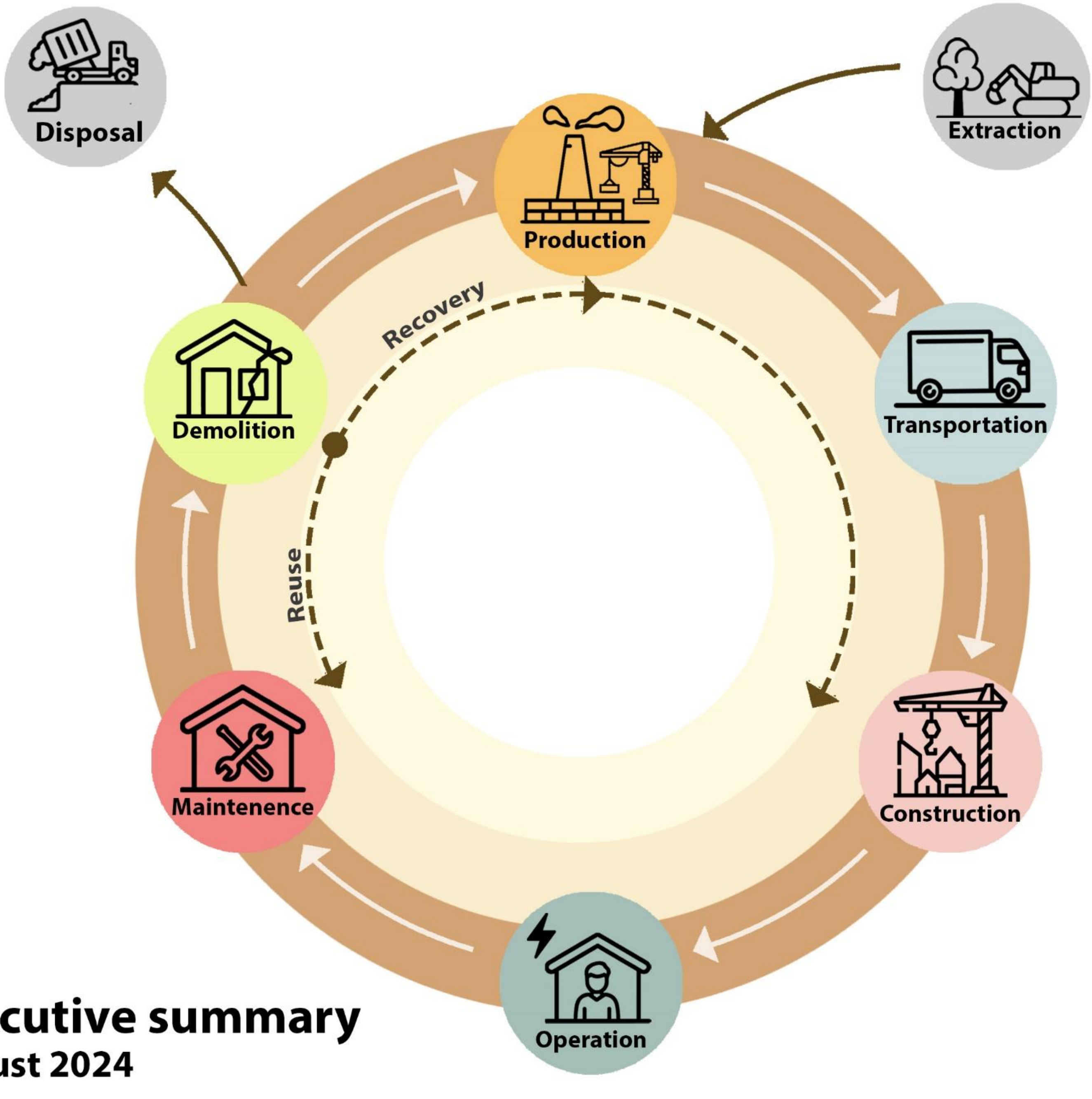
Whole-Life Carbon Analysis of Residential Buildings In India:

Three Case Studies From Bengaluru



Executive summary

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Greentech Knowledge Solutions Pvt. Ltd.

This study has been carried out by Greentech Knowledge Solutions Pvt. Ltd (GKSPL).

GKSPL is a research and advisory firm which offers services and solutions for improving energy efficiency in buildings, improving resource efficiency in the production of building materials and deployment of decentralized renewable energy systems. GKSPL has worked in the domains of building energy efficiency, resource-efficient building materials and renewable energy integration, by conducting technical research, providing policy support and facilitating transition through technical support, capacity building and policy implementation. (www.gkspl.in)

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Introduction

The buildings and construction sector contributes significantly to global greenhouse gas emissions and climate change. In 2022, buildings were responsible for 34% of global energy demand and 37% of energy and process-related carbon dioxide CO2 emissions (UNEP, 2024). The buildings sector in India constitutes 30% of energy demand and 25.6% of GHG emissions (CSTEP, 2024). If the global temperature rise during the 21st century is to be kept below 2oC above pre-industrial levels, the global buildings and construction sector must almost completely decarbonize by 2050 (UNEP, 2021).

India has committed to a net-zero target by 2070 at COP 26. In April 2024 Niti Aayog initiated first policy-level intervention towards the net-zero goal through the formulation of interministerial working groups to develop pathways for meeting national commitments on net zero and to propose strategies and interventions for achieving the same. As a part of the initiative, sectoral committees have been formed and one of the sectors is buildings, the other being transport, industry, power, and agriculture. Embodied carbon policy discussions are in their early phase in India, with the working group on embodied energy of building materials under the panel for sustainability, CED 46: P19 (National Building Code), and embodied carbon reporting requirements incorporated into the recently revised (draft) Energy Conservation and Sustainable Building Code (ESCBC) for commercial and office buildings by the Bureau of Energy Efficiency.

What does decarbonisation of the building and construction sector mean and entail in the Indian context? What should be the pathway to achieve decarbonisation of the building sector in India? To initiate discussion on these questions, baseline data is required on the whole life carbon or carbon footprint of typical buildings that are being constructed in India today (Rediff.com, July1,2024). There is a dearth of studies that provide data on whole life carbon emissions from different building typologies. Even a few studies that have been conducted, have mostly focussed on quantifying whole life energy rather than whole life carbon. In the first study of its kind, the present study provides results of whole life carbon analysis for three typologies of urban residential buildings located in Bengaluru and examines strategies to reduce whole life carbon emissions.

The life cycle of a building can be divided into four stages (BS EN 15978:2011) : a) Product stage (A1-A3) entails mainly mining and manufacturing of the building materials; b) Construction stage (A4-A5) entails transportation of the materials to the construction site and the construction of the building; c) Use stage (B1-B6) entails use, maintenance, refurbishment, repair, replacement and operation of the building; d) End of life stage (C1-C4) entails demolition, waste processing, disposal etc. The whole life carbon or carbon footprint of a building represents the carbon emissions during this entire lifecycle. The whole life carbon of a building has two components i.e. embodied carbon and operational carbon. Embodied carbon (A1-A5, B1-B5, C1-C4) denotes carbon emissions associated with materials and construction processes throughout the whole lifecycle of a building. Operational carbon (B6) are emissions associated with energy used to operate the building or in the operation of infrastructure.

Among various lifecycle stages, the largest carbon emissions of interest are:

(a) Upfront embodied carbon: The emissions caused during the building material production and construction phases (A1-A5) which are released into the atmosphere before the building is occupied or the infrastructure begins operation, and
(b) Operational carbon (B6): The emissions from the energy used for cooling, heating, lighting, operation of appliances and equipments, etc. in the operational life of the building.

The present study limits its scope to studying the upfront embodied carbon (A1-A5) and operational carbon (B6).

Many factors impact the whole-life cycle carbon performance of a building. Upfront embodied carbon appears to be influenced primarily by the choice of construction technology and building materials. Operational carbon is influenced by the passive design, thermal characteristics of the building envelope, efficiency of appliances and lighting systems, behaviour of the occupants, renewable energy generation, etc.

Residential building projects chosen for the study

Three residential building projects representing three different typologies of urban residential buildings located at Bengaluru (Figure 1) were taken up for the study:

- Project A is a high-rise multi residential building project using monolithic concrete technology for construction. The project consists of four residential towers of 27 and 29 stories of 527 housing units with two-level basement underneath. The construction technology used in the project i.e. monolithic concrete technology features as one of the emerging construction technologies for mass housing identified by the MoHUA and is now being widely used for high-rise residential construction in several metropolitan locations in the country.

- Project B consists of 3 different types of 119 low-rise (2-5 storeys) housing units in a gated community. A two-level basement caters to the parking and other service requirements of this project. The construction technology employed is a combination of RCC frame construction technology and load bearing masonry construction. A variety of walling materials including cement stabilised earth blocks (CSEB), solid concrete blocks and burnt clay bricks have been used in the project.

- Project C is 4 storey building, with 3 housing units, built on a plot of dimension of around 60’ x 40’. The project employs RCC frame construction technology with solid concrete blocks as the walling material. The project is representative of plotted housing and builder floor type of housing which is commonly found in Indian cities.

Project A *Project B* *Project C*

Figure 1: Three urban residential projects selected for the study

Methodology

For calculating the upfront embodied emissions (A1-A5), the detailed drawings and bill of quantities (BoQ), information of suppliers of building material and data on fuel and energy used at the construction site were collected from the builders. The building elements covered in the embodied carbon analysis includes sub-structure (foundations), structural elements like columns, beams, slabs etc., external and internal walls, pre-finishing e.g. plastering of walls and all fenestration (doors, windows, ventilators) and shading elements. Building elements which have relatively lower impact on embodied carbon like flooring finishes, paints, equipment & appliances, electrical and plumbing fixtures and fittings were not covered in the analysis.

The product carbon (A1-A3) is calculated by summing the product of the quantity of each building material and its respective "carbon emission factor" (CEF) or its "Global Warming Potential" (GWP).

$$Product\ Carbon\ (A1 - A3) = \sum_{i=1}^{n} (M_i \times CEF_i)$$

Where, M_i is the quantity of the material (kg, m^2 or m^3) of the building material and CEF_i is the carbon emission factor of the material given in $kgCO_{2e}/kg$, $kgCO_{2e}/m^2$ or $kgCO_{2e}/m^3$.

The CEF of each building material was determined by conducting primary and secondary research. The secondary research consisted of review of Environmental Product Declarations (EPDs) of Indian and international suppliers and research papers. The primary research involved visits to the building material manufacturing plants and collection of data on process and energy use as well as consultation with sectoral experts, wherever required. The analysis also required transport, fuel and electricity emission factors which were taken from research and government documents. The CEF used for the analysis of the three projects are given in Annexure I.

The operational carbon was evaluated for the 50 years lifetime of the building. To calculate the operational carbon, the operational energy use, of select dwelling units in each project, in terms of Energy Performance Index (EPI) was estimated through energy simulations using Design Builder simulation software. The energy simulation covered energy used for cooling, heating, lighting, and powering appliances. Energy used for water heating was determined separately.

Due to climate change the weather is expected to become hotter in coming years which will have an impact on operational energy, particularly the energy used for space cooling. Thus, energy simulations were carried out using the current weather file (2021) and artificially generated weather files for the year 2050 and 2080[1]. The estimated EPI of each project (for the years 2021, 2050 and 2080) is multiplied by the built-up area of all the dwelling units in the project to arrive at its annual electricity consumption. The yearly operational energy consumption was interpolated using the results for these three years. The cumulative CO_2 emissions for the building lifespan is calculated by multiplying the annual electricity consumption by the average annual emission factor of the Indian electricity grid (GEF).

$$Operational\ Carbon\ (B6) = \sum_{i=1}^{50} (EPI_i \times Built - up\ area\ of\ dwelling\ units \times GEF)$$

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[1] *The weather data file for future years 2050 and 2080 is generated using "Future-weather-generator" a Java based application developed under 'Energy for Sustainability Initiative' of the University of Coimbra.*

Where, EPI_i is the EPI for the i_{th} year and GEF is annual emission factor for Indian electricity grid for the year 2022-23 i.e. 0.71 $kgCO_{2e}/kWh$ (CEA, 2023).

The results of upfront embodied carbon and operational carbon over the lifetime of the building (50 years) are normalised over the total built-up area of each project and is presented in terms of $kgCO_{2e}/m^2$ of built-up area. The built-up area, for this study, is the area of a building measured to the external face of the perimeter walls at each floor level (Figure 2).

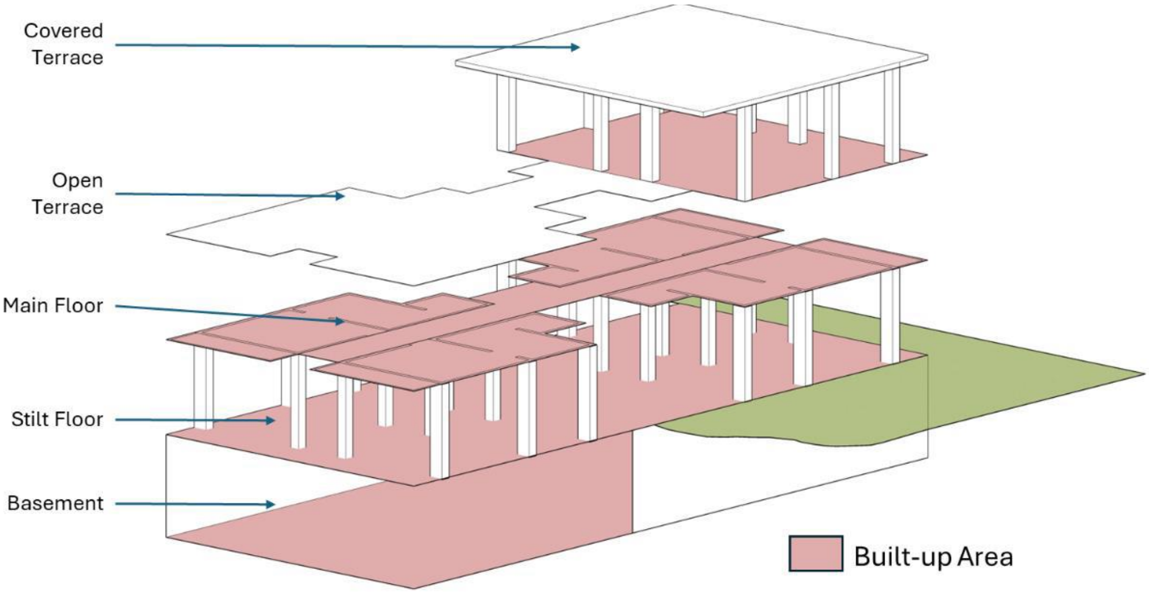

Figure 2: Diagram showing area considered as built-up area

Results

Upfront Embodied Carbon (A1-A5)

The upfront embodied carbon (A1-A5) along with the product stage carbon (A1-A3) for the three projects is presented in Table 1 and found to vary between 338 to 419 $kgCO_{2e}/m^2$ of built-up area.

Table 1 Upfront Embodied Carbon of the studied projects

Project	**Product Carbon (A1-A3) ($kgCO_{2e}/m^2$ of built-up area)**	**Upfront Carbon (A1-A5) ($kgCO_{2e}/m^2$ of built-up area)**
Project A	312 (Concrete- 52 %; steel -42 %) (Substructure -34%; building envelope & pre-finish -65%)	338
Project B	395 (Concrete- 42 %; Steel-38 %; Masonry and plaster- 16 %) (Substructure -51%; building envelope & pre-finish -49 %)	419

Project C	342 (Concrete-46%; Steel – 29%; Masonry and plaster-23%) (Substructure -14%; building envelope & pre-finish -86%)	374

Some of the important inferences which can be drawn from the data presented in Table 1 are:

- Product stage carbon (A1-A3) is the major contributor in the upfront embodied carbon with contributions ranging from 91-94% in the three projects. The contribution of transport (A4) and energy used for construction (A5) is relatively small.
- The two major building materials contributing to product carbon (A1-A3) are concrete and steel. In project A which is using monolithic concrete technology, concrete and steel together contribute to 94% of the product carbon(A1-A3). The contribution of concrete and steel reduces in the case of RCC framed construction e.g., Project C to 75%, with masonry (walling material and mortar) and plaster also having a significant contribution of 23%.
- Among building elements as expected the building envelope and pre-finishes have the largest contribution, ranging from 65 to 86%. However, the sub-structure depending on the type of foundation and presence of basement can also have a significantly large contribution on the product carbon. In project A, which has a two-level basement, the contribution of substructure in product carbon is 34%, while it reduces to 14% in case of project C which does not have a basement.
- Project A has taken some measures to reduce material intensity and increase utilisation of recycled materials. All concrete used in Project A had a 35% replacement of cement with Ground Granulated Blast-furnace Slag (GGBS) and the need for plastering of walls has been avoided, these measures contribute to reducing the upfront carbon emissions.

Operational Energy & Carbon

The comparison of the thermal performance of the building envelope and solar water heating, which have a significant impact on the space cooling and water heating energy requirement respectively, is given in Table 2. The Energy Performance Index (EPI) for the three building projects through energy simulations for the years 2021, 2050 and 2080 are presented in Figure 3

Table 2 Comparison of the thermal performance of the building envelopes and provision of solar water heating

Parameter	**Project A**	**Project B**	**Project C**
RETV (W/m^2)	14.5 -14.9	10.5-13.1	13.8
Roof -U value (W/m^2/K)	1.5	Roof of the low-rise houses are shaded with an insulated roof.	3.3
Solar Water Heater	No Provision	Almost 70% of the houses are equipped with SWH	No provision

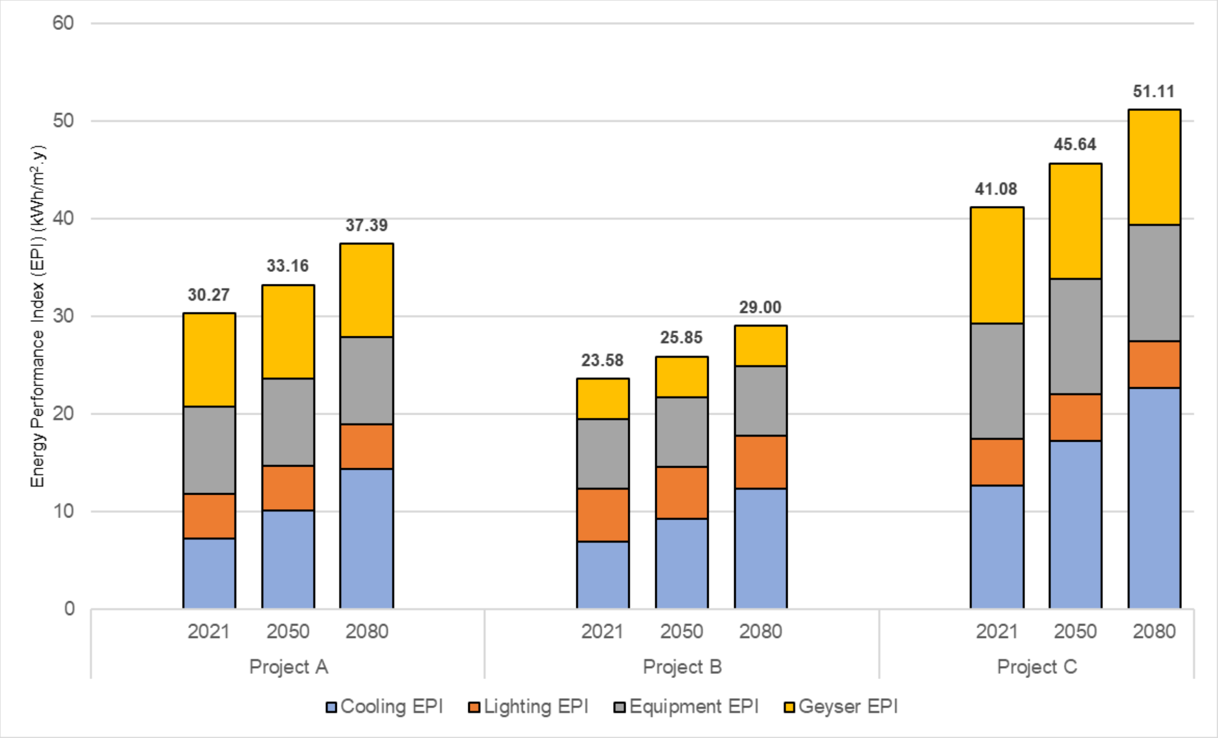

Figure 3: Energy Performance Index for the three projects for the year 2021, 2050 and 2080

Some of the important inferences that can be drawn are:

- The EPI for the base year 2021 varies between 23 kWh/m^2/year to 41 kWh/m^2/year for the three projects.
- For all the projects, the EPI is projected to increase with time as the climate becomes hotter and the energy simulation projection shows doubling of electricity required for space cooling by year 2080 compared to 2021.
- The two important end-uses that impact the operational energy in Bengaluru are the energy required for space cooling (fan and air-conditioner) and the energy used for heating water.
- Project B has the lowest EPI due to better envelope design (low RETV and insulated ventilated roof) and the use of solar water heater.

The estimated operational carbon (calculated over the 50-year lifetime) for the three-building project varies between 550 to 929 kgCO$_{2e}$/m^2 of built-up area Table 3.

Table 3 Operational Carbon for the three projects

Project	**Operational Carbon (kgCO$_{2e}$/m^2 of built-up area)**
Project A	654
Project B	550
Project C	930

It should be noted that the estimation of operational carbon emissions is based on several assumptions, which can lead to large uncertainties. Some of these are:

- The study has not considered the electricity consumed in the common areas and facilities, lifts and water pumping. This electricity will be considerably higher in Project A and are essential for its operation, and hence must be included in the analysis. Including common area electricity will significantly change the electricity consumption of the three projects.
- The efficiency of appliances is expected to improve, resulting in reduced electricity consumption. While the impact of higher future temperatures is considered in this study for determining cooling electricity, improved air-conditioner efficiency in future has not been considered.
- The effect of surrounding vegetation on the electricity consumption and hence, operational carbon, is not considered in the energy simulation. In well landscaped projects with low-rise buildings (Project B), the effect of vegetation in reducing the cooling demand can be significant, which will reduce electricity consumption.
- Another major factor for the uncertainty in operational carbon is that the progressive reduction in grid emission factor has not been considered. If India has to achieve net zero carbon by 2070, the grid carbon emission factor has to be near zero by 2070. This will hugely impact the operational carbon numbers over 50 years.
- The impact of on-site generation of electricity using rooftop solar photovoltaic panels have not been considered.

Whole life cycle carbon

The whole-life carbon results are shown in Table 4, while the share of upfront embodied carbon and operational carbon is shown in Figure 4. The whole-life carbon is lowest for Project B (969 kgCO_{2e}/m^2 of built-up area) and highest for Project C (1304 kgCO_{2e}/m^2 of built-up area). Project B which has the highest upfront carbon has the lowest operational carbon. It is observed that upfront embodied carbon makes a significant contribution ranging from 29% to 43% of the whole-life carbon. The percentage contribution of operational carbon varies from 57% to 71%.

Table 4: Whole-life carbon of the three building projects

	Upfront Carbon (A1-A5) (kgCO_{2e}/m^2 of built-up area)	Operational Carbon (B6) (kgCO_{2e}/m^2 of built-up area))	Whole-life Carbon (A1-A5 +B6) (kgCO_{2e}/m^2 of built-up area)
Project A	337	654	991
Project B	419	550	969
Project C	374	930	1304

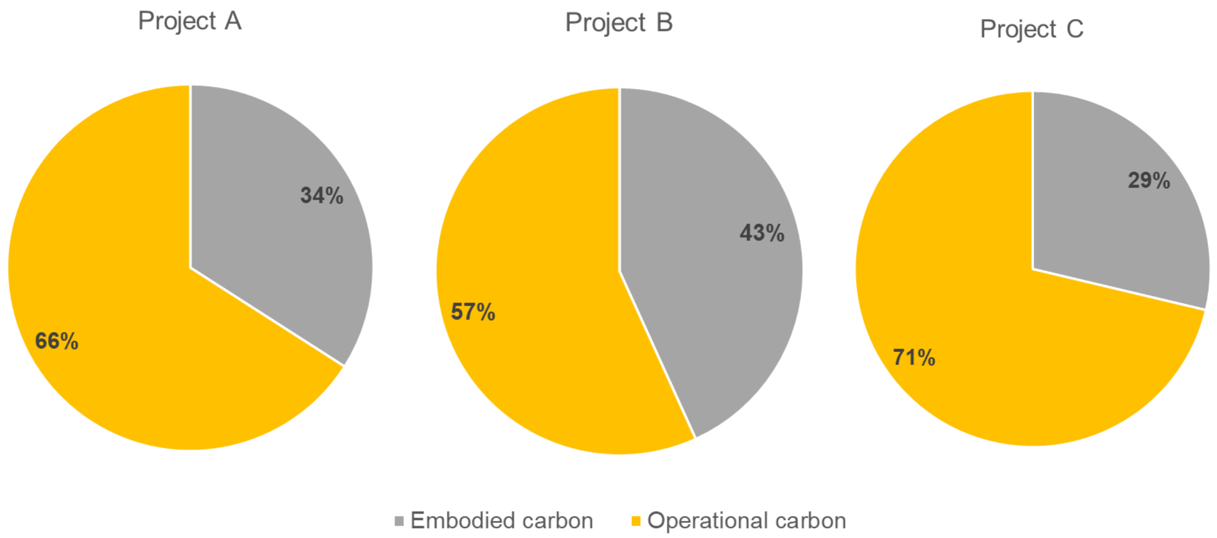

Figure 4: Share of upfront carbon and operational carbon in the three projects

Conclusions

Upfront embodied carbon baseline

The analysis shows that the upfront embodied carbon of the urban residential buildings is influenced significantly by the choice of construction technology, choice of building materials, and the design of the sub-structure (type of foundation and basement). Also, other factors like the seismic zone and the load bearing capacity of the soil, wind loads in taller buildings which impact the foundation and structural design, would also have a significant impact on the upfront embodied carbon. Table 5 presents a comparison of data presented in this study, with data from two other available studies.

Table 5 Data on upfront embodied carbon emissions from urban residential buildings in India.

Type of building & construction technology	**Upfront Embodied Carbon (kgCO$_{2e}$/m^2)**	**Source**	**Remarks**
High rise apartments – Monolithic concrete technology	400-415	Lodha Developers (2022)	Scope: sub-structure, building envelope, internal walls, paints, flooring, electrical and mechanical systems.
High rise apartments – Monolithic concrete technology (concrete with 35% GGBS)	337	Present study	Scope: sub-structure, building envelope, internal walls and pre-finishes
Low rise apartments and row housing (2-5 stories) – RC frame with masonry and RC roof	339- 419	Present study	Scope: sub-structure, building envelope, internal walls and pre-finishes
Low rise housing – Load bearing CSEB masonry & RC filler slab	229 -302	Reddy, et al (2020)	Scope: sub-structure, building envelope, internal walls and flooring.

It is observed that there are some differences in the scope of the studies presented in Table 5. Also, though not explicitly defined, it is assumed that in the other two studies the area used for normalization is the built-up area. Ideally, to construct a baseline, data from a larger number of buildings from different regions of the country will be needed. Also, perhaps the defining baseline based on typology and region may be more relevant. However, based on the limited data available, baseline upfront embodied carbon (A1-A5) for newly constructed Indian urban residential buildings is estimated to range from 250 to 450 kgCO$_{2e}$/built-up area.

The baseline upfront embodied carbon (A1-A5) for newly constructed Indian urban residential buildings is estimated to range from 250 to 450 kgCO$_{2e}$/built-up area.

Strategies to reduce upfront embodied carbon emissions

Following is some of the strategies to reduce upfront embodied carbon in urban residential buildings based on the analysis presented in this study:

a) *Reducing the quantity of concrete and steel through efficient structural design and choice of construction technology*: Concrete and steel together account for 75-94% of the product carbon (A1-A3) in the three projects analyzed in this study. Any strategy to reduce the quantity of concrete (m^3 /m^2) and steel (kg/m^2) would help in reducing the upfront carbon. The choice of construction technology influences the use of concrete and steel. A comparison of concrete and steel quantities for Project C (low-rise RC framed construction technology & RC roof) with that of townhouses of Project B (low-rise partially load bearing masonry & RC roof) is shown in Figure 5. It shows that the concrete and steel quantities show a 10-15% decrease in case of partially load bearing masonry construction compared to RCC framed construction. The work by Reddy et al (2020) shows that low-rise construction using load bearing masonry and RC filler slab results in further reductions in the concrete and steel requirement. Thus, through careful choice of construction technology and structural design substantial savings in concrete and steel requirements can be achieved.

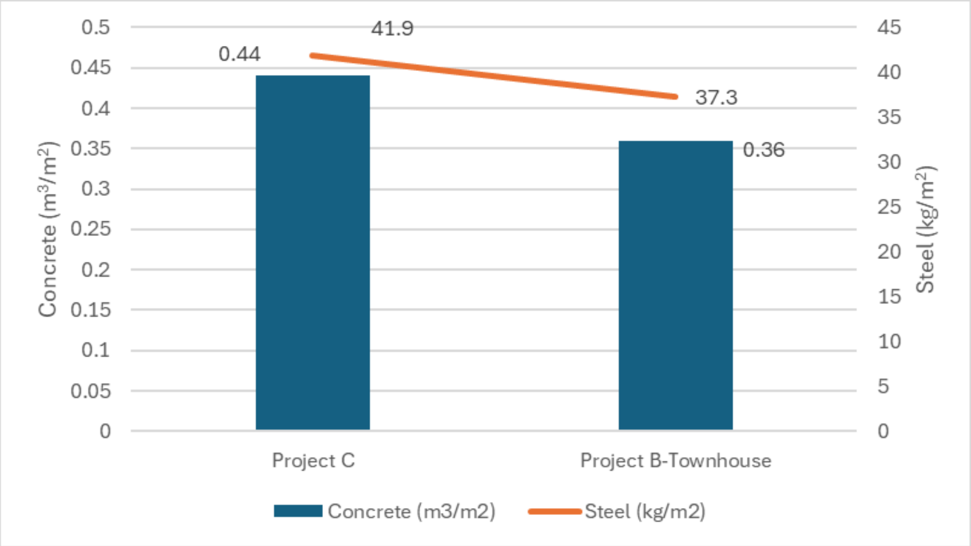

Figure 5: Comparison of concrete and steel between low-rise RCC frame construction (Project C) and partially load bearing construction (Project B-Townhouse)

b) Increasing the use of recycled material like GGBS and fly-ash in concrete: In Project A, which is a high-rise monolithic concrete building, 35% cement in the concrete was replaced with GGBS (Ground Granulated Blast-furnace Slag), a by-product of the steel manufacturing industry. This significantly reduced its upfront carbon by 22%.

c) Reducing the upfront carbon in masonry and plastering: In Project C, the contribution of masonry and plaster is 23% in product carbon. Similarly, in the 2-3 story houses of Project B the contribution of masonry and plastering is around 25%. In the projects using RC frame construction with masonry infill or masonry load-bearing construction, significant reduction in upfront carbon can be achieved by:

- Replacement of OPC with low carbon cement (Portland slag cement or PSC, portland pozollana cement or PPC, and limestone calcined clay cement or LC3).
- The use of low carbon masonry blocks e.g., cement stabilized earth blocks (CSEB), hollow concrete blocks, hollow and perforated clay fired bricks/blocks and AAC blocks.

Figure 6 shows Projects B and C, which use OPC based concrete and OPC for mortar and plaster, can reduce upfront carbon by 20%, by using concrete with 35% GGBS replacement and use of PSC for mortar and plaster.

Figure 6: Reduction in product carbon (A1-A3) through 35% replacement with GGBS in concrete and use of PSC for mortar & plaster

The main strategies to reduce upfront embodied carbon include:

- ***reducing the quantity of concrete and steel through efficient structural design and choice of construction technology***
- ***increasing the use of recycled material like GGBS and fly-ash in concrete***
- ***choice of low-carbon masonry materials and reducing wastages of construction materials on site.***

A combination of these strategies has the potential to lower upfront embodied carbon in the typical low-rise urban residential building construction in India by up to 30%.

Strategies to reduce operational carbon emissions

Following are some of the strategies to reduce operational carbon in urban residential buildings at Bangalore based on the analysis presented in this study:

a) *Reducing the demand for space cooling*: In the context of Bangalore, strategies such as proper orientation, insulation or shading of roof, reducing U-value of external walls, shading of windows, use of high SRI paints/treatment on external walls and roof, and increasing the natural ventilation potential through optimize sizing and placement of windows, contribute significantly in reducing the demand for space cooling.

b) *Use of solar water heaters*: In Bengaluru, for around 10 months in a year, hot water is required for bathing. If electricity is used for heating water, it contributes to around 25% of the EPI as shown for Project A and C. Installation of solar water heaters helps in reducing this electricity requirement by 70-80% (e.g. Project B) and is an important strategy to reduce operational carbon in Bangalore.

c) *Use of rooftop Solar PV*: The low-rise residential buildings have the opportunity to reduce operational carbon by generating electricity from rooftop solar PV. As shown in Table 6, for building up to 5 storeys (Project B and C), the available rooftop area is sufficient to meet the entire annual electricity requirements from rooftop solar PV. This potential is small for high-rise buildings (Project A). Given that the Bengaluru climate does not require long duration of air-conditioning use and with the use of passive strategies, it is possible for a low-rise residence to become net zero energy by offsetting their entire electricity requirement through on-site renewable energy generated from solar PV.

Table 6: Roof-top solar PV potential of Project A, B and C

	Project A	**Project B**	**Project C**
Roof area (m^2)	2106	5336	133
Available area for solar PV (m^2)	1264	2741	80
Solar PV system size (kWp)	126	273	8
Electricity from SPV (kWh/y)	192000	417500	12200
Energy requirement (kWh/y)	1583000	340500	14400
Solar PV share (%)	12	100	85

One of the key strategies to reduce operational carbon is reducing the demand for space cooling through passive design strategies. In the Bengaluru context, use of solar water heaters is also found to be effective in reducing operational carbon. Rooftop solar photovoltaic can result in large reductions in operational carbon, particularly in low-rise buildings. Given that the Bengaluru climate does not require long duration of air-conditioning use, it is possible for a low-rise residential building to become net zero energy by offsetting the entire electricity requirement through roof-top solar PV.

Annexure I

Project A

CEF of materials used in Project A

Material/Product	Unit	GWP (kgCO$_2$/unit)	Source
Cement (OPC)	kg	0.996	EPD Ultratech (2022)
M-sand	kg	0.0071	Calculated- partial plant data
Coarse Aggregates	kg	0.0058	Calculated- partial plant data
Steel	kg	2.397	Calculated- expert consultation
Solid Concrete Block	m^3	188.45	Calculated- plant data
Glass (6mm) ST 167	m^2	21.1	EPD Saint Gobain (2023)
uPVC	kg	3.3	Average value from several International EPDs
Gypsum Plaster	kg	0.102	EPD Gyproc Saint Gobain (2021)
XPS	m^2	3.2	Average value from several International EPDs
M30	m^3	273.683	Calculated- plant data
M40	m^3	313.960	Calculated- plant data
M10	m^3	135.635	Calculated- plant data
M7.5	m^3	103.042	Calculated- plant data
Cement Mortar (1:4)	m^3	469.90	Calculated-Standard literature
Extruded Aluminium	kg	26	IFC 2017
Glass (12mm) ST 167	m^2	38	EPD Saint Gobain (2023)
Steel sections (hot rolled coil)	kg	2.96	EPD JSW (2022)

*CEF for concrete grades have been calculated based on the composition of the concrete.

Product stage emissions (A1-A3) for Project A:

Material/Product	Material / Product components	Quantity (unit)	Emissions (kgCO_2)
Concrete	Cement, M-sand, fine aggregates, and coarse aggregates	55480.98 (m^3)	15103326.36
Reinforcement Steel		5125165.42 (kg)	12287102.59
Masonry	Solid Concrete Blocks, Cement, M-sand	2348.95 (m^3)	442664.98
Plastering		214.47 (m^3)	100781.73
Gypsum Punning		1261.15 (m^2)	121036.35
uPVC doors and windows	uPVC profiles, steel sections, glass	13510.74 (m^2)	762311.14
Timber		6570.93 (m^2)	303178.77
XPS		4043.00 (m^2)	13045.41
Total Emissions (kgCO_2)			**29133447.32**

Project B

CEF of materials used in Project B

Material/Product	Unit	GWP (kgCO_2/unit)	Source
Cement (OPC)	kg	0.996	EPD Ultratech (2022)
M-sand	kg	0.0071	Calculated- partial plant data
Coarse Aggregates	kg	0.0058	Calculated- partial plant data
Steel	kg	2.397	Calculated- expert consultation
CSEB block	m^3	142.932	Calculated- production data
Solid concrete block	m^3	188.45	Calculated- plant data
Mangalore tiles, Hourdi blocks	kg	0.213	Calculated- expert consultation
Stone	kg	0.16	One Click LCA database
Glass (4mm)	m^2	13	EPD Saint Gobain (2017)
Timber (Malaysian Honne)	kg	0.613	Calculated- partial plant data
Timber (Recycled Teak)	kg	0.046	Calculated- partial plant data
Timber	kg	0.627	Calculated- partial plant data
Sandwich roof panel with insulation	m^2	30.6	Average value from several International EPDs
M30 (Manual)	m^3	341.783	Calculated- plant data
M30 (RMC)	m^3	349.506	Calculated- plant data
M20 (RMC)	m^3	390.177	Calculated- plant data
M20 (1:2:3)	m^3	381.940	Calculated- plant data
M20 (1:1.5:3)	m^3	414.874	Calculated- plant data
M15 (1:2:4)	m^3	329.611	Calculated- plant data
M10 (1:4:8)	m^3	184.646	Calculated- plant data
M10 (1:5:7)	m^3	185.037	Calculated- plant data
Concrete mix 1:3:6	m^3	235.946	Calculated- plant data
Cement Mortar (1:3)	m^3	583.79	Calculated-Standard literature
Cement Mortar (1:4)	m^3	458.96	Calculated-Standard literature
Cement Mortar (1:5)	m^3	396.88	Calculated-Standard literature
Cement Mortar (1:6)	m^3	184.91	Calculated-Standard literature

*CEF for concrete grades have been calculated based on the composition of the concrete.

Product stage emissions (A1-A3) for Project B

Material/Product	Sub-Materials	Quantity (unit)	Emissions (kgCO$_2$)
Concrete	Cement, M-sand, fine aggregates, and coarse aggregates	9893.41 (m^3)	3996428.18
Reinforcement steel		1492316.43 (kg)	3577688.40
Masonry	Concrete blocks, CSEB, Aerocon blocks, Stone, Cement, M-sand	4403.13 (m^3)	856391.50
Cladding	CSEB, Hourdi blocks, Chappadi stone, Cement, M-sand	2282.45 (m^2)	39717.22
Plastering	Cement, M-sand	1456.54 (m^3)	627887.24
Pointing	Cement, M-sand	8884.75 (m^2)	8654.25
Mangalore roof tiles		1718.28 (m^2)	14458.05
Timber		11358.60 (cft)	125664.17
Glass		2692.15 (m^2)	37390.78
PUF		4645.67 (m^2)	142157.39
	Total Emissions (kgCO$_2$)		**9426437.18**

Project C

CEF of materials used in Project C

Material/Product	Unit	GWP (kgCO$_2$/unit)	Source
Cement (OPC)	kg	0.996	EPD Ultratech (2020)
M-sand	kg	0.0071	Calculated- partial plant data
Coarse Aggregates	kg	0.0058	Calculated- partial plant data
Steel	kg	2.397	Calculated- expert consultation
Solid concrete block	m^3	188.45	Calculated- plant data
Stone	kg	0.16	One Click LCA database
Glass (4mm)	m^2	13	EPD Saint Gobain (2017)
Timber	kg	0.627	Calculated- partial plant data
RMC M20	m^3	390.177	Calculated- plant data
M15	m^3	329.611	Calculated- plant data
M10	m^3	184.646	Calculated- plant data
Concrete Mix 1:6:6	m^3	186.026	Calculated- plant data
Cement Mortar (1:2)	m^3	770.70	Calculated- standard literature
Cement Mortar (1:3)	m^3	583.79	Calculated- standard literature
Cement Mortar (1:6)	m^3	343.48	Calculated- standard literature

*CEF for concrete grades have been calculated based on the composition of the concrete.

Product stage emissions (A1-A3) for Project C

Material/Product	Sub-Materials	Quantity (unit)	Emissions (kgCO$_2$)
Concrete	Cement, M-sand, fine aggregates, and coarse aggregates	254.449 (m^3)	92602.32
Reinforcement steel		24500.00 (kg)	58726.50
Masonry	Concrete blocks, Stone, Cement, M-sand	119.26 (m^3)	27377.73
Plastering	Cement, M-sand	40.93 (m^3)	17504.45
Timber		99.91 (m^2)	3622.88
	Total Emissions (kgCO$_2$)		**199833.87**

Transport emission factors

Category	**Payload Capacity (tonnes)**	**Emission Factor (kgCO2/km)**
MDV (Medium Duty Vehicles)	less than 12	0.5928
HDV (Heavy Duty Vehicles)	more than 12	0.7375

Source: *India Specific Road Transport Emission Factors, Chirag Gajjar, Atik Sheikh, India GHG Program, (PDF) India Specific Road Transport Emission Factors (researchgate.net)*

Fuel and electricity emission factors

Energy Input	**Emission Factor ($kgCO_2$/fu)**	**Functional Unit (fu)**
High Speed Diesel (IIT Bombay, 2020)	2.64	liter
Electricity (CEA,2023)	0.71	kWh

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