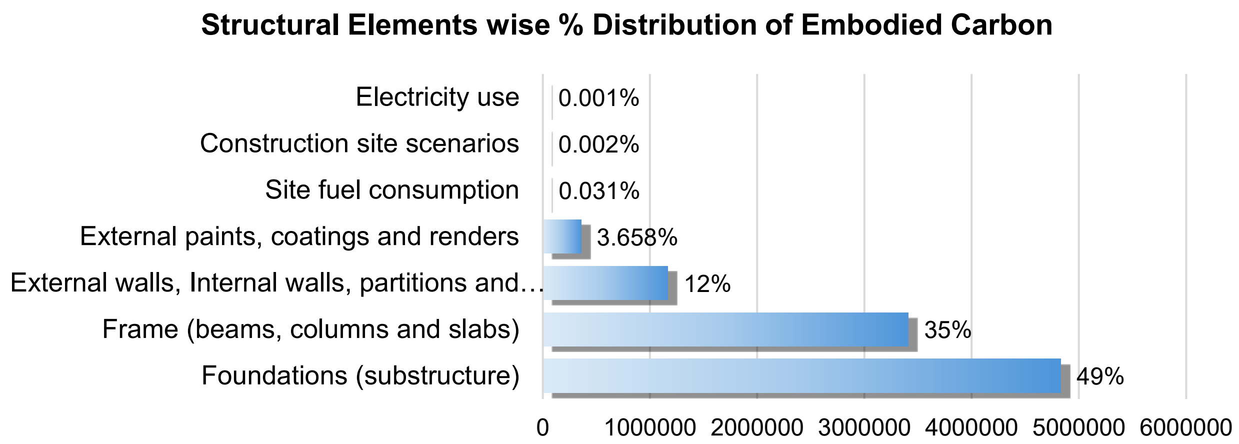



*Figure 52 Structural Elements wise % distribution of total Embodied Carbon, Sri Govind Guru University – Admin Block*

Materials: The top five materials contributing to embodied carbon were:

1. Reinforcement for concrete (rebar) – 42% (389 kg $CO_2$e/m²)
2. Ready-mix concrete for foundations and internal walls – 27% (255 kg $CO_2$e/m²)
3. Brick, common clay brick – 15% (145 kg $CO_2$e/m²)
4. Ready-mix concrete for external walls and floors – 11% (103 kg $CO_2$e/m²)
5. Lightweight concrete for auxiliary applications – 3% (31 kg $CO_2$e/m²)

The use of high-volume RCC and clay masonry significantly impacted the carbon profile, indicating opportunities for improvement through alternative low-carbon concrete mixes and resource-efficient wall systems.

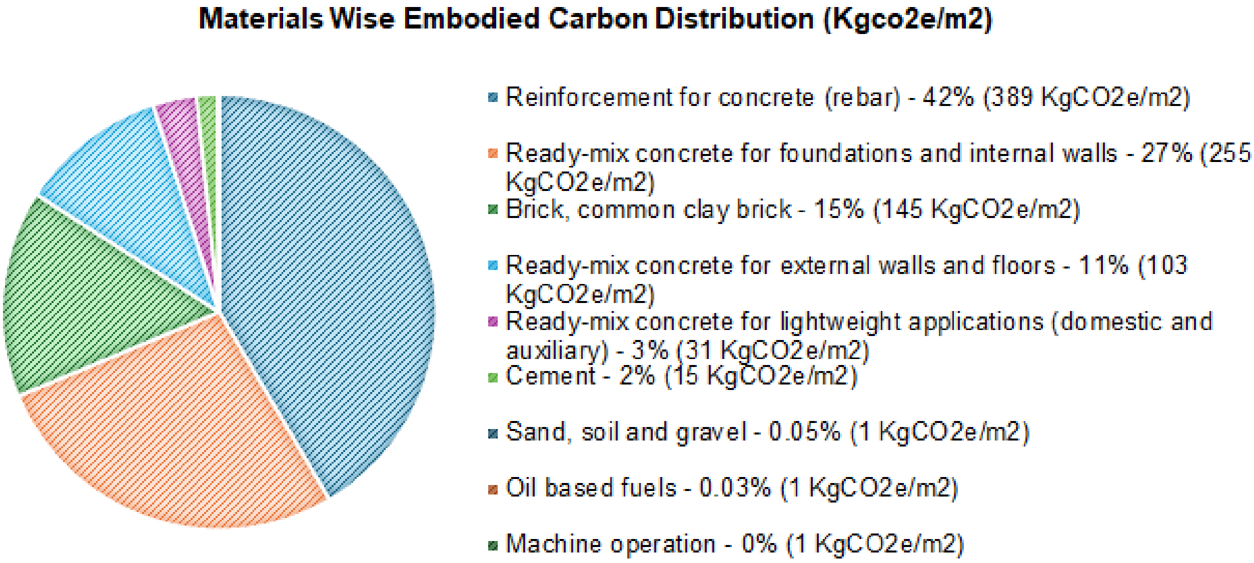



*Figure 53 Materials Wise Embodied Carbon Distribution (Kgco2e/m2) , Sri Govind Guru University – Admin Block*

## B. Commercial Building (Office) – Savvy Pragya, Gandhinagar, Gujarat

### Overview

Savvy Pragya is a commercial high-rise development located in Gandhinagar, Gujarat. The project comprises a ground floor and 24 upper floors, with a total built-up area of 51,306 m². Situated in a hot and dry climatic zone and Seismic Zone II, the project has been evaluated for whole life carbon impacts across modules A1–A3 (product stage), A4 (transportation), and A5 (construction installation).

| Parameter | Details |
|---|---|
| **Name of the project** | Savvy Pragya |
| **Building Typology** | Commercial Office |
| **Total Number of Floors** | G+24 |
| **Built-up Area (m²)** | 51,306 |
| **LCA Stages Included** | A1-A3, A4 , A5 |
| **Climate** | Hot & Dry |
| **Seismic Zone** | III |

## Results

The total upfront embodied carbon for Savvy Pragya is 25,950,556 kg$CO_2$e, corresponding to 506 kg$CO_2$e/m². The manufacturing stages (A1–A3) dominate the emissions profile at 24,244,904 kg$CO_2$e or 473 kg$CO_2$e/m² (93%), while transportation of materials (A4) and construction processes (A5) contribute 8 kg$CO_2$e/m² (2%) and 26 kg$CO_2$e/m² (5%), respectively. This distribution confirms the front-loaded nature of embodied carbon in high-rise commercial buildings with conventional RCC and concrete-intensive construction.

At the material level, the five highest contributors are reinforcement steel (190 kg$CO_2$e/m², 36%), ready-mix concrete for structural elements including beams, columns, and piling (114 kg$CO_2$e/m², 22%), ready-mix concrete for external walls and floors (57 kg$CO_2$e/m², 11%), cement (50 kg$CO_2$e/m², 9%), and glass façades and glazing (34 kg$CO_2$e/m², 6%). Additional contributions come from high-strength concrete (30 kg$CO_2$e/m², 6%) and aerated/autoclaved concrete products (24 kg$CO_2$e/m², 4%), reflecting the mix of structural and façade materials used in the high-rise design.

From a structural element perspective, the load-bearing structural frame is the largest contributor at 267 kg$CO_2$e/m² (51%), followed by foundations at 138 kg$CO_2$e/m² (26%), and floor coverings and finishes at 59 kg$CO_2$e/m² (11%). Façades contribute 34 kg$CO_2$e/m² (6%), internal walls, partitions, and doors add 24 kg$CO_2$e/m² (4%), while external paints, coatings, and renders contribute 3 kg$CO_2$e/m² (1%). Minor contributions arise from other systems, external walls, and stairs/ramps, each accounting for 1 kg$CO_2$e/m² or less.

## Inferences

The lifecycle stage distribution confirms that A1–A3 manufacturing stages dominate, accounting for 93% of the total embodied carbon, consistent with concrete- and steel-intensive commercial high-rises in seismic Zone II. The relatively small contributions from A4 and A5 indicate that material transport and on-site construction activities are limited compared to production emissions.

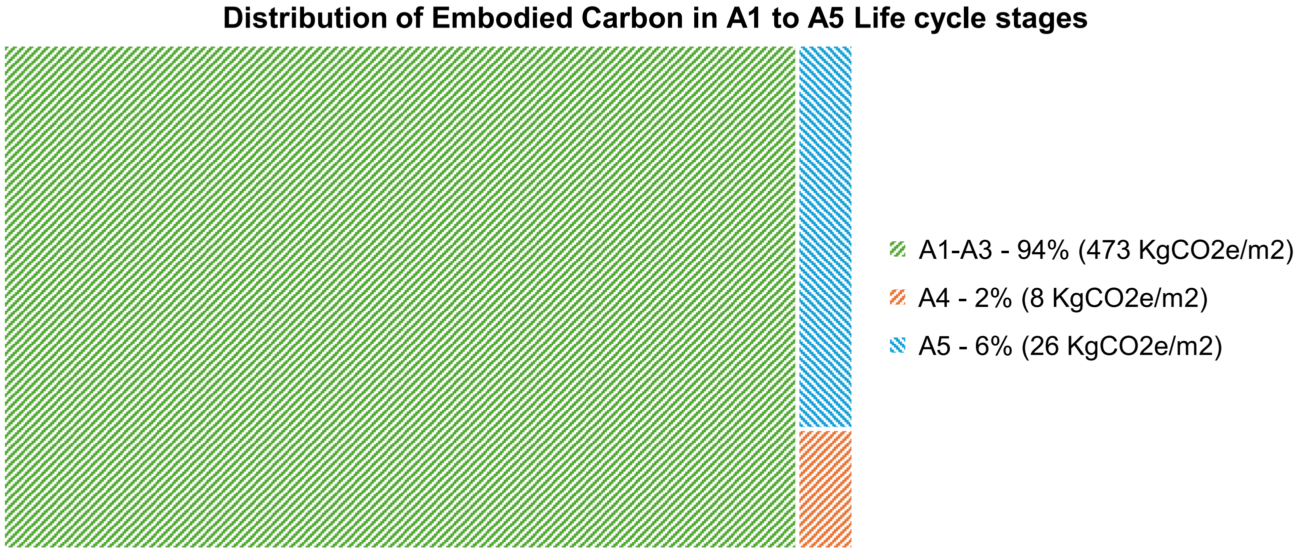



*Figure 54 Distribution of Embodied Carbon in A1 to A5 Life cycle stages, Savvy Pragya .*

Structurally, the combined impact of the load-bearing frame and foundations (405 kg$CO_2$e/m², 77%) highlights the influence of primary structural systems in determining the building's carbon footprint. Floor finishes and façades provide further contributions but remain secondary to the frame and substructure.

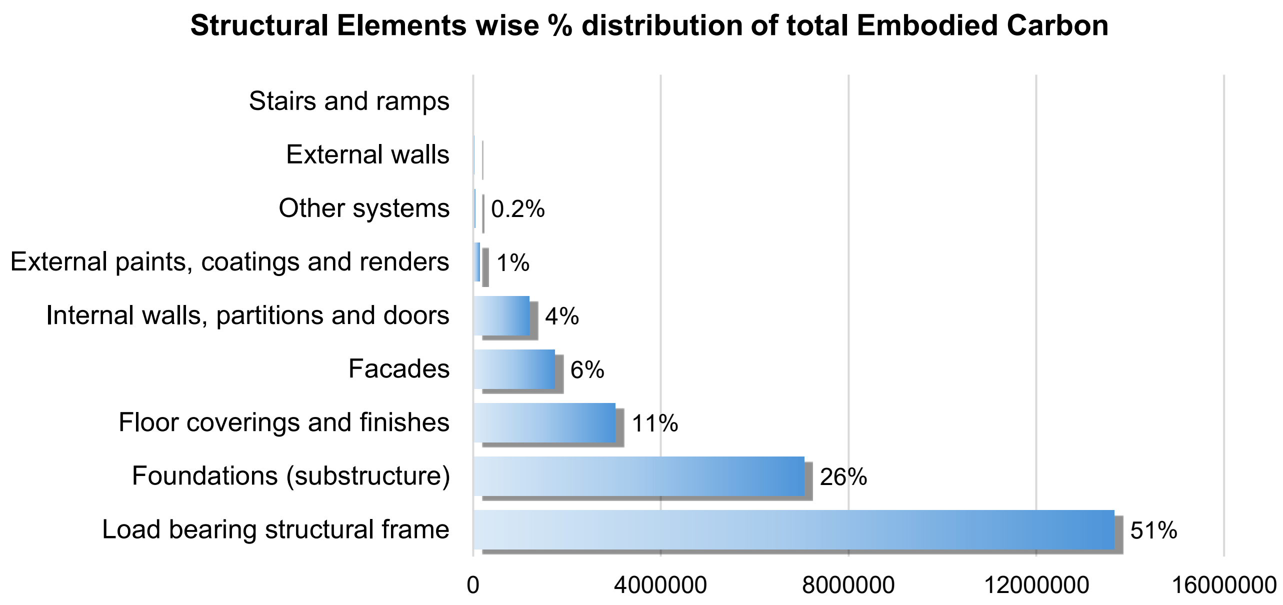



*Figure 55 Structural Elements wise % distribution of total Embodied Carbon, Savvy Pragya.*

At the material level, reinforcement steel, ready-mix concrete (structural and walls/floors), cement, and glass façades together contribute 445 $kgCO_2e/m^2$ (88%), defining the majority of the building's embodied carbon. These results indicate that targeted decarbonisation strategies could focus on optimised structural concrete mixes, high-recycled-content reinforcement, and efficient façade systems to achieve meaningful reductions in upfront carbon emissions without compromising structural performance or architectural functionality.

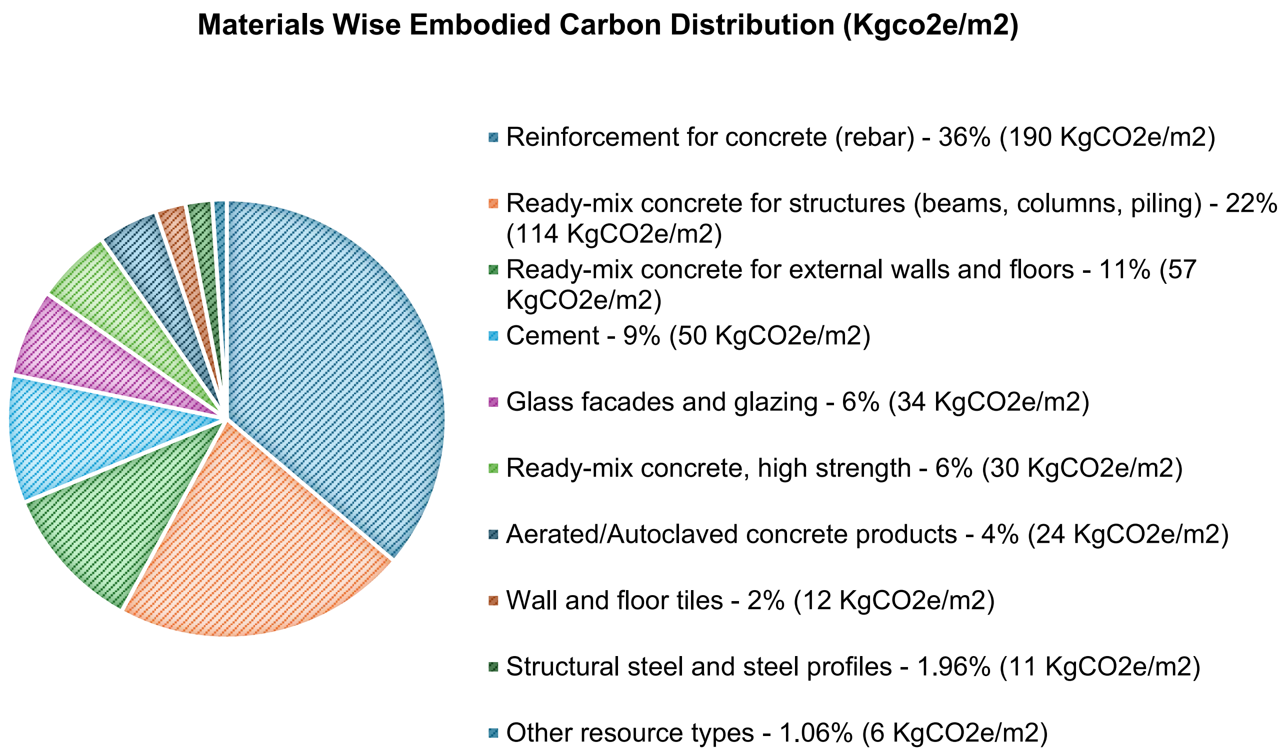



*Figure 56 Materials Wise Embodied Carbon Distribution (Kgco2e/m2 , Savvy Pragya.*

## C. Residential Building –Residential Tower, Gandhinagar, Gujarat

### Overview

Residential Tower is a high-rise residential development located in Gandhi Nagar, Gujarat, falling under Seismic Zone II and situated in a hot and dry climate zone. The building comprises G+ floors with a built-up area of 89,115 m². The Whole Life Carbon Assessment includes stages A1–A3, A4, and A5, focusing on product manufacturing, transportation, and construction installation phases.

| Parameter | Details |
|---|---|
| **Name of the project** | Residential Tower |
| **Building Typology** | Residential |
| **Total Number of Floors** | G+ 14 |
| **Built-up Area (m²)** | 89,115 |
| **LCA Stages Included** | A1–A3, A4, A5 |
| **Climate** | Hot & Dry |
| **Seismic Zone** | III |

### Results

The upfront embodied carbon emissions for Residential Tower amount to 49,779,008 $kgCO_2e$, translating to an intensity of 558 $kgCO_2e/m^2$. Of this, manufacturing emissions (A1–A3) dominate with 46,502,054 $kgCO_2e$, accounting for 93% of the total or 522 $kgCO_2e/m^2$. Transportation (A4) adds 956,993 $kgCO_2e$ (1.9%), equal to 11 $kgCO_2e/m^2$, while construction installation (A5) contributes 2,319,961 $kgCO_2e$ (4.7%), equal to 27 $kgCO_2e/m^2$.

At the material level, the single largest contributor is ready-mix concrete (high strength), at 23,494,153 $kgCO_2e$ (39%) or 264 $kgCO_2e/m^2$. This is followed by reinforcement steel (rebar) with 11,929,107 $kgCO_2e$ (20%), equal to 134 $kgCO_2e/m^2$, and wall finishes, insulation, and floor tiles with 8,811,844 $kgCO_2e$ (15%), equal to 99 $kgCO_2e/m^2$. Other significant contributors include cement for miscellaneous works (66 $kgCO_2e/m^2$, 10%), paints, coatings, and lacquers (48 $kgCO_2e/m^2$, 7%), aluminium (31 $kgCO_2e/m^2$, 4%), CMU (19 $kgCO_2e/m^2$, 3%), and PVC frame windows (8 $kgCO_2e/m^2$, 1%). Collectively, these nine categories account for almost the entirety of the material-related embodied carbon.

From the structural element perspective, the load-bearing structural frame is the highest contributor, with 26,606,030 $kgCO_2e$ (44%), translating to 299 $kgCO_2e/m^2$. Foundations contribute 13,675,456 $kgCO_2e$ (23%), or 154 $kgCO_2e/m^2$, while external walls add 9,863,665 $kgCO_2e$ (16%), equal to 111 $kgCO_2e/m^2$. Other notable contributors include stairs and ramps (53 $kgCO_2e/m^2$, 8%) and external paints, coatings, and renders (49 $kgCO_2e/m^2$, 7%). Smaller contributions come from floor finishes (9 $kgCO_2e/m^2$, 1%), façade openings (8 $kgCO_2e/m^2$, 1%), and marginal values from internal partitions, roofing, and site fuel consumption ($\leq$1 $kgCO_2e/m^2$ each).

### Inferences

Lifecycle stage analysis shows that manufacturing (A1–A3) dominates the embodied carbon profile, responsible for 93% of total upfront emissions. Transport (11 $kgCO_2e/m^2$, 2%) and installation (27 $kgCO_2e/m^2$, 5%) together account for less than 7%, underscoring that material production processes are the principal driver of carbon intensity in this project.

## Distribution of Embodied Carbon in A1 to A5 Life cycle stages

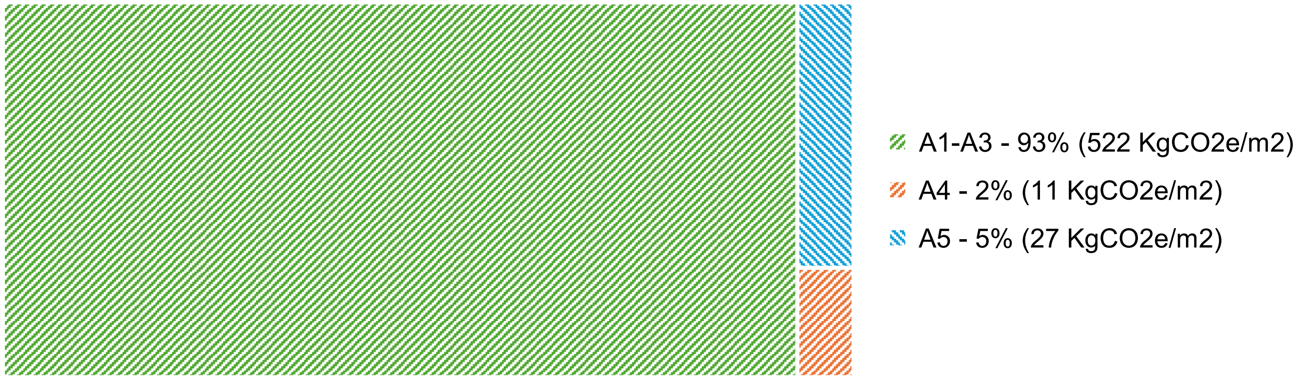



*Figure 57 Distribution of Embodied Carbon in A1 to A5 Life cycle stages, Westin Residential*

From the structural element perspective, the load-bearing frame and foundations together account for 67% of total emissions, highlighting the central role of RCC structures in determining the carbon profile of high-rise residential construction. External walls (16%), along with stairs and ramps (8%) and external coatings (7%), further emphasise the combined influence of structural and finishing components.

## Structural Elements wise % distribution of total Embodied Carbon

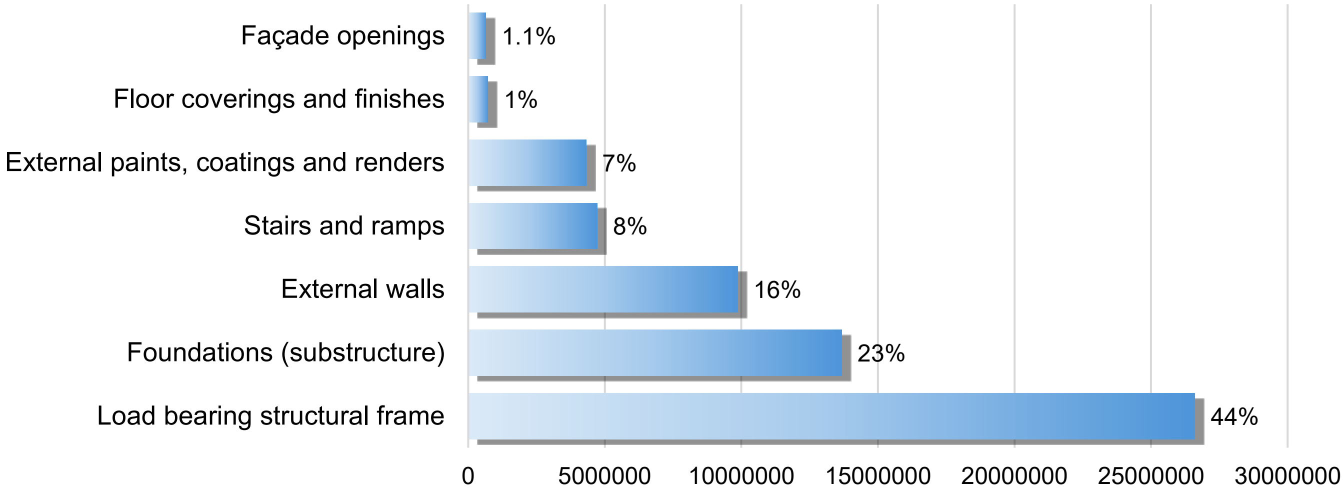



*Figure 58 Structural Elements wise % distribution of total Embodied Carbon, Westin Residential.*

At the material level, the top five contributors are:

- Ready-mix concrete (39%, 264 $kgCO_2e/m^2$)
- Reinforcement steel (20%, 134 $kgCO_2e/m^2$)
- Wall finishes, insulation, and tiles (15%, 99 $kgCO_2e/m^2$)
- Cement for miscellaneous works (10%, 66 $kgCO_2e/m^2$)
- Paints and coatings (7%, 48 $kgCO_2e/m^2$)

Together, these five categories make up over 90% of total emissions. This confirms that decarbonisation strategies must focus on reducing the footprint of concrete and cement through material efficiency and substitution, optimising steel use, and minimising the carbon intensity of finishes to achieve meaningful reductions.

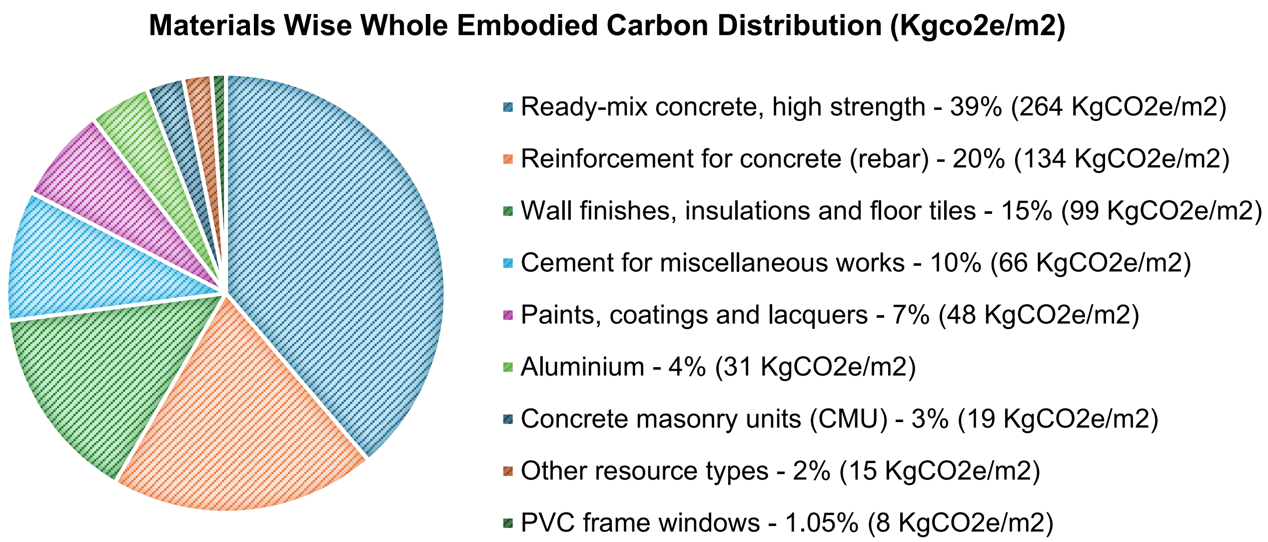



*Figure 59 Materials Wise Embodied Carbon Distribution (Kgco2e/m2) , Westin Residential.*

## D. Institutional Building (School) – Podar International School, Latur, Maharashtra

### Overview

Podar International School, located in Latur, is a G+3 educational facility with a built-up area of 6,485 m². Designed for a hot and dry climatic zone and situated in Seismic Zone II, the building was evaluated for its whole life carbon emissions covering life cycle stages A1–A3 (product stage), A4 (transport), and A5 (construction). The typology, structural design, and material choices reflect standard institutional construction methods, providing valuable insights into carbon emissions within the education sector in such climatic regions.

| Parameter | Details |
|---|---|
| **Name of the project** | Podar International School |
| **Building Typology** | School |
| **Total Number of Floors** | G+3 |
| **Built-up Area (m²)** | 6,485 |
| **LCA Stages Included** | A1-A3, A4 , A5 |
| **Climate** | Hot & Dry |
| **Seismic Zone** | III |

### Results

The total upfront embodied carbon for Podar International School amounts to 4,993,351 kg $CO_2$e, translating to **770 kg $CO_2$e/m².** The majority of emissions occur during the product stage (A1–A3), contributing 93% (720 kg $CO_2$e/m²), followed by 5% from construction (A5) and 2% from transportation (A4).

Material-wise, cement is the leading contributor, accounting for 37% (292 kg $CO_2$e/m²) of the emissions, followed by reinforcement steel (21%) and common clay bricks (18%). Among structural components, the frame (beams, columns, slabs) and foundations are the most emission-intensive, contributing 41% and 32%, respectively. This reflects a typical material-heavy load-bearing structure commonly used in institutional buildings across India.

## Inferences

Lifecycle Stage Insights: The embodied carbon is heavily concentrated in the product stage (A1–A3), which contributes 93% of the total emissions. This is consistent with cement-intensive construction in conventional RCC buildings. Construction-related activities (A5) contribute 5%, and transportation (A4) adds another 2%, indicating local sourcing of materials or efficient logistics.

**Distribution of Embodied Carbon in A1 to A5 Life cycle stages**

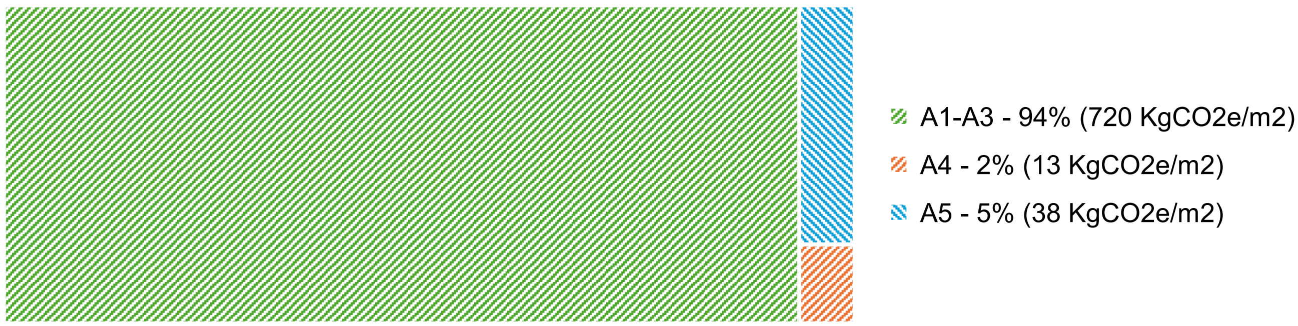



*Figure 60 Distribution of Embodied Carbon in A1 to A5 Life cycle stages, Podar International School*

Structural Element Insights: The frame and substructure are responsible for nearly three-fourths of the building's emissions. The frame alone contributes 321 kg $CO_2e/m^2$ (41%), driven by extensive use of RCC. Foundations follow closely at 250 kg $CO_2e/m^2$ (32%). These results highlight the carbon-intensive nature of reinforced concrete systems, especially in multi-storey buildings designed for institutional use.

**Structural Elements wise % distribution of total Embodied Carbon**

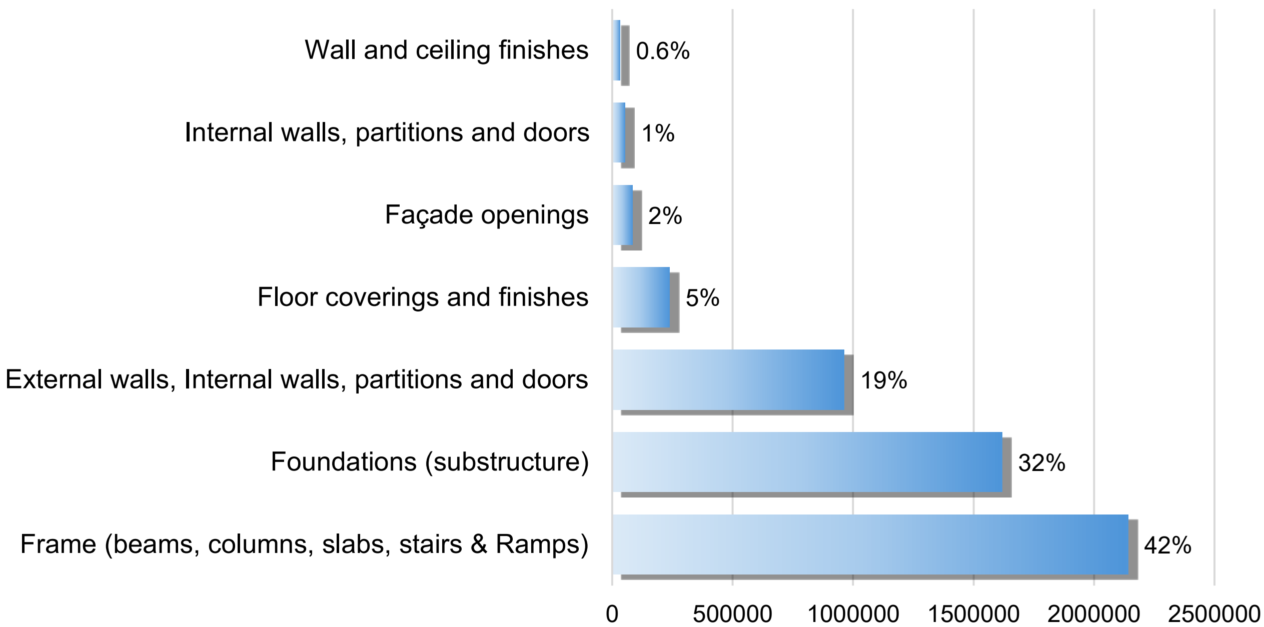



*Figure 61 Structural Elements wise % distribution of total Embodied Carbon, Podar International School*

Material-Level Insights: Cement (292 kg $CO_2e/m^2$), reinforcement steel (164 kg $CO_2e/m^2$), and clay bricks (142 kg $CO_2e/m^2$) dominate the material-related emissions. Together, they contribute over 75% of the building's GWP, underscoring the high-carbon profile of traditional masonry and RCC construction. Other materials such as tiles, aluminium windows, and glass contribute minimally, suggesting that emission reductions can be most effectively achieved by optimizing concrete, steel, and masonry usage.

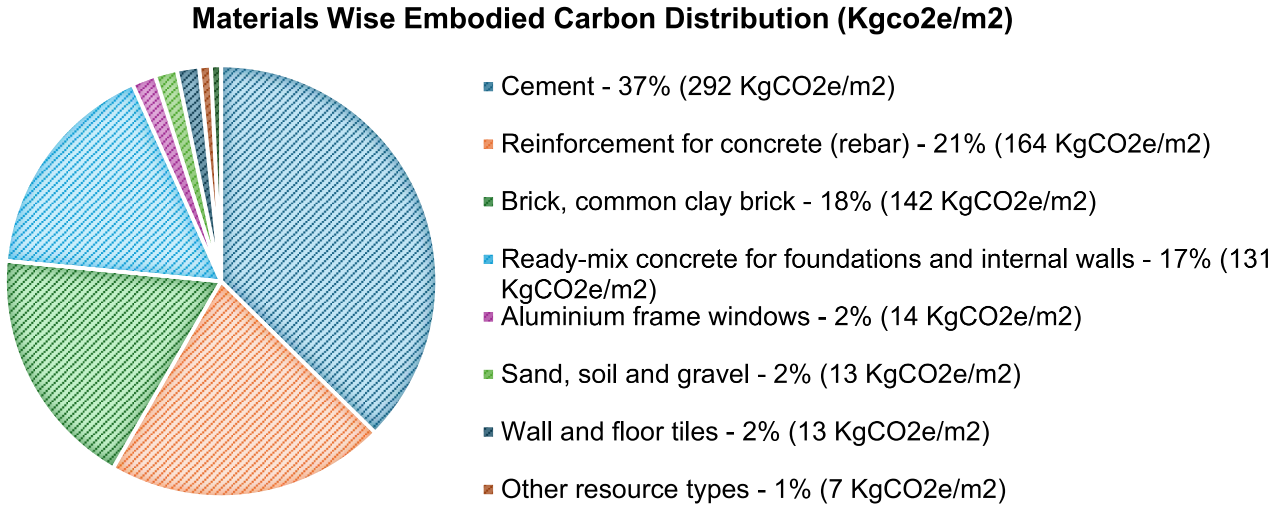



*Figure 62 Materials Wise Embodied Carbon Distribution (Kgco2e/m2) , Podar International School*

## E. Industrial Building (Factory) – Spirotech Heat Exchanger Factory, Bhiwadi, Rajasthan

### Overview

The Spirotech Heat Exchanger Factory is an industrial facility located in a hot and dry climate zone and falls within Seismic Zone II. The project consists of a ground floor and one upper floor (G+1), with a total built-up area of 13,858 m². The WLCA was carried out for life cycle stages A1–A3 (product stage), A4 (transport), and A5 (construction). The structural system primarily consists of reinforced concrete with a high proportion of lightweight concrete used for domestic and auxiliary areas, typical of factory typologies where floor and foundation robustness is prioritized to support heavy equipment and industrial loads.

| Parameter | Details |
|---|---|
| **Name of the project** | Spirotech Heat Exchanger Factory |
| **Building Typology** | Factory |
| **Total Number of Floors** | G+1 |
| **Built-up Area (m²)** | 13,858 m² |
| **LCA Stages Included** | A1–A3, A4, A5 |
| **Climate** | Hot and Dry |
| **Seismic Zone** | VI |

### Results

The upfront embodied carbon emissions for the Spirotech Heat Exchanger Factory amount to 5,625,425.93 kg $CO_2$e, resulting in a carbon intensity of 406 kg $CO_2$e/m². The majority of emissions stem from the product stage (A1–A3), which contributes 88% (356 kg $CO_2$e/m²). Transport emissions (A4) and construction emissions (A5) make up 8% (33 kg $CO_2$e/m²) and 5% (19 kg $CO_2$e/m²), respectively. Among resource types, ready-mix concrete used in lightweight domestic and auxiliary applications accounts for the highest share at 31% (140 kg $CO_2e/m^2$), followed by reinforcement steel (26%) and concrete used in foundations and internal walls (23%). Structural classification data shows that the foundations contribute 44% of total emissions (200 kg $CO_2e/m^2$), while the ground floor slab adds 33% (148 kg $CO_2e/m^2$) and the load-bearing frame contributes 13% (59 kg $CO_2e/m^2$). These results reflect the typical material load profile of a factory, with heavy-duty structural elements dominating the carbon footprint.

## Inferences

Lifecycle Stages**:** Stage A1–A3 dominates the emission profile at 88%, which aligns with the material-intensive nature of factory construction. The product stage's large contribution is due to the embodied carbon of ready-mix concrete and reinforcement materials. Transport and construction stages (A4 and A5) contribute 8% and 5%, respectively, and fall within expected values for industrial typologies located in regional production zones with standard construction practices.

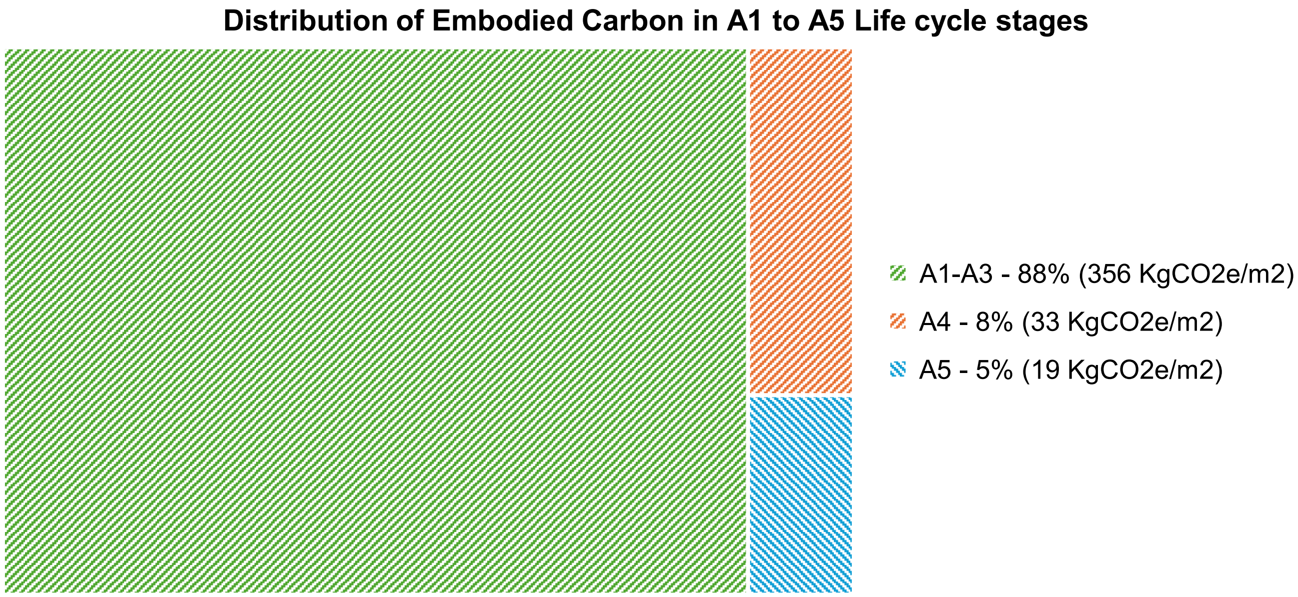



*Figure 63 Distribution of Embodied Carbon in A1 to A5 Life cycle stages, Spirotech Factory*

Structural Elements: Foundations are the most emission-intensive element, contributing 44% of the total emissions, owing to significant concrete volume and steel reinforcement to support factory loads. The ground floor slab follows with 33%, again reflecting the heavy-duty load-bearing role of floor systems in industrial buildings. The structural frame contributes 13%, and external walls and partitions together account for a smaller fraction of the total impact, consistent with open-plan factory design where enclosed space is minimal.

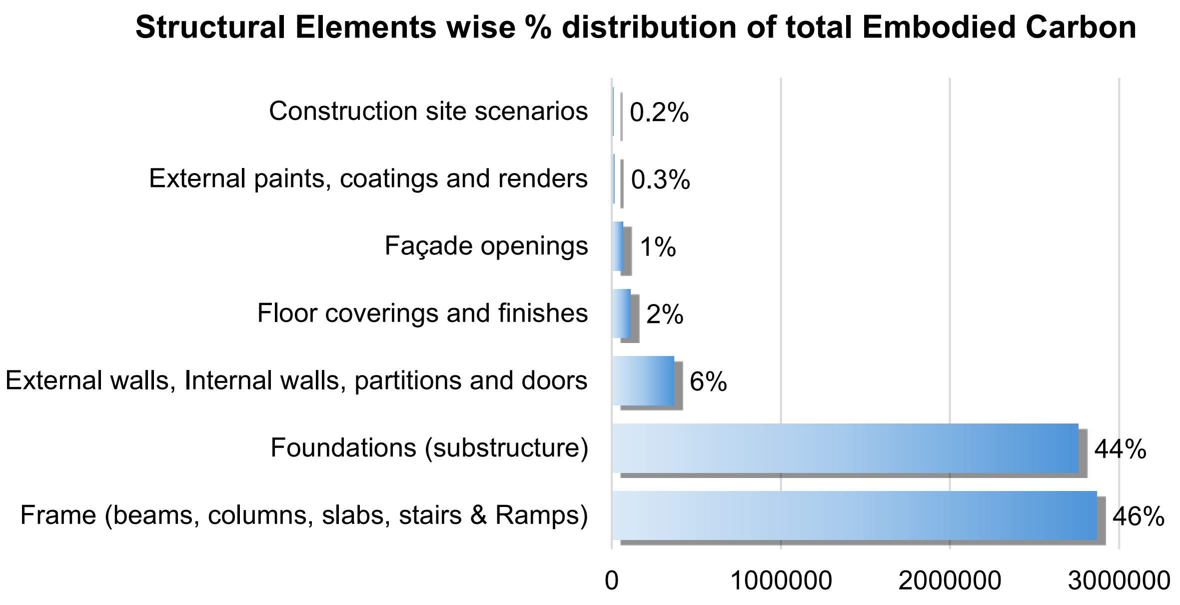



*Figure 64 Structural Elements wise % distribution of total Embodied Carbon , Spirotech Factory*

Materials: The top five material contributors to embodied carbon in this project are:

1. Ready-mix concrete (lightweight applications) – 31% (140 kg $CO_2e/m^2$)
2. Reinforcement for concrete (rebar) – 26% (117 kg $CO_2e/m^2$)
3. Ready-mix concrete for foundations and internal walls – 23% (104 kg $CO_2e/m^2$)
4. Plastic membranes – 5% (23 kg $CO_2e/m^2$)
5. Cement – 4% (18 kg $CO_2e/m^2$)

The high share of concrete across different applications and reinforcement steel drives most of the emissions, reinforcing the material-intensive nature of factory buildings. Plastic membranes and cement also contribute notably, likely due to moisture and durability treatments common in industrial environments.

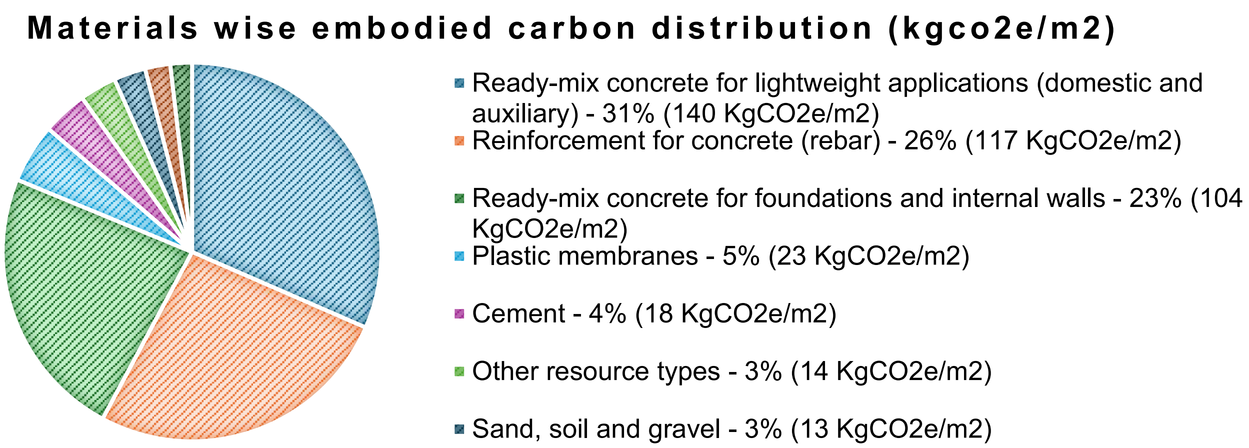


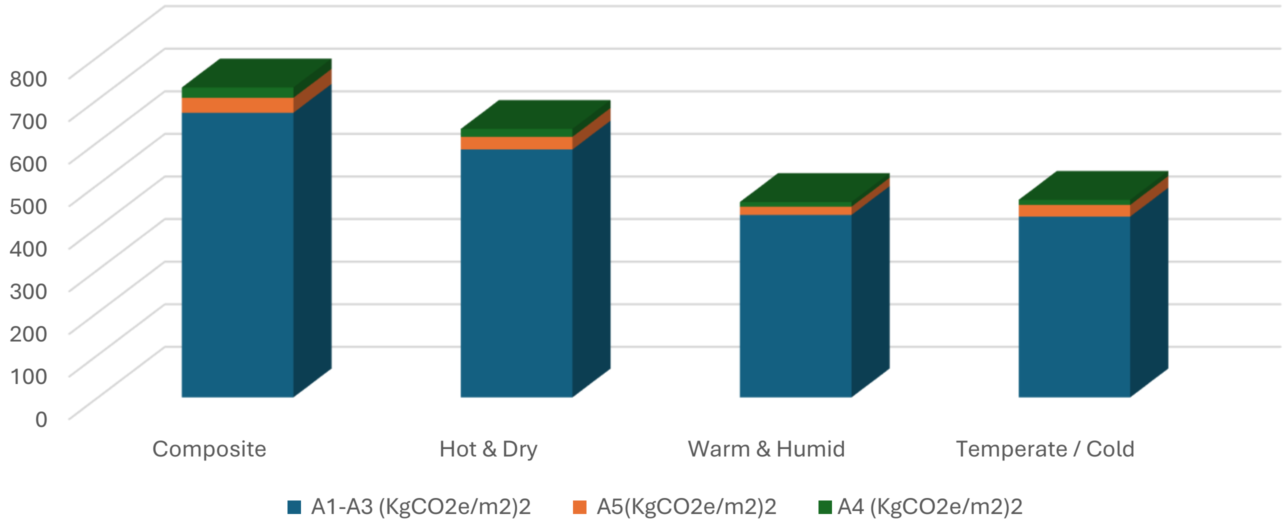

*Figure 65 Materials Wise Embodied Carbon Distribution (Kgco2e/m2) Spirotech Factory*

## 4.2 Comparative Analysis of Baseline Emissions

### I. Climate zone-wise

#### A. Lifecycle Stage Contribution Analysis by Climate

The lifecycle stage-wise distribution of embodied carbon across the four major climatic zones reveals marked differences in emissions intensity, particularly in the product stage (A1–A3).




| | Composite | Hot & Dry | Warm & Humid | Temperate/ Cold |
|---|---|---|---|---|
| **A1-A3 (KgCo2e/m2)** | 668 | 582 | 428 | 424 |
| **A4 (KgCo2e/m2)** | 35 | 30 | 19 | 27 |
| **A5(KgCo2e/m2)** | 24 | 19 | 11 | 12 |
| **A1 -A5(KgCo2e/m2)** | **728** | **630** | **459** | **464** |

*Figure 66 Climatic zone wise Lifecycle Stage Contribution Analysis, ($KgCO_2$ e /m²)*

- **Product Stage (A1–A3):**

  The Composite zone records the highest embodied carbon intensity at 728 $KgCO_2e/m^2$, driven by seismic design considerations—three of the five buildings fall under Seismic Zone IV—combined with extreme climatic variations and the use of material-intensive structural systems. The Hot & Dry zone follows closely at 630 $KgCO_2e/m^2$, where high emissions are primarily attributed to deeper foundations and reinforced frames necessitated by geotechnical conditions such as sandy and silty soils, along with seismic reinforcements typical of this region. Composite buildings are designed for both hot and cold extremes, heavy winds, and significant rainfall, driving greater use of reinforced concrete and structural steel. Warm & Humid and Temperate zones display lower values (428–424 $KgCO_2e/m^2$), reflecting more material-efficient construction and lower structural demands.

- **Transportation Stage (A4):**

  Emissions from transportation range from 19 to 35 $KgCO_2e/m^2$ and are largely independent of climate, instead reflecting supply chain distances and material sourcing logistics.

- **Construction Stage (A5):**

  Onsite construction emissions are modestly higher in Composite and Hot & Dry zones (24 and 19 $KgCO_2e/m^2$), reflecting more complex construction techniques and labour intensity due to seismic and climate resilience requirements.

In summary, Composite climatic conditions in India show higher embodied carbon, but as most buildings coincide with Seismic Zone IV, the influence of climate versus seismic design cannot be fully separated. Warm & Humid and Temperate zones offer benchmarks for efficient structural and material practices.

## B. Structural Element Emissions and Climate Responsiveness

Embodied carbon attributed to specific structural elements highlights how climatic and seismic conditions shape material intensity across zones.

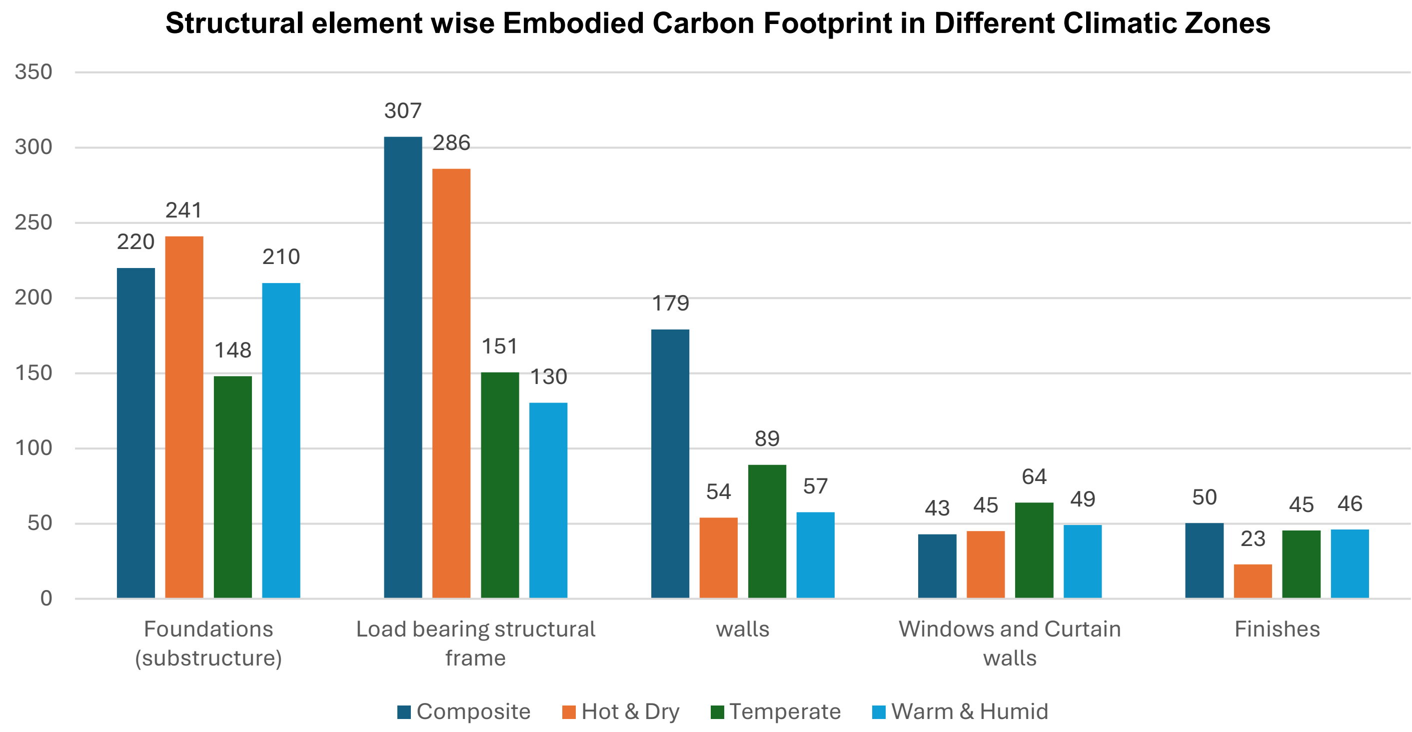



*Figure 67 Structural element wise Embodied Carbon Footprint in Different Climatic Zones ($KgCO_2$ e /m²)*

- In the Composite zone, frames (307 $KgCO_2e/m^2$) and walls (179 $KgCO_2e/m^2$) dominate, indicating heavy reliance on reinforced concrete and steel along with thick masonry systems. Foundations (220) and windows (43) further add to the load, while finishes (50) remain moderate. This profile reflects robust, all-round material use to address multiple stresses, including hot and cold extremes, heavy winds, and rainfall.
- In the Hot & Dry zone, foundations (241 $KgCO_2e/m^2$) and frames (286 $KgCO_2e/m^2$) together account for nearly 80% of total emissions. Most buildings in this zone fall under Seismic Zone IV and are located on sandy or silty soils, both of which demand deeper foundations and stronger structural

frames. These seismic and geotechnical drivers clearly outweigh purely climatic influences, making foundations the highest in this dataset.

- In the Temperate zone, windows and curtain walls (64 $KgCO_2e/m^2$) stand out, surpassing levels in other zones and reflecting design choices that prioritize openness and daylight. Frames (151) and

In the Warm & Humid zone, foundations (210 $KgCO_2e/m^2$) reflect adaptation to groundwater and moisture conditions. Frames (130), walls (57), and finishes (46) remain restrained, showing balanced construction suited to high-moisture environments.

## C. Material Carbon Footprint in Different Climatic Conditions

The embodied carbon footprint of buildings, which accounts for the greenhouse gas emissions associated with material extraction, manufacturing, transportation, and construction, is significantly influenced by the choice of materials and design strategies.

- **Hot & Dry and Cold Zones**: These zones rely heavily on high-thermal-mass materials such as adobe, masonry, and stone. When sourced locally, these materials exhibit lower embodied carbon due to minimal processing and transportation emissions. Features like green roofs and earthen pots further reduce embodied carbon by leveraging natural, low-impact materials. However, the use of manufactured materials like AAC blocks or reflective insulation may slightly increase embodied carbon due to energy-intensive production processes.

- **Warm & Humid and Temperate Zones:** These zones prioritize lightweight materials, such as low U-value insulation and processed materials (e.g., AAC blocks). These materials often have higher embodied carbon due to energy-intensive manufacturing. However, the use of lightweight roofs and natural cladding (e.g., roofing tiles) can mitigate some emissions if locally sourced.

- **Composite Zone**: This zone employs a mix of massive and lightweight materials, balancing thermal mass at lower levels with lighter, insulated structures at upper levels. The embodied carbon footprint depends on the proportion of manufactured materials (e.g., insulation) versus natural materials (e.g., creepers for pergolas). Careful material selection can optimize sustainability.

- **Fenestration and Insulation:** Large glazed fenestrations, particularly in Cold zones, and synthetic insulation in Composite and Warm & Humid zones, contribute significantly to embodied carbon due to the high energy required for glass and insulator production. Minimizing their use or opting for low-impact alternatives (e.g., recycled glass) can reduce emissions.

- **General Observations:** Across all zones, prioritizing locally sourced, low-impact materials—such as adobe, stone, and natural cladding—reduces transportation and processing emissions. Passive design strategies that minimize operational energy needs (e.g., shaded courtyards, windcatchers, and Trombe walls) enhance overall sustainability by lowering the lifecycle carbon footprint. Conversely, reliance on energy-intensive materials like glass, synthetic insulation, or processed blocks can elevate embodied carbon, necessitating careful consideration during design.

A comparative look at walling material preferences across India's major climatic zones reveals how construction practices and regional factors influence material selection more than climate itself. Three primary blockwork types—AAC blocks, common clay bricks, and concrete masonry units (CMU)—show overlapping usage across all zones, indicating that walling choices are shaped less by climatic responsiveness and more by broader practical considerations such as availability, cost, and construction familiarity.

Since the analysis is set in a tropical context, where the dominant design objective across the country is to minimize heat ingress and maintain internal comfort, most walling systems naturally gravitate toward materials with moderate thermal mass and insulation capacity. As a result, AAC blocks, clay bricks, and CMUs are used interchangeably, depending more on factors such as material availability, cost efficiency, construction familiarity, and structural compatibility than on precise climatic optimization.

Furthermore, regional supply chains and local construction practices play a stronger role than climatic drivers in determining blockwork choice. For instance, clay bricks remain common in areas with established kiln industries, while AAC blocks are preferred in urban projects emphasizing faster construction and lightweight systems. Overall, despite climatic diversity, the uniformity in blockwork selection across zones reflects a nationally consistent design priority—to limit solar heat gain through the envelope rather than to tailor wall systems uniquely to each climate.

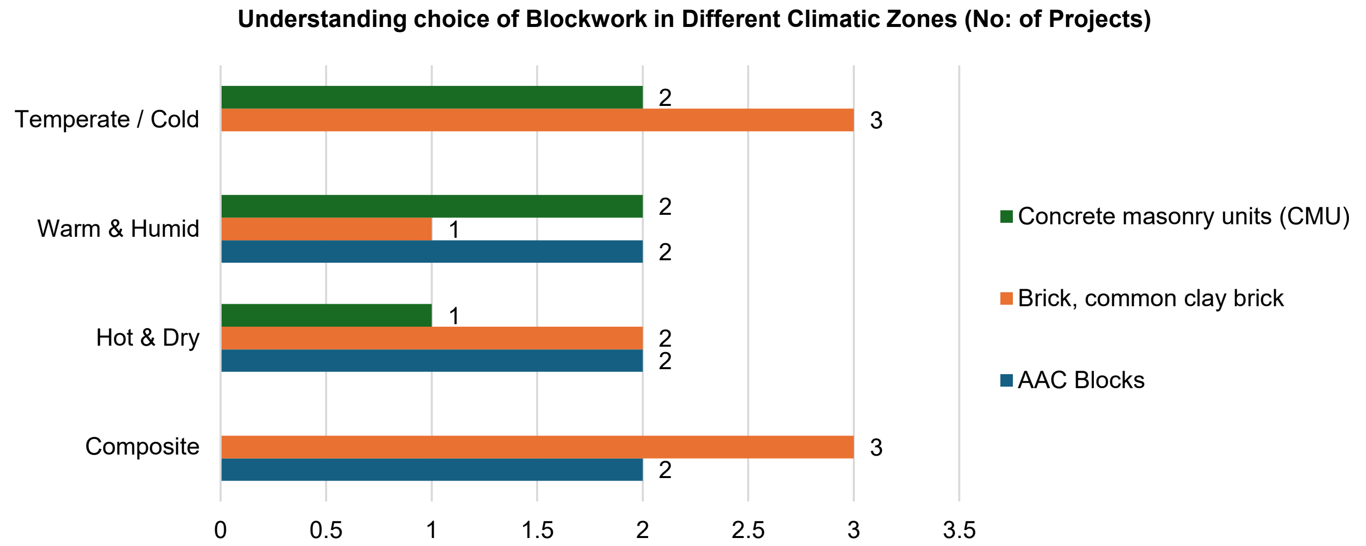



*Figure 68 Understanding choice of Blockwork in Different Climatic Zones (No: of Projects)*

## D. Overview of Passive Design Strategies for Major Climatic Zones in India

India's diverse climatic zones necessitate tailored passive design strategies for built forms, envelopes, fenestrations, and materials to optimize energy efficiency and occupant comfort. The study by Thakur et al. (2021) provides a detailed framework for these strategies across five climatic zones: Hot & Dry, Warm & Humid, Composite, Cold, and Temperate, as summarized below

| Climatic Zone | Hot & Dry | Warm & Humid | Composite | Cold | Temperate |
|---|---|---|---|---|---|
| **Built Form & Open Spaces** | Compact layouts with small open spaces for mutual shading | Open layouts to enhance air circulation | Compact, low-rise development | Small open spaces allowing southern sun exposure | Open planning for thermal comfort |
| **Plan Elements Integrated** | Shaded courtyards, fountains, wind towers, earth air tunnels, terrace gardens | Open courtyards, balconies, patios, wind tunnels, windcatchers | Shaded courtyards, fountains, hybrid summer/monsoon structures, earth air tunnels, pergolas with creepers | Sun spaces, greenhouses, Trombe walls, light wells, thermal chimneys, water walls | Shaded courtyards, fenestration shading devices, balconies, roof gardens |

| | | | | | |
|---|---|---|---|---|---|
| **Building Orientation** | North-South longer facades to reduce heat gain | North-South or wind-aligned facades | North-South facades to minimize heat gain and catch monsoon winds | Maximum southern sun exposure | North-South facades to minimize heat gain |
| **Roof Form & Overhangs** | Flat or shaded roofs to limit heat absorption | Pitched roofs with large overhangs for shading | Large eaves to shade walls and openings | Flat roofs to reduce heat loss | Lightweight roofs with deep overhangs |
| **Fenestration Pattern & Configuration** | Small, shaded openings with high-level vents to block sand | Large, body-level, shaded openings with cross-ventilation | Two-level, small, operable, shaded openings, maximized on monsoon windward side | Large, unshaded, well-sealed glazed areas | Large, shaded, sealed fenestrations |
| **Fenestration Orientation** | Primarily North-facing, with winter sun spaces | Staggered, aligned with airflow | South-facing for cold seasons, monsoon wind-facing for ventilation | South-facing | North-facing |
| **Walls** | High-thermal-mass adobe, masonry, AAC blocks, hollow blocks, reflective insulation | Low U-value, low-thermal-mass walls with insulation | Massive lower-level walls, lighter upper-level structures | Low U-value, high-thermal-mass walls, Trombe or water walls | Low U-value walls, Trombe or water walls |
| **Roof Materials** | High-thermal-mass adobe, green roofs, earthen pots, roofing tiles | Low U-value, lightweight roofs | Low U-value, well-insulated, lightweight roofs | Low U-value, high-thermal-mass adobe or stone roofs | Low U-value roofs with roofing tiles |

*Figure 69 Design Matrix for different climatic zones*

Embodied carbon intensity varies across climate zones, but the influence of climate alone is not strongly pronounced in the current dataset. Differences in building typology, scale, and structural design appear to play a more significant role in shaping embodied carbon, particularly in low- and high-rise projects. Examining each climate zone separately provides a clearer perspective on these patterns.

- In the hot-dry climate, embodied carbon is notably high for government buildings (912 $kgCO_2e/m^2$) and schools (770 $kgCO_2e/m^2$), reflecting a combination of specialized structural requirements and the presence of two high-rise projects within this climate. Factories, by contrast, show moderate values (406 $kgCO_2e/m^2$), highlighting that low-rise industrial buildings maintain lower material intensity even under hot-dry conditions. Residential and commercial projects fall in between, with embodied carbon influenced primarily by typical design and material choices rather than direct climate responsiveness.
- The temperate climate generally exhibits lower embodied carbon intensities across typologies, with factories (341 $kgCO_2e/m^2$) and commercial buildings (420 $kgCO_2e/m^2$) reflecting material-efficient low-rise designs. Residential and school buildings show moderate values (519 and 467 $kgCO_2e/m^2$, respectively), while government buildings remain slightly higher (573 $kgCO_2e/m^2$) due to structural requirements. The single high-rise residential project in this climate contributes to the marginal increase observed in that category, illustrating how building height can influence averages even in otherwise low-intensity zones.

- In the warm-humid climate, embodied carbon is relatively consistent across typologies, with commercial buildings (588 $kgCO_2e/m^2$) slightly higher, likely due to larger footprints or more complex structural layouts. Factories and residential buildings are lower (427 and 456 $kgCO_2e/m^2$), and schools register the lowest intensity (347 $kgCO_2e/m^2$). This trend suggests that typical low-rise construction dominates, and climate-specific design adjustments have limited impact on material intensity in these projects.

- The composite dataset—which includes all projects—shows the highest factory intensity (1348 $kgCO_2e/m^2$), reflecting the combined effect of high-rise projects and material-intensive designs across multiple climates. Other typologies show moderate values, with commercial and government buildings (640 and 751 $kgCO_2e/m^2$) slightly elevated due to larger-scale or specialized projects. Residential and school buildings remain comparatively lower, emphasizing that typology and structural demands largely drive embodied carbon outcomes in this dataset.

Overall, these observations indicate that while climate may influence embodied carbon to some degree, typology, building height, and structural complexity are stronger determinants. Hot-dry zones are skewed by high-rise projects, temperate and warm-humid zones show more consistent low- to mid-range values, and composite averages highlight the effect of outliers. A larger, more balanced sample set with climate-responsive designs would be necessary to isolate and quantify the true impact of climate on embodied carbon across building types.

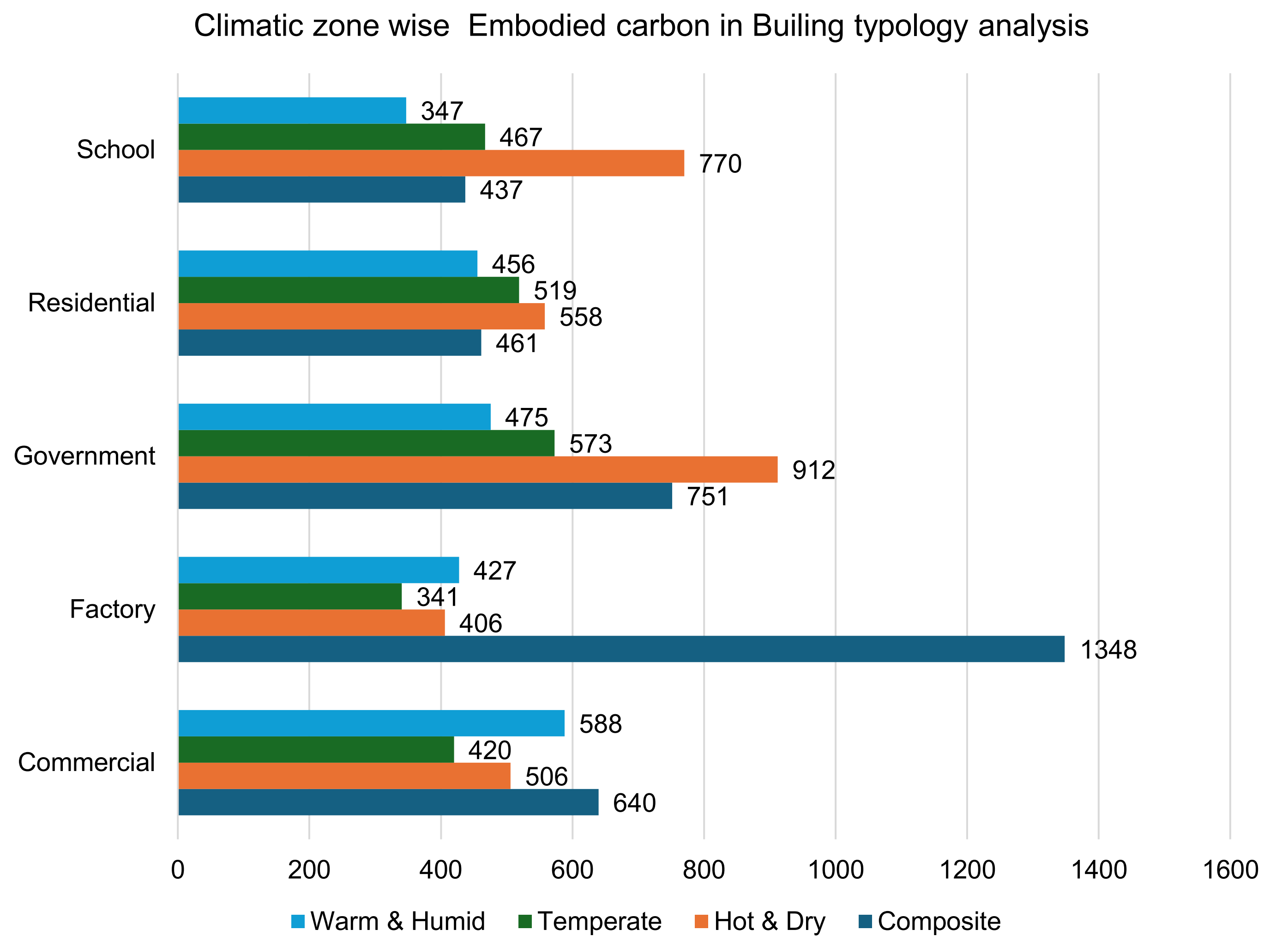



*Figure 70 : Climatic zone wise Embodied carbon in Building typology analysis ($KgCO_2$ e /m²)*

### E. Inferences

Across India's four major climatic zones, the influence of climate on embodied carbon is evident but not singularly decisive. The observed pattern indicates that embodied carbon is highest in the Composite zone, followed by the Hot & Dry zone, and lowest in the Temperate zone. However, this trend cannot be attributed solely to climatic factors. The climatic classification of the sample set also coincides with seismic bifurcation, where most buildings in the Composite and Hot & Dry zones fall under higher-risk seismic categories. Consequently, design decisions in these zones are more strongly shaped by seismic requirements—such as increased reinforcement, heavier frames, and deeper foundations—than by climate responsiveness alone. This interdependence will be further discussed in subsequent chapters.

From this analysis, it is understood that climate primarily influences thermal performance requirements and the selection of materials associated with insulation and envelope performance. However, the sample does not reveal a consistent pattern in the choice of walling materials based on thermal insulation capacity. Since the study covers a tropical country where the dominant design intent is to minimize heat ingress, the variation in wall systems across climatic zones remains limited. Overall, while climatic considerations guide thermal comfort strategies, seismic design demands emerge as the more dominant driver of embodied carbon in the current dataset.

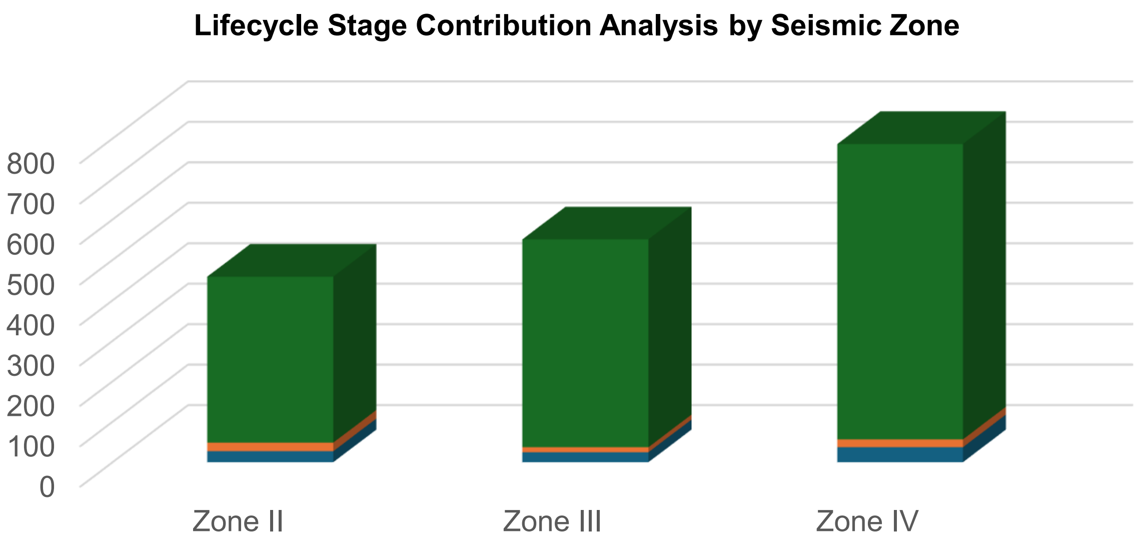
## II. Seismic zone-wise

### A. Lifecycle Stage Influence Under Varying Seismic Loads

The impact of seismic design extends across all life cycle stages, with marked variations observed in cradle-to-gate (A1–A3) emissions across different seismic zones. Zone IV, representing the highest seismic demand in the dataset, records the greatest embodied carbon intensity at 730 $kgCO_2e/m^2$, compared to 514 $kgCO_2e/m^2$ in Zone III and 410 $kgCO_2e/m^2$ in Zone II. This progressive rise underscores the material intensiveness of seismic-resilient design—where increased reinforcement ratios, thicker concrete sections, and the use of higher-grade materials are essential to ensure lateral stability and safety.

The construction stage (A5) mirrors this pattern, increasing from 27 $kgCO_2e/m^2$ in Zone II and 25 $kgCO_2e/m^2$ in Zone III to 37 $kgCO_2e/m^2$ in Zone IV. This trend reflects the greater complexity and duration of construction processes in highly seismic regions, involving extensive formwork, denser reinforcement handling, and additional on-site energy consumption. Conversely, transport emissions (A4) remain relatively less influenced by seismic considerations—ranging from 21 $kgCO_2e/m^2$ in Zone II and 12 $kgCO_2e/m^2$ in Zone III to 19 $kgCO_2e/m^2$ in Zone IV—largely governed by material sourcing distances and logistics rather than design intensity.

Overall, the influence of seismic design is most pronounced during the product and construction stages (A1–A3 and A5), where structural resilience directly drives embodied carbon through higher material demand. These findings highlight that early design interventions—such as optimizing material selection, structural efficiency, and foundation design—can substantially mitigate embodied carbon in seismically active zones. However, it should be noted that these observations are based on a limited dataset of 20 buildings, and results may vary with broader sampling or differing construction typologies.




| | Zone II | Zone III | Zone IV |
|---|---|---|---|
| **A1-A3 (KgCo2e/m2)** | 410 | 514 | 730 |
| **A4 (KgCo2e/m2)** | 21 | 12 | 19 |
| **A5(KgCo2e/m2)** | 27 | 25 | 37 |
| **A1 -A5(KgCo2e/m2)** | 458 | 551 | 786 |

*Figure 71 Lifecycle Stage Contribution Analysis by Seismic Zone*

## B. Structural Optimization Constraints Across Seismic Zone

Structural optimization in seismic-prone regions is inherently guided by stringent safety requirements, which often result in increased material intensity and embodied carbon. The influence of these constraints becomes evident when analyzing average emissions across key structural categories for different seismic zones. While the trends broadly align with seismic design principles, variations also reflect differences in soil conditions, design practices, and sample composition.

- Foundations (Substructure) : Embodied carbon for foundations shows considerable variation across zones, with Zone II recording the highest value of 135 $kgCO_2e/m^2$, followed by 219 $kgCO_2e/m^2$ in Zone III and 189 $kgCO_2e/m^2$ in Zone IV. Although this appears counterintuitive, the elevated value in Zone II is largely attributed to the majority of sampled projects being located in coastal or sandy–silty soil areas, which demand deeper and more heavily reinforced foundations to achieve stability. The substructure typically contributes 30–35% of total embodied carbon, underscoring the influence of soil conditions and foundation typology even beyond seismic design intensity.

- Frame (Beams, Columns, Slabs, Stairs & Ramps) : The frame system shows a clear upward trend with seismic intensity—from 160 $kgCO_2e/m^2$ in Zone II to 200 $kgCO_2e/m^2$ in Zone III, and 315 $kgCO_2e/m^2$ in Zone IV. This escalation is directly linked to structural design requirements aligned with local seismic codes, where higher zones require greater reinforcement densities, thicker sections, and high-strength concrete to withstand lateral forces. Frames represent the largest share of embodied carbon, typically accounting for 35–45%, reaffirming that structural systems dominate emissions in seismic-resilient buildings.

- Walls and Facades: Embodied carbon for walls and facades increases substantially with seismic demand—45 $kgCO_2e/m^2$ in Zone II, 58 $kgCO_2e/m^2$ in Zone III, and 124 $kgCO_2e/m^2$ in Zone IV. This reflects the greater use of shear walls and stiffer masonry materials in high-seismic regions to enhance stability. Moreover, a significant share of Zone IV projects employs common burnt clay bricks, which carry higher embodied carbon compared to lightweight or AAC alternatives. Walls and facades contribute approximately 10–15% of total embodied carbon, emphasizing the combined effect of material choice and structural necessity.

- Windows and Doors: The windows and doors category shows limited correlation with seismic intensity, with emissions varying between 31 $kgCO_2e/m^2$ in Zone II, 20 $kgCO_2e/m^2$ in Zone III, and 34 $kgCO_2e/m^2$ in Zone IV. These inconsistencies likely stem from incomplete detailing in Bill of Quantities (BoQ) data and variation in joinery specifications rather than seismic influence. A more refined dataset would be required to establish a definitive relationship. Typically, this category contributes 5–10% of total embodied carbon.

- Finishes: The finishes category exhibits the least variation, ranging from 35 $kgCO_2e/m^2$ in Zone II to 43 $kgCO_2e/m^2$ in Zone III and 49 $kgCO_2e/m^2$ in Zone IV. These differences are primarily driven by architectural choices rather than seismic requirements. Projects employing AAC blocks or shear walls tend to require less finishing material, whereas burnt clay brick constructions often necessitate more extensive plastering or putty layers. Finishes typically contribute 5–10% of embodied carbon, reflecting the secondary role of aesthetic decisions in influencing overall emissions.

Overall, the analysis reinforces that primary load-bearing systems—foundations and frames—account for over 65% of total embodied carbon in most buildings. While seismic zone classification is a key determinant, local soil conditions, material selection, and project typology also play crucial roles. It is important to note that these insights are derived from a limited dataset of 20 buildings, and broader sampling may further refine these correlations.

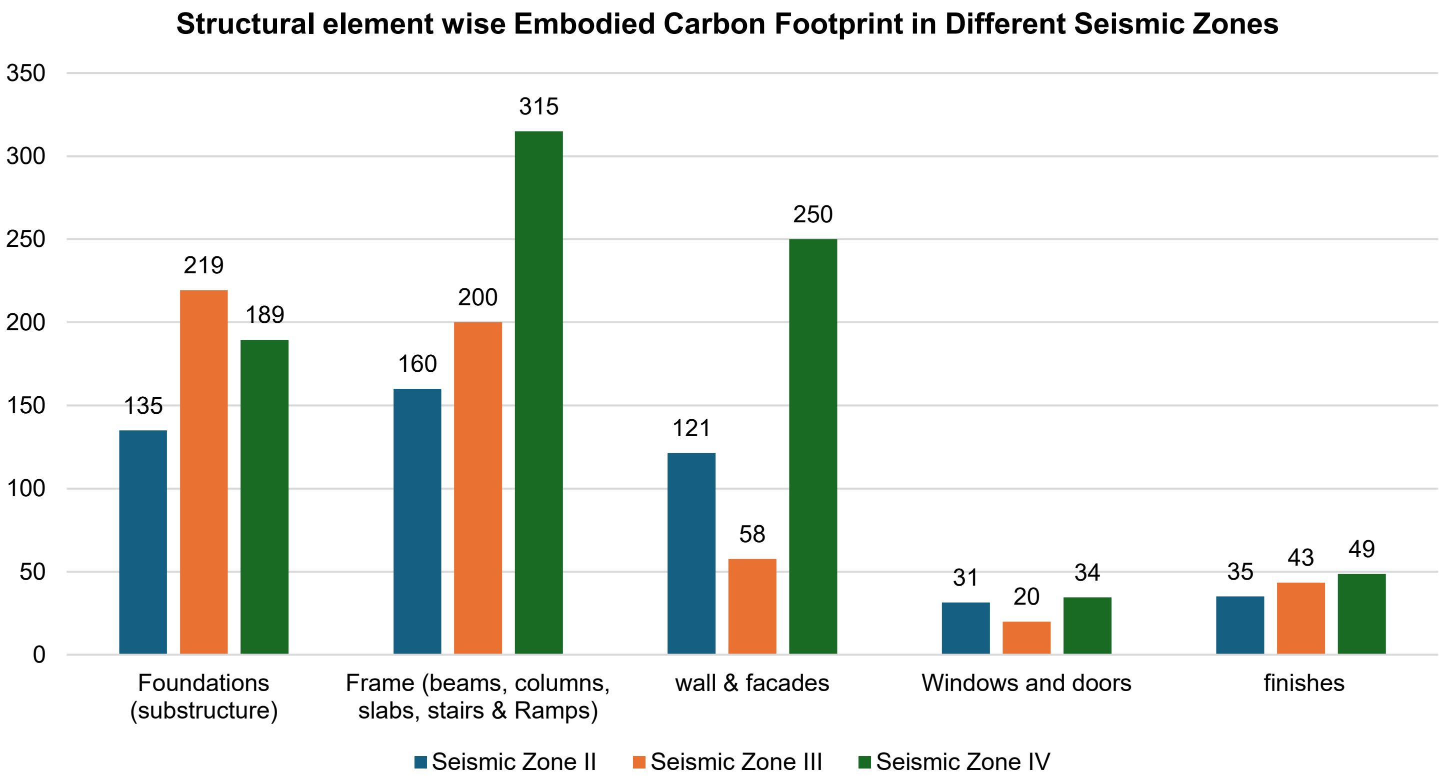



*Figure 72 Structural element wise Embodied Carbon Footprint in Different Seismic Zones*

## C. Impact of Seismic Forces on Material Intensity

Analysis of material-level embodied carbon highlights how seismic design requirements directly influence the intensity of key structural materials, particularly reinforcement steel and concrete.

- Steel Reinforcement Rebars: Steel exhibits the most pronounced escalation in embodied carbon, increasing from 156 $kgCO_2e/m^2$ in Zone II to 237 $kgCO_2e/m^2$ in Zone IV, with Zone III slightly lower at 144 $kgCO_2e/m^2$. This sharp rise is consistent with seismic design codes that mandate higher reinforcement densities to ensure ductility, energy dissipation, and lateral load resistance in high-risk zones. The data reflects how structural robustness and redundancy directly drive embodied carbon in steel, making it the primary contributor to material-related emissions in seismic-sensitive buildings.

- Concrete: Concrete emissions also increase progressively—from 159 $kgCO_2e/m^2$ in Zone II to 218 $kgCO_2e/m^2$ in Zone IV, with Zone III at 184 $kgCO_2e/m^2$. This trend underscores the heavier reliance on reinforced concrete systems in both substructure and superstructure. Higher seismic demands necessitate thicker slabs, stronger columns, and more robust foundations, increasing material intensity and overall embodied carbon.

- Cement: Cement shows a less consistent pattern, ranging from 97–120 $kgCO_2e/m^2$ across zones. The slight increase in Zone IV is likely associated with non-structural applications such as plastering, floor levelling, and internal mortar works rather than seismic design alone. This indicates that cement's contribution is more project- and finishing-dependent, rather than directly influenced by structural requirements.

The material-level analysis demonstrates that reinforcement steel and concrete are the primary drivers of embodied carbon in seismic-prone buildings, reflecting the direct impact of structural design requirements on material intensity. Steel emissions rise sharply with seismic zone, highlighting the need for ductility, energy dissipation, and lateral load resistance, while concrete follows a similar trend due to thicker slabs, stronger columns, and more robust foundations. In contrast, cement shows limited sensitivity to seismic design, with variations largely linked to non-structural applications such as plastering or internal mortar work. These findings emphasize that material function and performance requirements are critical in interpreting embodied carbon, rather than aggregate quantities alone. Furthermore, the insights are drawn from a limited dataset of 20 buildings, suggesting that while trends are indicative, broader sampling may refine these patterns and help identify targeted opportunities for low-carbon design interventions.

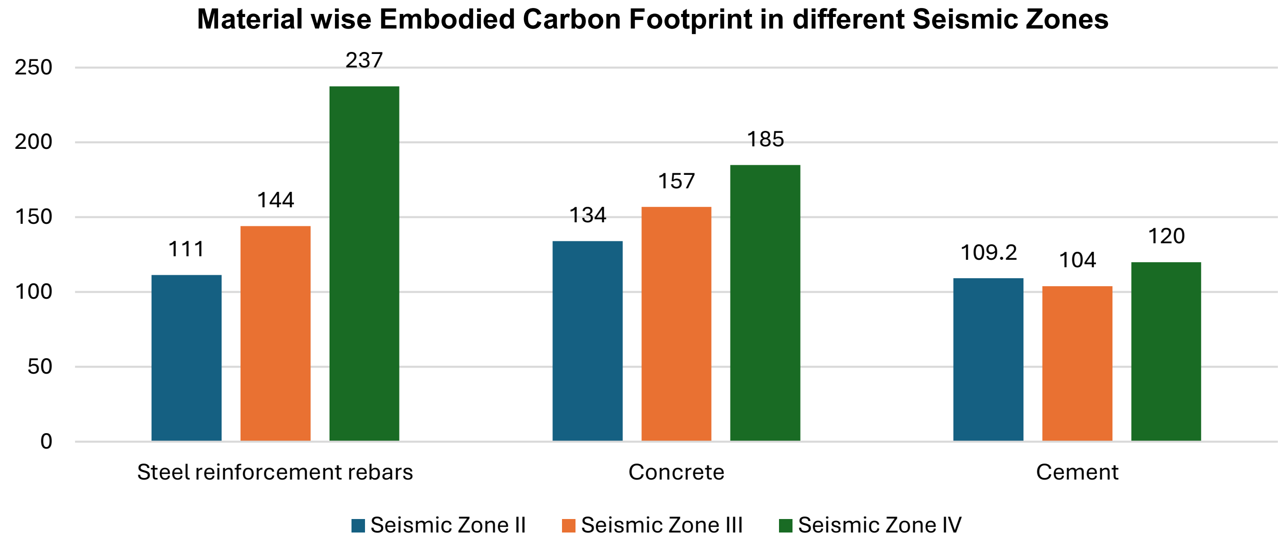



*Figure 73 Material wise Embodied Carbon Footprint in different Seismic Zones*

## D. Observed Impact of Seismic Zones on Embodied Carbon

The influence of seismic design extends across all life cycle stages, with distinct variations observed in cradle-to-gate (A1–A3) emissions across seismic zones. Projects located in higher seismic zones consistently demonstrate greater material intensity to comply with stricter safety standards, resulting in elevated embodied carbon values. The average embodied carbon from material production (A1–A3) in Seismic Zone IV stands at 730 $kgCO_2e/m^2$, significantly higher than 514 $kgCO_2e/m^2$ in Zone III and 410 $kgCO_2e/m^2$ in Zone II. This represents an approximate 78% increase from Zone II to Zone IV, reflecting the material intensiveness of seismic-resilient design—marked by heavier reinforcement, thicker concrete sections, and more robust substructures to resist seismic forces.

Seismic design inherently prioritizes safety and structural integrity over material efficiency, often leading to conservative design choices. Emissions from critical structural components—such as frames, foundations, and slabs—are considerably higher in high-risk zones due to increased reinforcement ratios, denser concrete mixes, and stronger cross-sections. In contrast, buildings in lower seismic zones adopt lighter structural systems with reduced material demand. The slightly irregular trend in Zone III, where emissions appear lower than Zone IV but higher than Zone II, can be attributed to sample limitations, as the dataset includes only one project (EMC Kerala), a low-carbon, green institutional building with minimal structural demand. Thus, while an upward trajectory in embodied carbon from Zone II to Zone IV aligns with seismic logic, the temporary variation at Zone III stems from sample composition rather than design divergence.

Across other life cycle stages, a similar relationship is observed. Construction stage emissions (A5) rise from 27 $kgCO_2e/m^2$ in Zone II and 25 $kgCO_2e/m^2$ in Zone III to 37 $kgCO_2e/m^2$ in Zone IV, reflecting greater construction complexity, including increased reinforcement placement, formwork handling, and higher on-site energy consumption. Transport emissions (A4) remain relatively steady across zones—21 $kgCO_2e/m^2$ in Zone II, 12 $kgCO_2e/m^2$ in Zone III, and 19 $kgCO_2e/m^2$ in Zone IV—suggesting that logistics and sourcing distances are less sensitive to seismic factors and depend more on project location and supply chain efficiency.

Material-wise assessments further reinforce this correlation, with reinforcement steel and concrete showing consistent increases in embodied carbon intensity in higher seismic zones, driven by enhanced ductility and stiffness requirements. These findings collectively underscore that seismic resilience is a key driver of embodied carbon, particularly during the product and construction stages (A1–A5). However, given that this analysis is based on a limited dataset of 20 buildings, including few Zone IV projects, future studies with broader and more balanced sampling across all seismic zones would provide stronger statistical evidence and deeper insights into the full impact of seismic design on whole-life carbon performance.

## E. Inferences

The analysis clearly shows that higher seismic zones, particularly Zone IV, drive significant increases in embodied carbon, primarily through heavier use of reinforcement steel and concrete and more robust foundations and frames. Steel rises from 111 $kgCO_2e/m^2$ in Zone II to 237 $kgCO_2e/m^2$ in Zone IV, while concrete increases from 134 $kgCO_2e/m^2$ to 185 $kgCO_2e/m^2$, reflecting structural overdesign necessary for seismic safety. Foundations and load-bearing frames also escalate with seismic demand, highlighting that substructures bear a major portion of carbon intensity in high-risk zones.

Secondary elements like walls, finishes, and glazing show smaller, more variable contributions, indicating that seismic design primarily affects core structural components rather than non-structural or architectural elements.

Lower seismic zones consistently show lower material intensity, with lighter frames and reduced reinforcement, demonstrating how seismic risk directly influences design decisions and carbon outcomes.

The single Zone III project (EMC Kerala) is a low-carbon building, which lowers the average for that zone and underscores that sample size and typology can skew apparent trends.

The key takeaway is clear: embodied carbon is highly sensitive to seismic design, and reductions are possible only by optimizing steel, concrete, and foundation use without compromising structural safety. Efficient structural design and material selection in high-risk seismic regions offer the greatest opportunity for meaningful carbon savings.

## III. Typology-wise

### A. Lifecycle Stage Impact by Building Use Typology

The lifecycle carbon impact of buildings varies significantly across typologies, reflecting differences in material scale, functional intensity, and construction complexity.

Government buildings consistently exhibit the highest overall emissions, with A1–A3 at 623 $KgCO_2e/m^2$ and construction-stage emissions (A5) at 39 $KgCO_2e/m^2$. This pattern highlights large, durable structures built with extensive steel and concrete use, coupled with complex on-site activities.

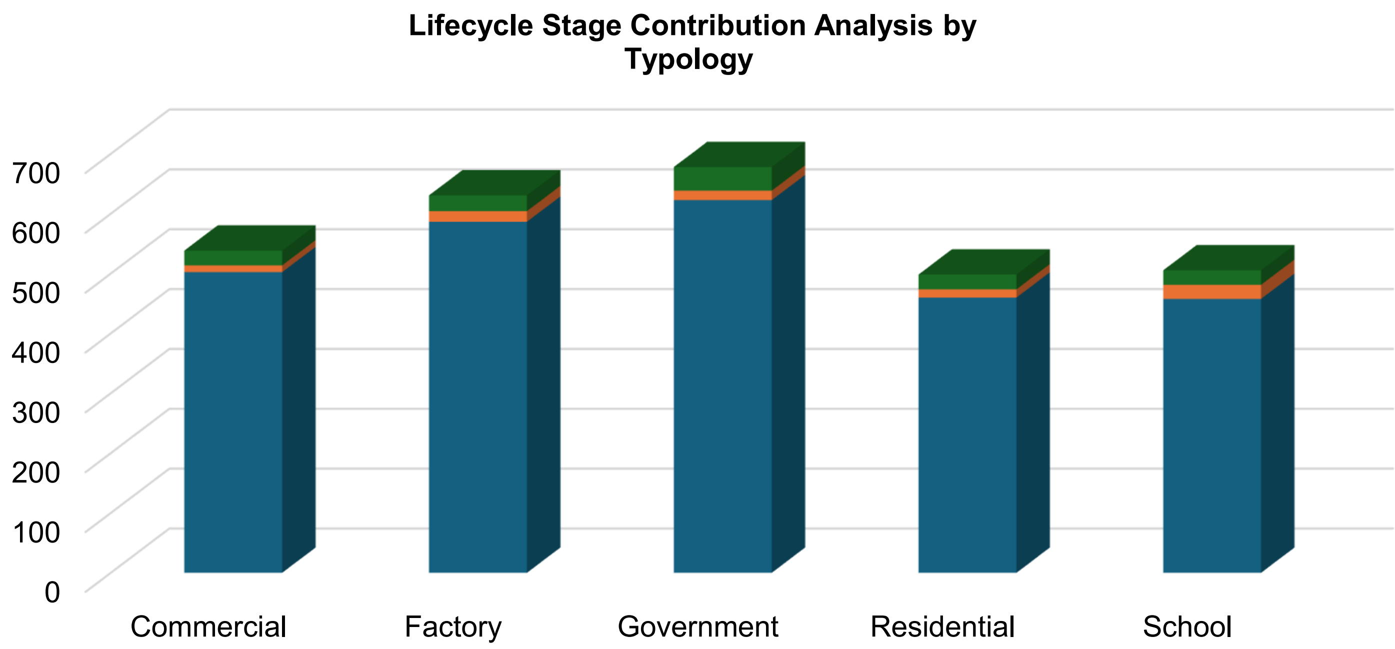
Factory buildings follow closely, showing high product-stage emissions at 587 $KgCO_2e/m^2$, moderate transportation emissions (A4: 18 $KgCO_2e/m^2$), and construction impacts of 26 $KgCO_2e/m^2$. These values reflect robust material requirements and the logistics-heavy nature of industrial projects.

Commercial buildings present substantial product-stage carbon (502 $KgCO_2e/m^2$) while keeping construction emissions relatively lower at 25 $KgCO_2e/m^2$, suggesting the use of prefabricated elements or material-efficient construction practices, even with high-quality finishes.

School buildings show moderate product-stage emissions (458 $KgCO_2e/m^2$) but the highest transportation impacts (A4: 23 $KgCO_2e/m^2$), indicating dispersed site locations or phased material deliveries contributing to higher logistics emissions.

Residential buildings consistently demonstrate the lowest embodied carbon across all stages, with A1–A3 at 460 $KgCO_2e/m^2$ and A5 at 25 $KgCO_2e/m^2$. This aligns with smaller building footprints, simpler structural systems, and less intensive site activities.

Overall, the data underscores that typology strongly influences lifecycle carbon profiles, with material-intensive, large-scale projects like government and factory buildings driving the highest emissions, while residential and school buildings benefit from simpler, more efficient construction practices.




| | Commercial | Factory | Government | Residential | School |
|---|---|---|---|---|---|
| A1-A3 (KgCo2e/m2) | 502 | 587 | 623 | 460 | 458 |
| A4 (KgCo2e/m2) | 11 | 18 | 16 | 14 | 23 |
| A5(KgCo2e/m2) | 25 | 26 | 39 | 25 | 24 |
| **A1 -A5(KgCo2e/m2)** | **538** | **631** | **678** | **498** | **505** |

*Figure 74 Lifecycle Stage Contribution Analysis by Typology*

### B. Typology-Based Structural Carbon Emissions

The embodied carbon associated with structural elements varies significantly across building typologies, reflecting functional requirements, design strategies, and material intensity.

- Government buildings exhibit the highest emissions in key structural components, particularly in foundations (348 $KgCO_2e/m^2$) and frames (196 $KgCO_2e/m^2$). This aligns with heavy reinforced concrete frameworks and deep, load-bearing substructures typical of large-scale public infrastructure designed for durability and long-term service.

- Factory buildings follow closely, with high frame emissions (333 $KgCO_2e/m^2$) and foundations (162 $KgCO_2e/m^2$), consistent with industrial buildings designed to support heavy machinery, large spans, and high live loads. Windows remain minimal (4 $KgCO_2e/m^2$), reflecting functional, opaque envelope strategies.

- Commercial buildings show a different pattern. While frames (109 $KgCO_2e/m^2$) and walls (156 $KgCO_2e/m^2$) are moderate, emissions from windows and curtain walls are the highest among all typologies (65 $KgCO_2e/m^2$), highlighting the contemporary preference for glazed façades in office and retail buildings, which enhances daylighting and aesthetics.

- Residential buildings maintain lower carbon intensities across all structural elements. Frames (186 Kg$CO_2$e/m²) and foundations (135 Kg$CO_2$e/m²) are moderate, walls (76 Kg$CO_2$e/m²) and windows (17 Kg$CO_2$e/m²) are modest, and finishes (36 Kg$CO_2$e/m²) indicate attention to interior comfort and detailing.

- School buildings emphasize structural robustness with higher frame (206 Kg$CO_2$e/m²) and foundation (154 Kg$CO_2$e/m²) emissions. Walls (60 Kg$CO_2$e/m²) and finishes (48 Kg$CO_2$e/m²) support durability, hygiene, and acoustic performance, reflecting design priorities for educational spaces.

Overall, structural carbon intensity mirrors typology-specific demands: from massive, durable frameworks in government and factory buildings to material-efficient, user-focused designs in residential and school typologies. The high curtain wall contribution in commercial buildings underscores the increasing trend of glazed façades in modern offices and retail environments.

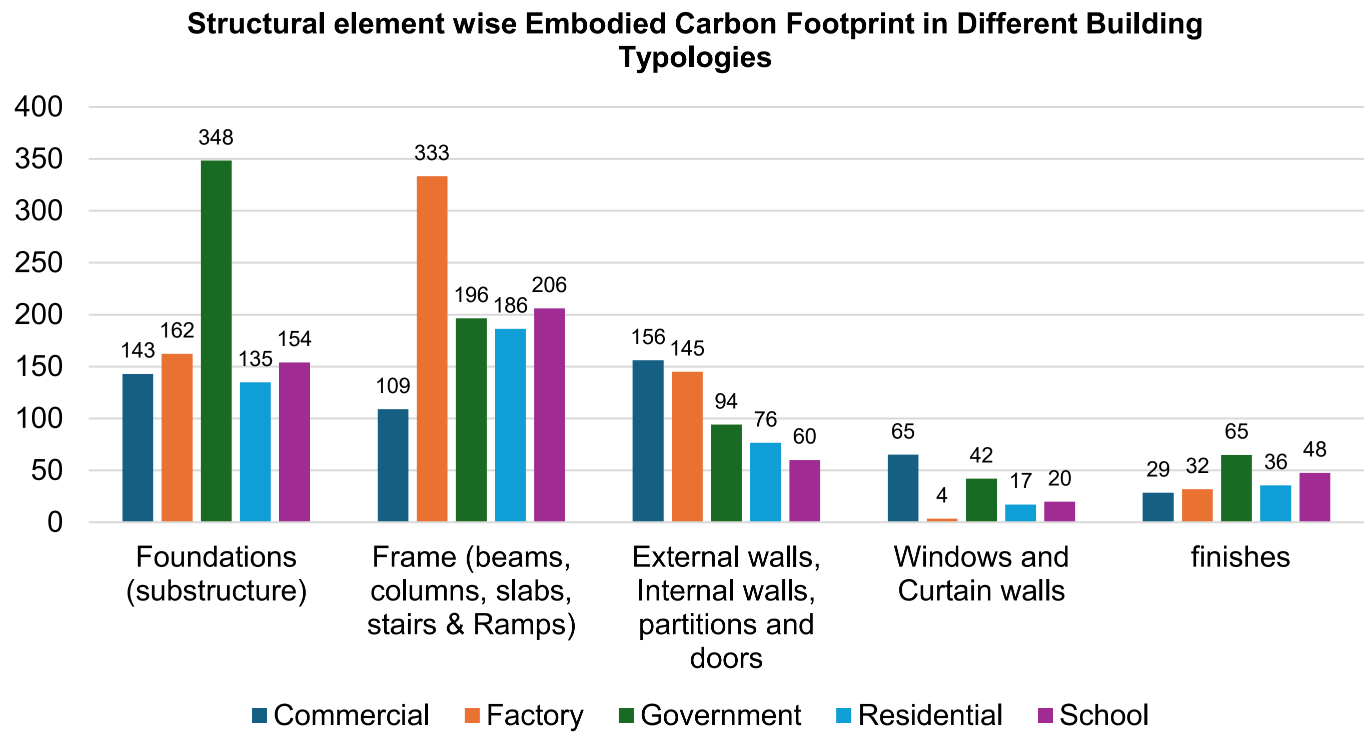



*Figure 75 Structural element wise Embodied Carbon Footprint in Different Building Typologies*

## C. Dominant Material Contributions by Building Typology

The dominant materials contributing to embodied carbon vary considerably across building typologies, reflecting the unique structural and functional demands of each type.

- Government buildings record the highest emissions from steel reinforcement (235 Kg$CO_2$e/m²) and concrete (144 Kg$CO_2$e/m²), highlighting the reliance on reinforced concrete frameworks typical of institutional construction. Cement use (68 Kg$CO_2$e/m²) further supports these robust structural systems designed for durability and long-term service.
- Factory buildings show high contributions from concrete (188 Kg$CO_2$e/m²) and steel reinforcement (201 Kg$CO_2$e/m²), consistent with industrial buildings requiring strong load-bearing elements and large spans. Cement (79 Kg$CO_2$e/m²) also supports substructure and internal masonry, while the material profile emphasizes structural robustness.

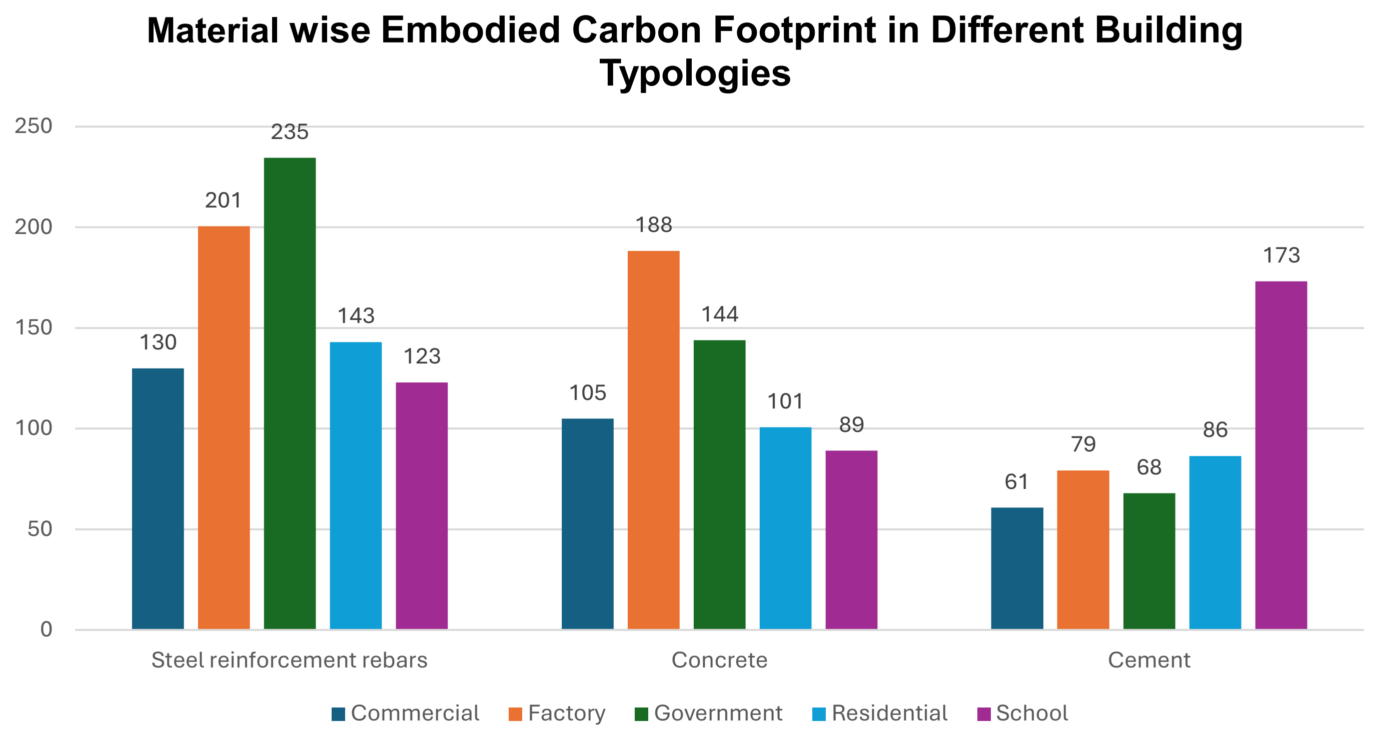



*Figure 76 Material wise Embodied Carbon Footprint in Different Building Typologies*

- Commercial buildings maintain a relatively balanced material mix, with steel reinforcement (130 $KgCO_2e/m^2$) and concrete (105 $KgCO_2e/m^2$) as primary contributors and lower cement use (61 $KgCO_2e/m^2$). This indicates lighter framing strategies and optimized material use, typical of office and retail structures, while still allowing for features like curtain walls.
- Residential buildings emphasize cement (86 $KgCO_2e/m^2$) alongside moderate concrete (101 $KgCO_2e/m^2$) and steel reinforcement (143 $KgCO_2e/m^2$), reflecting common use of plaster, masonry, and moderate structural framing suitable for low- to mid-rise housing.
- School buildings display the highest cement use among all typologies (173 $KgCO_2e/m^2$) with notable steel reinforcement (123 $KgCO_2e/m^2$) and concrete (89 $KgCO_2e/m^2$), underscoring a design focus on durable masonry and reinforced structures that ensure safety, longevity, and robust performance under frequent occupancy.

Overall, steel and concrete dominate embodied carbon contributions across all typologies, while cement use is particularly significant in residential and educational buildings, highlighting material choices aligned with functional and structural priorities.

## D. Embodied Carbon Footprint by Typology

Based on the sample considered in this study, government buildings exhibit the highest embodied carbon intensity, averaging 678 $KgCO_2e/m^2$. This trend is consistent across the projects studied, reflecting the use of robust structural systems, large spans, and conservative design practices often mandated in public sector construction. The material palette in these buildings is more carbon-intensive, particularly due to higher use of concrete and steel reinforcement to meet durability and performance standards.

Factory buildings show considerable variation in embodied carbon, averaging 631 $KgCO_2e/m^2$. This reflects the diversity of industrial building types—some employ lightweight or pre-engineered systems that optimize material efficiency, while others incorporate heavily reinforced concrete frames or specialized infrastructure to support high operational loads. The upper-bound emissions in factories are among the highest across all typologies, highlighting how functional demands can drastically influence material intensity.

The residential dataset includes two high-rise projects—one in the hot-dry climate (558 $kgCO_2e/m^2$) and one in the temperate climate (519 $kgCO_2e/m^2$)—and two low-rise projects—one in the warm-humid climate (456 $kgCO_2e/m^2$) and one in the temperate climate (519 $kgCO_2e/m^2$). The average embodied carbon for high-rise residential buildings is 539 $kgCO_2e/m^2$, compared to 486 $kgCO_2e/m^2$ for low-rise projects, reflecting the increased material use required for taller structures, including reinforced concrete frames, thicker slabs, and larger foundations. These numbers highlight that building height, more than climate, is a key driver of embodied carbon in residential typologies, even when projects span different climate zones.

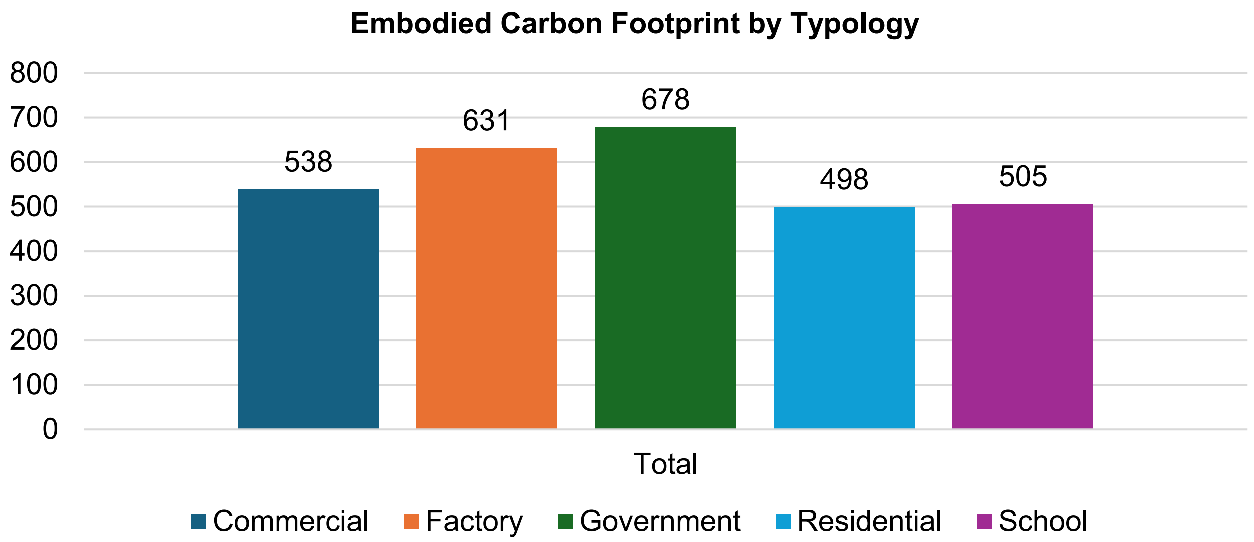



*Figure 77 Embodied Carbon Footprint by Typology*

Commercial buildings and schools fall in the mid-range, averaging 538 $KgCO_2e/m^2$ and 505 $KgCO_2e/m^2$, respectively. Commercial projects tend to follow consistent design approaches, often with high-quality finishes and curtain walls, while schools show a wider spread due to diverse functional requirements and variations in structural and spatial configurations.

Overall, these observations underscore that embodied carbon is strongly influenced by building function, structural and material choices, and design strategies. It is important to note that conclusions are indicative, as the analysis is based on a limited sample of four buildings per typology.

## E. Inferences

Embodied carbon performance across building typologies is strongly shaped by functional requirements, structural complexity, and material strategy. Government buildings consistently exhibit the highest carbon intensity, driven by heavy reinforced concrete frameworks, deep foundations, and extensive use of steel reinforcement. The combination of long spans, conservative design provisions, and durability-focused materials underscores why institutional infrastructure carries a substantial carbon footprint.

Factory buildings show notable emissions as well, reflecting the structural demands of industrial operations, including steel-intensive frames and robust foundations. The wide variability observed within this typology indicates that while some factories leverage pre-engineered or lightweight systems, others rely on high-carbon, large-span concrete structures, amplifying embodied emissions.

School buildings demonstrate moderate carbon levels but highlight targeted investment in structural robustness and durable finishes, reflecting priorities around safety, longevity, and occupant well-being in educational spaces. Commercial buildings, by contrast, balance efficiency with design ambition; high glazing ratios, partitioned interiors, and curtain wall systems elevate emissions in walls and fenestration, even where frames and foundations are optimized.

Residential buildings consistently record the lowest embodied carbon across typologies. This outcome reflects simpler layouts, smaller spans, and material-efficient systems, though finishes contribute disproportionately due to attention to comfort and aesthetics.

Overall, embodied carbon outcomes are not purely a function of building size or typology. They emerge from the interplay of functional intent, performance requirements, material selection, and structural strategy. These insights underscore the importance of typology-specific design approaches and highlight opportunities to optimize material use while maintaining performance and resilience. The patterns observed are indicative, based on the limited sample of four buildings per typology, but provide clear guidance for targeted carbon reduction strategies.

## The Impact of Sample Diversity on Embodied Carbon Benchmarking

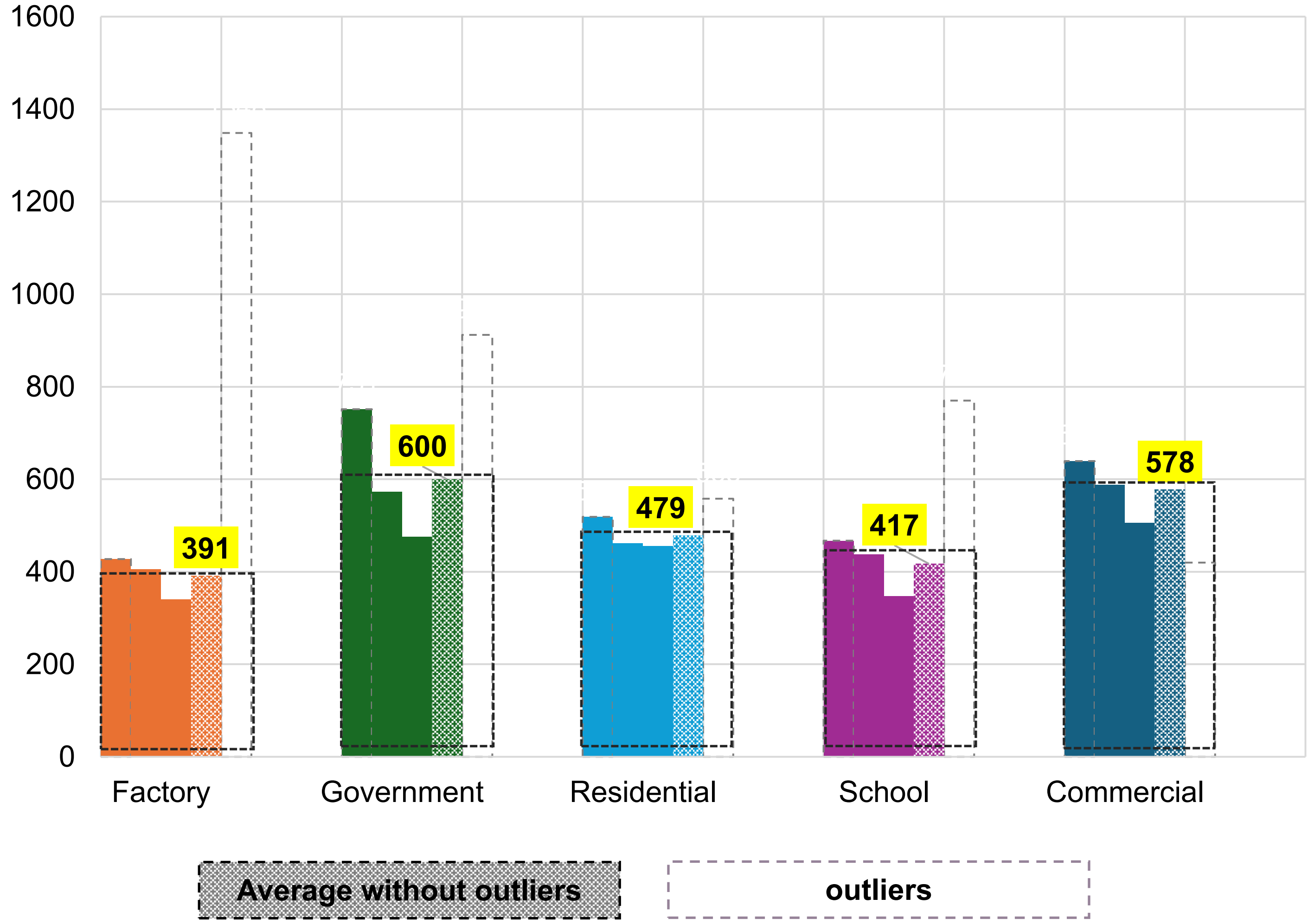



*Figure 78 Embodied Carbon Benchmarking across typologies.*

Embodied carbon benchmarking provides essential insights for evaluating environmental performance across building typologies. However, the reliability of these benchmarks is strongly influenced by the diversity and representativeness of the dataset. Variations in building function, design complexity, construction practices, and material specification can lead to significant dispersion in reported embodied carbon values. In this study, the availability and completeness of Bill of Quantities (BoQs) posed a key challenge, limiting both sample size and typology coverage.

Among the identified projects, differences in scale and structural design contributed to wide variability in embodied carbon intensities. To ensure meaningful comparison and robust typology-level benchmarks, projects with extreme embodied carbon values were identified as outliers and excluded from the analysis. When three or more remaining samples within a typology showed closely aligned values, these were considered representative for calculating typology averages.

**Effect of Outlier Adjustment**

Outlier removal significantly improved the coherence of typology benchmarks, minimizing the influence of atypical project scales, material choices, or reporting inconsistencies. The adjusted averages for each building category are presented below:

| Building Typology | Average Embodied Carbon (without Outliers ($kgCO_2e/m^2$) |
|---|---|
| Factory | 391 |
| Government | 600 |
| Residential | 479 |
| School | 417 |
| Commercial | 578 |

This refinement provides a clearer picture of typical embodied carbon values within each typology, supporting more accurate comparisons and better-informed decisions for material selection, design optimization, and decarbonization planning. The analysis highlights that sample curation is critical: without careful adjustment, unrepresentative datasets can overstate emission intensities and misinform policy or design guidance.

Overall, the findings demonstrate that robust benchmarks rely not only on comprehensive data collection but also on systematic filtering and validation, ensuring that embodied carbon values reflect practical, real-world construction practices.

# 5 CHALLENGES AND OPPORTUNITIES

- Challenges
- Opportunities

# 5. Challenges and Opportunities

## 5.1 Challenges

### A. Lack of Awareness and Policy Recognition

- Limited Policy Mandates: Embodied carbon is not currently regulated in national building codes such as the National Building Code (NBC) or mainstream green rating frameworks beyond voluntary initiatives.
- Stakeholder Knowledge Gaps: Developers, architects, contractors, and even some policymakers often have limited understanding of embodied carbon, its impact, or how to measure and mitigate it
- Operational Bias: The focus remains skewed toward operational energy and efficiency, neglecting the substantial upfront emissions from material use.

### B. Data Gaps and Lack of Standardization

- Absence of Indian EPDs: There is a severe lack of Environmental Product Declarations (EPDs) for Indian construction materials, which limits accurate life cycle assessment (LCA).
- Generic Databases: Many assessments rely on international datasets (e.g., ecoinvent, ICE) that do not reflect Indian manufacturing processes, fuel types, or material composition.
- Non-standard BoQs and Documentation: Inconsistent or incomplete Bills of Quantities (BoQs), lack of digitized construction records, and diverse formats hamper reliable data collection.

### C. Fragmented Construction Industry

- Informal Sector Dominance: A significant share of India's construction labour and material production (e.g., brick kilns, sand mining) operates informally, outside regulatory frameworks.
- Decentralized Supply Chains: Sourcing of materials from small-scale local suppliers makes it difficult to trace emissions accurately or implement decarbonization strategies.
- Lack of Aggregation: Unlike developed markets, India lacks centralized procurement or prefabrication systems that enable bulk carbon-efficient construction.

### D. Financial and Technical Barriers

- Cost Sensitivity: Most developers prioritize cost and speed over sustainability, especially in affordable housing and government infrastructure.
- High Upfront Costs: Low-carbon materials (e.g., AAC blocks, recycled steel, GGBS-based cement) often come at a higher upfront cost or are perceived to do so.
- Limited Access to Tools and Experts: LCA tools like One Click LCA, Tally, or SimaPro require licenses, expertise, and technical training that most professionals lack.

### E. Supply Chain and Logistics Constraints

- Long Transportation Distances: India's large geographic size and centralization of cement and steel production mean that construction materials often travel long distances, increasing emissions in Stage A4.
- Fuel-Intensive Transport: Most material transport depends on diesel-powered trucks, with little penetration of low-carbon logistics options.
- Inadequate Construction Waste Management: There is minimal emphasis on reusing demolition waste, leading to increased demand for virgin materials.

### F. Institutional and Regulatory Inertia

- Lack of Enforcement Mechanisms: Even where voluntary green norms exist, enforcement is weak due to insufficient institutional capacity at local levels (e.g., Urban Local Bodies).
- Fragmented Policy Landscape: Building and construction are governed by multiple ministries (MoHUA, MoEFCC, MoP, BIS, state governments), leading to fragmented regulation.

## 5.2 Opportunities

### A. Growing Global and Domestic Momentum

- Net Zero Targets: India's net-zero by 2070 and sectoral decarbonization targets offer a macro policy mandate to act on embodied emissions.
- Corporate Sustainability (ESG): Large corporations and industrial developers are increasingly embracing ESG norms, which include carbon disclosure and product sustainability.
- Green Public Procurement (GPP): Government-led GPP initiatives can mandate low-carbon materials and reward suppliers with EPDs.

### B. Advancement in Digital Tools and LCA Platforms

- User-Friendly LCA Tools: Cloud-based tools like One Click LCA, EC3, and others make embodied carbon accounting more accessible to practitioners.
- BIM Integration: Embodied carbon can now be embedded in Building Information Modelling (BIM), enabling real-time material-impact trade-offs during design.
- Automated Reporting: Integration of LCA into automated compliance and certification processes can reduce barriers to adoption.

## C. Material Innovation and Circular Economy

- Low-Carbon Cement Alternatives: India is a leader in using blended cements (e.g., PPC, PSC), which reduce clinker content and carbon intensity.
- Recycled Aggregates and Fly Ash: Large volumes of industrial by-products like fly ash, GGBS, and construction & demolition (C&D) waste remain underutilized.
- Bio-based Materials: Bamboo, agro-residue boards, hempcrete, and compressed stabilized earth blocks (CSEB) are gaining ground in specific markets

## D. Green Building Movement and Rating Systems

- Green building rating systems like IGBC are increasingly incorporating LCA and embodied carbon considerations into their frameworks.
- Net Zero Carbon Buildings: Frameworks by WorldGBC and local adaptations are gaining traction among progressive developers and institutions.

## E. Policy Levers and Urban Regulations

- Energy Conservation Building Code (ECBC): Future versions could integrate embodied carbon metrics, incentivizing low-carbon materials.
- Development Control Regulations (DCRs): Local governments can offer FSI incentives or fast-track clearances for low-carbon construction.
- Taxation and Subsidies: Differential GST or subsidies for green materials can promote adoption at scale.

## F. Education, Capacity Building, and Skill Development

- Integration into Curricula: Architecture, engineering, and construction management courses can integrate LCA, sustainability, and carbon accounting modules.
- Skilling Initiatives: Programs through National Skill Development corporation (NSDC), CII, IGBC, and MoHUA can train contractors, builders, and officials in embodied carbon tools and techniques.
- Knowledge Platforms: Open-access knowledge hubs and case study libraries (e.g., Carbon Leadership Forum, India LCA Network) can drive peer learning.

# 6 REDUCTION OF EMBODIED CARBON EMISSIONS

- Technical Solutions for Reducing Embodied Carbon Emissions

# 6. Technical Solutions for Reducing Embodied Carbon Emissions

With embodied carbon accounting for a growing share of building-related emissions—especially as operational energy efficiency improves—it has become imperative to deploy technical solutions that can mitigate the climate impact of construction activities. The upfront emissions from material production, transportation, and on-site construction are locked in once a building is completed, making it critical to address embodied carbon at the design and construction stage.

This chapter outlines technical solutions organized across five key categories:

1. Low-carbon materials and material substitution
2. Optimized structural design and construction methods
3. Digital tools for carbon quantification and decision-making
4. Circular economy practices in construction
5. Renewable energy integration and low-impact logistics

## I. Low-Carbon Materials and Material Substitution

❖ **Blended and Alternative Cements**

- Pozzolana Portland Cement (PPC) and Portland Slag Cement (PSC), which incorporate fly ash or GGBS, emit significantly less $CO_2$ than Ordinary Portland Cement (OPC).
- Low-clinker cements: Reducing clinker ratio in cement lowers process emissions (which contribute ~90% of cement's embodied carbon).
- Calcined clay cement (LC3): Combining calcined clay, limestone, and gypsum, LC3 offers 30–40% lower emissions and is well-suited for Indian conditions.

❖ **Recycled Aggregates and Industrial By-products**

- Recycled Concrete Aggregate (RCA): Produced from crushed C&D waste, reduces demand for virgin aggregate.
- Manufactured Sand (M-sand): Sustainable alternative to river sand, reducing ecological impact and carbon footprint.
- Fly ash bricks, AAC blocks, and CSEB (Compressed Stabilized Earth Blocks): These offer lower embodied emissions compared to traditional burnt clay bricks.

❖ **Sustainable Timber and Bio-based Materials**

- Engineered wood products (e.g., cross-laminated timber, glulam) sequester carbon and reduce emissions associated with steel or concrete.
- Bamboo-based panels, agri-residue boards, and hempcrete offer excellent insulation and low-carbon performance, particularly in low-rise buildings.

❖ **Green Finishes and Interiors**

- Low-VOC paints, lime plasters, and earth-based finishes reduce carbon and improve indoor air quality.
- Modular furniture and pre-finished panels reduce waste and emissions from site finishing.

## II. Optimized Structural Design and Construction Methods

### ❖ Material Efficiency and Structural Optimization

- High-strength steel and concrete grades allow for material reduction without compromising structural integrity.
- Optimized member sizing, grid planning, and load path rationalization help reduce material volumes in beams, columns, and slabs.

### ❖ Modular and Prefabricated Construction

- Precast concrete elements, modular wall panels, and steel modules reduce on-site waste, speed up construction, and improve quality control.
- Pre-engineered buildings (PEBs) are especially useful in industrial and institutional projects, using less steel through efficient design.

### ❖ Light-weight Construction Systems

- Drywall systems (e.g., gypsum boards, metal studs) and hollow-core slabs reduce dead load and embodied emissions.
- Post-tensioned slabs reduce concrete usage by enhancing slab span and strength.

### ❖ Passive Design Integration

- While typically discussed under operational efficiency, passive strategies such as shading, daylighting, and natural ventilation reduce the need for carbon-intensive mechanical systems, influencing both embodied and lifecycle carbon.

## III. Digital Tools for Carbon Quantification and Decision-Making

### ❖ Life Cycle Assessment (LCA) Tools

- One Click LCA, eToolLCD, Tally, and SimaPro allow for rapid modeling of embodied carbon across life cycle stages (A1–A5, B, C).
- These tools support comparison between material alternatives and help optimize construction assemblies for lower emissions.

### ❖ Building Information Modeling (BIM) Integration

- BIM-integrated carbon modeling enables early-stage carbon analysis, allowing architects and engineers to tweak form, structure, and material choices before finalization.
- Combined with parametric design, BIM can automate identification of low-carbon options in real time.

### ❖ Digital EPD Libraries

- Tools like EC3 (Embodied Carbon in Construction Calculator) offer searchable databases of material-specific carbon data based on EPDs.
- Integration of Indian manufacturers into such platforms would significantly enhance data transparency and comparability.

## IV. Circular Economy Practices in Construction

❖ **Design for Deconstruction (DfD)**

- Buildings designed with reversible connections, standardized modules, and bolted rather than welded joints can be disassembled and reused.
- This approach extends material life cycles and minimizes end-of-life emissions.

❖ **Construction and Demolition (C&D) Waste Reuse**

- On-site crushing of demolished concrete for sub-base applications.
- Use of recycled steel and aluminium with known recycled content.
- Material banks and salvage systems can facilitate reuse of doors, windows, tiles, and even MEP components.

❖ **Adaptive Reuse of Existing Buildings**

- Upgrading or repurposing existing structures avoids the carbon cost of new construction.
- Retrofitting old government or institutional buildings instead of demolishing them reduces both embodied and operational emissions.

❖ **Circular Material Supply Chains**

- Encouraging take-back schemes for packaging, insulation, tiles, and panels.
- Contracts with suppliers who guarantee material recyclability or cradle-to-cradle certification.

## V. Renewable Energy Integration and Low-Impact Logistics

❖ **Renewable Energy in Material Production**

- Cement plants and steel manufacturers powered by solar, biomass, or waste heat recovery can dramatically cut emissions.
- Green hydrogen in steel manufacturing (DRI process) is emerging as a game-changer for industrial decarbonization.

❖ **Electrification of Construction Equipment**

- Use of electric cranes, concrete mixers, and forklifts, powered by on-site solar or grid-tied renewable sources.
- Hybrid or electric transport vehicles for material delivery and intra-site logistics.

❖ **Just-in-Time Material Delivery**

- Reduces the need for large storage areas and rework.
- Helps minimize material degradation and wastage at site.

❖ **Construction Process Optimization**

- Digital twins and construction sequence simulation can optimize resource allocation, reduce idle time, and improve efficiency.
- AI-based planning and construction robotics (e.g., 3D concrete printing) offer material efficiency and precision.

# 7 FRAMEWORK FOR NET ZERO CARBON TRANSITION

- Roadmap for Decarbonization of Embodied Carbon
- Incentives and Financing Mechanisms
- Collaboration with Industry and Government
- Policies and Regulations

# 7. Framework for Net Zero Carbon Transition

India's ambition to become a net-zero economy by 2070 presents an unprecedented opportunity to transform the country's building and construction sector into a cornerstone of climate action. While much of the policy discourse and technical innovation has focused on operational emissions, embodied carbon — the emissions arising from material extraction, processing, transport, and construction — is rapidly gaining attention as a critical piece of the decarbonization puzzle. In this context, a well-structured and multi-pronged framework is required to guide the transition toward Net Zero Carbon (NZC) buildings through embodied carbon reduction.

This chapter outlines such a framework, structured around four key pillars:

1. A roadmap for decarbonization
2. Incentives and financing mechanisms
3. Collabourative action between government and industry
4. Policies and Regulations

Each of these components is critical in enabling India's construction ecosystem to move from intent to action on embodied carbon reduction, fostering innovation, scalability, and alignment with national climate goals.

## 7.1 Roadmap for Decarbonization of Embodied Carbon

A strategic and phased roadmap is essential to guide stakeholders from the current high-emission status quo to a future of low or zero embodied carbon in buildings. The roadmap should consider both near-term actions and long-term structural shifts.

### Phase I: Baseline Assessment and Capacity Building (2025–2027)

❖ **Establish National and Regional Baselines**

- Conduct a national-level embodied carbon mapping for key building typologies (residential, commercial, industrial, institutional) across India's four climate zones.
- Identify high-carbon "hotspots" in commonly used construction assemblies and materials (e.g., RCC structures, burnt bricks, OPC cement).
- Develop typology-wise emission intensity benchmarks ($KgCO_2e/m^2$) for reference use.

❖ **Build India-Specific LCA Databases**

- Develop a centralized database of India-specific emission factors and EPDs for locally produced materials such as bricks, cement, steel, aluminium, AAC blocks, and bamboo.
- Collabourate with BIS, BEE, NITI Aayog, CPCB, and academic institutions to build an open-access national embodied carbon database.

❖ **Launch Pilot Projects and Demonstrations**

- Identify and document 50–100 low-carbon construction pilot projects across geographies, building types, and material systems.
- Integrate LCA tools like One Click LCA into the design and execution of public buildings.

❖ **Capacity Building and Training**

- Introduce LCA, carbon footprinting, and material optimization in architecture, engineering, and planning curricula.

- Train urban local bodies (ULBs), public works departments (PWDs), and housing boards in embodied carbon accounting.
- Certify professionals (architects, engineers, quantity surveyors) as "Carbon Assessors" through national skill councils.

## Phase II: Market Development and Tool Integration (2027–2030)

❖ **Integration with Green Rating Systems**

- Mandate embodied carbon disclosure and credit weightage in IGBC for new construction.
- Develop specific carbon targets for pre-certification and platinum-level ratings.

❖ **Digital Tool Adoption**

- Promote BIM-LCA integration, enabling real-time carbon accounting during design iterations.
- Develop plug-ins for commonly used BIM platforms (e.g., Revit, ArchiCAD) to streamline carbon modeling.
- Promote Indian-specific LCA tools and APIs for regional use.

❖ **Low-Carbon Material Innovation and Manufacturing**

- Incentivize R&D and commercialization of:
  - LC3 (Limestone Calcined Clay Cement)
  - Geo-polymers
  - High-volume fly ash and GGBS concretes
  - Bamboo composites
  - Recycled aggregates and C&D waste
- Offer grants or soft loans for setting up manufacturing units in Tier II and III cities.

❖ **Regional Material Mapping and Policy Alignment**

- Map low-carbon materials availability by district/state to reduce transport emissions.
- Align state-level ECBC and DCR regulations with availability of green materials.

## Phase III: Policy Mainstreaming and Public Procurement Reform (2030–2035)

❖ **Embodied Carbon Mandates in National Codes**

- Integrate embodied carbon intensity limits into:
  - National Building Code (NBC)
  - ECBC and Eco-Niwas Samhita
  - Smart Cities Mission guidelines
  - Urban design bylaws
- Define typology-wise carbon intensity ceilings

❖ **Green Public Procurement (GPP) Requirements**

- Mandate EPDs for construction materials in public sector projects.
- Create GPP thresholds based on life cycle emissions instead of cost alone.

- Train PWD engineers and procurement officials on carbon-informed tender evaluation.

❖ **Taxation and Regulatory Incentives**

- Provide GST reductions for verified low-carbon materials and LCA-compliant projects.
- Introduce “carbon bonus” in FAR allocation, fast-track clearances, and property tax rebates.

❖ **Labeling and Disclosure Standards**

- Launch India’s own “Embodied Carbon Label” for construction materials.
- Require carbon intensity disclosure for all large buildings as part of environmental clearance documentation.

## Phase IV: Sectoral Decarbonization and Industry Alignment (2035–2045)

❖ **Industry-Wide Roadmaps**

- Collabourate with cement, steel, brick, and aluminium sectors to develop:
    - Material-specific embodied carbon reduction pathways
    - Roadmaps aligned with India’s Low-Carbon Development Strategy
- Set industry carbon intensity reduction targets under a National Industrial Emissions Framework.

❖ **Material Circularity and C&D Waste Management**

- Mandate recycled content standards for materials in new construction
- Enforce segregation, tracking, and reuse of C&D waste under stricter rules.
- Incentivize adaptive reuse of existing buildings to extend their lifecycle and avoid new emissions.

❖ **Carbon Pricing and Offsets**

- Introduce embodied carbon trading or offset mechanisms within domestic carbon markets.
- Allow large developers to offset excess emissions through certified material reuse or afforestation.

❖ **Technology Ecosystem Development**

- Fund incubation hubs for carbon capture, green hydrogen for steelmaking, carbon-sequestering materials, and AI-based LCA platforms.
- Promote blockchain traceability for green materials and verified EPD data chains.

## Phase V: Net Zero Alignment and Regulatory Enforcement (2045–2070)

❖ **Mandatory Compliance with Net Zero Embodied Carbon Goals**

- Mandate Net Zero Embodied Carbon for:
    - All government buildings after 2045
    - Private buildings >10,000 $m^2$ after 2050
- Establish maximum allowable cradle-to-gate carbon limits for key materials.

❖ **Monitoring, Reporting, and Verification (MRV) Systems**

- Deploy nationwide MRV platforms for embodied carbon monitoring using IoT, real-time reporting dashboards.

- Create third-party verification mechanisms for carbon disclosure.

❖ **International Alignment and Carbon Export Readiness**

- Harmonize Indian embodied carbon regulations with global systems (e.g., EU CBAM).
- Enable Indian material producers and developers to qualify for international green building markets.

❖ **Resilience, Equity, and Affordability**

- Ensure low-carbon solutions are accessible to low-income and informal housing sectors.
- Support community-led housing retrofits using low-carbon, climate-resilient materials.
- Promote equity in embodied carbon strategies through inclusive planning and local employment in green industries.

## 7.2 Incentives and Financing Mechanisms

Reducing embodied carbon in the building sector—especially in a fast-growing economy like India—requires targeted and well-structured incentives to overcome the initial cost barriers, enable early adopters, and scale innovative practices. Unlike operational carbon reductions, which often result in direct energy savings over time, embodied carbon reductions are less immediately tangible and require upfront investments in new materials, technologies, tools, and capacity.

This section presents a comprehensive framework of fiscal, financial, and market-based incentives, aligned with India's economic structure, construction practices, and climate commitments. These mechanisms aim to shift the market toward low-carbon construction while ensuring affordability, competitiveness, and job creation.

### 1. Fiscal Incentives and Subsidies

❖ **Differential GST for Low-Carbon Materials**

- Proposal: Introduce a tiered Goods and Services Tax (GST) structure based on embodied carbon intensity of materials.
    - Lower GST slabs (5–12%) for verified low-carbon materials such as AAC blocks, fly ash bricks, GGBS, LC3 cement, bamboo panels.
    - Higher GST (18–28%) for conventional carbon-intensive products lacking EPDs.
- Impact: Reduces cost barriers for sustainable material adoption in mass-market projects, especially affordable housing.

❖ **Capital Subsidies for Green Manufacturing**

- Offer upfront capital subsidies for:
    - Establishing factories for low-carbon material production (e.g., precast concrete, recycled aggregates, bio-based materials).
    - Setting up construction & demolition (C&D) waste recycling plants.
    - Expanding capacity for EPD certification and LCA consultancy services.

❖ **Rebate on Municipal Charges**

- Provide rebates or waivers on:
    - Building plan approval fees.
    - Property tax for certified low-embodied carbon buildings.

- Construction waste disposal charges for projects that reuse or recycle materials.

❖ **Performance-Based Incentives**

- Disburse incentive payments based on third-party verified embodied carbon reduction performance per m² or per ton of $CO_2e$ avoided.
- Could be modeled like Perform Achieve Trade (PAT) schemes for buildings.

## 2. Green Financing Instruments

❖ **Green Construction Finance Facility (GCFF)**

- A dedicated facility managed by SIDBI, NABARD, or IREDA for:
  - Low-interest loans to developers constructing low-carbon buildings.
  - Working capital loans to MSMEs manufacturing green construction materials.

❖ **Embodied Carbon-Linked Loans**

- Commercial banks and housing finance companies to offer:
  - Differential interest rates for buildings that meet specific embodied carbon thresholds.
  - Green Home Loans for buyers purchasing apartments in low-embodied carbon housing projects (especially affordable and EWS categories).

❖ **Carbon Credit Monetization**

- Enable developers to earn carbon credits through embodied carbon reduction and participate in:
  - Indian carbon markets under the Carbon Credit Trading Scheme (CCTS).
  - Voluntary markets such as Verra or Gold Standard with India-specific methodologies.
- Revenues from trading credits can be used to offset the initial cost of green materials.

❖ **Blended Finance and Public-Private Partnerships (PPPs)**

- Mobilize concessional capital (e.g., from World Bank, ADB, KfW) blended with domestic private equity for:
  - Urban redevelopment projects targeting circularity and carbon neutrality.
  - Industrial clusters producing net zero construction inputs (green cement, recycled steel).

## 3. Green Public Procurement (GPP)

❖ **Mandatory Procurement Criteria**

- Mandate the use of materials with certified EPDs and low embodied carbon in all:
  - Central and state government buildings.
  - Public infrastructure projects funded by taxpayer money (e.g., roads, schools, hospitals).
- Use embodied carbon thresholds (e.g., ≤450 $KgCO_2e$ /m²) as pre-qualification criteria in government tenders.

❖ **Preferential Procurement and Scoring**

- Introduce carbon performance as a scoring criterion in tender evaluation—alongside cost and technical qualifications.

- Projects with certified embodied carbon reductions can receive higher technical scores or cost relaxations.

❖ **Long-Term Supply Contracts**

- Government can enter into long-term offtake contracts with green material manufacturers (e.g., recycled steel, carbon-sequestering concrete), improving financial stability and enabling investment.

## 4. Planning Incentives and Urban-Level Tools

❖ **Additional FAR/FSI for Low-Carbon Buildings**

- Offer additional built-up area (Floor Area Ratio/FSI) for projects achieving low embodied carbon benchmarks. For example, buildings achieving a cradle-to-gate carbon intensity below 350 $KgCO_2e$ /$m^2$ can be granted 5–10% additional FAR.

❖ **Fast-Track Approvals**

- Expedite clearances for projects that submit verified LCA documentation and use green materials with EPDs.
- Especially beneficial in urban areas with high approval delays.

❖ **Tax-Free Zones for Material Innovation**

- Declare Special Economic Zones (SEZs) or innovation parks for:
    - Carbon-negative construction material production.
    - R&D units working on digital LCA tools, AI-BIM integration, and circular design.

## 5. Market-Based and Performance Instruments

❖ **Embodied Carbon Credits in National Carbon Market**

- Create a standardized methodology for embodied carbon reductions.
- Allow developers and manufacturers to generate credits per ton of $CO_2e$ avoided and trade on Indian Carbon Market (ICM) platforms.

❖ **Reward Mechanism for Circular Construction**

- Offer financial rewards for:
    - Demolition projects that achieve high material recovery rates.
    - Projects using ≥20% recycled materials.
    - Projects that incorporate Design for Disassembly (DfD).

❖ **Green Labeling and Branding Support**

- Provide marketing and promotional support to real estate projects achieving low-carbon construction targets.
- Enable use of a government-backed "Low Embodied Carbon Certified" label for housing and commercial advertisements.

## 6. Institutional and Capacity Support Mechanisms

❖ **Risk Guarantee Funds**

- Set up a risk guarantee mechanism to:
    - Protect financiers investing in first-of-a-kind low-carbon material manufacturing units.
    - Underwrite performance risk in construction projects using innovative but unproven technologies.

❖ **Insurance Rebates**

- Partner with insurance providers to:
    - Offer reduced premiums on project insurance for low-carbon certified buildings.
    - Cover risks associated with new green material adoption.

❖ **Results-Based Financing (RBF)**

- Pay construction companies or developers upon achievement of verified carbon reduction outcomes.
- Can be implemented at scale in public housing, Smart Cities, and government campuses.

## 7.3 Collaboration with Industry and Government

The transition to a Net Zero Carbon (NZC) building sector, particularly in the context of embodied carbon emissions, cannot be achieved by government action alone. The construction ecosystem is vast and highly fragmented, involving material manufacturers, real estate developers, contractors, architects, industry associations, research institutions, certification bodies, and multiple layers of government. Therefore, deep collaboration between industry and government is essential to unlock systemic change, scale low-carbon solutions, and ensure consistent adoption of embodied carbon reduction strategies across the value chain.

### 1. Industry-Led Action and Innovation

❖ **Voluntary Commitments and Roadmaps**

- Encourage industry stakeholders—cement, steel, brick, aluminium, glass, and timber manufacturers—to sign voluntary Net Zero embodied carbon roadmaps aligned with India's climate targets.
- Examples: CII Cement Low Carbon Taskforce, SteelZero pledges, Real Estate Developers' NZC charters.

❖ **Product Innovation by Manufacturers**

- Promote R&D investments in low-carbon materials like LC3 cement, alkali-activated materials (AAMs), carbon-cured concrete, bamboo composites, AAC blocks, and geopolymer bricks.
- Partner with government innovation agencies (e.g., DST, DBT, BIRAC) and international labs for tech transfer and pilot scaling.

❖ **Lifecycle Tools and Services**

- Encourage Indian firms to develop home-grown LCA and carbon estimation software tailored for Indian supply chains, labour, and regional practices.
- Industry can support integration of LCA into existing BIM workflows and costing software used by developers and consultants.

❖ **Sector-Wide Data and Disclosure**

- Promote voluntary carbon disclosures from developers and material suppliers.
- Encourage publishing Environmental Product Declarations (EPDs) verified by third-party certification agencies for transparency and comparability.

## 2. Government's Role: Policy, Regulation, and Procurement

❖ **Public Procurement Leadership**

- Use public procurement as a market-shaping tool: all central and state construction projects to include embodied carbon performance as a tender criterion.
- Ministries like MoHUA, MoRTH, and CPWD can integrate embodied carbon clauses in tenders and DPR formats.

❖ **National Standards and Codes**

- Update standards under BIS to reflect low-carbon alternatives:
  - IS codes for blended cements (e.g., IS 455 for PPC, IS 1489 for PSC)
  - Codes for AAC, CSEB, recycled aggregates, and alternative masonry.
- Align National Building Code (NBC), Energy Conservation Building Code (ECBC), and Eco-Niwas Samhita with embodied carbon accounting.

❖ **Urban Planning and Local Regulations**

- Work with ULBs to integrate embodied carbon metrics into:
  - Development Control Regulations (DCRs)
  - Environmental clearance (EC) processes
  - Town Planning Schemes and Master Plans

❖ **Support for MSMEs**

- Government to launch dedicated schemes for MSMEs in construction material production, including:
  - Green technology upgradation funds
  - R&D partnerships with CSIR labs
  - Soft loans and capacity-building programs

## 3. Joint Platforms and Institutional Mechanisms

❖ **National Embodied Carbon Taskforce**

- Establish an inter-ministerial taskforce (MoEFCC, MoHUA, BIS, MNRE, NITI Aayog, and MoSPI) to:
  - Develop national embodied carbon roadmap
  - Set thresholds and compliance frameworks
  - Coordinate with industry for implementation

❖ **State and City-Level Platforms**

- Create State Embodied Carbon Cells (SECCs) within state urban development departments to implement regional strategies.
- Support pilot initiatives in lighthouse cities (e.g., Ahmedabad, Pune, Bhubaneswar) with industry and academia.

❖ **Collaboration with Industry Associations**

- Leverage platforms like:
    - Confederation of Indian Industry (CII)
    - FICCI, CREDAI, NAREDCO (for real estate and housing)
    - IEEMA, INSDAG, IGBC (for standards and certification)
- Co-develop carbon benchmarks, training modules, and outreach campaigns.

❖ **Universities, Think Tanks, and R&D Hubs**

- Fund interdisciplinary research collaborations between:
    - Architecture and civil engineering schools (e.g., SPA Delhi, IITs, NITs)
    - LCA experts and environmental scientists
    - Material engineers and lifecycle economists

## 4. International Cooperation and Global Alignment

❖ **Participation in Global Alliances**

- Enhance India's engagement with platforms like:
    - Global Alliance for Buildings and Construction (GlobalABC)
    - World Green Building Council (WorldGBC)
    - UNFCCC's Buildings Breakthrough Initiative

❖ **Bilateral and Multilateral Partnerships**

- Collabourate with countries that have developed embodied carbon regulations:
    - UK (Part Z), Sweden (climate declarations), Netherlands (carbon caps)
- Leverage technical assistance and financing from:
    - World Bank, IFC, ADB
    - KfW (Germany), JICA (Japan), SE4All, UNEP, UNIDO

❖ **Harmonization of Standards**

- Align India's EPD and carbon disclosure frameworks with EN 15804, ISO 21930, and other globally accepted protocols.
- Enable Indian materials and building projects to qualify for export markets with embodied carbon disclosure requirements.

## 5. Collabourative Pilots and Living Labs

❖ **Low-Carbon Demonstration Projects**

- Co-create and fund demonstration projects between government departments and industry showcasing:
    - Low-carbon housing clusters
    - Green industrial parks using low-embodied carbon construction
    - Retrofit of public institutional buildings

❖ **Living Labs and Testbeds**

- Establish testbeds in academic institutions or smart cities to:
    - Monitor embodied carbon through sensors, digital twins, and AI analytics
    - Compare material performance and carbon efficiency over time

    - Share open-source data for replication

### 6. Education, Outreach, and Public Awareness

- **Nationwide Awareness Campaigns**

  - Jointly run mass campaigns highlighting the importance of embodied carbon and low-carbon building choices
  - Use television, digital media, and influencer outreach to reach developers, architects, and homeowners.

- **Professional Certification and CPD**

  - Develop collabourative training programs and certification for:
    - Embodied Carbon Analysts
    - Lifecycle Design Consultants
    - Low-Carbon Contractors

- **Knowledge Portals and Open Data**

  - Create government-supported platforms hosting:
    - Emission factors, case studies, LCA tools
    - Policy briefs and downloadable guides for local bodies and professionals

## 7.4 Policies and Regulations

As India scales up its infrastructure and urban development to meet the aspirations of a growing population and economy, the environmental consequences—especially embodied carbon emissions—are becoming increasingly significant. Policies and regulations are essential instruments to steer the construction sector toward low-carbon pathways.

While India has made considerable progress in operational energy efficiency (e.g., through the Energy Conservation Building Code (ECBC) and Eco-Niwas Samhita), the embodied carbon footprint of buildings remains largely unregulated and unaccounted for. Unlike operational carbon, which occurs over decades, embodied carbon is emitted upfront and is therefore irreversible once construction is complete.

This section outlines a robust policy and regulatory framework that can drive systemic change by embedding life cycle thinking into construction practices, codes, approvals, and market incentives.

### 1. National-Level Policies and Frameworks

- **National Building Code (NBC) Revision**

  - Revise the NBC to:
    - Introduce embodied carbon as a performance parameter across building types.
    - Recommend benchmarks (e.g., $KgCO_2e$ /m²) for structural systems and materials.
    - Include design guidelines for material efficiency, modularity, and circularity.
  - Mandate carbon intensity disclosures in the planning and approval process.

❖ **Expansion of ECBC to Life Cycle Carbon**

- Extend the Energy Conservation Building Code (ECBC) to address total lifecycle emissions by integrating embodied carbon alongside operational energy.
- Develop a dedicated section or "ECBC Plus" for embodied carbon, targeting:
    - Carbon intensity limits per square meter.
    - Material efficiency and reuse credits.
    - Rewarding design for disassembly and adaptability.

❖ **National Low Carbon Building Code**

- Introduce a new Low Carbon Building Code under the Bureau of Energy Efficiency (BEE) and MoHUA to:
    - Provide a framework for achieving Net Zero Carbon in new construction.
    - Harmonize with global practices (e.g., UK's Part Z, Sweden's Climate Declarations).
    - Serve as a compliance tool under state town planning laws.

## 2. Product Standards and Material Certification

❖ **Bureau of Indian Standards (BIS) Updates**

- Revise IS codes to:
    - Mandate minimum recycled content in steel, concrete, and aluminium.
    - Introduce carbon performance criteria for cement and bricks.
    - Define durability, strength, and safety parameters for emerging materials (e.g., LC3, bamboo composites).
- Include embodied carbon limits in standards for building envelope components, glazing, insulation, and roofing.

❖ **Mandatory Environmental Product Declarations (EPDs)**

- Phase in a requirement for EPDs for high-volume materials such as:
    - Cement, steel, glass, aluminium, bricks, and insulation products.
- Align EPD formats with EN 15804, ISO 14025, and ISO 21930.
- Provide compliance grace periods and subsidies for MSMEs to adapt.

❖ **Green Labelling Schemes**

- Scale up government-backed labelling programs (e.g., ISI, EcoMark) to include embodied carbon metrics.
- Link embodied carbon disclosure to green rating points in IGBC.

## 3. Urban Development Policies and Planning Instruments

❖ **Integration into Development Control Regulations (DCRs)**

- Modify municipal DCRs and town planning guidelines to:
    - Require embodied carbon estimation reports (via LCA tools) for large projects.

- Provide FAR/FSI incentives for low-carbon designs.
- Encourage reuse of building components and salvaged materials in retrofits and redevelopments.

❖ **Environmental Impact Assessment (EIA) Reform**

- Include embodied carbon evaluation in the EIA process for:
  - Large commercial, industrial, and infrastructure projects.
  - Smart city developments and urban redevelopment projects.
- Make life cycle carbon footprint disclosure a condition for environmental clearance.

❖ **Construction & Demolition (C&D) Waste Rules**

- Enforce the C&D Waste Management Rules, 2016 with updated provisions:
  - Mandatory segregation of reusable materials.
  - On-site recycling or offsite reuse targets.
  - Reporting and carbon accounting of recovered vs. new material use.

## 4. Fiscal and Regulatory Instruments

❖ **Carbon Taxation and Pricing**

- Introduce an embodied carbon levy on carbon-intensive construction materials like OPC cement, virgin steel, and bricks.
- Revenues to be channeled into a Green Construction Innovation Fund supporting low-carbon technology and MSMEs.

❖ **Inclusion in the Indian Carbon Market**

- Allow construction projects that achieve embodied carbon reductions to generate tradable carbon credits under the Carbon Credit Trading Scheme (CCTS).
- Develop sector-specific methodologies for credits based on life cycle assessment and third-party verification.

❖ **Green Public Procurement (GPP) Mandates**

- Mandate embodied carbon criteria in government construction tenders:
  - Minimum % of low-carbon material use.
  - Requirement for LCA report submission.
  - Bonus points for projects with EPD-certified inputs.
- Align procurement policies across central and state ministries (e.g., CPWD, MoRTH, MoHUA, NHAI).

## 5. Subnational Policies and State-Level Leadership

❖ **State-Specific Green Codes**

- Empower states to develop or adopt tailored Green Building Codes or Sustainable Urban Development Guidelines integrating embodied carbon aspects.

- Example: Maharashtra, Tamil Nadu, and Gujarat could lead pilot implementation in Smart Cities.

❖ **Municipal-Level Carbon Norms**

- Cities to set local regulations requiring:
    - Material passports and embodied carbon audits for new buildings.
    - Carbon ceilings for mass housing and redevelopment projects.
    - Use of city-level C&D waste in public infrastructure.

## 6. Compliance Mechanisms and Enforcement

❖ **Certification and Audit Requirements**

- Mandate third-party verified LCA reports for:
    - Projects above 10,000 m² built-up area.
    - All buildings seeking green incentives or FSI bonuses.
- Create a pool of certified carbon auditors and lifecycle assessors.

❖ **Digital Compliance Platforms**

- Create a centralized digital platform where developers:
    - Upload embodied carbon estimates using approved LCA tools.
    - Access city/state-wise carbon benchmarks and compliant materials.
    - Submit for approvals, monitoring, and incentives.

❖ **Penalty and Reward Mechanisms**

- Penalize non-compliant construction with:
    - Reduced environmental clearances.
    - Exclusion from government tenders or incentive schemes.
- Reward compliant projects with:
    - Tax rebates, subsidies, and FAR incentives.
    - Preferential treatment in government leasing or tenancy agreements.

## 7. Capacity Building and Institutional Reforms

❖ **Institutional Frameworks**

- Set up a National Centre for Embodied Carbon in Buildings under BEE or MoEFCC to:
    - Develop guidelines and tools.
    - Provide technical support to cities and states.
    - Facilitate stakeholder capacity building.

❖ **Training for Urban Local Bodies (ULBs)**

- Create technical training programs on:
    - Embodied carbon assessment using tools like One Click LCA, Tally.
    - Green procurement evaluation.
    - C&D waste circularity and enforcement.

# 8 CONCLUSION AND WAY FORWARD

- Conclusion
- Way Forward

# 8. Conclusion and Way forward

## 8.1 Conclusion

India's construction sector stands at a critical inflection point as it balances the need for rapid infrastructure development with the imperative of reducing carbon emissions. This study, through the application of LCA methodologies, provides a first-of-its-kind baseline of embodied carbon emissions across diverse climate zones, seismic zones, and building typologies in India. The findings clearly demonstrate that embodied carbon is not uniform; rather, it is shaped by contextual factors such as seismic risk, building function material use strategies, and climate conditions. Each of these dimensions plays a defining role in shaping the carbon profile of buildings, reinforcing the importance of localized, data-driven, and performance-based decision-making in India's pathway to a net-zero building sectors.

Building design is the most decisive factor shaping embodied carbon in Indian buildings. It defines how materials and structures come together and, ultimately, how much carbon a building carries before it is even occupied. Architectural design sets the form, layout, and material choices, while structural design determines how the building stands and responds to loads. Together, they decide both performance and carbon outcomes.

The analysis of the 20-building sample shows a clear escalation in embodied carbon with increasing seismic risk. Embodied carbon rises by more than 30% from Seismic Zone II to Zone III and by over 60% when comparing Zone III to the higher-risk Zone IV, reflecting the significant influence of seismic demands on material intensity. Average values range from approximately 450 $kgCO_2e/m^2$ in Zone II to 550 $kgCO_2e/m^2$ in Zone III, reaching nearly 775 $kgCO_2e/m^2$ in Zone IV. This progression is primarily driven by the additional structural reinforcement, larger foundation systems and denser material requirements necessary to meet safety and performance criteria in higher-risk zones. Overall, the findings reaffirm that heightened seismic exposure directly contributes to increased embodied carbon, highlighting the need for improved structural efficiency—such as advanced modelling and performance-based design—to achieve lower-carbon outcomes in seismically sensitive regions.

Across building typologies, embodied carbon varied according to architectural requirements, functional demands, and material choices. Although the sample size remains limited at four buildings per typology, the trends provide useful indicative insights. Government buildings exhibited the highest embodied carbon intensity—approximately 670 $kgCO_2e/m^2$—largely due to traditional in-situ construction methods, supply chain constraints, and the typical technical capabilities of government project contractors. These buildings often follow standardised codes and conventional practices, indicating considerable scope for improvement when compared to private-sector construction. Factory buildings also showed higher values (around 630 $kgCO_2e/m^2$) due to heavier structural systems and larger spans. Commercial buildings averaged 530 $kgCO_2e/m^2$, while residential and school buildings were comparatively lower at roughly 500 $kgCO_2e/m^2$. While these differences generally align with variations in design intent and structural demand, a larger dataset is required to establish stronger typology-wise conclusions, as no definitive pattern can be confirmed from a sample of four buildings per category.

In the climatic zone segregation which has an intertwined impact on the embodied carbon from both architectural and structural design, it was observed that, the Composite zone records the highest embodied carbon intensity at 728 $kgCO_2e/m^2$, driven by seismic design considerations—three of the five buildings in this category fall under Seismic Zone IV—along with wide climatic variations and the use of material-intensive systems. The Hot & Dry zone follows at ≈630 $kgCO_2e/m^2$, where higher values stem from deep foundations and reinforced frames suited for sandy or silty soils, combined with seismic detailing typical of the region. Composite buildings are designed to withstand both hot and cold extremes, heavy winds, and high rainfall, resulting in greater use of reinforced concrete and structural steel. Warm & Humid and Temperate zones show relatively lower values (428–424 $kgCO_2e/m^2$), reflecting lighter structures and less reinforcement demand. It is also important to note that most buildings in Composite and Hot & Dry zones are located in Seismic Zone IV, indicating that climatic variation overlaps with seismic influence in this dataset.

Overall, the study highlights that embodied carbon performance in Indian buildings is fundamentally a design outcome—shaped by how architectural form and structural systems respond to seismic and climatic conditions. Although based on a finite yet representative sample of twenty buildings, the patterns are consistent and insightful. As the sector moves toward carbon-efficient construction, integrating carbon awareness into early design decisions—where form, structure, and materials are decided together—will be key to building both sustainable and resilient infrastructure.

After removing outliers, the typology benchmarks became more consistent and representative of real-world practices. The refined averages—Factory: 391*, Government: 600*, Residential: 479*, School: 417*, and Commercial: 578* $kgCO_2e/m^2$—provide a more reliable baseline for comparing building types and guiding material selection, design optimization, and decarbonization planning. These numbers are indicative averages derived after outlier adjustment.

**These numbers represent central tendencies within the current dataset and are not standardized benchmarks. Variations may occur due to limited sample size and differing project contexts.*

## 8.2 Way Forward

The findings of this study underscore the growing importance of integrating embodied carbon considerations into India's mainstream construction practices, policies, and regulatory frameworks. As operational emissions continue to decline due to improvements in building efficiency, embodied carbon will become an increasingly dominant component of the buildings sector total emissions. Addressing this aspect comprehensively will be critical for India to achieve its long-term Net Zero targets and to promote a truly sustainable construction ecosystem.

The potential expansion of the study may aim to enhance the scope and depth of the existing baseline, thereby improving the statistical robustness and representativeness of the dataset. Phase 1, which analysed twenty buildings across typologies, has provided valuable preliminary insights. However, a broader sample will be necessary to capture the diversity of India's construction practices and regional variations. The proposed Phase 2 shall therefore expand the dataset to twice the size of the existing study — eight buildings per typology — while also incorporating additional typologies such as hospitality and healthcare. This will enable finer analysis of embodied carbon trends, improve data reliability, and strengthen the evidence base needed for informed decision-making.

In this expanded phase, the Whole Life Carbon Assessment (WLCA) methodology may continue to be adopted to evaluate material production, transport, construction, and early-life emissions. The analysis may also extend beyond climatic and seismic variations to include a wider range of construction systems such as precast, modular, composite, Mivan, tunnel form, and post-tensioned structures, along with emerging technologies like 3D printing. This approach will help benchmark modern construction techniques against conventional RCC and cast-in-situ systems, identifying measurable carbon reduction opportunities and promoting material efficiency.

The outcomes from such an expanded study could deliver a statistically robust, technology-specific baseline for embodied carbon in India's building sector. These insights may inform policy recommendations, guide the development of best-practice frameworks, and support wider adoption of low-carbon construction technologies. By deepening the evidence base and advancing technical understanding, India will be better positioned to embed embodied carbon reduction as a central pillar of its sustainable construction strategy—ensuring that national growth remains both climate-resilient and resource-efficient.

### Strategic Implications of the Study

This study provides critical insights and tools to accelerate the adoption of low-embodied-carbon construction in India:

- Inform Policy and Regulations: Data from the study can guide the integration of embodied carbon thresholds into regulatory frameworks such as the National Building Code (NBC), Energy Conservation Building Code (ECBC), and local development control rules, enabling performance-based benchmarks across building types, climates, and seismic zones.

- Enable Material and Technology Innovation: Policymakers and developers can use the findings to promote low-carbon materials (e.g., alternative cements, recycled aggregates, engineered timber) and construction techniques (prefabrication, modular construction), while public procurement norms can prioritize low-carbon designs and mandatory disclosure.

- Mainstream Life Cycle Assessment (LCA): The study reinforces the importance of embedding LCA into early-stage design and planning, supported by capacity-building programs, standardized templates, and sector-specific emission factors.

- Establish a National Embodied Carbon Database: The study lays the groundwork for a centralized, publicly accessible inventory of building material emission factors based on Indian manufacturing, transport, and construction practices.

- Promote Climate- and Seismic-Responsive Design: Best practices from diverse zones can inform design codes and architectural education, ensuring buildings are efficient, resilient, and context-sensitive.

- Enhance Green Certification Systems: The embodied carbon benchmark set in the IGBC Net Zero Carbon Rating System can be rethought in light of this data, enabling rating systems to reward measurable carbon reductions, material reuse, and circularity.

- Foster Collaboration: Findings support public-private-academic partnerships to co-develop tools, demonstration projects, and pilot programs across climate and seismic zones.

- Mobilize Finance and Circular Economy Practices: Insights can guide green financing mechanisms, ESG-linked investments, and strategies for material reuse, design for disassembly, and construction waste recovery.

This study equips stakeholders with a credible, India-specific evidence base, enabling informed decisions and scalable action to transform embodied carbon from an invisible burden into a measurable opportunity for sustainable, resilient, and low-carbon construction

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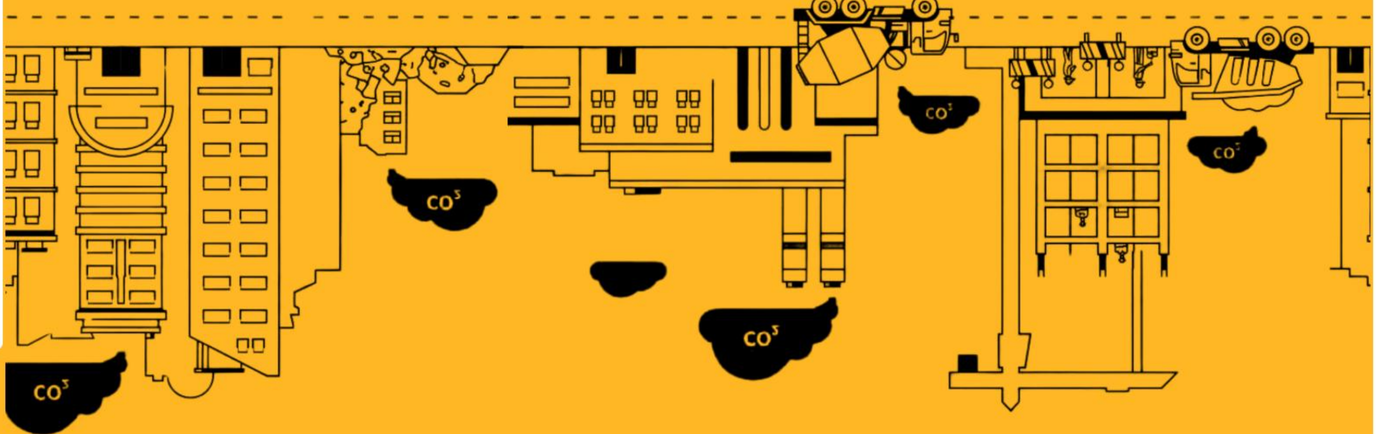

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# Embodied Carbon Emissions Baseline Estimation for Buildings in India

**Research Direction and Author:** Inderjit Ahuja

**Co - Author**: Sahithya T and Ipsita Subudhi

**Research Support:** Asphia Taimur, Manisha Shetty, Pavankumar Tadepalli and Yasin Khan

Confederation of Indian Industry



**Prepared by**

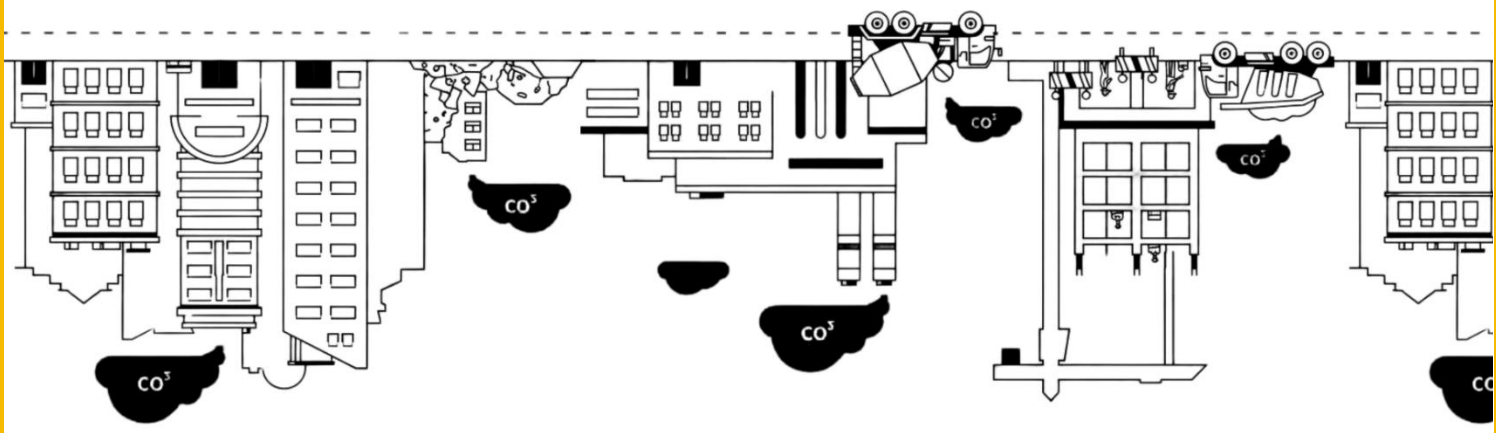
CII - Indian Green Building Council (IGBC),

Survey Number 64, Kothaguda Post, Near HITECH City,

Hyderabad – 500084, India,

www.cii.in | www.igbc.in

# EMBODIED CARBON EMISSIONS BASELINE ESTIMATION FOR BUILDINGS IN INDIA



## About SED Fund

The Sustainability, Equity and Diversity Fund (SED) is dedicated to supercharging energy transition across Asia through a collaborative response. We aim to support economies in meeting their ambitious clean energy goals by providing seed funding to innovative programs and early-stage organisations.

## About CII - Green Business Centre (CII- GBC)

CII established the CII - Green Business Centre (CII- GBC) in the year 2004 as CII's developmental institute on green practices & businesses, aimed at offering world class advisory services on conservation of natural resources. The services offered CII-GBC include energy and resource management, green buildings, a rating system for green companies (GreenCo), renewable energy, GHG inventorisation, green product certification (GreenPro), waste management, promotion of innovative clean technologies, etc. Prior to 2004, since about 1990, the team had already been working on energy efficiency studies.

## About CII-Indian Green Building Council (CII- IGBC)

The Indian Green Building Council (IGBC) is a part of CII-GBC and has initiated and is promoting the green building movement in India. IGBC is India's premier Green Building Council and has extensive experience in green and low-carbon buildings in the country. IGBC has experience and expertise across all building typologies and climatic zones in India. IGBC brings a set of unique strengths to this assignment, which is unmatched by any other agency, viz.,

1. An extensive network around the country, consisting of:
    1. 32 IGBC regional/local chapters (who engage at the city/state level)
    2. 255+ Founding members and 2,574+ Organisation members
    3. 395+ student chapters, that build the sustainability leaders of tomorrow
    4. 110+ Green Building Consulting Firms
2. 8,600+ accredited professionals 70+ in-house technical experts consisting of architects, civil engineers, urban planners, interior designers, etc.
3. Access to deep sectoral expertise around the country and the globe through a) the networks indicated above and b) other linkages created through the broader CII network consisting of service providers, technology manufacturers, academicians, scientists, and international consultants.
4. Deep knowledge of low-carbon buildings, brought in by over 2 decades of experience with green buildings and, in the recent past, with net zero buildings; these are exemplified by the 32+ building rating systems that IGBC has developed over the years, including one on net zero emissions buildings.

For any further details and information,
please contact:

Mr. Inderjit Ahuja
Senior Counsellor
Confederation of Indian Industry
CII-Sohrabji Godrej Green Business Centre (GBC)
Survey No. 64, HiTech City, Hyderabad 500 084, India
Email: inderjit.ahuja@cii.in

The Confederation of Indian Industry (CII) works to create and sustain an environment conducive to the development of India, partnering Industry, Government and civil society through advisory and consultative processes.

For 130 years, CII has been engaged in shaping India's development journey and works proactively on transforming Indian Industry's engagement in national development. With its extensive network across the country and the world, CII serves as a reference point for Indian industry and the international business community.

In the journey of India's economic resurgence, CII facilitates the multifaceted contributions of the Indian Industry, charting a path towards a prosperous and sustainable future. With this backdrop, CII has identified "Accelerating Competitiveness: Globalisation, Inclusivity, Sustainability, Trust" as its theme for 2025-26, prioritising five key pillars. During the year, CII will align its initiatives to drive strategic action aimed at enhancing India's competitiveness by promoting global engagement, inclusive growth, sustainable practices, and a foundation of trust.


Confederation of Indian Industry
The Mantosh Sondhi Centre, 23, Institutional Area, Lodi Road, New Delhi – 110 003 (India)
T: 91 11 45771000; E: info@cii.in • W: www.cii.in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