

Article

Cradle-to-Gate Assessment and Mitigation of Embodied Carbon in Commercial Buildings

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Abstract

According to the U.S. Environmental Protection Agency (2024), carbon dioxide is the leading greenhouse gas driving global warming. The building sector accounts for about 39% of global energy-related carbon emissions, with 11% from embodied carbon generated during material extraction, manufacturing, transport, and assembly. This study examines embodied carbon in the Harold L. Martin Sr. Engineering Research and Innovation Complex at North Carolina A&T State University, a four-story, 130,000 square-foot facility completed in 2021. Using architectural and structural documents, verified material quantities were analyzed to calculate cradle-to-gate embodied carbon (A1–A3 stages) for major components, including concrete, steel, glazing, and finishes. Results show structural materials, especially concrete and steel, dominate embodied emissions, followed by envelope systems. Sensitivity analyses indicate that substituting materials, such as recycled steel, low-carbon concrete, and bio-based finishes, can reduce total embodied carbon by 15–30% while maintaining performance.

Keywords: embodied carbon; cradle-to-gate emissions; building materials; decarbonization strategies; sustainability; material substitution

1. Introduction

The building sector is a major contributor to global energy use and greenhouse gas emissions. Within this sector, commercial buildings, including offices, retail spaces, hospitals, and educational facilities, are especially significant due to their high energy intensity, extended operating hours, and growing reliance on electricity-driven services. As nations pursue net-zero targets, decarbonizing commercial buildings has become a critical element of climate mitigation and energy transition strategies.

Despite advances in energy efficiency and building automation, emissions reductions in commercial buildings remain inadequate. Existing studies often assess individual measures, such as envelope retrofits, in isolation. Moreover, research tends to emphasize residential or new construction, leaving the diverse existing commercial building stock insufficiently explored. This fragmented approach limits the ability to identify cost-effective, scalable, and operationally feasible decarbonization pathways for commercial building applications.

Motivated by these research gaps, this study presents a cradle-to-gate assessment of embodied carbon and mitigation strategies for commercial buildings. A detailed case study of the College of Engineering building at North Carolina A&T State University (North



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Carolina, USA) is conducted, explicitly quantifying emissions associated with life-cycle stages A1–A3, including raw material extraction, transportation, and manufacturing of all building materials. The results advance understanding of embodied carbon reduction pathways and support informed decision-making for building designers, owners, and policymakers.

As aforementioned, the global building sector plays a critical role in climate change mitigation due to its substantial contribution to greenhouse gas (GHG) emissions. Buildings account for approximately 39% of global energy-related carbon emissions, encompassing both operational and embodied sources [1–4]. Historically, most of the research, policy initiatives, and design strategies have focused on operational carbon, which refers to emissions generated during a building's use phase from energy consumed for heating, cooling, ventilation, lighting, and equipment. These emissions accumulate gradually over the building's lifespan and have traditionally represented the dominant portion of total building-related emissions [1,5].

Operational carbon reductions have been widely pursued through improvements in building energy codes, high-performance envelopes, efficient HVAC systems, electrification, and on-site renewable energy generation. As a result, many new buildings, particularly high-performance and net-zero-energy facilities, now demonstrate dramatically reduced operational energy demand when compared to conventional buildings. In some cases, operational emissions can be offset entirely through the procurement of renewable energy, leading to carbon-neutral or carbon-free operations over time [6].

Embodied carbon comes from producing and transporting construction materials. In commercial buildings, early production, especially of concrete and steel, accounts for 80–90% of these emissions, making early material choices critical for reduction. Strategies such as optimized concrete mixes, use of supplementary cementitious materials, and high-recycled content steel can substantially reduce cradle-to-gate impacts [2–4,7,8].

However, as operational energy use declines, embodied carbon has emerged as a critical and often overlooked driver of total building-related emissions. Embodied carbon refers to the greenhouse gas emissions associated with the extraction of raw materials, the manufacturing of construction products, transportation, and on-site construction activities. Unlike operational emissions, which can be reduced over time through retrofits or changes in energy supply, embodied carbon is released predominantly upfront, before a building is occupied, and cannot be reversed once construction is complete [9]. This characteristic gives embodied emissions a disproportionately high impact on near-term climate change, particularly within the next several decades, which are critical for meeting global climate targets.

Life Cycle Assessment (LCA) is the primary approach for measuring cradle-to-gate embodied carbon, using material inventories and emission factors from sources such as the UK's ICE database. Comprehensive assessments cover emissions from raw material extraction through manufacturing, with emerging methods also considering the embodied carbon of manufacturing equipment [10]. Environmental Product Declarations (EPDs) offer a standardized source of cradle-to-gate carbon data for specific materials, enabling material comparisons and carbon-informed procurement by disclosing embedded emissions in products like concrete, steel, and finishes. However, variations in data quality and regional specificity still pose challenges for consistent assessment [11,12].

Embodied carbon is measured in the A1–A3 life-cycle stages (Figure 1), or cradle-to-gate phase, which includes raw material extraction and processing (A1), material transport to manufacturing (A2), and product manufacturing (A3) [13]. These stages account for most pre-installation emissions and offer the greatest potential for reduction at the design stage. Because they occur early in the building's life, these emissions immediately add to

atmospheric greenhouse gases, amplifying their climate impact compared with emissions released gradually over time [14].

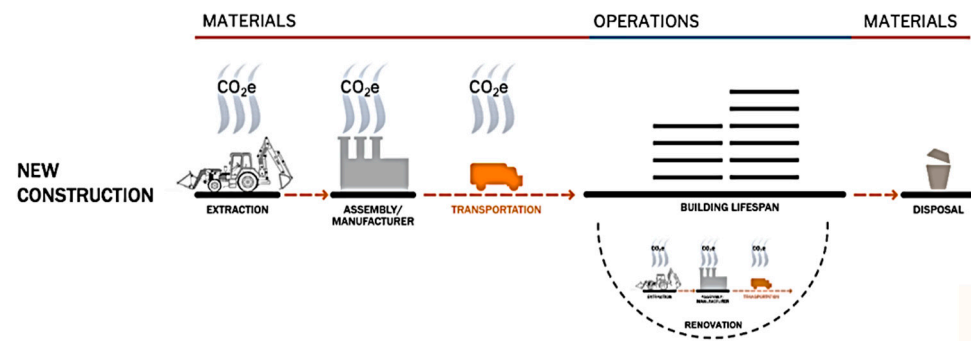


Figure 1. Embodied Carbon Life Cycle.

Recent research indicates that embodied emissions can account for 40–60% of a building’s total life-cycle carbon footprint, particularly for energy-efficient and high-performance buildings with low operational loads [15]. In extreme cases, embodied carbon can exceed operational emissions entirely over a building’s lifetime, especially when operational energy is supplied by low-carbon or renewable sources. This shift fundamentally changes how building sustainability must be evaluated and prioritized.

The global construction industry is expected to add about 230 billion square meters of new floor space over the next 40 years [16]. Around 60% of the buildings expected to exist by 2050 have yet to be constructed [17]. Thus, the urgency to tackle whole-life carbon emissions, particularly embodied carbon, is growing [18]. The World Green Building Council (WGBC) defines upfront carbon, in its 2019 report [19], as the emissions from material production and construction (LCA stages A1–A5) that occur before a building or infrastructure enters use. Upfront carbon is projected to account for half of the total carbon footprint of new construction through 2050, posing a significant risk to the remaining global carbon budget. Consequently, reducing upfront carbon in new buildings is essential for achieving net-zero carbon targets. Recent studies show that current practices can cut embodied carbon by 40–60%, mainly through low-carbon material substitution, with additional gains from design optimization and construction strategies [20].

As illustrated in Figure 2, projected global carbon emissions from new construction between 2020 and 2050 demonstrate a critical shift in emissions composition. While operational emissions are expected to decline due to improved efficiency, electrification, and cleaner electricity grids, embodied carbon remains relatively constant because it is directly tied to material production volumes and construction activity levels [21]. This trend results in embodied carbon representing nearly half of all construction-related emissions by mid-century under business-as-usual scenarios. The figure underscores that even aggressive operational decarbonization strategies will be insufficient if material-related emissions are not addressed simultaneously.

This evolving emissions profile places increased responsibility on architects, engineers, and construction professionals. Design decisions made during early project phases, such as structural system selection, material specification, and envelope design, can determine the majority of a building’s embodied carbon footprint. Once these decisions are finalized and materials are procured, opportunities for meaningful embodied carbon reduction are severely limited [14]. Materials such as steel and concrete are particularly impactful due to their energy-intensive production processes and widespread use in structural systems. Glass, gypsum board, insulation, and flooring materials also contribute substantial emissions depending on their composition, manufacturing conditions, and transportation distances [22].

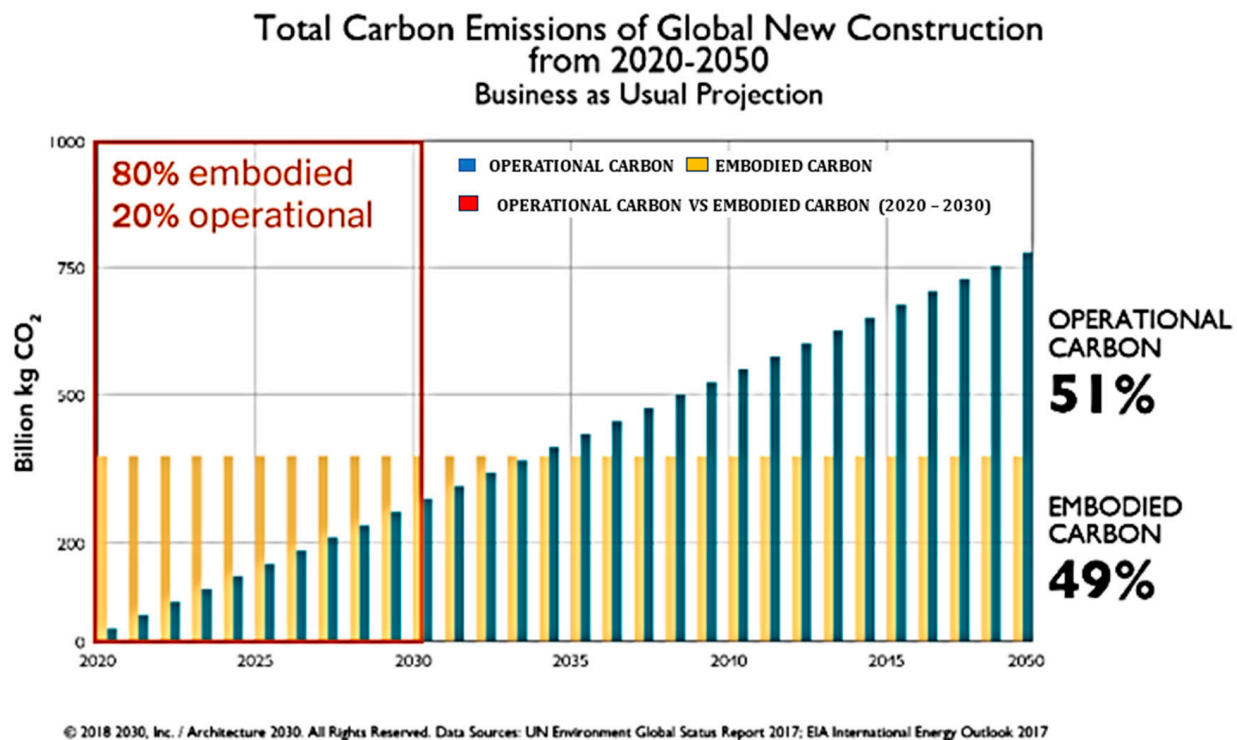


Figure 2. Projected total carbon emissions of global new construction with business as usual.

Figure 3 highlights how structural material choice drives embodied carbon in a 175,000 ft² office building, with timber systems showing significantly lower emissions than steel or concrete, emphasizing the value of early material decisions.

Embodied Carbon - 175,000 SF Office

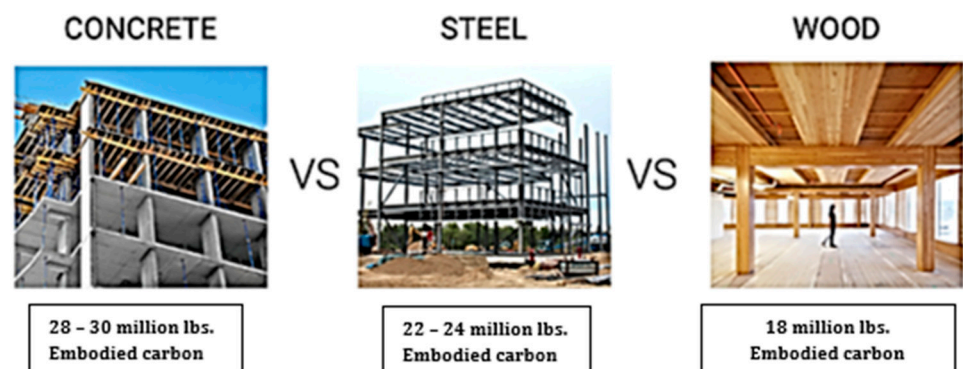


Figure 3. Comparison of Embodied Carbon for a 175,000-SF Office Building Constructed with Concrete, Steel, and Wood [23].

The literature identifies several effective mitigation strategies for cradle-to-gate embodied carbon: (1) Material Optimization and Substitution: Using low-carbon concrete, recycled aggregates, mass timber, and alternative structural systems can reduce emissions from high-impact materials, while structural optimization improves material efficiency and lowers overall material demand [8,20]; (2) Design for Circularity: Designing for disassembly, reusing components, and incorporating reclaimed materials reduce demand for new material production and can significantly lower cradle-to-gate emissions [12]; (3) Service Life Extension: Extending the lifespan of building components and systems lowers the

annualized embodied carbon, while lifespan simulation tools help stakeholders evaluate trade-offs between durability and carbon impact [24]; (4) Data and Decision Support Tools: Emerging digital tools like the Embodied Carbon in Construction Calculator (EC3) and custom cradle-to-gate modeling platforms support data-driven material selection and transparent carbon accounting, enabling early integration of embodied carbon targets into design and procurement [25].

In reviewing the literature, the authors examined five case studies highlighted by the Stanford Building Decarbonization Learning Accelerator [24], as outlined below.

Case Study 1: Lewis and Clark State Office Building

The Lewis and Clark State Office Building illustrates how architectural daylighting strategies can substantially reduce operational carbon while indirectly affecting embodied carbon. The design incorporates external and internal light shelves, daylight-responsive dimming systems, and high-efficiency LED lighting to minimize reliance on artificial lighting during occupied hours. By improving daylight penetration and lighting uniformity, the building achieved a 40% reduction in lighting energy use, directly lowering operational carbon from electricity consumption [26]. These passive strategies also enhance occupant comfort by reducing glare and stabilizing interior temperatures.

Beyond operational savings, the project illustrates how architectural decisions can indirectly reduce embodied carbon. By minimizing cooling and lighting loads, the building was able to reduce the required size and capacity of mechanical and electrical systems. Smaller HVAC equipment, reduced ductwork, and fewer lighting fixtures translate to lower material quantities, thereby reducing embodied carbon associated with system manufacturing and installation. While embodied carbon was not the primary focus of the project, this case highlights the interconnected relationship between passive design, operational efficiency, and material-related emissions.

Case Study 2: The Exelixis Office Building in Alameda, California, demonstrates how advanced mechanical systems can drive operational decarbonization. The building integrates a Dedicated Outdoor Air System (DOAS) with Variable Air Volume (VAV) distribution and Variable Refrigerant Flow (VRF) heat pumps, completely eliminating on-site combustion-based heating. By separating ventilation from thermal conditioning, the system conditions only the required outdoor air rather than the entire indoor volume, enhancing both energy efficiency and indoor air quality [27].

This system-level strategy reduces operational carbon by lowering overall energy demand and leveraging electrified heating and cooling compatible with a decarbonizing electrical grid. Additionally, the optimized HVAC design reduces embodied carbon by minimizing the amount of mechanical equipment, piping, and ductwork required, compared to conventional boiler-chiller systems. The case underscores how early mechanical system selection can influence both operational and embodied emissions simultaneously, reinforcing the importance of integrated design approaches in high-performance buildings.

Case Study 3: Gundersen Sparta Clinic

The Gundersen Sparta Clinic serves as a comprehensive example of achieving carbon-free operations in a high-energy-use healthcare facility. The building integrates geothermal heat pumps, VAV-DOAS ventilation with energy recovery, LED lighting, and on-site and community-based renewable energy sources to offset 100% of operational energy demand [28]. Despite the inherently high energy requirements of healthcare facilities, the clinic achieves a significantly reduced Energy Use Intensity (EUI) through envelope optimization, efficient mechanical systems, and strategic building orientation.

From an embodied carbon perspective, the project demonstrates how envelope and system optimization can reduce material-related emissions. High-performance insulation,

controlled glazing ratios, and solar shading reduce heating and cooling loads, enabling smaller mechanical systems and reducing associated embodied carbon. The integration of geothermal systems also shifts emissions away from fossil fuels while minimizing long-term operational impacts, illustrating how lifecycle thinking can be applied even in complex building typologies such as healthcare.

Case Study 4: St. Peter Residential Building

The St. Peter Residential Building in New Orleans is a notable example of explicitly prioritizing embodied carbon reduction alongside net-zero operational performance. The project utilizes a wood-based structural system, timber piles, and minimized concrete use to significantly reduce upfront emissions associated with construction materials [29]. Timber, as a renewable material with lower embodied carbon intensity, plays a central role in achieving a reported total embodied carbon of approximately 1.04 million pounds of CO₂e—substantially lower than comparable steel or concrete multifamily buildings.

Operationally, the building achieves net-zero energy through high-performance envelope design, ducted mini-split heat pumps, efficient lighting, and on-site solar photovoltaics with battery storage. This case study highlights the importance of balancing material selection with operational efficiency, demonstrating that deep carbon reductions are achievable when both embodied and operational emissions are addressed simultaneously. The project further emphasizes the role of electrification and resilience, particularly in climate-vulnerable regions prone to power outages.

Case Study 5: Baton Rouge Commercial Office Building Renovation

The Baton Rouge Commercial Office Building renovation illustrates the significant carbon reduction potential of adaptive reuse. By retaining the existing foundation, structural frame, and portions of the building envelope, the project avoided the majority of emissions associated with new material production, resulting in an estimated 85% reduction in embodied carbon compared to new construction [30]. This strategy demonstrates that the greenest building is often the one that already exists, particularly when structural components can be preserved.

Operational carbon reductions were achieved through mechanical system upgrades, including the replacement of legacy VAV systems with VRF heat pumps and the introduction of a DOAS for improved ventilation efficiency. Interior reconfiguration enhanced daylight access, reduced lighting loads, and improved occupant comfort without requiring extensive material replacement. Collectively, the project highlights adaptive reuse as one of the most effective strategies for reducing both embodied and operational carbon, especially in commercial office buildings with long remaining service lives.

Collectively, these case studies emphasize several cross-cutting principles: the importance of reducing material quantities, selecting lower-carbon alternatives, maximizing passive design strategies, and strategically integrating electrified, high-efficiency mechanical systems. They also highlight the increasingly symbiotic relationship between operational and embodied carbon in high-performance building design. As buildings become more efficient operationally, embodied carbon represents an increasingly larger proportion of total life-cycle emissions, underscoring the importance of quantifying and mitigating material impacts early in the design process.

As illustrated, significant strides have been made in reducing operational carbon through energy efficiency and renewable energy integration. However, embodied emissions from materials and construction processes remain an underregulated and under-assessed contributor [31,32]. To achieve the Paris Agreement, the global buildings and construction sector must become net-zero-carbon by 2050, and all new buildings must be net-zero carbon from 2030 [33]. Despite the advances in measurement and mitigation,

key research gaps remain. Cradle-to-gate assessments often face inconsistent data quality across materials and regions, and few studies focus specifically on commercial buildings, with most targeting residential or mixed-use projects. Integrating cradle-to-gate analysis with whole-life carbon, including operational and end-of-life phases, is still essential for comprehensive sustainability [34].

2. Methodology

The embodied carbon assessment of the MERIC building (Figure 4) followed a structured, systematic methodology to ensure accuracy, consistency, and replicability. The analysis focused on cradle-to-gate emissions (A1–A3), encompassing raw material extraction, transportation, and manufacturing. Material quantities were obtained from architectural and structural documents—including plans, schedules, specifications—and verified in the field. These quantities were organized by material category to maintain a clear and consistent measurement framework throughout the study.

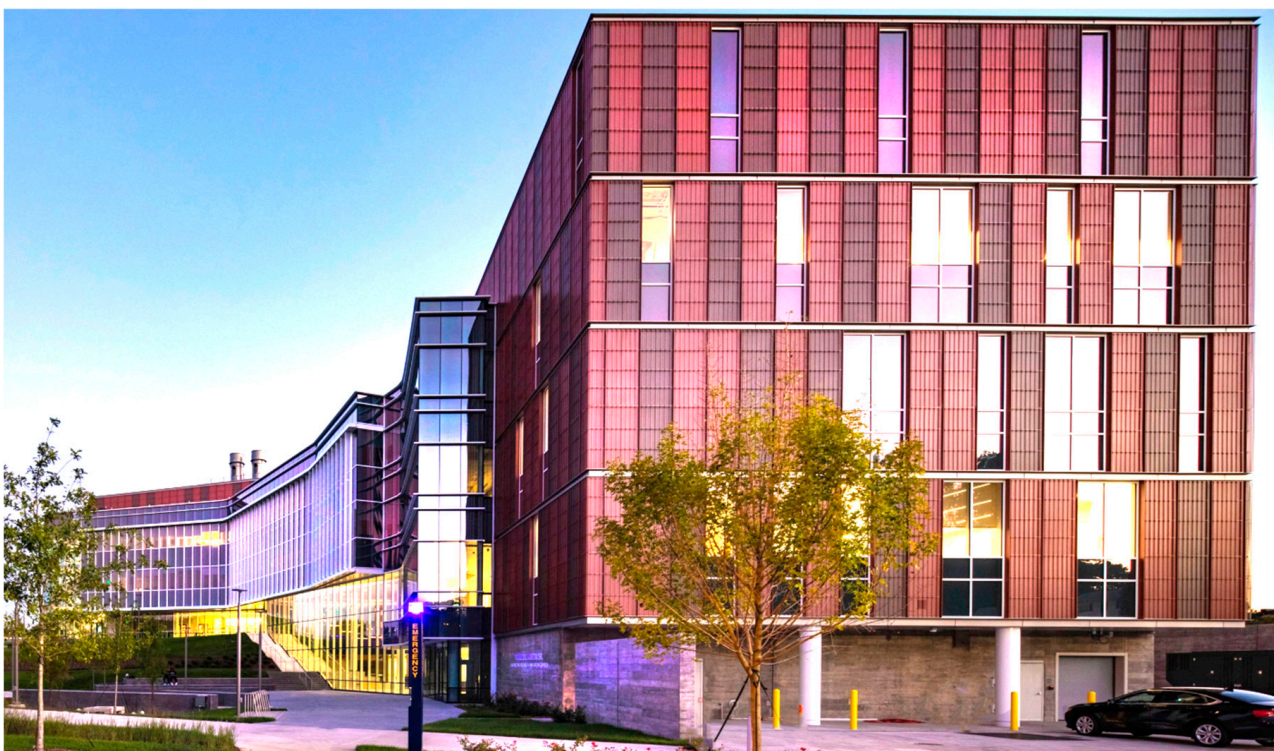


Figure 4. The MERIC building.

The baseline embodied carbon of the MERIC Building is 5,563,537 kg CO₂e, or roughly 42.8 kg CO₂e per ft². By substituting low-emission materials, total embodied carbon could be reduced to 1,443,655 kg CO₂e, or about 11.1 kg CO₂e per ft², representing a potential 74% reduction compared with the baseline.

Figure 5 shows the distribution of total embodied carbon (CO₂e) across all major material categories for the MERIC Building under baseline conditions. Steel accounts for the largest share of emissions (52.5%), followed by doors (27%), concrete (10.9%), gypsum board from partitions (4.3%), floor finishes (1.8%), glass (2.1%), and aluminum exterior siding (1.3%). The chart highlights the dominance of structural materials (particularly steel, doors, and concrete) in the building's overall embodied carbon footprint.

After organizing all material quantities, the calculation followed a consistent workflow. Each quantity (by volume or mass) was multiplied by its corresponding emissions factor (kg CO₂e/kg or kg CO₂e/m²), and totals were aggregated by material category. This

standardized approach ensured comparability across assemblies and identified the building systems contributing most to total embodied emissions. It also enabled sensitivity analyses, where alternative materials—such as low-carbon concrete, recycled steel, or bio-based flooring—could be evaluated for potential reductions. These analyses guided strategies to lower embodied carbon by 15–30% without compromising building performance or architectural intent.

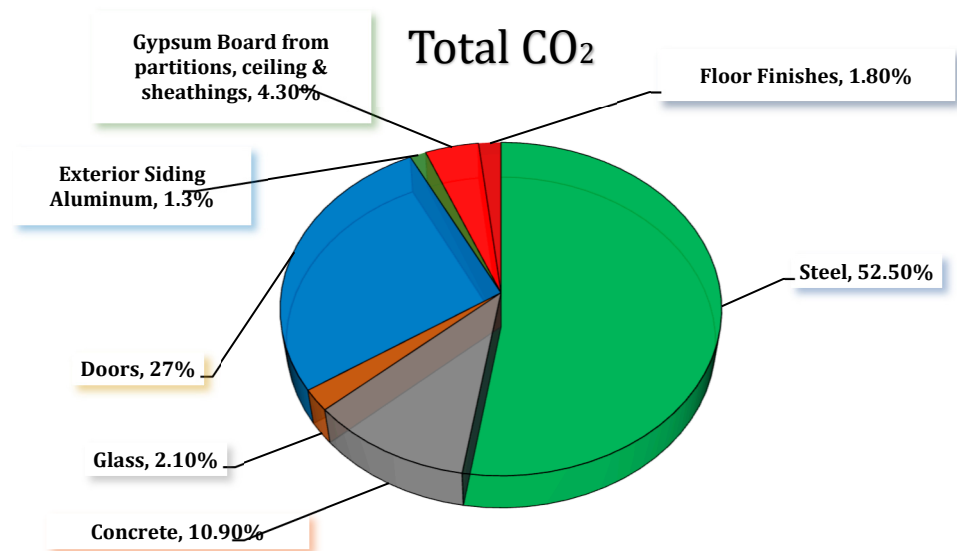


Figure 5. Material contribution percentages to total baseline embodied CO₂ emissions.

2.1. Selection and Applicability of Emission Factors

Baseline emission factors for major construction materials were selected from peer-reviewed literature and widely used life cycle assessment (LCA) databases to ensure methodological consistency and comparability across material categories. Emission factors were defined on a cradle-to-gate basis (A1–A3), capturing emissions associated with raw material extraction, transportation to manufacturing facilities, and product manufacturing. This boundary was selected to isolate material-related impacts occurring prior to construction and to align with common embodied carbon assessment practices reported in the literature.

Wherever possible, emission factors representative of North American or U.S. production conditions were prioritized. However, for several materials, particularly concrete, steel, and finish products, region-specific Environmental Product Declarations (EPDs) were not consistently available across all material categories. In these cases, global or industry-average emission factors reported in established databases and peer-reviewed studies were used as proxies. For example, concrete and steel emission factors cited in this study reflect widely adopted average values reported in the literature rather than plant-specific U.S. manufacturing data.

2.2. Concrete Calculations

Concrete components included foundations, footings, slabs, stair elements, elevator cores, and structural walls. The total cubic footage of concrete was obtained by summing all individual elements based on geometric measurements. Table 1 summarizes the concrete Emissions calculations by structural element. Each value was converted to cubic meters and then multiplied by the density of concrete (2400 kg/m³). The final mass was multiplied by the baseline emissions factor of 0.10 kg CO₂e/kg [3]. For alternative scenarios, a low-carbon concrete emissions factor of 0.065 kg CO₂e/kg was applied.

Table 1. Concrete Emissions Calculations by Structural Element.

Concrete Emissions Calculations									
	Volume (CF)	Conversion Factor (CF to m ³)	Volume (m ³)	Density (kg/m ³)	Weight (Kg)	CO ₂ Emission Factor (CO ₂ e/kg)	CO ₂ Emission(kg)	Alternative CO ₂ Emission Factor	Alternative CO ₂
Footing Foundation	15,560.9	0.028	440.6	2400.0	1,057,525.5	0.10	105,752.5	0.065	68,739.2
Slabs (All Floors)	54,136.0	0.028	1533.0	2400.0	3,679,105.9	0.10	367,910.6	0.065	239,141.9
First Floor Exterior Concrete Wall (CMU)	11,056.0	0.028	313.1	2400.0	751,370.5	0.10	75,137.1	0.065	48,839.1
One Elevator walls (Area A)	6953.6	0.028	196.9	2400.0	472,569.7	0.10	47,257.0	0.065	30,717.0
Two Elevators walls (Area B)	10,648.5	0.028	301.5	2400.0	723,678.7	0.10	72,367.9	0.065	47,039.1
Stair 1 & 2 Concrete Walls	30,238.0	0.028	856.2	2400.0	2,054,987.5	0.10	205,498.8	0.065	133,574.2
Stair 1, 2, & 3 Concrete Steps	273.0	0.028	7.7	2400.0	18,553.2	0.10	1855.3	0.065	1206.0
Totals	128,866		3649		8,757,791.0		875,779.1		
						Total CO ₂ from Concrete	875,779		569,256
								15% Fly Ash CO ₂ Reduction	−35%

2.3. Steel Calculations

Steel quantities were extracted directly from the structural schedules, which listed all girder and column types with lengths, weights, and quantities (Table 2). The total steel weight was reported in pounds and converted to kilograms using the conversion factor (1lb = 0.453592 kg). Structural steel used the baseline emissions factor of 1.70 kg CO₂e/kg, consistent with global average blast furnace-basic oxygen furnace (BF-BOF) production [9]. An alternative recycled steel scenario used in emissions of 0.18 kg CO₂e/kg, reflecting electric arc furnace (EAF) production.

Table 2. Embodied Carbon Emissions from Steel Girders, Beams, and Columns.

Girders/Beams & Columns Emissions Calculations							
	Quantity	Weight (lbs)	Weight (kg)	CO ₂ Emission Factor	CO ₂	Alternative CO ₂ Emission Factor	Alternative CO ₂
1st Floor Girders	401	638,424	289,584	2.71	784,773	0.44	127,417
2nd Floor Girders	525	577,345	261,879	2.71	709,692	0.44	115,227
3rd Floor Girders	518	477,188	216,449	2.71	586,576	0.44	95,237
4th Floor Girders	660	705,727	320,112	2.71	867,504	0.44	140,849
Total	2104	2,398,684	1,088,024		2,948,545		478,730.50
Columns	123	377,392	171,182	2.71	463,903	0.44	75,320.08
						Recycled Steel CO ₂ Reduction	75,320.08

2.4. Glazing and Curtain Wall Calculations

Curtain walls and storefront glazing were analyzed based on their area (length $\times$ height) and a standard thickness of 6mm. Volumes were converted to m^3 and multiplied by glass density ($2500 \text{ kg}/\text{m}^3$). Double-pane units were multiplied by two to capture both layers (Table 3). An emissions factor of $0.86 \text{ kg CO}_2\text{e}/\text{kg}$ was applied [15].

Table 3. Embodied Carbon Calculations for Glass and Glazing Systems.

Glass Emissions Calculations								
	Size (ft^2)	Thickness (m)	Glass Volume (m^3)	Weight (kg)	Emissions Factor ($\text{CO}_2\text{e}/\text{kg}$)	CO_2 Emissions (kg)	Alternative CO_2 Emission Factor	Alternative CO_2
Store Front Windows & Outside Curtain Walls	7167.1	0.006	4.0	9987.7	0.86	8589.4	0.55	5493.2
Doors with Glass counts 44 size 20'	880.0	0.006	0.5	1226.3	0.86	1054.6	0.55	674.5
Total Glass Including Double Pane of 6 mm	90,355.0	0.006	50.4	125,913.8	0.86	108,285.8	0.55	69,252.6
Totals				137,127.8		117,929.9		75,420.3
Secondary Glass CO_2 Reduction								36%

2.5. Exterior Metal Panel Systems

Exterior wall metal panel assemblies were calculated based on area and a nominal material thickness of 0.003 inches. Volumes were converted from ft^3 to m^3 and multiplied by aluminum density ($2710 \text{ kg}/\text{m}^3$). Insulation and interior sheathing layers within the same panel assembly were also included, each calculated using its respective thickness and density (Table 4). Emission factors came from the ICE and EPD databases [6].

Table 4. Exterior Wall and Roof Metal Panel Areas and Emissions Calculations.

Exterior Walls/Metal Panels										
Metal Panels	Material	Sq/ft (All Floors)	Thickness 5/8"	Conversion Factor (cf to m^3)	Volume (m^3)	Density (kg/m^3)	Weight (kg)	CO_2 Emissions Factor ($\text{CO}_2\text{e}/\text{kg}$)	CO_2 Emissions (kg)	Alternative CO_2 Emission Factor
Metal Panel Aluminum		33,982.0	0.0025	0.0283	2.4	2710.0	6519.3	11.46	74,711.4	1.69
										11,017.7

Table 4. Cont.

Exterior Walls/Metal Panels												
Exterior Wall Insulation	Material	Area (sq/ft)	Thickness (3in)	Volume (cf)	Fiberglass Density (lb/cf)	Weight of Mineral Fiber Insulation (lbs)	Conversion Factor (lb to kg)	Fiberglass Insulation (kg)	CO ₂ Emissions Factor (CO ₂ e/kg)	CO ₂ Emissions (kg)	Alternative CO ₂ Emission Factor	Alternative CO ₂
General Insulation		12,615.0	0.25	3153.8	8.0	25,230.0	0.45	11,444.1	1.86	21,286.1	0.19	2174.4

2.6. Interior Partitions

Gypsum board partitions were categorized by type and layer count (e.g., 1 layer on each side, 2 layers on each side, or staggered combinations). Partition volumes were computed using wall length, height, and total gypsum thickness, accounting for the number of layers on each side (Table 5). The number of layers refers to the number of gypsum board layers applied on each face of the partition system (for example, GYP BD C30: 1 layer on one side and 2 layers on the other). This ensured accurate volumetric representation of multi-layer assemblies. Volumes were converted to mass using a density of 650 kg/m³. CMU partitions were elevated separately using a density of 1800 kg/m³.

Table 5. Embodied Carbon Calculations for Interior Partitions.

Partitions Emissions Calculations							
	Volume (cf)	Conversion Factor (cf to m ³)	Volume (m ³)	Density (kg/m ³)	Weight (kg)	CO ₂ Emissions Factor (CO ₂ /kg)	CO ₂ Emissions (kg)
CF cubic feet _ GYP BD (ABCD + G + H + J)	99,621.5	0.028	2821.0	650.0	1,833,627.5	0.12	220,035.3
Gypsum Board Area of Sheathing	7884.0	0.028	223.3	650.0	145,112.5	0.12	17,413.5
Gypsum Board Ceiling	501.0	0.028	14.2	650.0	9220.4	0.12	1106.5
Area of Sheathing Gypsum Board (Interior Side of the Metal Panel)	657.0	0.028	18.4	650.0	11,958.0	0.12	1435.0
Total							237,448.8

2.7. Doors

Doors were analyzed by material category: hollow metal (HM), aluminum (AL), wood (WD), and aluminum/glass (AL/GL). The area of each door was taken from the door schedule. Because commercial doors have hollow interiors, calculations assumed an effective thickness of 0.75 inches for HM, AL, and AL/GL. To capture both metal face panels on either side of the hollow interior doors, the width was multiplied by two, ensuring that embodied carbon calculations accurately reflected the full material surfaces used in fabrication. Glass components in AL/GL doors were subtracted from the metal area and added to the glazing category. Table 6 illustrates door emissions by material type.

Table 6. Door Emissions Calculations by Material Type.

Doors Emissions Calculations										
Material	Quantity	Volume (cf)	Conversion Factor (cf to m ³)	Volume (m ³)	Density (kg/m ³)	Weight (kg)	CO ₂ Emissions Factor (CO ₂ e/kg)	CO ₂ Emissions (kg)	Alternative CO ₂ Emission Factor	Alternative CO ₂
HM	76.0	708.3	0.028	20.1	2723.0	54,613.2	11.5	625,867.1	1.7	92,296.3
AL	13.0	4.0	0.028	0.1	2723.0	308.4	8.2	2541.4	1.7	521.2
WD	182.0	2133.9	0.028	60.4	400.0	24,169.9	0.4	8459.5	0.3	7492.7
AL/GL*	32.0	133.1	0.028	3.8	2723.0	10,262.9	11.5	117,613.0	1.7	17,344.3
Total Door counts and areas	303.0	2979.3		84.4		89,354.4		754,481.0		117,654.5
Note: * Glass portions were deducted from the AL area and included in the Glass							Recycled Aluminum and Recycled Wood CO ₂ Reduction		—84%	

Note: * Glass portions were deducted from the AL area and included in the Glass.

2.8. Flooring Systems

Flooring materials, carpet, epoxy, rubber, porcelain tile, and terrazzo, were quantified using floor finish schedules. Areas were grouped by material and converted to m². Where thickness was required (rubber, porcelain, terrazzo), volumes were derived, and densities applied. Emission factors were sourced from published EPDs, peer-reviewed literature [21], and ClimaTiq databases [9]. Table 7 illustrates floor material emission.

2.9. Ceiling Systems

All ceilings were assumed to be Acoustical Ceiling Panels (ACP), as supported by finish schedules. This assumption streamlined calculations and reflects the most common ceiling material used throughout the MERIC building. Since the emissions factor for ACP was given per square foot, no conversions to kg were necessary. Table 8 illustrates the ceiling material emission.

Table 7. Floor Material Emission Calculations.

Floors Emissions Calculations											
Material (Floors)	Area (sq/ft)	Conversion Factor (sq/ft to m ²)	Volume (m ²)	Volume (m ³)	Density (kg/m ³)	Weight (kg)	CO ₂ Emissions Factor (CO ₂ /kg)	CO ₂ Emissions (kg)	Alternative CO ₂ Emission Factor	Alternative CO ₂	Notes
RST/RT/RS	13,921	0.093	1293.3	8.2	900	7391.2	2.7	19,660.7	0.12	886.9	
SC (Concrete Sealer)	5881.0	0.093	546.4	-	-	-	-	neglected	-	-	
SF (Epoxy)	27,481	0.093	2553.1	-	-	20,610.8	10.3	26,194.5	0.12	2473.3	Emissions Factor is kg/m ²
PFT (Porcelain)	4734.0	0.093	439.8	6.6	2.3	15.2	0.8	11.5	0.12	1.8	
CPT (Carpet)	54,372	0.093	5051.3	-	-	120,705.8	9.8	49,503.0	0.12	14,484.7	Emissions Factor is kg/m ²
TER (Terrazzo)	22,619	0.028		20.0	2100	42,042.0	0.12	5045.0	0.12	5045.0	Conversion Factor (cf to m ³)
Total		CO ₂ from all types of floors except SC Sealer						100,414.6		22,891.8	

Table 8. Ceiling Material Emissions Calculations.

Ceiling Emissions Calculations						
Material	Area (sq/ft)	Thickness 3/4"	Volume (cf)	Volume (m ³)	CO ₂ Emissions Factor (CO ₂ e/kg)	CO ₂ Emissions (kg)
ACP (Acoustical Ceiling Panel)	108,161.0	0.063	6760.1	191.4	0.187	35.8
					CO ₂ from all ceiling	35.8

2.10. Decarbonization Strategies

The case study showcases practical strategies for decarbonizing commercial buildings. These include using steel structural systems with high recycled content and bolted connections, concrete incorporating fly ash, ceramic tile flooring, and wooden doors. Additional measures involve the adaptive reuse of existing components and material selection guided by Environmental Product Declarations (EPDs) to reduce cradle-to-gate emissions. Sustainability and efficiency are further enhanced through local sourcing, prefabrication, and modular construction. Together, these strategies offer transferable, low-carbon, cost-effective, and operationally resilient solutions for sustainable building design.

Key strategies include: (1) Steel with high recycled content and bolted connections—reduces embodied carbon and allows for future reuse; (2) Adaptive reuse of existing components—minimizes demolition waste, avoids new material emissions, and promotes a circular economy; (3) Material selection guided by EPDs—ensures verified low embodied carbon (A1–A3) and supports informed decision-making; (4) Local sourcing of materials—lowers transportation emissions and improves supply-chain efficiency; (5) Prefabrication and modular construction—decreases on-site waste and enhances construction efficiency.

3. Results

The results show that embodied carbon in the MERIC building is primarily driven by structural materials. Steel is the largest contributor, generating over 2.9 million kg CO₂e, followed by concrete at roughly 600,000 kg CO₂e. Glass and glazing account for about 118,000 kg CO₂e, while partitions and gypsum board contribute 237,000 kg CO₂e. Floors and ceiling finishes add approximately 100,000 kg CO₂e, and ceilings contribute around 26 kg CO₂e due to their lower mass and density.

Doors contributed approximately 754,000 kg CO₂e, including hollow metal, wood, and aluminum/glass assemblies. Using alternative materials with higher recycled content reduced door-related emissions by 84%, highlighting the significant impact of material substitutions.

When low-carbon materials were applied across all categories, total embodied carbon dropped from about 5.7 million kg CO₂e to 1.4 million kg CO₂e, achieving a nearly 75% reduction. The largest savings occurred in steel, concrete, and door assemblies, reflecting both their high mass and the availability of lower-carbon alternatives.

These results demonstrate the substantial carbon reduction potential of targeted material substitutions. Figure 6 summarizes total CO₂ emissions, showing that alternative low-emission materials lead to significant reductions in steel, concrete, and glass. Floors and glazing also show meaningful decreases when lower-carbon alternatives are used.

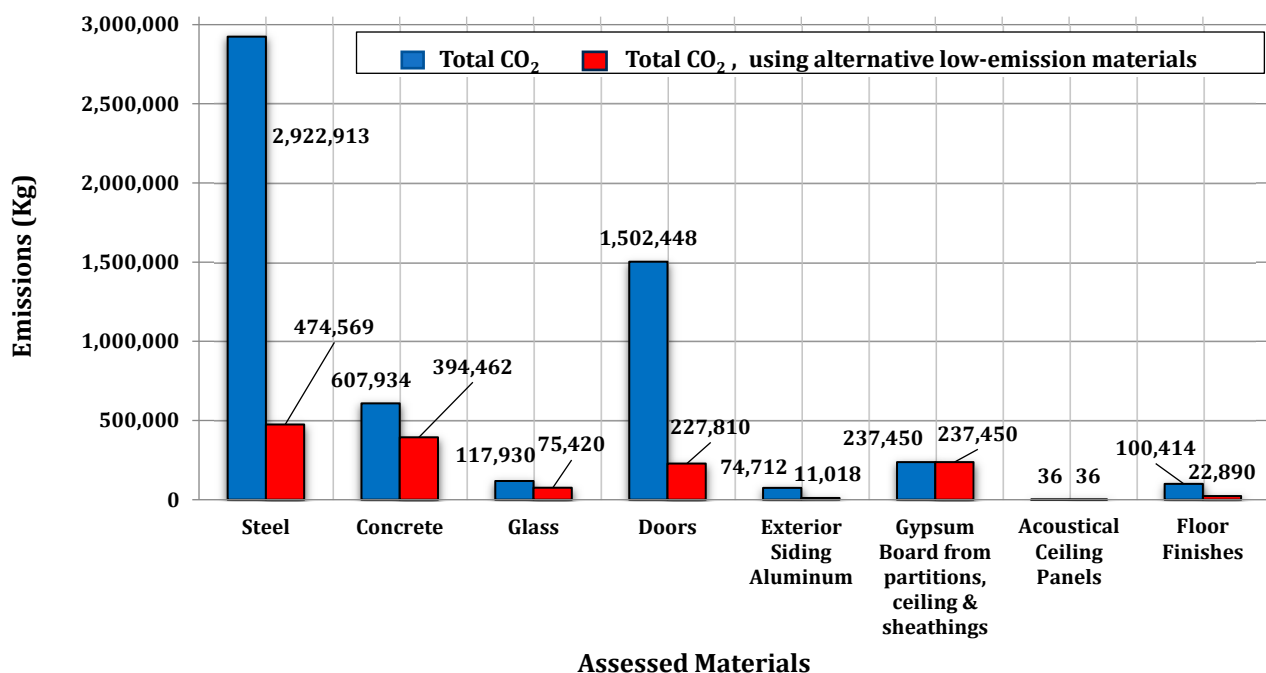


Figure 6. Total embodied CO₂ emissions relative to emissions calculated using alternative low-emission material options.

4. Conclusions

This study quantifies the embodied carbon of key building components in a large institutional facility. Findings show that structural materials contribute the most to cradle-to-gate emissions, followed by glazing, partitions, doors, and finishes. Sensitivity analyses reveal that incorporating recycled content, low-carbon mixes, and alternative assemblies can substantially reduce embodied carbon without affecting performance or functionality.

The findings show that structural materials, especially concrete and steel, account for the largest share of embodied carbon, consistent with global research highlighting their dominant role in building carbon profiles. Envelope components such as glazing, metal

panels, and insulation also contribute significantly due to their widespread use and energy-intensive manufacturing. While interior materials like flooring, ceilings, and partitions contribute less individually, their cumulative impact is notable given frequent renovation and replacement over a building's lifespan.

By examining strategies across five case studies, this study underscores the importance of addressing both operational and embodied carbon in building design. High-performance envelopes, efficient mechanical systems, advanced daylighting, and electrification can significantly reduce operational emissions, while careful material selection and reuse are the most effective means of lowering embodied carbon.

Holistic carbon reduction strategies, including adaptive reuse, renewable energy integration, smart material selection, and high-performance design, can advance the building sector toward net-zero carbon goals. As operational emissions decline with stricter energy standards, embodied carbon will become the dominant portion of life-cycle emissions, making early design-phase decisions essential for achieving significant reductions.

The results of this study confirm that embodied carbon associated with structural and envelope materials represents a dominant share of total life-cycle emissions for institutional buildings. Consistent with prior research, concrete and steel accounted for the majority of embodied carbon in the MERIC building due to their high mass and energy-intensive production processes. As operational energy efficiency improves and electrical grids decarbonize, the proportional contribution of embodied carbon becomes increasingly significant, reinforcing the need to address material impacts early in the design process.

The sensitivity analysis demonstrated that substituting conventional materials with lower-carbon alternatives, such as recycled steel, low-cement concrete mixes, and bio-based finishes, can reduce total embodied carbon by approximately 15–30%. While these substitutions were evaluated conceptually, their practical implementation depends on factors including cost premiums, regional material availability, supply chain constraints, and structural design requirements. For example, low-carbon concrete may require adjustments to curing time or mix design, while increased recycled steel content on access to electric arc furnace production facilities powered by low-carbon electricity.

Study Limitations

This study is subject to several limitations. The embodied carbon assessment was limited to cradle-to-gate (A1–A3) stages and did not include transportation to site (A4), construction activities (A5), use-phase maintenance and replacement (B1–B5), or end-of-life stages (C1–C4). Additionally, biogenic carbon storage associated with timber materials was not explicitly accounted for, which may underestimate the benefits of wood-based construction. Uncertainty associated with emission factors, material qualities, and regional variability was not quantified through probabilistic analysis. Future research should expand system boundaries and incorporate region-specific EPDs and uncertainty modeling to improve result accuracy.

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