

A Review of Embodied Energy Strategies to Reduce the Carbon Emissions in Sustainable Buildings

Baishali Pradhan^{1*}, Bandana Jha²

Abstract

Buildings in India account for almost one-fifth of the nation's carbon emissions, making it the third-largest carbon emitter globally. These emissions are expected to climb by 50% over the next 20 years, which is the biggest increase of any nation. You would have to go into a jungle to avoid concrete, steel, and aluminium since they are so common. Just these three substances are responsible for 23% of the world's carbon emissions. They are widely employed in modern buildings and infrastructures. To achieve our climate targets, we must cut and eliminate emissions connected with these materials. Buildings account for roughly 40% of annual carbon emissions, with 12% coming from embodied carbon and 28% from operational carbon. Construction materials are extracted, processed, and manufactured before being delivered to the site and combined to form the building. These emissions are expected to climb by 50% over the next two decades, the most of any country. During this period, India's built floor space is predicted to more than double, resulting in a large need for building materials. Cement consumption will more than treble, steel demand will nearly quadruple, and brick demand will rise three to fourfold. Buildings have long lifespans, so the effects of embodied carbon are locked in for decades. The International Energy Agency believes that currently available alternative materials might lower world cumulative emissions by 70%. This study investigates techniques for lowering CO₂ emissions by addressing embodied energy in sustainable buildings. This study examines the impact of embodied energy in the building, materials specification, lifecycle energy analysis using embodied energy, and solutions for optimizing embodied energy from buildings.

Keywords: Embodied energy, CO₂ emissions, materials, sustainable buildings, LCEA

INTRODUCTION

In the world, 55% of people live in cities, and by 2050, that number is predicted to rise to 68%. Urban residents worldwide have been growing from 50% as of 2018 to 68% by 2060, according to reports. Global footprint is projected to increase by almost 8 billion square meters in 2060 to meet the demand for housing and transportation, compared to a decrease of only 5% from 2020 [1]. Furthermore, cities account for 60–80% of energy consumption and 75% of CO₂ emissions. Specifically, buildings account for 40% of emissions and 36% of energy use.

*Author for Correspondence

Baishali Pradhan
E-mail: baishalipr93@gmail.com

¹Ph.D. Research Scholar, Department of Architecture, School of Planning and Architecture, New Delhi, India

²Professor, Department of Architecture, School of Planning and Architecture New Delhi, India

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According to estimates, the built environment in India accounts for 40% of embodied carbon emissions and 60% of operational carbon emissions [2]. The main cause of this is the widespread use of carbon-intensive building materials like steel and concrete. According to estimates, 40–50% of resources taken globally are utilized for housing, building, and infrastructure. The fabrication of building materials accounts for between 20 and 25% of India's energy consumption. Building material production is a resource- and energy-intensive operation. The production of steel and cement, with their extensive use and labour-

intensive manufacturing procedures, is the main source of these emissions. As a result, other widely used building elements like glass, aluminium, and insulation also increase emissions. India is the world's second-largest producer of cement and steel frames; and reinforced concrete make up a major portion of the building foundation in India [3]. In 2020, India's urban building industry utilized over 60 million cement and 14 million steel tonnes. The primary driver of steel demand, especially in residential and commercial spaces, is the construction industry [4]. By 2022, this industry supplied 45% of the world's steel needs; by 2030, this percentage is predicted to reach 60%. Energy and pollutant emissions including carbon dioxide (CO₂) may be perceived to be tied to the energy and other resources used in the manufacturing of materials [5]. Therefore, the embodied energy is the process of the quantity of energy needed for production and the delivery of the material to the construction site that is under review [6]. Embodied carbon is the amount of carbon released as millions of tons of carbon dioxide (CO₂) emitted into the atmosphere during the lifecycle of building materials, which includes sourcing, manufacture, transport, construction, maintenance and disposal. Both steel and concrete account for greater carbon emissions. This issue, which generates 11% of global greenhouse gas emissions, requires greater attention from manufacturers, builders and policy-makers if we are to achieve our climate ambitions [7]. Reducing embodied carbon is a practical and rapid means of enacting valuable climate action because most emissions occur before the building's construction phase. All elements are so that embodied carbon has started to attract the attention of leaders in architecture and design, manufacturing, and construction as a particularly complex aspect of building decarbonization [8].

The aim of this study is to develop a strategy to reduced embodied energy form the building to make sustainable cities. This study shows the impact of embodied energy in the building, materials specification, lifecycle energy analysis through embodied energy and strategies to optimise the embodied energy from the buildings [9].

EMBODIED ENERGY OF BUILDING

The energy required for every step of building construction, from resource extraction and mining to product manufacturing, transportation, and delivery, is referred to as embodied energy (Figure 1). It is the upstream or front-end part of a home's life cycle impacts. Buildings are made from processed materials, which explains some of the total embodied energy found in a building. It is critical to consider the materials used in a building, as this will greatly influence the embodied energy relating to the structure [10]. Embodied energy is accumulated in the construction elements during the construction of the building, it is delayed until the building is constructed before being accounted for.

The embodied energy is increasingly considered as an important metric to evaluate the sustainability of the building, especially in light of the efforts to reduce operational energy [11]. It is calculated that embodied energy represents between 10 and 25% of the total lifetime energy consumption of a typical building. The percentage of embodied energy within the whole life energy consumption can be as high as 50% in low-energy buildings; that will get up to 57% or even 83% of total energy in the facility lifetime use of low energy buildings when renewable energy resources are used for electricity production in the future [12]. In zero-energy building, embodied energy may equal the percentage of operational energy (up to 100%) in the life cycle, while a noteworthy reduction of the total life cycle energy has been documented This is significant because this points to the building materials becoming more critical to building energy-efficient buildings [13].

Importance of the Embodied Energy Over Operational Energy

In 2022, 2.5 Gt CO₂ was attributed to building construction, which included the production and processing of cement, steel, and aluminium for building purposes, in addition to the direct and indirect emissions from building operations. Over one-third of all emissions connected to energy are produced by building operations and construction combined [14]. The complete buildings value chain requires mitigation and adaptation strategies.

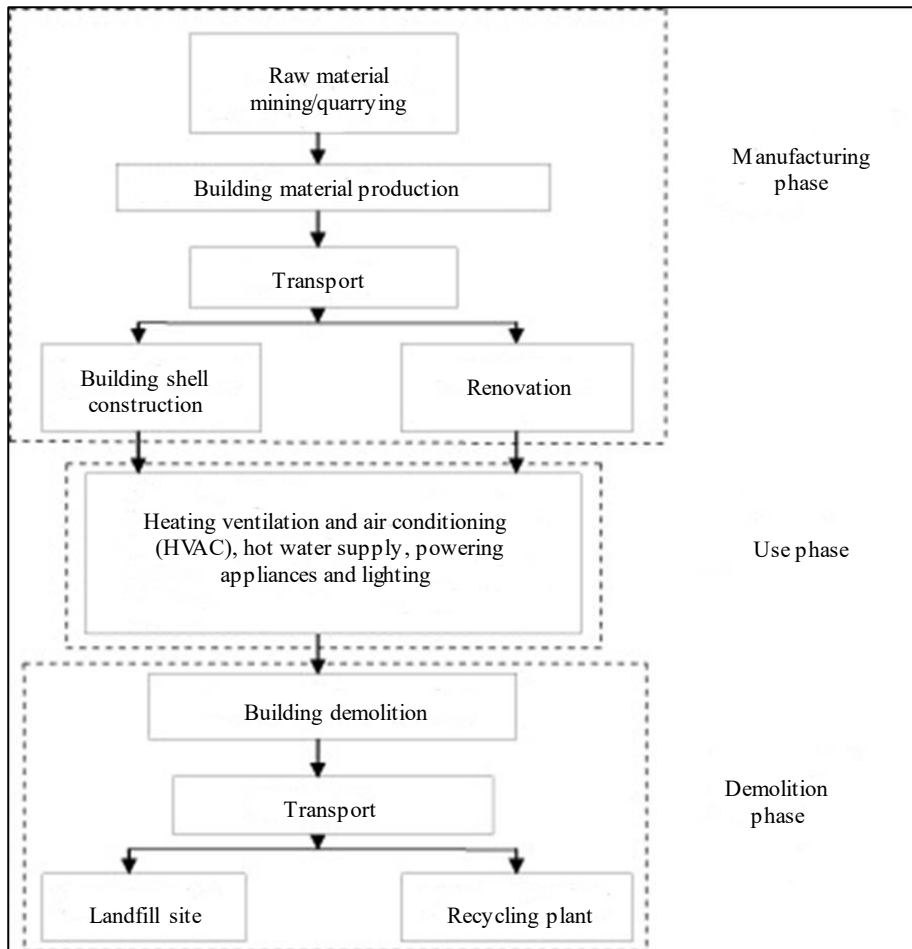


Figure 1. Embodied energy carbon from construction.

The number of residential buildings in India is expected to increase from 272 million dwelling units (more than 15 billion m²) in 2017–18 to 386 million (more than 28 billion m²) by 2037–2038. This amount of Figure 2. Global CO₂ emissions from buildings, including embedded emissions from new construction the commercial building sector is expected to show an increase, growing from 1.2 billion m² in 2017–2018 to 3.1 billion m² by 2037–2038. The manufacturing of household appliances in India accounts for roughly 25% of the country's overall primary energy demand and 30% of its greenhouse gas emissions. Therefore, there is a need for reduction in operational energy with the increasing embodied energy.

CO₂ emissions from the building sector have kept going up by almost 1% yearly since 2010. If builders stick to the usual ways of doing things, embodied carbon will cause about 50% of the emissions from new buildings between 2020 and 2050 (Figure 3) [16]. During the same time, its part is expected to be even bigger (60%) for buildings that perform well (Figure 4).

It is feasible to lessen the operational energy consumption of new buildings without increasing embodied energy. It should be possible to incorporate strategies that could lead to lower embodied energy in buildings without affecting operational energy efficiency [17].

Building Materials

The choice of building materials and construction methods can significantly impact the amount of energy embodied in a structure because embodied energy varies widely between them. At the end of a

building's life, recovering the embodied energy can be facilitated by the fact that different materials have different capacities for recycling or reuse. Recall that selecting materials with low embodied energy could lead to increased operational energy use. A building with a larger embodied energy might, on the other hand, have a lower operating energy [18]. Three materials: concrete, steel, and aluminium, account for 23% of all emissions worldwide, with the majority coming from the built environment. Through specification, design, policy, and material selection, there is a tremendous opportunity to reduce embodied carbon in these high-impact materials [19]. Generally speaking, more processing results in a higher embodied energy for a substance. Buildings typically use large quantities of materials with relatively low embodied energy, such as lumber and bricks, and smaller quantities of materials with high embodied energy, such as steel. Since most of the embodied energy of materials is used in the production process, energy efficiency improvements in the manufacturing sectors can have the largest influence on lowering this energy [20].

Embodied Energy of Building Materials

Concrete, bricks, and wood; materials with the lowest embodied energy intensities, are typically used in huge amounts (Table 1). Stainless steel and other materials with a high energy content are frequently utilized in far lower quantities (Table 2). Therefore, low embodied energy materials like concrete or high embodied energy materials like steel might provide the most embodied energy in a construction [21].

Reuse and recycling

Various construction materials are recyclable or reusable. The amount of money that may be saved by recycling different materials varies greatly; for example, aluminium can save up to 95% of its cost whereas glass can only save 20%. Additionally, if lengthy transit distances are involved, some materials might need to be reprocessed before they can be reused [22], which will increase the energy cost. When selecting a building material, one should take into account the entire spectrum of environmental effects related to building construction, use, and end-of-life, even if embodied energy is a significant environmental concern [23]. Aspects including the usage of water and land, the depletion of raw materials, the production of greenhouse gases and pollutants, the loss of habitat for biodiversity, and greenhouse gas emissions are all examples of environmental consequences.

LIFE CYCLE ENERGY ANALYSIS FROM EMBODIED ENERGY

The energy use of buildings is a common method to gauge the environmental impact of a building. Several studies have shown the significance of both operational and embodied energy within buildings throughout their lifespan (Table 3) [24]. LCEA is a technique used to measure life cycle of building energy. LCA is a simple life cycle assessment for the construction industry. Energy that is used in the manufacturing phase of a building is known as embodied energy. In addition to the energy required during building construction and renovation, the energy content of all materials used in technical installations and construction determines energy consumption [25].

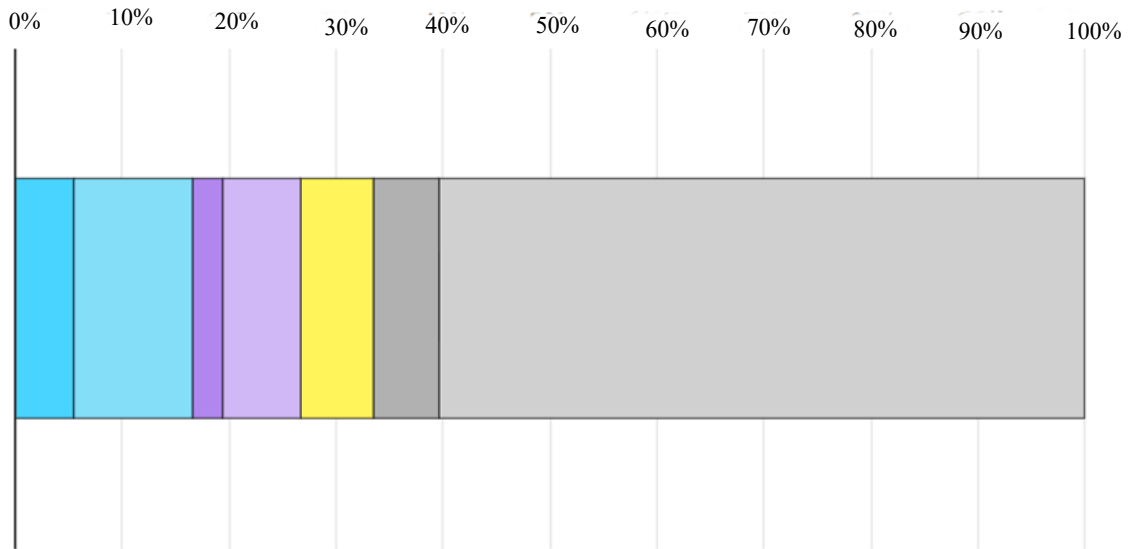
The amount of energy needed to procure, manufacture, and deliver raw materials to the construction site is known as the energy content of materials. Initial embodied energy and recurrent embodied energy are the two components of embodied energy [26].

Initial Embodied Energy

The energy required for a building's initial construction is known as its initial embodied energy. The formula is as follows:

$$EE_i = m_i M_i + E_c \quad (1)$$

where EE_i is the building's initial embodied energy, m_i is the quantity of building material (i), M_i is the energy content of material (i) per unit quantity, and E_c is the energy utilized on site during building erection and construction [27].



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- Residential: direct ● Residential: indirect ● Non-residential: direct
- Non-residential: indirect ● Buildings construction industry ● Other construction industry
- Other

Figure 2. Global CO₂ emissions from buildings, including embodied emissions from new construction, 2022.

Source: IEA (IEA 2023).

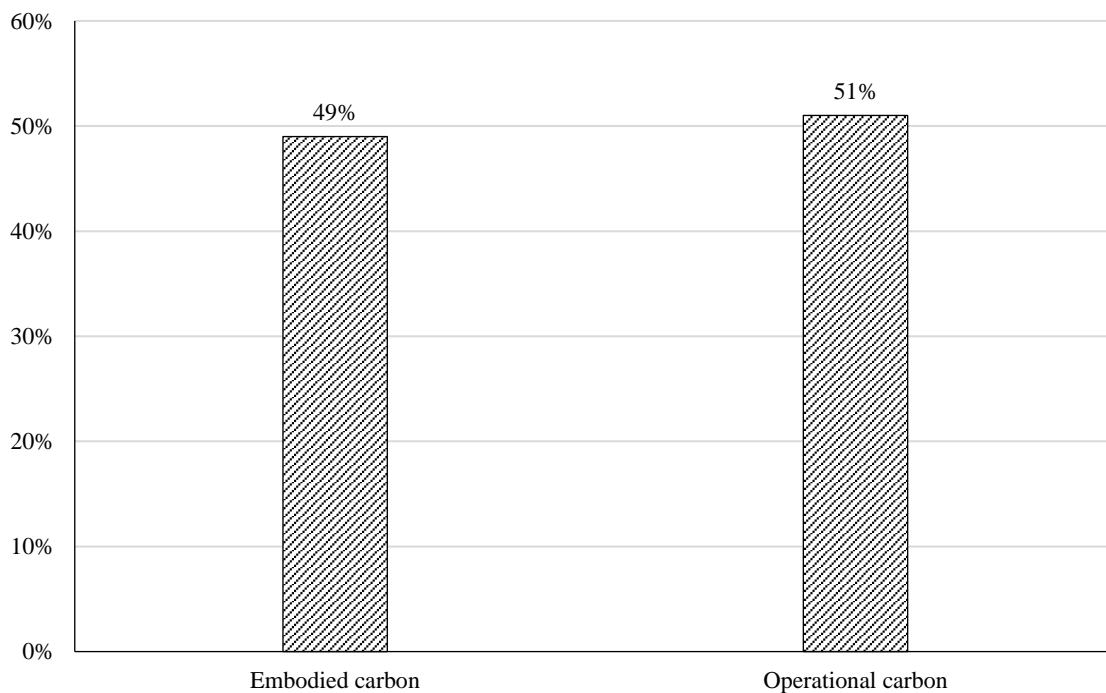


Figure 3. Total carbon emissions of global new construction: BAU buildings.

Source: US EIA.

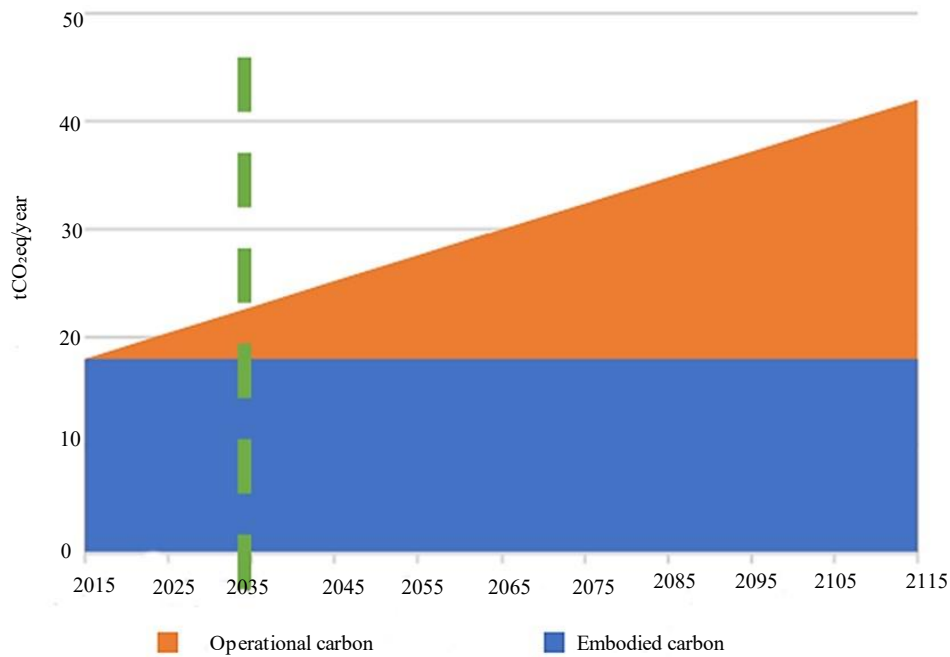


Figure 4. Carbon emissions of new construction typical for a high performance building. *Source: Carbon leadership forum.*

Table 1. Embodied energy of common building materials.

Material	EE (MJ/kg)	Material	EE (MJ/kg)
Cement	6.4	Gypsum and Gypsum products	1.8
Lime	0.9	Glass fibre insulation	28
Glass	15	PVC	77.2
Aluminium	280	Polyurethane insulation	120
Steel	56.7	Polystyrene insulation	85
Brick	3	Iron	25
Concrete	1.1	Plywood	15

Table 2. Embodied energy and Thermal conductivity of different insulation materials.

Insulation materials	Embodied energy (MJ/kg)	Insulation materials	Embodied energy (MJ/kg)
Straw bale	0.6	Mineral wool	16.6
Sheep wool	2.5	Rock wool	16.8
Cellulose	3.6	Cellular glass	27
Cork insulation	8.3	Glass wool	37
Wood wool	12	Expanded Polystyrene	85
Stone wool	15	Polyurethane	120

Recurring Embodied Energy

The construction of buildings uses a wide range of materials. Some of them might not last as long as the structure. Consequently, they are changed in order to renovate the structure. Additionally, structures need to have some annual upkeep done [28]. The energy used for such replacement and repair (rehabilitation) must be tracked during the buildings' whole lifespan. Referred to as recurrent embodied energy, the total energy contained in the material utilized for maintenance and rehabilitation can be written as follows:

$$EE_r = m_i M_i [(L_b / L_{mi}) - 1] \tag{2}$$

where L_b is the building's life span, L_{mi} is the material's life span, and E_{Er} is the building's recurring embodied energy (i). The type of materials used, the main energy sources, and the effectiveness of conversion processes in the production of building materials and products all have a significant impact on embodied energy [29].

Table 3. Embodied energy of Assembly Source.

Assembly	PER embodied energy (MJ/m ²)	Assembly	PER embodied energy (MJ/m ²)
Floors		Wall	
Elevated timber floor	293	Single Skin AAC Block Wall	440
110 mm concrete slab on ground	645	Single Skin AAC Block Wall gyprock lining	448
200 mm precast concrete T beam/infill	644	Single Skin Stabilised (Rammed) Earth Wall (5% cement)	405
		Steel Frame, Compressed Fibre Cement Clad Wall	385
Roofs		Timber Frame, Reconstituted Timber Weatherboard Wall	377
Timber frame, concrete tile, plasterboard ceiling	251	Timber Frame, Fibre Cement Weatherboard Wall	169
Timber frame, terracotta tile, plasterboard ceiling	271	Cavity Clay Brick Wall	860
Timber frame, steel sheet, plasterboard ceiling	330	Cavity Clay Brick Wall with plasterboard internal lining and acrylic paint finish	906
		Cavity Concrete Block Wall	465

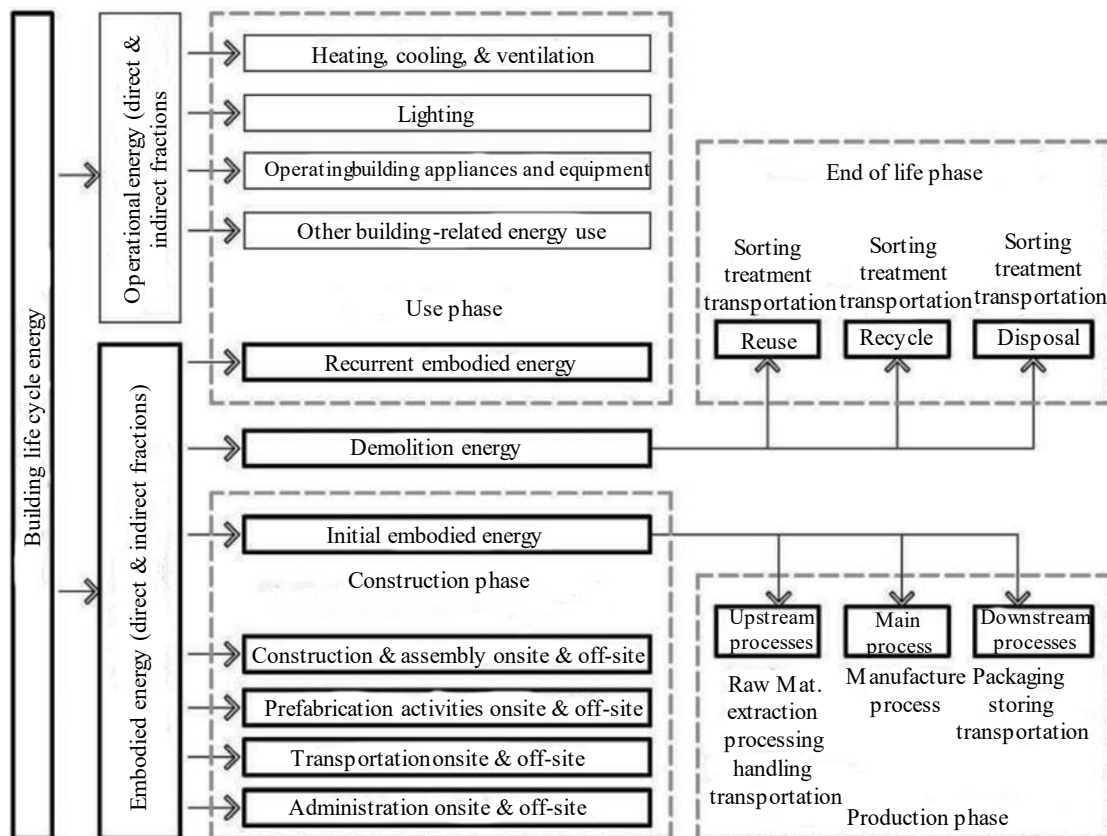


Figure 4. Embodied energy model for a building.

Table 4. Design strategies to reduce embodied carbon emissions.

Stage 1	Pre-design and site selection	Reuse Old Buildings
		Reuse of building materials
		Soil assessment to select sites which require less quantity of materials for foundation
Stage 2	Conceptual Design	Design Compact right sized structural system
		Design for flexibility, and space efficiency
		Use low carbon, locally available building systems and materials
		Consider efficient architectural solutions for massing, envelope foundation and landscape.
Stage 3	Detailed Design	Substitute high embodied carbon materials with like for like materials with low global warming potential
		Refine architectural and structural designs
Stage 4	Bidding and Procurement	Set and incorporate clear embodied carbon goals in all documents
		Request EPD data from all vendors
		Design sub-contractor selection process that incentivizes bidders to offer low embodied carbon solutions
		Include requirement for product and materials substitutions
Stage 5	Construction	Set a guideline to reduce construction waste
		Hold contractors accountable for delivering low embodied carbon design
		Document and publish as built embodied carbon content of building
Stage 6	Occupancy: maintenance and Renovation	Debrief and apply learnings for future projects
		Establish embodied carbon reduction targets for future renovations and tenant fit outs.

THE APPROACHES FOR UTILIZING EMBODIED ENERGY FOR REDUCING EMISSIONS

It is our responsibility as architects to weigh a multitude of options and pieces of information before attempting to determine which is the best. Based on factors including budget, embodied energy content, climate, transportation distances, and material availability, each design should choose the ideal mix for its intended use. The strategies that would reduce the embodied energy of new buildings include:

1. Developing more stringent definitions of mass mainstream building materials (e.g. steel and cement) to reduce their embodied energy and carbon impact; Selecting alternative materials with less embodied energy such as timber, rammed earth, hempcrete, etc. [30].
2. Creating more efficient and lighter structure to reduce the amount of full structure volume and, hence, the volume of embodied energy.
3. Design for the materials to be reused and reclaimed once the building is decommissioned.
4. Design and plan for materials to be in continuous cycles of use (Table 4).
5. Designing for future use, adaptability, and flexibility, i.e. for secondary uses.
6. Selecting materials with low embodied energy and high thermal performance is an important aspect to strike that balance between competing operating and embodied energy.

Selecting these materials is one way the potential trade-off in the future of adding operational energy can perhaps be lessened [31].

CONCLUSION

Approximately 30–40% of greenhouse gas emissions worldwide are caused by the building sector. The importance of lifetime carbon emissions, especially from embodied carbon, has grown together with the efficiency of building methods and equipment. Thus, it is essential to identify practical ways to lower the embodied carbon of a building. The research on embodied energy in buildings is reviewed in this study, which also looks at the effects of high embodied energy materials. Furthermore, it offers methods for lowering embodied energy from the pre-design phase all the way through to maintenance.

This analysis demonstrates that selecting construction materials with low embodied carbon can significantly contribute to reaching net zero goals and help create a more sustainable future. The choice

of building materials has a huge potential to reduce embodied carbon and prevent climate change as the world continues to experience extreme weather, rising sea levels, and rising temperatures.

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