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# Assessing Opportunities for Circularity in Buildings

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Energy Technologies Area

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# 1 Introduction/Background

The building industry is responsible for consuming more than 32% of the world's resources (25% water, 40% energy, and 12% land), generates over 25% of its solid waste, and emits about 35% of the total greenhouse gases (GHGs) globally (Yeheyis et al., 2013; Soust- Verdaguer et al., 2017).

With the global imperative to address climate change through decarbonization, the building sector is moving from its current industrial linear economic (LE) model of "take-make-waste" to a circular economic (CE) approach, where it "aims to overcome the divergent interests of economic and environmental prosperity by closing material loops through technological innovation, including recycling and reuse, as well as by introducing new business models, relying on sale-and-take-back or lease contracts." (Ellen MacArthur Foundation, 2015; see Figure 1-1).

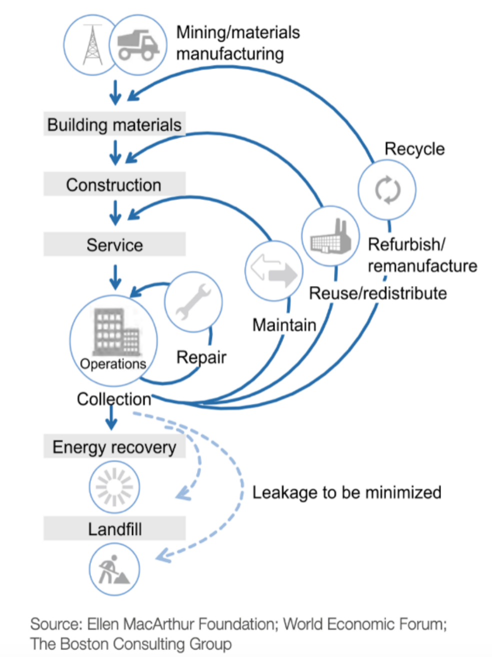



Figure 1-1. Idealized material flows in a Circular Economy

Currently, only 20%–30% of construction and demolition waste is recycled or reused. The remaining 70%–80% of discarded building materials that end up primarily in landfill are comprised of lumber (40%), asphalt products (14%), concrete, rock/brick (11%), and gypsum board (10%). To close material loops, a CE designed approach to building products and materials considers their reuse and recycling capacity at the onset of their use through their end of life (EOL) planning (Figure 1-2).

Much of the initial research in the area of circular economy has been conducted in Europe with its broad vision and more recent comprehensive guides to circularity principles for the building industry being published by the Ellen MacArthur Foundation (EMF), the Royal Institution of Chartered Surveyors (RICS), and the United Kingdom Green Building Council (UKGBC). These principles were influenced by the need to assess the whole-life carbon impact of buildings, components, and materials over their distinct life cycles.

Our goal for looking of this project was to identify circularity strategies throughout the entire life cycle of materials and buildings, including the design of building products and assemblies, the waste flows of high impact materials, and products and the design and construction of buildings.

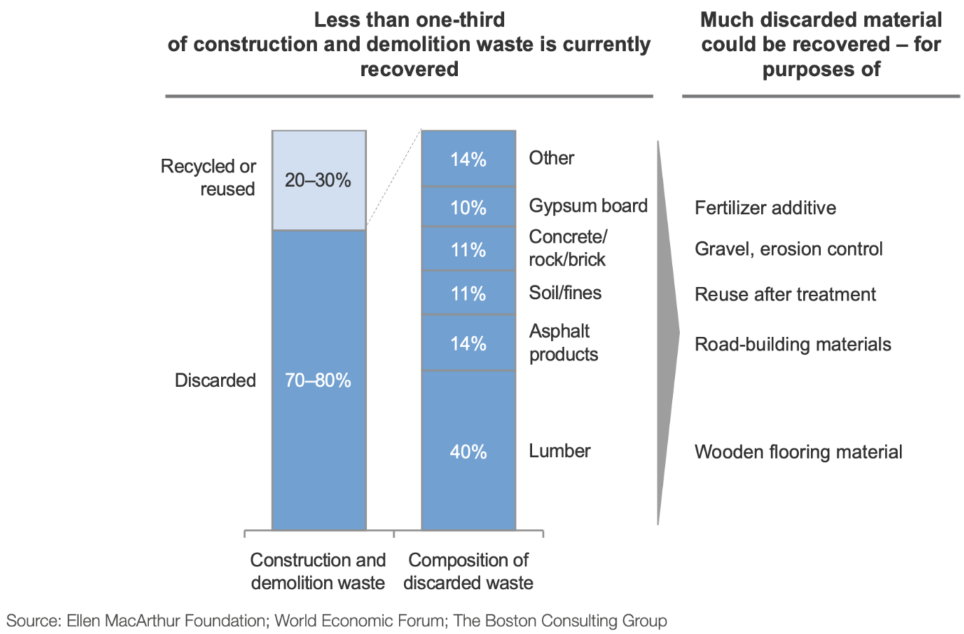



Figure 1-2. Composition and fate of construction and demolition waste

Life cycle assessment (LCA) as an analytic tool has been adopted by architectural and construction industries as a more comprehensive method to evaluate and reduce environmental impacts by buildings (Bayer et al. 2010). LCA as an established methodology provides comprehensive data on the environmental impacts of products and processes during the entire life cycle. The application of the life cycle assessment process is now being expanded to include circular characteristics and their impact on a building asset. Frameworks such as the LEED rating system[1] and LCA tools such as OneClick LCA[2] are already incorporating circular attributes into their overall scope. With LCA becoming the de facto analytic tool for building circular analysis, it is important to note that limitations do exist and need to be addressed, including, the use of consistent

[1] LEED (Leadership in Energy and Environmental Design) is the most widely used green building rating system in the world. Available for virtually all building types, LEED provides a framework for healthy, highly efficient, and cost-saving green buildings. LEED certification is a globally recognized symbol of sustainability achievement and leadership. https://www.usgbc.org/help/what-leed

[2] One Click LCA – A https://www.oneclicklca.com

data and functional units, life cycle stage or system boundary of a material or product, the integration of circular concepts such as design for disassembly and adaptation, etc. Efforts are currently underway to address these areas in a standardized life cycle assessment process.

Based on the methods and examples identified from the literature sources described in our literature review (delivered to DOE February 12, 2021 and incorporated into the following chapters), we have identified three building life cycle concepts to guide the selection of circularity case studies: 1) material selection, 2) building use flexibility, and 3) off-site assembly. We then developed a *material flows through buildings* modeling framework, which accounts for the different building components and the type and quantity of materials that make up those components. This material accounting approach uses RSMeans (Gordian, 2021), which is an industry database used for estimating construction project material costs based on template buildings and construction metrics. Embodied energy and carbon emissions are then estimated based on reviewed Environmental Product Declarations. Chapter 2 describes the modeling framework and evaluates the material, energy, and carbon impacts associated with the U.S. office building stock based on material selection. Chapter 3 looks at building use flexibility with a case study on the design and conversion of obsolete buildings for reuse, as one circularity principle discussed in much of the Circular Economy literature was the need for flexible, adaptable space to allow buildings to accommodate changes in utilization to prolong a building asset. This case study explores the potential lifetime impact reduction in converting an existing office building to residential housing rather than constructing a new structure. Chapter 4 is an off-site assembly case study that explores the implications of using off site assembled interior modular, demountable walls in a non load-bearing capacity and considers material or products that incorporate off site Design for Disassembly and Adaptation strategies.

The material flows through buildings modeling framework is used to evaluate the select case studies in this report, but its accounting of lifetime embodied energy and emissions provides a pathway to assess Circular Economy strategies for buildings more broadly. Future work includes adding more building types and additional building components to broaden the framework applicability and improve result fidelity.

# 2 Embodied Greenhouse Gas Emission Trends from Major Construction Materials of U.S. Office Buildings Constructed after the Mid-1940s

## 2.1 Abstract

While recognized as important, the calculation of embodied energy and greenhouse gas (GHG) emissions associated with buildings, especially at a large scale, is not aided by a decision-support tool or publicly available methods or data. A model has been created for estimating the inventory of structural and non-structural materials and building components and associated embodied energy and GHG emissions of office buildings constructed in the United States between 1946 and 2018. The 807,000 buildings erected in the period represent 90% of the current office building stock (970,000), and they were modeled using eight prototypical, representative 1-, 5-, and 16-floor designs with reinforced concrete, steel, or wood structures and various façade systems and interior configurations. However, 90% of U.S. office buildings are low-rise, with just one to three floors. The total floor space in such buildings constitutes 57% of the national total.

We estimate that 1,100–1,300 million metric tons of materials are embodied in these 807,000 buildings, six to seven years' worth of national construction and demolition waste. The key materials that drive the embodied numbers are concrete and steel. About 76% of construction material use by mass in the 1946–2018 period was due to concrete and 15% due to steel. Steel contributed 44% to the total embodied energy and GHG emissions, respectively, while concrete's allocation was 14% and 22%. The substructure (foundation and slab on grade) and the structure (primarily concrete) contribute the largest percentage of embodied emissions: 50%–70%.

Most of the concrete used in the studied period is in buildings that are now 22 to 52 years old and will be coming up for demolition soon. Using building stock data, we estimated how much carbon dioxide ($CO_2$) would be sequestered by concrete, both during its service life and after demolition. Over 50 years of service life, concrete can uptake 3% of the embodied $CO_2$ emissions. Estimating the maximum theoretical carbon uptake, if the concrete were to be crushed and disposed of as carbonate, carbon uptake over 50 years after demolition (landfilling demolished concrete) would result in an additional 33%–37% of concrete's embodied $CO_2$ emissions. To replicate a realistic setup, over 5 and 10 years after demolition, uptake would amount to 13% and 18% of the concrete's embodied $CO_2$ emissions, respectively.

One-floor steel and wood buildings were about equally energy intensive to construct from structural as well as combined structural and non-structural materials perspectives, while reinforced concrete (RC) buildings were about 20% and 30%-40% more energy intensive, respectively. Five-floor RC and wood buildings were 10%–15% more energy intensive to construct than steel buildings. Sixteen-floor RC and steel buildings needed about the same amount of embodied energy.

One-floor steel and wood buildings are about equally GHG intensive to construct from structural as well as combined structural and non-structural materials perspectives, while RC buildings are about 50% and 27%–47% more GHG intensive, respectively. From the all-materials-use perspective, five-floor steel buildings are 54% more GHG intensive to construct than wood buildings, and in turn RC buildings are 68% more GHG intensive than steel buildings (i.e., wood buildings are responsible for only 39% of the embodied GHG of RC buildings). Sixteen-floor RC and steel buildings need about the same amount of embodied GHGs.

Increasing returns to scale (scale economies) can be observed as the number of floors increases. From the perspective of combined structural and non-structural materials use per square meter, 16-floor RC buildings needed just 66% and 50% of the embodied energy of 5-floor and 1-floor buildings, respectively. The same numbers for steel buildings were 84% and 63%. Five-floor wood buildings needed 87% of the embodied energy of 1-floor buildings to erect. Sixteen-floor RC buildings needed just about half of the embodied GHG emissions of 5-floor and 1-floor buildings. Five-floor and 16-floor steel buildings needed about 60% of the GHG emissions of 1-floor buildings to erect. Five-floor wood buildings needed half of the embodied GHG emissions of 1-floor buildings to erect.

Results from the analysis constitute points of reference for those who seek to understand major contributors to embodied energy and GHG emissions in their buildings, as well as to find ways of reducing the carbon footprint of buildings with future choices regarding building materials and components, along with methods used in their manufacturing and end-of-life stages.

## 2.2 Introduction

The built environment globally accounts for about 75% of energy use-related annual greenhouse gas (GHG) emissions, with construction and operation of buildings accounting for 37% on their own (UNEP, 2021). Between 2020 and 2050, it is predicted that about 50% of emissions associated with new buildings will be embodied and half will come from the operational stage (WGBC, 2021). The embodied GHG emissions are attributed to the materials and energy required to construct and maintain the building, and they result primarily from the burning of fossil fuels (for electricity, transportation, and on-site energy) and chemical reactions (of carbon dioxide [$CO_2$] during the calcination of limestone to produce cement) (Simonen et al., 2017). The manufacturing of construction materials used for new buildings and maintenance of existing ones represents 11% of global overall energy- and process-related GHG emissions, with more than half related to the manufacturing of steel and concrete (mostly from cement) (IEA, 2019). The fraction due to all construction materials and activities has been estimated at 6% of the U.S. total (Simonen et al., 2017). We were interested to run our own estimate for the United States. Based on the quantities of concrete, steel, and wood consumed in buildings in 2019, we estimate 138 million metric tons (Mmt) of carbon dioxide equivalent ($CO_2$eq) emissions, corresponding to 2.1% of the total U.S. GHG emissions (6,572 Mmt of $CO_2$eq [U.S. EPA, 2022]) (Figure 2-1).

Furthermore, materials utilized in the construction of buildings and infrastructure account for half of the solid waste generated in the world. As much as 32% of the total landfilled waste comes from construction sites, and 13% of materials delivered to a construction site end up being sent directly to landfills (WGBC, 2022).

With the increasing manifestations of climate change and the depletion of natural resources used in the construction industry, sustainability has gained wide importance, and the term *circular economy* (CE) has emerged as one of the most important factors leading to sustainable development (Al-Hamrani et al., 2021). As opposed to the prevailing traditional economic system, which is based on a methodology of "make, use, and finally, dispose of," the circular economy aims for continuous use of products by recycling and reusing instead of disposing them to create a closed-loop system and reduce resource consumption (Ellen Macarthur Foundation, 2013). Circular economy strategies such as reuse, recycling, repurposing, design for disassembly, and extending service lifetimes are proposed to close the material loop, reduce natural resource extraction, and minimize waste and the related environmental impacts of buildings (Arup, 2016). However, buildings are often one-of-a-kind projects where designs are based, importantly, on geography, climate, purpose, building codes, and available technologies. Therefore, implementation of CE strategies is a complicated task that requires extensive data and information about the building stocks, materials, and product flows through buildings, as well as their embodied impacts.

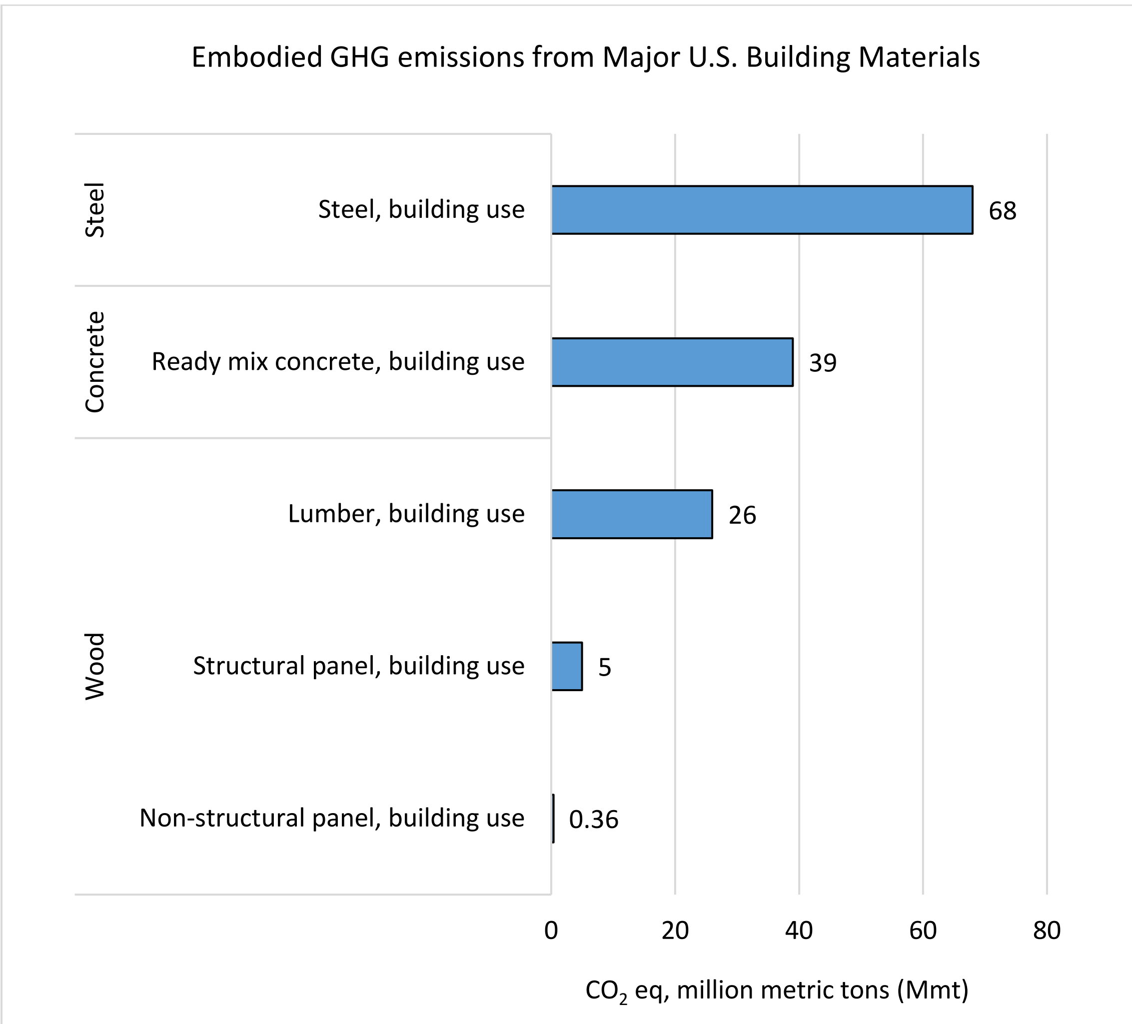



Figure 2-1. GHG emissions from major building materials in 2019. (See Appendix A, Table A-1 for the details about data sources, calculations, and assumptions.)

In this chapter, we describe a method to account for the stock of office buildings constructed in the United States between 1946 and 2018, with the purpose of estimating the quantities of building materials (both structural and non-structural) and associated embodied energy and GHG emissions. The functional unit of the analysis is embodied energy and GHG emissions per square meter of floor space. Results from the analysis constitute points of reference for those who seek to understand major contributors to embodied energy and GHG emissions in their buildings, as well as to find ways of reducing the carbon footprint of buildings with future choices regarding building materials and components, along with methods used in their manufacturing and end-of-life (EOL) stages (Figure 2-2).

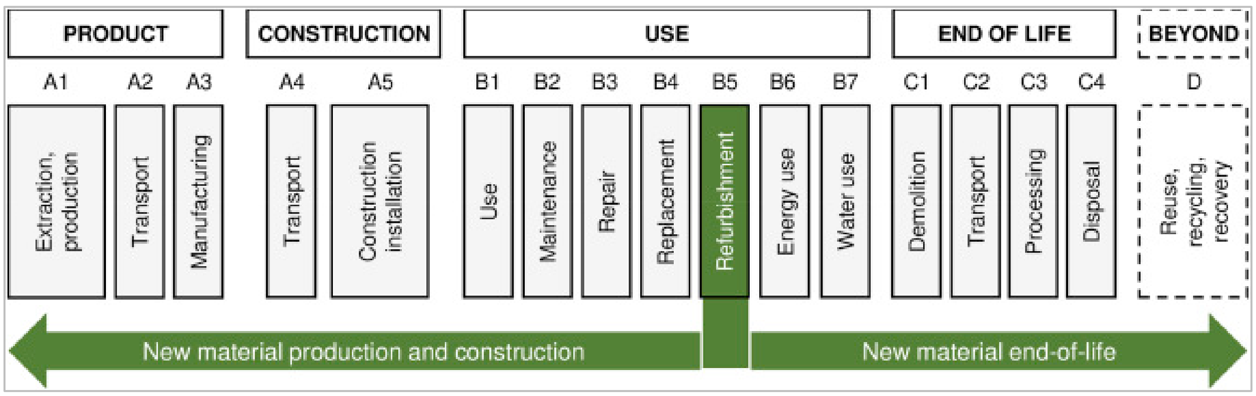



Figure 2-2. Building life-cycle stages and modules adapted in the analysis are A1–A3 and D (EN 15978)

## 2.3 Background

Existing studies typically focus on only one or just a few buildings to examine how individual buildings and their site-specific characteristics would affect the magnitude of the embodied GHG emissions (in terms of carbon dioxide equivalents [$CO_2$eq], i.e., emissions arising from manufacturing and processing of building materials or their contribution to life-cycle GHG emissions (Simonen et al., 2017). Only a few studies have investigated a larger number of buildings that represent a given region, a city, or a nation (De Wolf et al., 2017). In an early research study, Reyna and Chester (2015) developed a framework for analyzing the construction and demolition of urban building stock, including both residential and non-residential, and for identifying the corresponding materials, embodied energy use, and GHG emissions changes over time. Their urban growth model estimated the turnover rates of Los Angeles' building stock based on prototypical buildings. The model used three representative time periods of growth to estimate embodied energy use and GHG emissions, capturing the start of urbanization in Los Angeles (approximately the year 1900) and continuing to 2014. One of the shortcomings of this study is that the analysis was based on only three materials (concrete, steel, and aluminum) due to scarce literature on the life-cycle assessment (LCA) of other building materials. Changes in transportation, fuel mixes, or other supply-chain factors over time were excluded as well.

Another study by De Wolf et al. (2016) identified the embodied GHG emissions and material quantities in building structures based on survey data from the construction of 200 existing building projects worldwide (extracted from proprietary BIM examples of existing projects or published results). The results showed a wide range of variability, as structural material quantities varied between 200 kilograms (kg)/$m^2$ and 1,800 kg/$m^2$ and total-building embodied $CO_2$eq between 150 and 600 kg $CO_2$eq/$m^2$. Röck et al. (2020) assessed the life-cycle GHG emissions of more than 650 buildings worldwide, including European Union (EU) countries and the United States. Their analysis was based on a systematic compilation of an existing whole-building LCA literature survey that provided high-level embodied versus operational carbon equivalent results. Major limitations of the article included having very little to no transparency on the building material compositions and the different scopes of the included building LCAs. The analysis revealed an important message in regards to an increase in relative and absolute contributions of embodied GHG emissions: The average share of embodied GHG emissions from buildings following current energy performance regulations was approximately 20%–25% of life-cycle GHG emissions. However, this figure escalates to 45%–50% for highly energy-efficient buildings and surpasses 90% in extreme cases, highlighting the "carbon spike" from building materials manufacturing (Röck et al., 2020). De Wolf et al. (2020) developed a database of structural material quantities in buildings globally and calculated embodied GHG emissions in structures based on projects obtained from industry or published literature results. Malabi Eberhardt et al. (2021) performed in-depth and transparent LCAs of four Danish buildings (a school, an office, a residential building, and a hospital) to identify where the largest embodied GHG emissions existed. Project-specific data, e.g., building information models (BIM) provided by the construction company, were used to determine the buildings' material quantities. These buildings were stated to be representative for the type of concrete structures in Denmark. The analysis highlighted the interconnectedness between the building components and materials as a determining factor for identifying feasible emission-reduction opportunities. Hence, the study provided building design and construction strategies that would be considered in optimising embodied carbon-intensive components and materials based on their different design- and location-specific contexts.

As our analysis of the available literature has concluded, only a handful of studies have investigated a larger number of buildings, and they focused only on a limited number of building characteristics. There is no multibuilding or large-scale building stock study from the United States. Therefore, there is a need for an insightful and practical approach to analyzing the building material stock at a national level to contribute to making better environmental decisions in the building sector.

To help fill this gap, we have developed a transparent and bottom-up method to compile a building stock inventory and associated structural and non-structural material compositions in the United States. The results provide estimates of material use, embodied energy, and embodied GHG emissions of the office building stock in the United States spanning construction over a 73-year period.

## 2.4 Methodology

Our approach is based on bill of materials (BOM) data and energy use and GHG emission factors for construction materials in order to come up with estimates of embodied energy and GHG emissions. Data on the number of office buildings and their structural systems is also needed.

### 2.4.1 Estimation of the Office Building Stock in the United States

There is no central database of all office buildings in the United States. The best we can do is estimate their number and floor space from surveys. The U.S. Department of Energy's Commercial Buildings Energy Consumption Survey (CBECS) microdata (EIA, 2021) have provided information about the location, floor space, number of floors, and year of construction for the office buildings in our study. The microdata file contains 6,436 records, 1,332 of which are characterized as office buildings. They represent commercial buildings from all 50 states and the District of Columbia. Each record corresponds to a single survey response. The sample represents an estimated 5.9 million buildings (with about 9 billion square meters [$m^2$]) in the United States, 970,000 (1.54 billion $m^2$) of which are office buildings (Figure 2-3). The floor area was scaled up to the national level using the multipliers provided for each office building type in the microdata.

As Table A-4 in Appendix A shows, the 1946–2018 period was a boom for office building construction in the United States: 807,400 were built; about 90% of the still surviving stock.

(In contrast, only 163,000 were built before 1946.) Fifty-six percent of all office buildings are 1 floor high, 28% have 2 floors, 11% have 3 floors, 4.5% have between 4 and 14 floors, and only 0.5% are tall (with 15 floors or more), thus almost all U.S. office buildings are low-rise, with just 1–3 floors. (The total floor space in such buildings constructed between 1946 and 2018 constitutes 57% of the total, as per Figure A-1 in Appendix A.) This means they occupy a lot of land, and if they reach functional obsolescence (when they are no longer needed as office space), they are prime candidates for conversion and repurposing (adaptive reuse) into multifamily residential buildings because most people would likely not mind living in low-rise buildings.

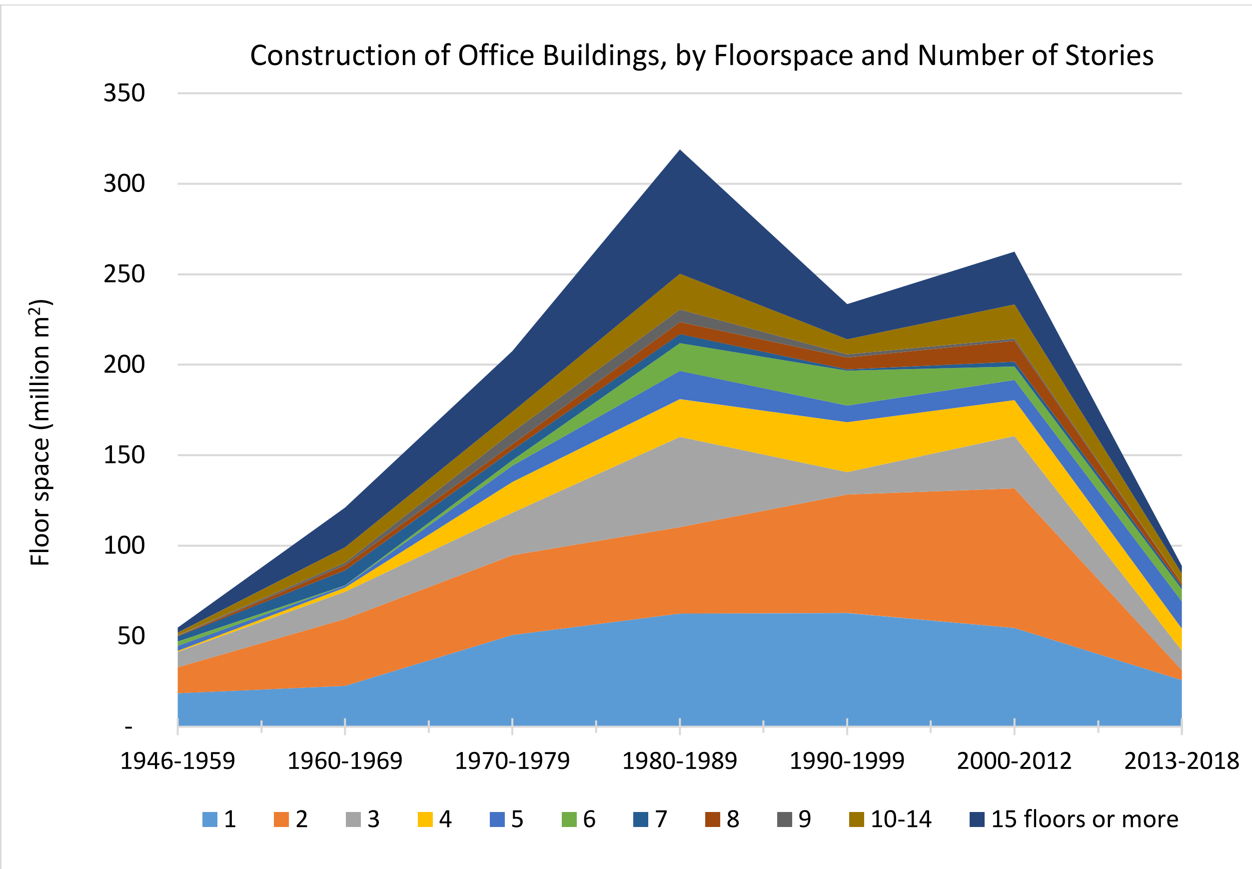



Figure 2-3. U.S. office building construction statistics, based on (EIA, 2021).

### 2.4.2 Estimation of Bill of Materials for Office Buildings

In contrast to the De Wolf et al. (2016) study that extracted structural material quantities from proprietary BIM examples of existing projects (which are publicly unverifiable) or published results or other studies that focused on a single building, to characterize the U.S. office building stock, we used *prototypical office building designs* in our study based on designs and BOM data obtained from the RSMeans database (Gordian, 2021). It is a U.S. industry-standard, pay-per-use building information database that provides cost information on material and construction activities, but also, very helpfully, BOMs for prototypical building designs of many sizes and uses, including residential, commercial, and industrial. The data are representative of how buildings are built across the United States and are updated yearly, thus they represent actual building designs with allowance for differences in insulation between U.S. climatic zones and differences in the structural system (steel, reinforced concrete, structural wood). Façade type, interior wall systems, and finishes can be modified by the database's user. The data are representative for 2021 in the latest edition.

Interior furnishings (equipment, fixtures, furniture) are outside the scope of the analysis since these portable components are traditionally not part of the analysis of embodied energy and emissions.

The study's scope includes manufacturing of materials and building components (including any recycled content) for the initial construction stage. The end-of-life stage analysis is focused on concrete's carbon uptake after demolishing the building. (Reuse of office-building materials and components is not practiced in the United States.)

To characterize the U.S. office building stock, we identified eight types of prototype office building designs, with variations of structural frame options (reinforced concrete, steel, and wood) and façade systems spanning small (1–2 floor), medium (3–4 and 5–10 floor), and large (10 or more floor) buildings (Gordian, 2021) (Table 2-1).

The BOM for the eight building types were then converted into material quantities in units of weight and/or volume used in building assemblies and components. The quantification of materials required a number of assumptions, especially when calculating the amount of concrete, steel reinforcement, and steel and wood members in major structural components, which constitute about 55%–65% of the total weight of these buildings. Other building components that needed substantial assumptions were related to quantification of exterior and interior wall systems, studs, and the water/wastewater pipes located throughout the buildings. Detailed calculations and assumptions can be referenced in Table A-3 of Appendix A. Furthermore, the conversion step was crucial for coupling units of material quantities with functional units defined in environmental product declarations (EPDs) and for the purpose of comparing our results to other building LCA studies in a transparent fashion. The major building materials and components/subcomponents covered are included in Table 2-2.

Table 2-1. Prototype office buildings focused on in the study. Data based on (Gordian, 2021).

| ***Building Type*** | ***Floor Count*** | ***Floor Height, ft (m)*** | ***Floor Area, $ft^2$ ($m^2$)*** |
|---|---|---|---|
| Office, 1 floor with Exterior Insulation and Finish Systems (E.I.F.S) (Cement board); Steel frame | 1 | 12 (3.65) | 7,000 (650) |
| Office, 5-10 floors, with E.I.F.S.; Steel frame | 5 | 12 (3.65) | 50,000 (4,600) |
| Office, 11-20 floors with E.I.F.S.; Steel frame | 16 | 12 (3.65) | 400,000 (37,160) |
| | | | |
| Office, 1 floor with glazing facade; Wood frame | 1 | 12 (3.65) | 7,000 (650) |
| Office, 2–4 floors with glazing facade; Wood frame | 4 | 12 (3.65) | 50,000 (4,600) |
| | | | |
| Office, 1 floor with stucco façade; Reinforced concrete frame | 1 | 12 (3.65) | 7,000 (650) |
| Office, 5–10 floors with metal panel façade; Reinforced concrete frame | 5 | 12 (3.65) | 50,000 (4,600) |
| Office, 11–20 floors with metal panel façade; Reinforced concrete frame | 16 | 12 (3.65) | 400,000 (37,161) |

Table 2-2. Major building materials and components/subcomponents considered in the study.

| | |
|---|---|
| Substructure (foundation + slab on grade) | Concrete, rebar, and structural steel used in construction of:<br>• Footings<br>• Slab-on-grade<br>• Foundation walls<br>• Piles and grade beams (only for tall buildings) |
| Structural Frame (reinforced concrete – steel – wood) | • Concrete<br>• Rebar<br>• Structural steel<br>• Structural wood<br>• Fiber for fireproofing in steel structures only |
| Exterior Façade | • Exterior wall materials (vary, e.g., metal panels, stucco, cement board, glass wall panels, or concrete masonry unit [CMU] blocks) |

| | |
|---|---|
| | • Insulation materials (vary)<br>• Windows (aluminum, glass) and door (aluminum, steel, and/or glass) on the façade<br>• Roof coverings (asphalt shingles, aluminum, plywood sheathing)<br>• Roof insulation (vary) |
| Interiors Partitions | • Partition wall systems (gypsum board, CMU)<br>• Studs (wood or steel)<br>• Interior doors (aluminum, glass, wood, or steel) |
| Staircase | • Galvanized steel |
| Interior Finishes | • Wall finishes (wall paint, ceramic tiles)<br>• Floor finishes (carpet, vinyl tiles, ceramic tiles)<br>• Ceiling finishes (gypsum board, fiberglass for insulation) |
| Service Assemblies | • Elevator<br>• Air handling, cooling, heating, ventilation systems<br>• Water heater<br>• Roof drainage pipes<br>• Piping for water supply and sewage<br>• Miscellaneous |

There is no publicly available dataset at the national level that would enable the calculation of embodied energy and GHG emissions from the construction of the office building stock. One of the key pieces of missing information is the distribution of office buildings by their structural frame type, necessary in estimating embodied impacts. Therefore, in addition to the use of CBECS microdata, we had to make assumptions based on professional judgment to capture the variation in structural systems:

- Large office buildings are composed of 50% high-rise (10 or more floors) and 50% midrise
  (5–9 floors) buildings by floor space.
- Large office buildings are 50% reinforced concrete and 50% steel frame by floor space.
- Small office buildings are low-rise (1–4 floors) and constitute the following:
  - Scenario 1: 50% wood and 50% steel frame by floor space (the case for California buildings, where concrete structures are rare due to seismic codes).
  - Scenario 2: 33% reinforced concrete, 33% steel, and 33% wood frame by floor space.
  - Scenario 3: 40% reinforced concrete, 40% steel, and 20% wood frame by floor space.

Table 2-3 presents the distribution of office buildings with respect to their floor space, number of floors, and type of structural frame for the three scenarios.

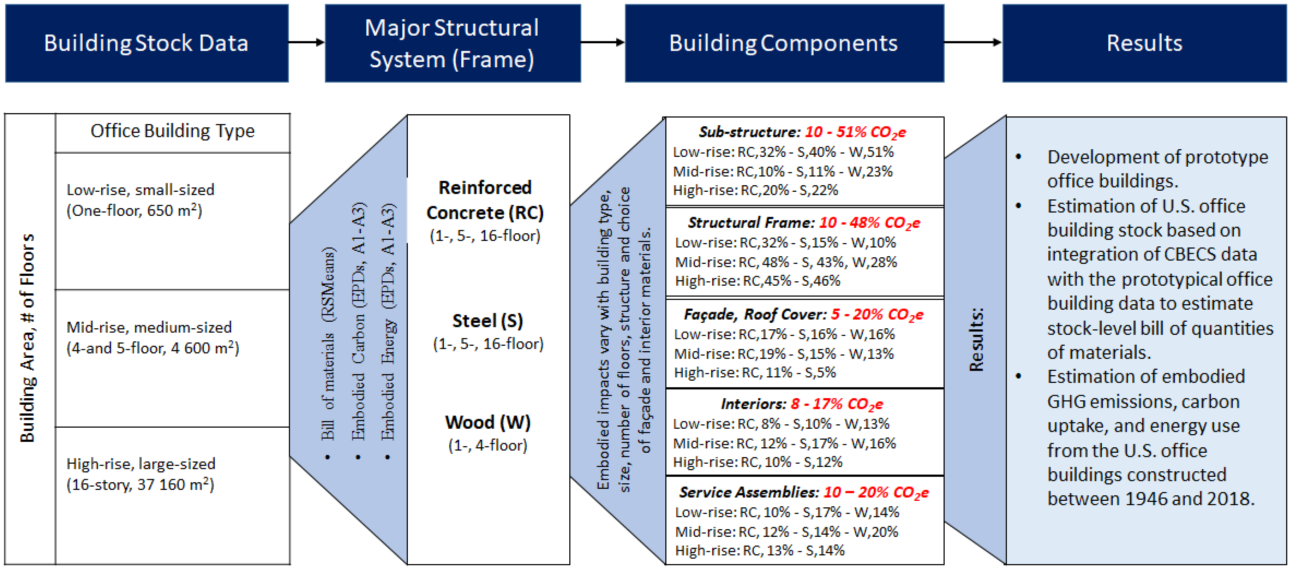
Table 2-3. Distribution of office buildings by floor space (million $m^2$), estimated on the basis of CBECS microdata and aforementioned assumptions. Note that 5+ floor buildings are assumed to be 50% reinforced concrete (RC) and 50% steel for all three scenarios, whereas percent distribution of structural frames for 1–4 floor buildings are 50% wood/50% steel; 33% RC/33% steel/33% wood; 40% RC/40% steel/20% wood by floor space for Scenarios 1, 2, and 3, respectively.

| | | **RC** (million $m^2$) | **Steel** (million $m^2$) | **Wood** (million $m^2$) |
|---|---|---|---|---|
| **1-4 floors** | Scenario 1 | | 419 | 419 |
| | Scenario 2 | 279 | 279 | 279 |
| | Scenario 3 | 335 | 335 | 168 |
| **5-9 floors** | Scenarios 1–3 | 98 | 98 | - |
| **10 or more floors** | Scenarios 1–3 | 126 | 126 | - |

### 2.4.3 Estimation of Embodied Energy and GHG Emissions

Publicly available, life-cycle assessment-based EPDs constitute the source of energy use and emission factors for embodied energy (in gigajoules, GJ) and GHG emissions (in $CO_2$eq) calculations based on the functional unit of the materials used in the construction of the office buildings. The selected EPDs are specific to U.S.-made building materials, are the newest available (completed in years between 2015 and 2021), and represent transparent and trackable sources of data for a consistent analysis that can be easily verified since they are publicly available. Details about the material and building component definitions and the EPD-derived data are available in Appendix A, Table A-3.

Having summarized the methodological steps above, Figure 2-4 depicts the overview of our methodological approach and calculated GHG emissions by building component.




Note: The office building stock was represented by eight prototypical buildings with variations in structural frame options (reinforced concrete [RC], steel [S], and wood [W]), number of floors, floor area, façade system, and interior components. Material quantities were taken from bill of materials on the basis of estimations from the RS Means building information database. The embodied energy and GHG ($CO_2$eq) emission factors from EPDs were assigned to the materials used in the construction of the eight prototype buildings. Calculated GHG emissions by percent by component type for eight prototypical buildings are shown under "Building Components" tab. Coupling CBECS microdata with prototype office building data, stock-level material quantities, and associated embodied energy and GHG emissions for office buildings constructed between 1946 and 2018 were estimated.

Figure 2-4. Methodological approach and percent $CO_2$ equivalent estimates from the prototypical building conceptualization and formation analysis.

## 2.5 Embodied GHG Emission Analysis of U.S. Office Buildings Constructed after the Mid-1940s

We calculated the embodied energy and GHG emissions of office buildings constructed in the United States between 1946 and 2018 based on the available CBECS datasets and representative office building types described in the methodology section. Section 5 in Appendix A provides data on the weight of materials used in construction of representative buildings and the associated embodied energy and GHG emissions (figures A-2 through A-4). As we lacked more detailed data, we had to assume that the designs for the different prototypical buildings stay constant in the time period.

### 2.5.1 Embodied Materials, Energy, and Emissions of Office Building Stock

About 30% of the current building stock by floor space was constructed before 1970, 50% between 1970 and 1999, and 20% after 2000. Embodied GHG emissions from office buildings constructed before 1970 are 33% of total GHGs, while 48% and 19% are from buildings constructed between 1970 and 1999, and after 2000, respectively (Figure 2-5). Among the three scenarios (Figure 2-5), Scenario 1 shows the smallest embodied GHG emissions distribution over time, attributed to the higher percentage of wood-framed construction in low-rise office buildings. Scenario 2 and Scenario 3 are estimated to generate 12%–16% and 16%–20% higher GHG emissions compared to Scenario 1, with increased share of reinforced concrete and steel structural frames.

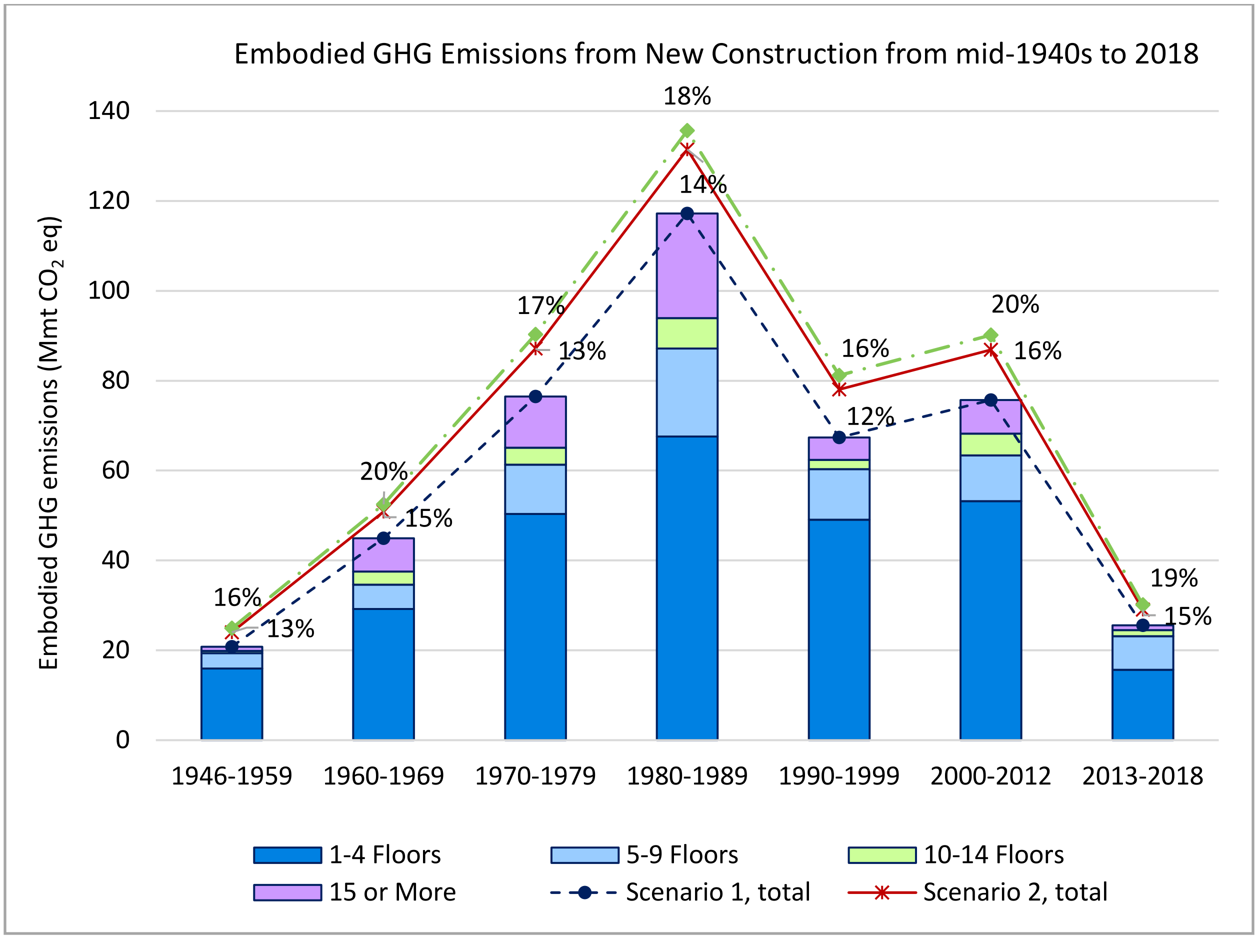



Figure 2-5. Embodied GHG emissions from construction of new office buildings from 1946 to 2018. Percentages next to red solid line and green dash line show deviation of Scenario 2 and Scenario 3 from Scenario 1, respectively. (Refer to Table 2-3 for description of scenarios.) Mmt: million metric tons.

Historical changes in embodied energy of office buildings follow a similar trend to GHG emissions. We have estimated that 33%, 49% and 18 % of the embodied energy are from buildings constructed before the 1970s, between 1970 and 1999, and after 2000, respectively (Figure 2-6). Scenarios deviate less with embodied energy use (Figure 2-5 versus Figure 2-6). This can be explained with the higher variation of embodied $CO_2$-eq intensities of three major building materials (steel, concrete, and aluminum) compared to their energy intensities per unit weight.

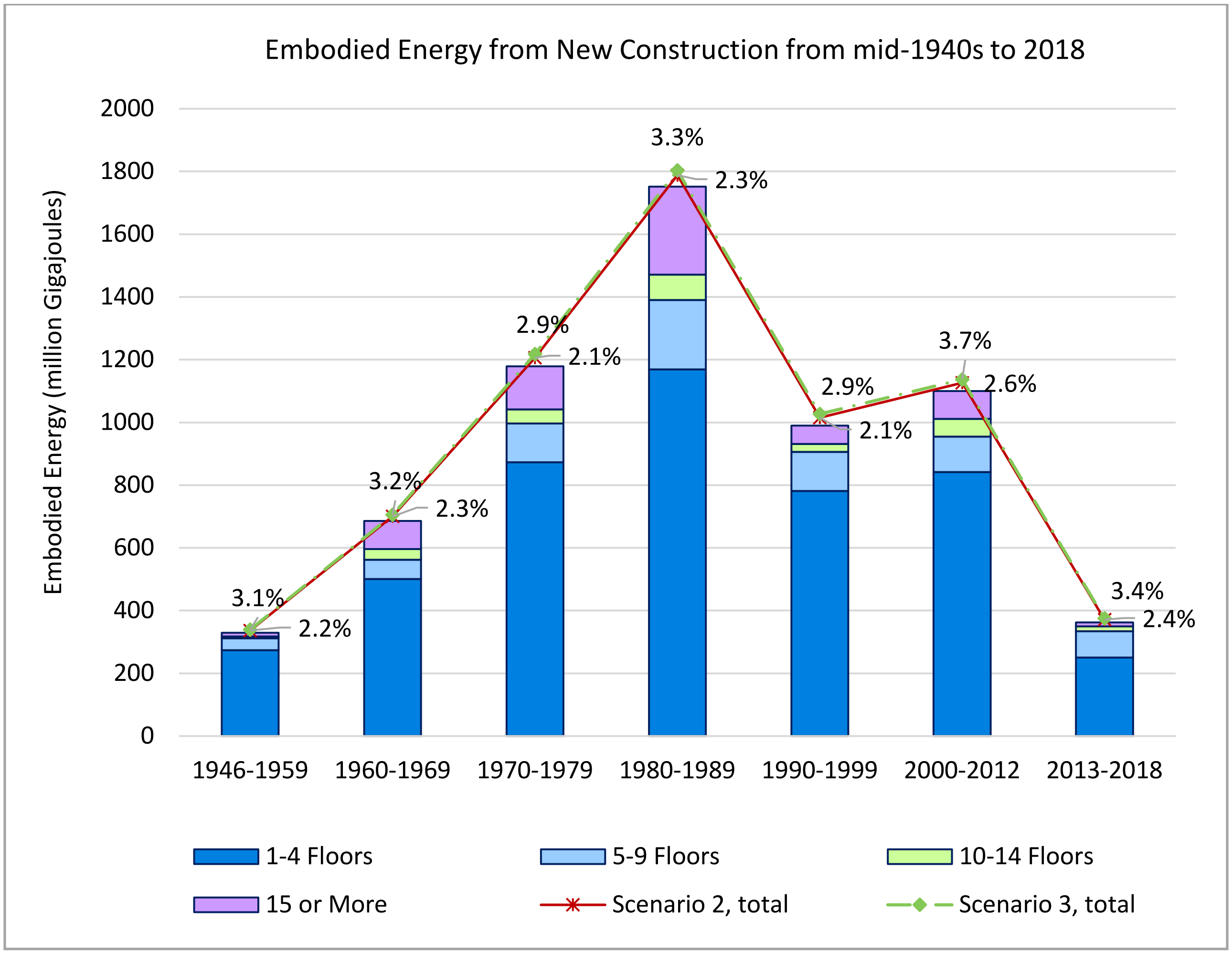



Figure 2-6. Embodied energy use of U.S. office building stock constructed from 1946 to 2018 (based on CBECS and EPD data).

Higher spikes in office building material uses have occurred in the 1980–1989 period in parallel with the growth in non-residential building demand (Appendix A, Figure A-7). Total building material weight has been dominated by concrete use. Over the 73-year period, concrete makes up about 75% of the total building material weight. Of the total weight of concrete, 22%, 36%, and 17% have been consumed during the periods before 1970, between 1970 and 1999, and after 2000, respectively, in all three scenarios (Appendix A, Figure A-5).

Steel, other building materials, and concrete, in decreasing order, are the major sources of embodied GHG emissions, with steel at 11%, 19%, and 9% (a total of 49%); other building materials at 10%, 18%, and 9%; and concrete at 6%, 11%, and 5% of total GHG emissions for the periods before the 1970s, between 1970 and 1999, and after 2000, respectively, for all three scenarios. Figure 2-7 represents the embodied GHG emissions from the materials used in construction of new office buildings over time for Scenario 3. (Refer to Appendix A, Figure A-6 for results from Scenarios 1 and 2.)

Similarly, steel, other building materials, and concrete are responsible for the largest portion of embodied energy, with steel at 12%, 22%, and 10%; other building materials at 10%, 19%, and 9%; and concrete at 4%, 7%, and 3% for the periods before the 1970s, between 1970 and 1999, and after 2000, respectively, for all three scenarios. (Refer to Appendix A, Figure A-7 for all three scenarios.)

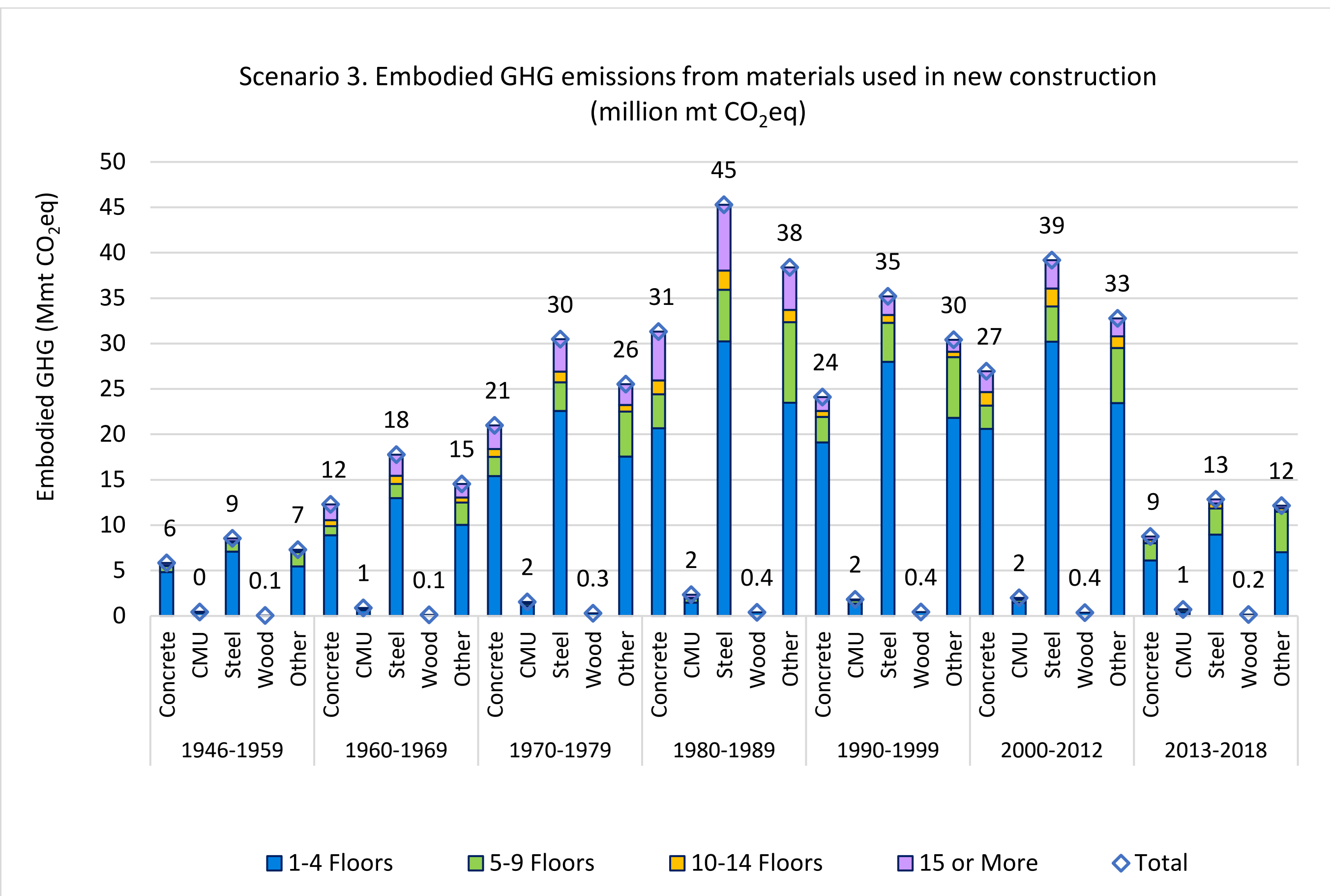


Figure 2-7. Embodied GHG emissions from major building materials used in construction of office buildings over time (Scenario 3).

### 2.5.2 Obsolescence of Buildings and End-of-Life Implications

Physical and functional obsolescence and subsequent demolition of the building stock are inevitable. The construction of new office buildings peaked in the 1980–1989 period and the growth has slowed since (Figure 2-3). Assuming that office buildings reach obsolescence after about 50 years of service life, a large number of buildings constructed before the 1980s will likely be demolished by 2030, indicating an increase in annual construction debris. Replacing them will have significant implications pertaining to demolition waste, end-of-life (EOL) options, and demand for new building materials and components.

Based on the U.S. Environmental Protection Agency’s data, 544 million metric tons (Mmt) of construction and demolition (C&D) debris were generated in 2018 in the United States. This is more than twice the amount of generated municipal solid waste: 265 Mmt (USEPA, 2020a). C&D debris consists of waste generated during construction, renovation, and demolition of buildings, roads, bridges, and other structures. About one third of C&D in 2018, 171 Mmt, was from buildings (Figure 2-8). Concrete made up the largest portion of C&D waste at 68% (367 Mmt) and 59% (92.5 Mmt) of total and buildings-related C&D, respectively, in 2018 (Appendix A, Figure A-8 and Figure A-10). More than 90% of the U.S. C&D waste was from demolition, while the share of waste from construction activities was less than 10% (Appendix A, figures A-9 through A-11). Concrete waste grew consistently between 2013 and 2018, adding about 412 Mmt to the buildings-related C&D waste stream in the period (USEPA, 2020b) (Figure 2-8).

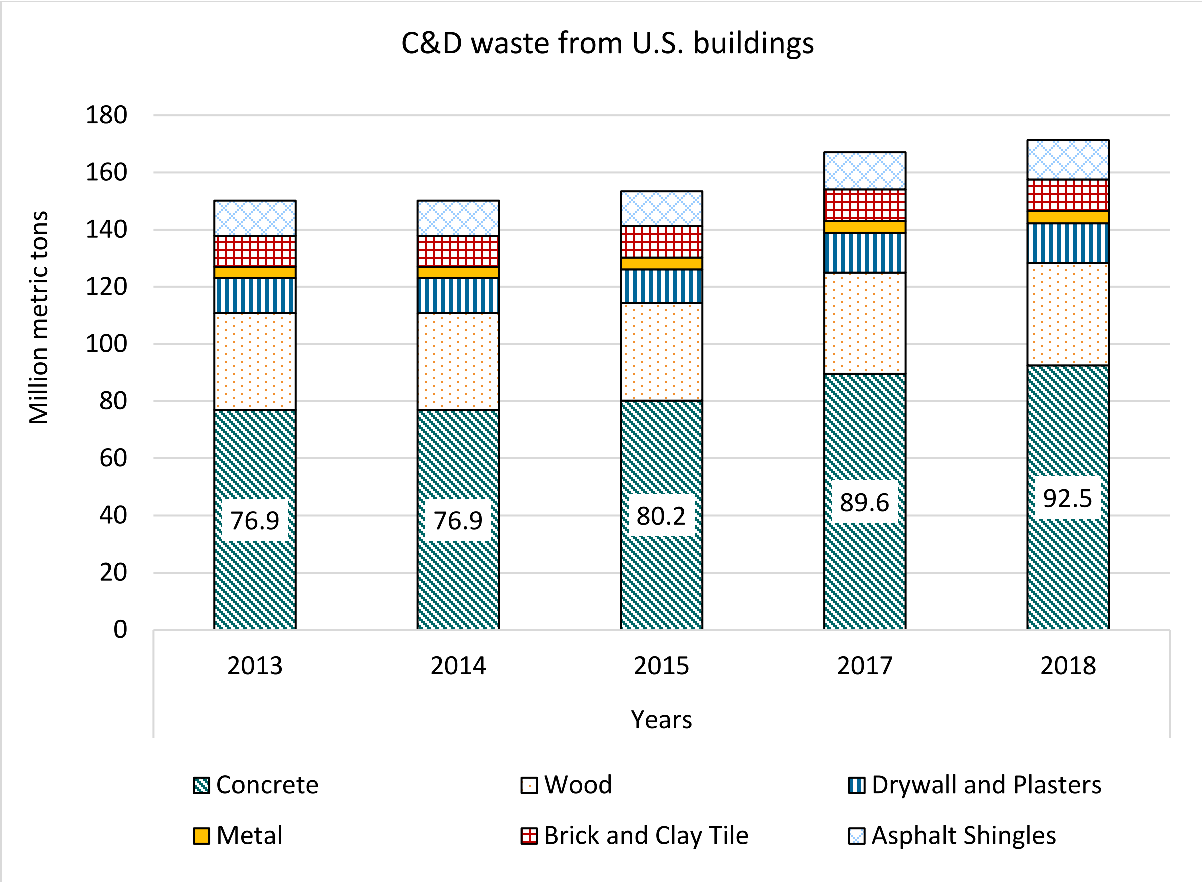



Figure 2-8. Composition of C&D waste from U.S. buildings from 2013 to 2018 (estimated based on USEPA [2020b]). Note that data for 2016 were not available.

While steel is mainly recycled, and wood can be used as a source of fuel following the demolition of buildings, waste concrete uses are more limited. It is typically disposed of in a landfill, sometimes used as a landfill daily cover, recycled into aggregates in new concrete-mix applications, or used as a non-structural fill. Assuming that the office buildings constructed before 1980 were all demolished (Figure 2-9), concrete waste from demolition would amount to 245 Mmt for Scenario 1, 291 Mmt for Scenario 2, and 309 Mmt for Scenario 3, respectively. These estimates are in and of themselves reasonably close to EPA's concrete C&D data for the 2013–2018 period, without accounting for other sources of concrete waste, such as from industrial and residential buildings and roads.

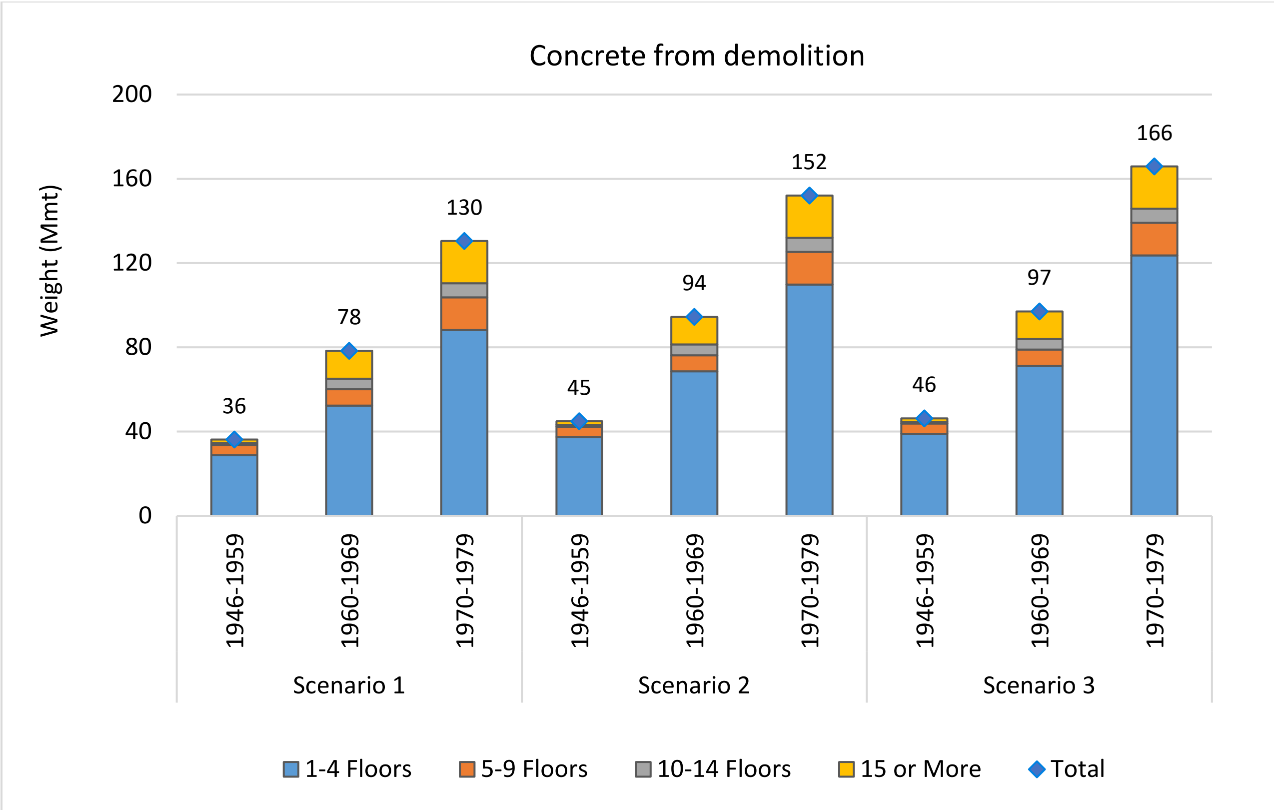



Figure 2-9. Estimated amount of concrete from the demolition of buildings prior to 1980.

The recycling of concrete waste can be considered comparable to crushed-stone aggregate production, and it is reasonable to assume that the energy demand is similar for both processes. When compared to the extraction of natural river aggregate, results from Marinković et al. (2010) show that the impacts of the aggregate and cement production phases are slightly larger for recycled aggregate concrete than for natural aggregate concrete, but the total environmental impacts depend on the transport distances of the natural and recycled aggregates and on transportation modes. Demolished concrete after the end of life of buildings is assumed to be disposed in a landfill or a laydown area, enabling carbon uptake over time.

### 2.5.3 Discussion of Uncertainties

In our approach, data sources can be easily accessed by researchers, engineers, and decision-makers. However, uncertainties are inevitable and should be considered when evaluating the results. Here are the uncertainties we have identified:

1. Results could change if bills of materials were obtained from construction documents of a large number of actual buildings instead of prototype buildings obtained from the RSMeans database.
2. The RSMeans database's BOM units were converted to material weight units for the purpose of coupling them with declared units defined in EPDs. Such conversions required the use of a unit weight factors (e.g., weight/surface area, weight/volume, weight/piece, weight/length) as described in EPDs and/or product description labels.
3. The BOM was then converted into material quantities in units of weight and/or volume used in building assemblies and components. The quantification of materials required a significant number of assumptions, especially when calculating the amount of concrete, steel reinforcement, and steel and wood members in major structural components. Similarly, we estimated the configuration of studs in wall assemblies, the roof geometry, configuration, and materials, as well as a grid system for water and sewage pipes in the building.
4. Due to the long lifetime of buildings, estimating the changes and patterns in the use and maintenance of building components and materials would be a source of uncertainty.
5. When EPDs for certain components and materials were missing, we used life-cycle inventories (LCIs) from literature and various sources. The quality of LCI data can affect the accuracy and local or regional representativeness of the results. Data availability during different stages of building life cycles may hinder the performance of a full LCA. This is because buildings are more complicated than a single product; they have comparatively long life and multiple functions and would often undergo various changes (Chau et al., 2015).

The case buildings that form the basis for this chapter are representative of the type of concrete, steel, and wood structures found in office buildings in the United States. The interior walls and finishes and the façade systems are also typical and representative. The identified uncertainties are not significant for the purposes of our analysis, especially if the resulting numbers are interpreted on the basis of one to two significant digits. Therefore, we conclude that the methodology and the parameters and numerical values used in this research are useful for the analysis of low-rise, mid-rise, and high-rise RC-, steel-, and wood-framed office buildings in the United States with variations of façade and interior wall systems. The results provide an acceptable basis for information about the building stock and any decisions one might want to make.

## 2.6 Discussion

We quantified embodied energy and GHG emissions associated with U.S. office buildings constructed between 1946 and 2018. Based on the CBECS microdata, 807,400 office buildings were built during this period.

These buildings, plus the ones erected before 1946, add up to 970,000 office buildings currently in use, which represent 16% of U.S. commercial buildings (5.9 million) and 0.87% of all U.S. buildings (111 million; Potter [2020]). However, about 6.4 billion GJ of primary energy use (Figure 2-6, Scenario 1), 6.2% of the U.S.'s 2021 consumption (102.7 billion GJ; EIA (2022), and 430 million metric tons of $CO_2$eq emissions (Figure 2-5, Scenario 1), 8.2% of the U.S.'s 2020 total (5,222 million; U.S. EPA [2022]), are estimated to be embodied in them.

The key materials that drive the embodied numbers are concrete and steel. About 76% of construction material use by mass in the 1946–2018 period was due to concrete. About 22%, 37%, and 17% of the total mass of concrete was utilized during the periods before the 1970s, between 1970 and 1999, and after 2000, respectively. Thus, most of the concrete used in the studied period is in buildings that are now 22 to 52 years old and will be coming up to be demolished soon.

In the 73-year period, steel contributed to 15% of material use. Steel is used in structural systems in the form of structural steel shapes and reinforcing in concrete, in wall systems mainly as studs, and in metal staircases and doors. Its use by weight corresponds to 4%, 7%, and 3% of the total amount of steel over the above-stated three time intervals, respectively.

Steel contributed 44% to the total embodied energy since the mid-1940s (12%, 22%, and 10% of total embodied energy from steel for the periods before the 1970s, between 1970 and 1999, and after 2000, respectively), while concrete's allocation was 14% (4%, 7%, and 3% of total energy from concrete through the respective time periods).

Steel has been the largest source of embodied GHG emissions in the 1946–2018 period, with 39% of the total (11%, 19%, and 9% of the total GHGs from steel for the periods before the 1970s, between 1970 and 1999, and after 2000, respectively). Concrete's contribution was 22% (6%, 11%, and 5%) of the total GHG from concrete through the respective time periods.

Reinforced concrete-structured office buildings took 1,800–3,700 megajoules (MJ)/$m^2$, steel buildings 1,800–2,600 MJ/$m^2$, and wood buildings about 2,800 MJ/$m^2$ to construct (depending on the number of floors and structural and façade configurations; see Table A-5 in Appendix A for details) when accounting for structural materials. Non-structural materials added another 940–2,200 MJ/$m^2$ for RC, 900–2,000 MJ/$m^2$ for steel, and 1,100–1,700 MJ/$m^2$ for wood buildings. Therefore, they were found to be significant contributors to the total embodied energy of office buildings: 32%–55% for RC (i.e., for five-floor buildings, they were about as significant as structural materials), 31%–44% for steel, and 28%–37% for wood buildings. One-floor steel and wood buildings were about equally energy intensive to construct from structural as well as combined structural and non-structural materials perspectives, while RC buildings were about 20% and 30%–40% more energy intensive, respectively. From the all-materials-use perspective, five-floor RC and wood buildings were 10%–15% more energy intensive to construct than steel buildings. Sixteen-floor RC and steel buildings needed about the same amount of embodied energy.

Increasing returns to scale (scale economies) can be observed for RC buildings as the number of floors increases: 5- and 16-floor buildings took half of the embodied energy to construct per square meter than 1-floor buildings took for structural materials. (There was no significant difference between 5- and 16-floor RC buildings.) Sixteen-floor RC buildings took half of the energy to construct compared to the non-structural materials needs of 1- and 5-floor buildings. Economies of scale were less dramatic for steel buildings: a 25%–30% reduction in structural materials was observed between 16-floor and 1- or 5-floor buildings, but a 50% reduction for non-structural materials was observed. There were no 16-floor wood buildings, and while there were no significant economies of scale between 1- and 5-floor buildings for structural materials, there was a 40% reduction in energy use for non-structural materials as the building got larger. From the perspective of combined structural and non-structural materials use per square meter, 16-floor RC buildings needed just 66% and 50% of the embodied energy of 5-floor and 1-floor buildings, respectively. The same numbers for steel buildings were 84% and 63%. Five-floor wood buildings needed 87% of the embodied energy of 1-floor buildings to erect.

The embodied GHG emissions due to structural materials were found to be 180–350, 150–210, and 94–220 kg $CO_2eq/m^2$ for reinforced concrete, steel-, and wood-structured buildings, respectively (depending on the number of floors and structural and façade configurations; see Table A-5 in Appendix A). For non-structural materials, the respective numbers were 91–290, 79–190, and 89–120 kg $CO_2eq/m^2$ for RC, steel, and wood buildings, respectively. In a similar pattern to embodied energy, non-structural materials were found to be significant contributors to the total embodied GHG of office buildings; in some cases as significant or even more so than structural materials: 31%–61% for RC, 32%–47% for steel, and 35%–49% for wood buildings. One-floor steel and wood buildings are about equally GHG intensive to construct from a structural perspective, as well as a combined structural and non-structural materials perspective, while RC buildings are about 50% and 27%–47% more GHG intensive, respectively.

From the all-materials-use perspective, five-floor steel buildings are 54% more GHG intensive to construct than wood buildings, and in turn RC buildings are 68% more GHG intensive than steel buildings (i.e., wood buildings are responsible for only 39% of the embodied GHG of RC buildings). Sixteen-floor RC and steel buildings need about the same amount of embodied GHG.

Again, economies of scale can be observed as the number of floors increases. Five- and 16-floor RC buildings took half of the embodied GHG to construct per square meter than 1-floor buildings for structural materials. (There is no significant difference between 5- and 16-floor RC buildings.) Sixteen-floor RC buildings took about one-half of the embodied GHGs to construct compared to the non-structural materials needs of 1- and 5-floor buildings. Economies of scale were less dramatic for steel buildings: a 20%–25% reduction was observed between 5- and 16-floor buildings compared to 1-floor buildings for structural materials, but a 50% reduction for non-structural materials between 16-floor and 1-floor buildings was observed. There are no 16-floor wood buildings. While 5-floor wood buildings took only about one-half of the embodied GHGs to construct due to structural materials, there was no significant reduction due to non-structural materials as the building got larger. From the perspective of combined structural and non-structural materials use per square meter, 16-floor RC buildings needed just about half of the embodied GHG emissions of 5-floor and 1-floor buildings. Five-floor and 16-floor steel buildings needed about 60% of the GHG emissions of 1-floor buildings to erect. Five-floor wood buildings needed half of the embodied GHGs of 1-floor buildings to erect.

How do our results compare to previous studies? Reyna and Chester (2015) analyzed embodied energy and $CO_2$eq emissions from concrete, steel, and aluminum for low-rise and high-rise office buildings. For the low-rise buildings, embodied energy was between 6,690 and 10,450 MJ/$m^2$ and embodied GHG emissions were in the range of 285–447 kg $CO_2$eq/$m^2$. High-rises resulted in lower embodied energy (570–870 MJ/$m^2$) and GHG emissions (110–170 kg $CO_2$eq/$m^2$). Our embodied energy results for low-rise buildings (3,500–5,400 MJ/$m^2$, including more materials) were by one-half lower, but about the same for embodied GHG emissions (280–500 kg $CO_2$eq/$m^2$). For high-rise buildings, our embodied energy results (about 2,800 MJ/$m^2$, including more materials) were three to four times higher and embodied GHG emissions (about 250 kg $CO_2$eq/$m^2$) were about twice higher. We are not sure where the differences came from, but the Reyna and Chester study had to contend with scarce building materials LCA data availability when it was written eight years ago, while we were able to use EPDs (which have proliferated in the meantime) specific to the United States.

De Wolf et al. (2016) estimated embodied $CO_2$eq emissions for structural materials (concrete and steel) used in 200 different commercial buildings. Of these buildings, office buildings resulted in 130–340 kg $CO_2$eq/$m^2$, which are similar to our embodied GHG numbers for structural materials (79–288 kg $CO_2$eq/$m^2$). In the Simonen et al. (2017) study, embodied GHG emissions varied between 200 and 500 kg $CO_2$eq/$m^2$ for the few office buildings analyzed. These numbers are about twice the magnitude of our numbers. The office building analyzed by Malabi Eberhardt et al. (2021) resulted in 250 kg $CO_2$eq/$m^2$ of total embodied GHG, which is in our range. Except for Reyna and Chester (2015), none of these studies provided the embodied energy in their results. We estimated the embodied energy and the embodied GHG emissions from both structural and non-structural components, as well as materials (see in Table A-3 of Appendix A).

The results lead us to conclude that we must consider structural frame type, building height, floor area, technologies used in production of major building materials, selection of non-structural materials, and frequency of maintenance, as well as service life and EOL strategies, in estimation of embodied energy and GHG emissions of buildings.

# 3 Assessing the Potential Energy and Environmental Benefits from Repurposing Office Buildings into Apartments

## 3.1 Highlights

- The need to build more homes in urban areas is urgent.
- Repurposing has been proposed as a strategy to address housing shortages.
- Embodied energy, greenhouse gas (GHG) emissions, and waste avoided by repurposing prototypical office buildings into apartment buildings have been quantified.
- Repurposing existing 155,000 midsize U.S. office buildings into apartments would create about 6 million new apartments and avoid approximately 140–180 million metric tons of GHG emissions.

## 3.2 Abstract

Quantitative studies of the environmental benefits of repurposing (adaptively reusing) buildings are very rare. It is generally believed that the structure can be saved in repurposing, but much of the façade and interior materials are often replaced. Instead of individual, one-off case studies, we focused on two classes of buildings: (1) prototypical midsize, 4,600 square meter, five-story office buildings (of which there are about 155,000 in the United States alone, some in excess of market needs) and (2) same-size, prototypical apartment buildings in the United States. Using bills of materials and environmental product declarations (which are based on life-cycle assessment), we quantitatively analyzed the material use, embodied energy, and embodied greenhouse gas (GHG) emissions of two scenarios over a 50-year time frame: (1) demolition of an office building in year 0, followed by new construction and 50-year service life of a same-size apartment building, and (2) repurposing an office building into an apartment building with a service life of 50 years. Scenario 2 has two options: (2.a) keep both structure and façade systems and (2.b) keep only the structure and replace everything else. The key materials driving the embodied energy and emissions are concrete, steel, façade materials, carpet, and paint. We find that repurposing an existing midsize office building can create 45 apartments while avoiding 54%–74% of energy, 57%–76% of GHG emissions, and 76%–96% of generated waste when compared to constructing a new midsize apartment building.

## 3.3 Introduction

Buildings are responsible for large amounts of resource use, waste generation, and emissions. By the latest estimates (2020), buildings accounted for 36% of global energy demand, 37% of energy-related carbon dioxide ($CO_2$) emissions, 30% of raw materials consumption, and 40% of solid waste generation (Malabi Eberhardt et al., 2021). Of those total $CO_2$ emissions, building operations are responsible for 28%. Energy-related emissions from the manufacturing of construction materials accounted for about 10% of total global energy-related $CO_2$ emissions in 2020 (UNEP, 2021). Three major materials (concrete, steel, and aluminum), most of which are used in the built environment (Architecture 2030, 2022), account for 23% of total global GHG emissions. Thus, material, energy, and emissions savings from buildings should be a priority.

Unlike operational GHG emissions, which can be reduced with building energy efficiency investments and increased use of renewable energy, embodied GHG emissions (i.e., associated with materials) are locked in place as soon as a building is completed, also significantly determining future material and construction needs in the maintenance phase. As buildings become more energy efficient in operation through low-energy and net-zero efforts, the embodied energy will represent a larger portion of the total energy impact (Chastas et al., 2016). Röck et al. (2020) showed a reduction trend in life-cycle GHG emissions due to improved operational energy performance of more than 650 buildings (residential and commercial) around Europe, but their analysis also revealed an increase in both relative and absolute contributions of embodied GHG emissions. While the average percentage of embodied GHG emissions from buildings following current energy performance regulations was approximately 20%–25% of life-cycle GHG emissions, this figure escalated to 45%–50% for highly energy-efficient buildings and surpassed 90% in extreme cases, highlighting the "carbon spike," i.e., the jump in GHG emissions from the use of building materials at the time of construction (Röck et al., 2020).

Possible strategies to reduce the impacts from materials are to select materials with low embodied energy and emissions, reuse or recycle materials at the end of their useful lives, and extend the life of installed building materials, including repurposing (adaptively reusing, or rebuilding) buildings, to slow the flow of materials. Adaptive reuse is a key concept in achieving a circular economy (EN 15978; European Commission, 2020; Rahla et al., 2021) (see Figure B-1 in Appendix B).

The need to build more homes is urgent in urban areas, especially those that have been experiencing population growth, and repurposing has been proposed as a strategy to address housing shortages (National Association of Realtors, 2021). Repurposing and rebuilding commercial, government, and other buildings can provide a relatively speedy way to address the need for more residential housing. Moreover, with higher occupancy rates, the repurposed buildings can accommodate more persons without the need for additional new construction. But is repurposing environmentally preferable compared to the demolition–new construction cycle?

Systematic analyses of the environmental, economic, and social advantages of repurposing are rare (Wijesiri et al., 2021). The current implementations of adaptive reuse are based on descriptive approaches with little to no quantitative analysis, and often depend on the intuition and the experience of practitioners (Sanchez and Haas, 2018).

We found a small number of quantitative analyses of adaptive reuse at the whole-building level. Many of the prior studies focused on the environmental impact assessment of refurbishment versus demolition-and-reconstruction of particular building components, with specific attention to their thermal properties, such as building envelope, insulation materials, windows, lighting, and HVAC systems. Most of them studied environmental impacts from the refurbishment or retrofit of buildings and compared the results with the initially constructed building, not with a new equivalent building that did not have to be constructed (Pittau et al., 2020; Ardente et al., 2011; Sierra-Pérez et al., 2018; Assiego De Larriva et al., 2014; Ghose et al., 2017; Cetiner and Ceylan, 2013).

The first known study that applied a whole-building approach in adaptive reuse was the Australian Greenhouse Office's report, claiming that reuse of buildings had saved 95% of embodied energy that would otherwise be wasted as a result of building demolition (Kerr, 2004). Then came the Ferreira et al. (2015) study that compared the environmental impacts of refurbishment of a historical building (Palace of the Counts of Murça from the seventeenth century in Lisbon, Portugal) with a hypothetical new construction meeting the same requirements in terms of structural aspects, using a cradle-to-gate life-cycle assessment (LCA) approach. Their results showed that the refurbishment solution was environmentally more sustainable than a new equivalent construction. Estimated savings were 13% in global warming potential (GWP), 34% in acidification potential, 266% in eutrophication potential, 10% in primary energy, and 542% in generated waste. Later, Assefa and Ambler (2017) estimated savings of 33% and 34%, respectively, in GHG emissions and fossil fuel consumption as a result of rebuilding a high-rise university building in Western Canada rather than demolishing and replacing it.

More recently, a cradle-to-grave LCA by Marique and Rossi (2018) compared the GHG emissions and energy consumptions of office buildings in Belgium under renovation and reconstruction scenarios, and stated that renovating a building has lower life-cycle emissions than constructing a new building due to the high embodied emissions from construction and material manufacture. Overall, the impacts of the retrofit project only represented 55% of the rebuild project in terms of energy and 57% in terms of $CO_2$ emissions. An analysis by Sanchez et al. (2019) found a 35%–38% decrease in primary energy demand, GWP, and water consumption, and 70% savings in construction costs for the adaptive reuse (referring to renovation) of a courthouse building compared to a new courthouse construction in Ontario, Canada. Hasik et al. (2019) applied LCA to compare adaptive reuse of a historical beer bottling/warehouse facility into an equivalent-size office building in Philadelphia, U.S., and determined that reusing the existing facility helped to avoid 75% of GHG emissions compared to new construction. Finally, Feng et al. (2020) evaluated the life-cycle GHG emissions of six different renovation and reconstruction scenarios using a building information modeling (BIM)-LCA combined approach for single-family housing in Vancouver, Canada. The results showed that in the reconstruction scenarios, about 40% of the emissions were attributed to the material manufacturing stage. The embodied emissions generated from the reconstruction scenarios were five to six times higher than the renovation scenarios.

The limited available literature calls for additional studies that quantify the environmental implications of repurposing projects compared to new construction. Our research adopted office and apartment building designs that are typical in the United States and many parts of the world. We developed a bottom-up, time-resolved material flow analysis, associated with building components and materials used for construction and maintenance, of these buildings over their 50-year service lives. Based on the mass of materials and building components (substructure, structural frame, exterior façade, roof system, interior wall system, and service assemblies) we quantified the embodied energy and GHG emissions, as well as waste avoided by repurposing prototypical office buildings into apartment buildings.

To our knowledge, this is the first quantitative and systematic study to analyze the embodied energy and GHG emissions associated with repurposing of representative-design office buildings into apartment buildings in the United States.

## 3.4 Methods and Data

The number of office buildings in the United States, as of 2018, was 970,000 (EIA, 2021). They occupy 1.55 billion square meters ($m^2$), with about 15% of that floorspace being medium-sized, 5- to 10-story office buildings.

In 2019, it was estimated that 139 million housing units existed in the United States; 8% (~11 million) of which are multifamily apartment buildings (with four or more stories) that are comparable to medium-sized office buildings and occupy about 1.3 billion $m^2$ (6% of total housing floorspace) (U.S. Census, 2022). The vast majority of housing units are single-family detached houses.

In this study, we estimated embodied energy and GHG emissions associated with the materials needed to repurpose a prototypical office building into a prototypical apartment building with similar architectural (size, shape, height, floorspace, number of stories) and structural configurations. The selected buildings are five-story, 4,600 $m^2$ reinforced concrete-structured (RC) buildings with metal panel façade for the offices and stucco-on-concrete masonry unit (CMU) façade for the apartment buildings.

There are about 155,000 such midsize office buildings in the United States. As many companies increasingly allow employees to telework, it is expected that many office buildings will become increasingly empty. Converting one five-story, 4,600 $m^2$ office buildings can provide 45 housing units (80 $m^2$ per unit, 9 per floor), assuming 80% of the floorspace is dedicated to residential purposes. Repurposing all of them into apartments would create about 6 million new apartments. Assuming an average of two people per unit, repurposing could give 12 million people access to housing.

The bill of materials (BOM) data, which provides the quantities of building materials used in construction of both building types were sourced from the U.S. industry-standard, pay-per-use building information database, the RSMeans Data (Gordian, 2021), which provides both material and construction cost information, as well as BOMs for prototypical buildings of many sizes, designs, and uses, from residential to commercial. The data are representative of how buildings are built across the United States, thus they are actual building designs, with allowance for differences in insulation between climatic zones, and for differences in the structural system (steel, reinforced concrete, structural wood). Façade type, interior wall systems, and finishes can be modified by the tool's user. The data are representative for 2021 in the latest edition.

The BOMs for both buildings are categorized into the following building components:

- Substructure (foundation + slab on grade): Concrete, rebar, and structural steel used in construction of footings, slab-on-grade, foundation walls, and piles and grade beams
- Structural frame: Concrete, rebar, structural steel, structural wood, and fiber for fireproofing of steel structures
- Exterior façade: Exterior wall materials (several: metal panels, stucco, cement board, glass wall panels, CMU blocks), several different insulation materials, steel studs, windows (aluminum, glass) and doors (aluminum, steel, and/or glass) on the façade
- Roof coverings (asphalt shingles, aluminum, plywood sheathing), and insulation
- Interior partitions: Partition wall systems (gypsum board, CMU), studs (wood or steel), and interior doors (aluminum or steel)
- Staircase: Galvanized steel
- Interior finishes:
  - Wall finishes (wall paint, ceramic tiles)
  - Floor finishes (carpet, vinyl tiles, ceramic tiles)
  - Ceiling finishes (gypsum board, fiberglass for insulation)
- Service assemblies: Elevators, air conditioning units, water heater, roof drainage pipes, piping for water supply and sewage

BOMs from these two building types were used to quantitatively analyze material use, waste generation, embodied energy, and embodied GHG emissions of two scenarios over a 50-year time frame.

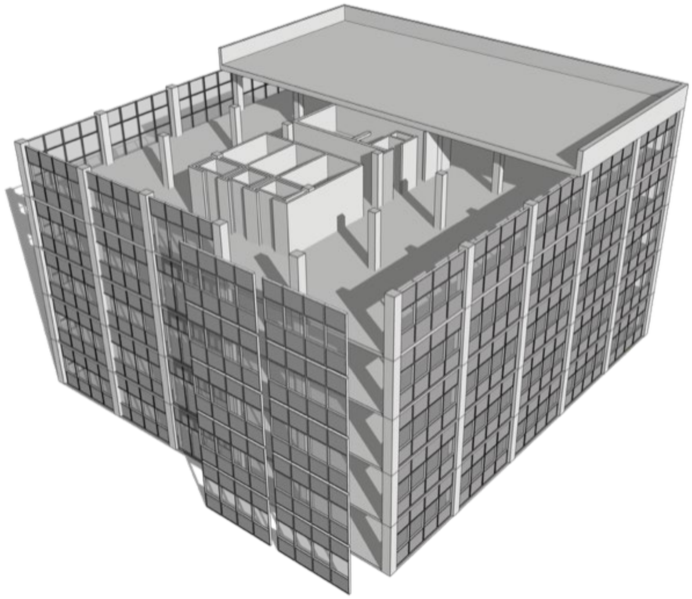
- *Scenario 1* analyzed demolition of an office building followed by new construction of a same-size apartment building.

- *Scenario 2* analyzed repurposing (rebuilding) of an office building into an apartment building in two subscenarios:
    - Scenario 2.a looked at keeping the structural components (foundation, beams, columns, and slabs), steel staircases, and the façade while replacing the rest of the building, i.e., the partition walls, and the interior finishes.
    - Scenario 2.b looked at keeping the structural components and steel staircases, and replacing the rest of the building, including the façade. We assume the energy efficiencies of both the apartment and the repurposed office building are the same in Scenario 2.a as a result of keeping the façade system. The ramification of façade removal in Scenario 2.b is the requirement for additional insulation for residential settings.

Figure 3-1 is a representation of the approach for the two scenarios, showing what is demolished versus replaced. Table B-1 in Appendix B provides further details about the material composition of the buildings and corresponding changes and substitutions that occur in both Scenario 1 and Scenario 2a and 2b.

| **Scenario 1. Demolish Office Building and Construct a New Apartment** | **Scenario 2.a. Repurpose Office into Apartment – Keep Structure and Façade** | **Scenario 2.b. Repurpose Office into Apartment – Keep Structure only** |
|---|---|---|
| Demolish office building and construct the apartment structure (same reinforced concrete design approach) | Keep the building structure | Keep the building structure |
| Construct the apartment façade:<br>• Three-coat stucco on self-furring metal lath and CMU for exterior wall system<br>• Additional door and window openings<br>• Same roof design | Keep the façade and roof system | Demolish and construct new façade:<br>• Replace with stucco on CMU for exterior wall system<br>• ***Keep studs***<br>• Additional door and window openings<br>• Same roof design |
| Construct the apartment interior wall system:<br>• Increased partition wall length<br>• Additional door openings<br>• Staircase, same design<br>Interior finishes – change in composition, quantity, and material type<br>Piping – additional length, same material<br>New service assemblies | Remove and replace with new interior wall system and finishes – composition, quantity and material type change<br>Keep staircase<br>Remove piping and replace with new piping – additional length, same material<br>Remove service assemblies and replace with new ones (same design) | Remove and replace with new interior wall system and finishes – composition, quantity and material type change<br>Keep staircase<br>Remove piping and replace with new piping – additional length, same material<br>Remove service assemblies and replace with new ones (same design) |

Bathrooms, cabinets and other interior furnishings are excluded in the analysis.



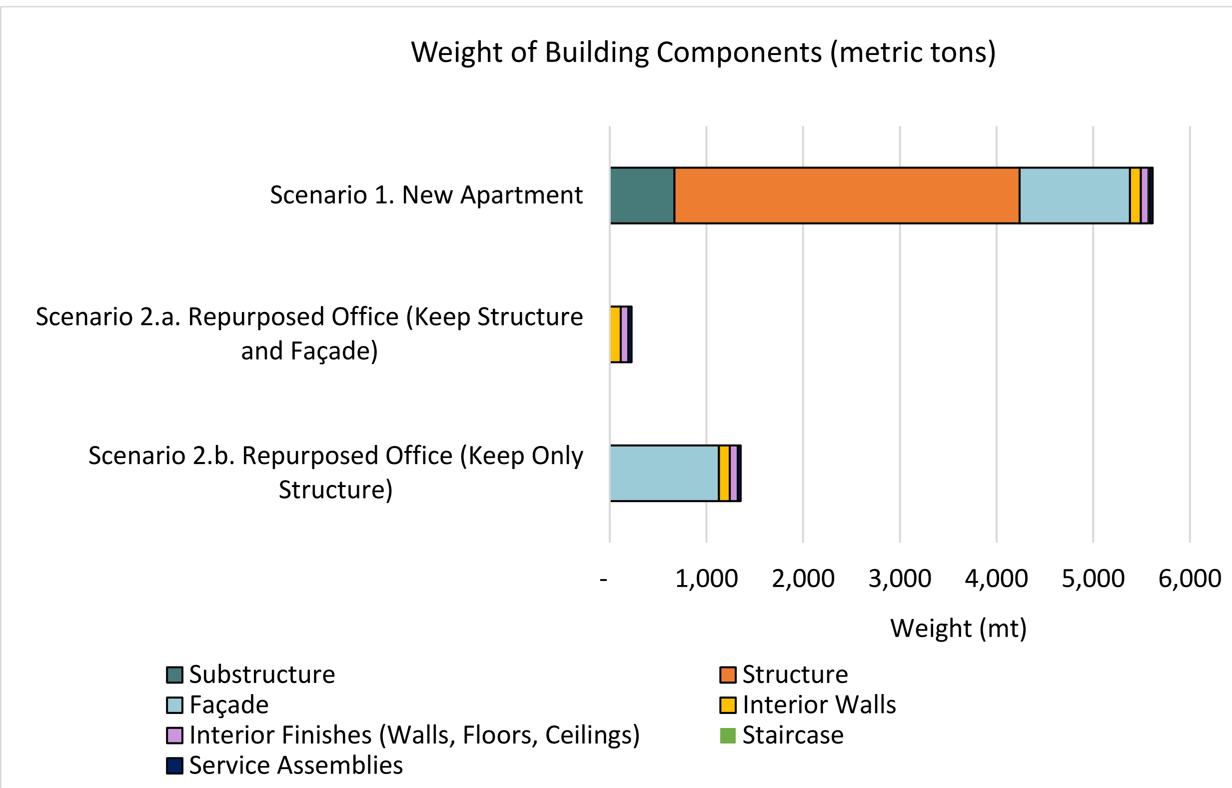
Notes: CMU stands for *concrete masonry unit*. Service assemblies include elevators, air conditioning units, water heater, roof drainage pipes, and piping for the water supply and sewage.

Figure 3-10. Schematic representation of a typical mid-rise reinforced concrete building and what is replaced in Scenario 1 (demolish the old building and construct the new one) and in Scenario 2 (repurpose the old building into an apartment, with options to (2.a) keep both structure and façade systems and (2.b) keep only the structure and replace everything else). Bathrooms, kitchens, and other interior furnishings are excluded because they are the same in both repurposed and newly constructed buildings.

Façade designs of the repurposed office-building-to-apartment building and the newly constructed apartment building are different from the office building's original façade design, according to the RS Means data. As already mentioned, the prototypical office building has a metal panel façade with large windows, which is rebuilt into a stucco-on-CMU façade with smaller windows for the apartment building (because the office building has a larger window area on the façade than the apartment building needs). Another notable difference between the apartment and the office building is the surface area of the partition walls, since apartments require more partitions to serve their purpose as residential spaces as opposed to open-space office configurations. Therefore, partition wall areas are about 6,360 $m^2$ (2,610 m in length) and 3,420 $m^2$ (1,400 m in length) in the apartment building and the office building, respectively. Both building types have the same thermal performance (and are assumed to be located in the Mediterranean climate of California), thus the wall insulation value is the same.

The use (maintenance and operation) phase is outside the scope of this analysis because the focus is on estimating the embodied energy and GHG emissions from repurposing of an existing building versus demolition and construction of a new apartment building. By definition, “Embodied carbon consists of all the GHG emissions associated with building construction, including those that arise from extracting, transporting, manufacturing, and installing building materials on site, as well as the end-of-life emissions associated with those materials” (McKinsey and Company, 2020). Interior furnishings are outside the scope too because these portable components are not embodied in the building.

The structural materials (concrete and steel together) make up 86% and 76% of the total mass of the office and the apartment buildings, respectively, and the façade materials make up 10% and 20% (Figure 3-2). The remaining 4% by mass consists of interior partition walls, ceiling/floor/wall finishes, and service assemblies.




Notes: Scenario 1: Demolition of an office building followed by new construction of an apartment building; Scenario 2: Repurposing an office building into an apartment building by keeping: (Scenario 2.a) Structural components and façade or (Scenario 2.b) Structural components only and replace everything else.

Figure 3-11. Contribution of building components to total weight of apartment and repurposed office buildings

Embodied energy and GHG emissions were estimated by coupling material quantities with their related energy use and carbon dioxide equivalent ($CO_2$eq) intensities obtained from environmental product declarations (EPDs) (Table B-2 in Appendix B). The latest EPDs, as specific to U.S. manufacturing and construction material use in our prototypical buildings as possible, were sought out. EPDs reflect the emissions, or emissions savings, associated with recycled content of the materials analyzed (e.g., steel reflects any recycled content embedded in the material itself as provided in the EPD). GHG emissions associated with the recycling of metals and some portion of concrete after demolition of the building in year 50 were not included in the analysis. This was because emissions, or potentially avoided emissions, associated with end-of-life management (including landfilling and recycling) are factored into the manufacturing of the new materials that will be used in the next new building.

## 3.5 Results

Earlier studies analyzed potential GHG emissions from repurposing of single building case studies in Canada and Europe (Sanchez et al., 2019; Assefa and Ambler, 2017; Ferreira et al., 2015; Marique and Rossi, 2018; Feng et al., 2020). This study used representative, specific, geographically consistent building materials data (RS Means data for prototypical U.S. buildings), and the most-recent EPDs to calculate embodied energy and GHGs, yielding relevant and transparent results. For details of the calculations, see Table A-3 of Appendix A.

The embodied impacts have been calculated as 14,600 gigajoules (GJ) of energy use, 1,460 metric tons (mt) of $CO_2$eq, and 4,840 mt of materials for the initial construction of the office building. The demolition of the office building to construct a new apartment building in Scenario 1 results in 4,840 mt of waste. It is estimated that about 3,100 mt of the total waste has been landfilled and the remainder (about 1,740 mt) has been recycled.

The embodied impacts for the construction of the new apartment building were estimated as 17,100 GJ, 1,580 mt $CO_2$eq, and 5,620 mt of materials. The buildings' structure and substructure constitute the largest source of embodied GHG emissions (Figure 3-3) and energy (55%–58% and 50%–58%, respectively) depending on building type (Appendix B, Figure B-2). These numbers are in the range of the findings (50%–67%) from the only comparable published study (Assefa and Ambler, 2017). Interior finishes, especially carpet and paint, are also significant contributors.

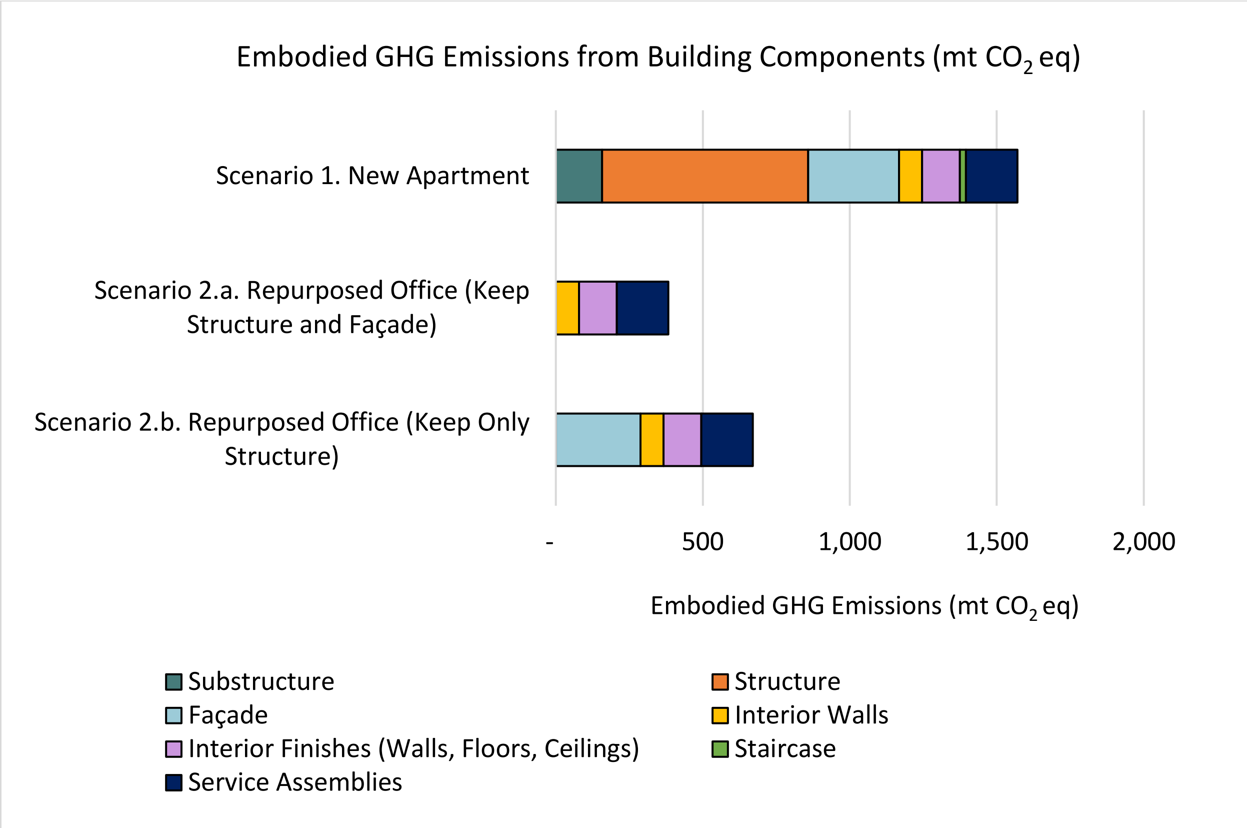



Figure 3-12. Comparison of scenario results in terms of embodied GHG emissions by building components

Repurposing can be accomplished with material investments amounting to 4,460 and 7,900 GJ of embodied energy (Appendix B, Figure B-3), 380 and 670 mt of $CO_2$eq of embodied GHG emissions (Figure 3-3), and 230 and 1,350 mt of materials (Figure 3-2) for scenarios 2.a and 2.b, respectively. Overall, 12,590 and 9,140 GJ of energy (74% and 54%), 1,190 and 800 mt $CO_2$eq (76% and 57%) of emissions, and 5,390 and 4,260 mt of materials (96% and 76%) can be avoided relative to building a new apartment building compared to Scenario 2.a and Scenario 2.b, respectively.

Figure 3-4 shows the net GHG emissions if Scenario 2.a or 2.b were selected over Scenario 1. In year 0, GHG emissions are attributed to the construction of a new apartment building in Scenario 1 and repurposing the office into an apartment in Scenario 2.a, when both the structure (including the foundation) and the façade systems are assumed to remain, while in Scenario 2.b only the structure (including the foundation) from the repurposed office is kept. Repurposing an existing office building into a new apartment building would save 900 mt $CO_2$eq (196 kg $CO_2$eq per $m^2$) if the existing structural frame and the foundation are kept instead of demolishing them completely and constructing a new apartment building. The savings would go up to 1,190 mt $CO_2eq$ (258 kg $CO_2eq$ per $m^2$) if the existing structural frame, foundation, and façade system were kept.

Embodied energy savings from repurposing an existing office building into a new apartment building would correspond to about 2,740 and 1,990 MJ/$m^2$, or 12,590 and 9,140 GJ, for Scenario 2.a and Scenario 2.b, respectively (see Appendix B, Figure B-4).

Depending on the type and condition of the materials that come out of the construction and demolition phases, as well as the existence of recycling industries, they are either landfilled or recycled (refer to Appendix B, Table B-2 for construction materials landfilling and recycling rates). By making the decision to choose repurposing scenario 2.a or 2.b, 747 or 594 kg of waste per $m^2$, respectively, would be eliminated from disposal in landfills while 423 and 336 kg per $m^2$ of material would be diverted from the recycling stream. Therefore, repurposing scenario 2.a and 2.b would eliminate 1,170 and 930 kg per $m^2$ or a total of 5,390 and 4,260 metric tons of materials, respectively, that would otherwise be landfilled or recycled (Appendix B, Figure B-5). Concrete and steel rebar constitute the majority percentages of the saved materials.

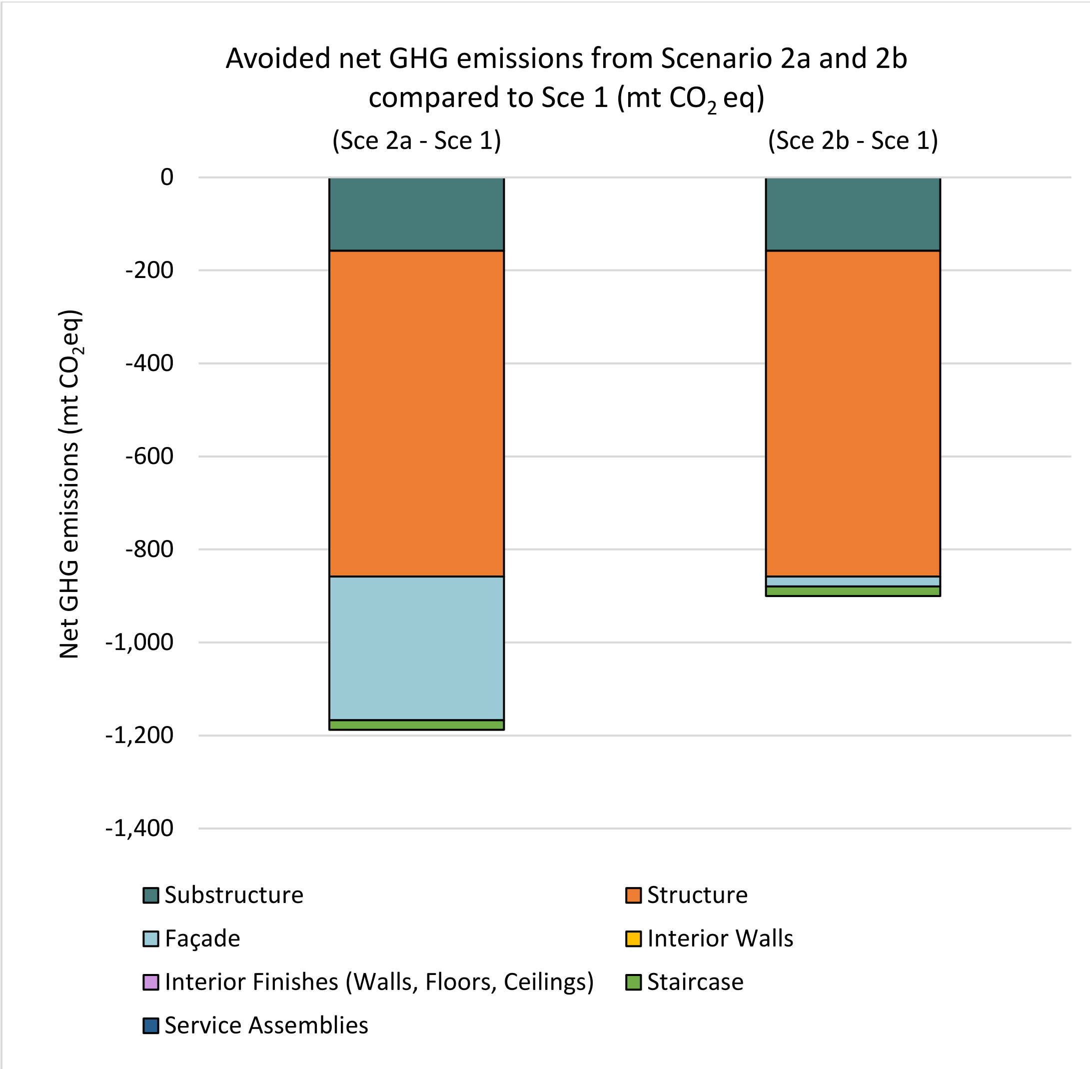



Figure 3-13. Summary of net GHG emissions avoided and quantity of materials (either landfilled and/or recycled) by selecting Scenario 2 (repurposing) over Scenario 1 (construction of new apartment building).

## 3.6 Uncertainties in Modeling and Data

The purpose of this study was to analyze and compare embodied energy and GHG emissions of repurposing versus demolishing and newly constructing representative office and apartment buildings using a practical, yet comprehensive approach. All data sources can be accessed by the readers. Uncertainties are inevitable and result mainly from the following:

- The new apartment building (after the demolition of the office building in Scenario 1) would occupy the same footprint; have the same number of floors, shape, and orientation; and thus use the same quantity of materials in the substructure (foundation) and structural frame. Scenario results would change if the BOM were obtained from construction documents of actual buildings instead of prototype buildings developed from the RS Means database.

- Quantity units obtained from BOM in RS Means were converted to mass units for the purpose of comparison and coupling units of material quantities with functional units defined in EPDs. Such conversions require the use of unit mass factors (e.g., mass per surface area, mass per volume, mass per piece, mass per length) as described in EPDs and/or product description labels.
- When quantities of materials and their configuration were not explicitly given in the BOM, we estimated the quantities based on the descriptions and component dimensions provided in the RSMeans database. These materials include concrete and reinforcing steel bars (rebar) used in structural components (e.g., beams, columns, foundation, and slabs); studs in wall assemblies; roof geometry and configuration; or the grid system for water/sewage pipes, etc. Please see Table A-3 of Appendix A.
- When EPDs for certain components or materials were missing, we used life-cycle inventories (LCIs) from literature and various sources. The quality of LCI data can affect the accuracy and local or regional representativeness of the results. Data availability during different stages of a building's life cycle may hinder the development of an accurate LCA. This is because buildings are more complicated than a single product with a comparatively long life and multiple functions, and would often undergo various changes (Chau et al., 2015).

The above notwithstanding, we consider the quality of the data used in this research to be relatively high. The RS Means data are based on nationally representative surveys, and the emission factors are based on the latest EPDs. The building materials, energy, and GHG emissions data for both analysis scenarios came from the same sources, which allows for consistent comparisons. Overall, the uncertainties are not significant, and we reported the results to three significant digits.

## 3.7 Discussion

Repurposing the existing 155,000 midsize office buildings in the United States into apartments would create about 6 million new apartments and avoid approximately 140–180 million metric tons of GHG emissions. The total numbers would depend on the options considered in repurposing, such as keeping both the structural and façade system or keeping only the structural components while demolishing the rest of the existing office buildings. Results from this study indicate that the value of repurposing depends on the prioritization of environmental goals. Repurposing reduces material-related embodied energy and emissions, but the benefits are limited partly because so much of the embodied energy and emissions during the service lifetime are involved with maintenance after initial construction, which highlights the importance of post-construction material selection. The impacts from repurposing become much more significant when considering material flows and waste avoidance.

The prototypical case buildings that form the basis of this analysis are representative of medium-size reinforced concrete structures in the United States and elsewhere in the world; hundreds of thousands of such buildings have been and are being built. The BOMs would be, therefore, relevant in analyses in other countries. If EPDs representative of another country's materials manufacturing practices could be obtained, this analysis could be successfully repeated.

For a more representative assessment, future work should consider the inclusion of low-rise and high-rise reinforced concrete and steel buildings, as well as low-rise wood-framed structures with variations of façade and interior wall systems, to capture a greater variety of building types. Moreover, even though adaptive reuse/repurposing performs better from an environmental perspective than constructing a new building, the life-cycle cost and societal aspects of these strategies should be considered in future assessments.

# 4 Building Design for Circular Economy: Residential Wall Assemblies

## 4.1 Abstract

To address the impacts of climate change, the building sector is moving from a linear to a circular paradigm to ensure waste reduction, resources recovery and resource-efficient construction. This study focused on the environmental impacts of wall assemblies used in linear constructed U.S. residential buildings compared with circular designed Design for Adaptation + Reuse (DfA+R) wall types. Wall assembly data were extrapolated from three prototypical building typologies created using initial build and cyclical renovation material mass, waste generation, embodied carbon, and embodied energy over a 100-year building life span. Our results indicate that compared to fixed-in-place wall construction, circular designed wall assemblies reduce material resources an average of 73%, reduce waste generation 56%, reduce embodied carbon related to greenhouse gas emissions an average of 88%, and increase embodied energy an average of 44%. Use of DfA+R Wall Type 3 resulted in a 52% reduction of embodied energy over fixed in place wall construction during the building lifetime. These findings illustrate the importance of circular designed building materials and assemblies within the larger context of decarbonizing residential buildings in the United States.

## 4.2 Building Layers, Material Flows, and Design for Adaptation + Reuse

Circular economic principles universally require the building sector to adopt a life cycle approach to the production, construction, use, reuse and eventual disassembly of buildings and building materials. In Europe, the UK Green Building Council (UKGBC) has defined five circularity principles for the built environment to encompass: (1) reuse (existing asset, recovered materials/product, share material/product); (2) optimization (design for longevity, flexibility, adaptability, assembly, disassembly and recoverability); (3) standardization or modularization; (4) services and leasing; (5) design and construct responsibly (UKGBC, 2019).

To incorporate these five categories, the UKGBC has recommended a layered approach to construction: "building in layers – the concept of designing adaptable and flexible buildings by considering the intended life span of each independent building layer, optimizing building longevity and maximizing material reclamation at end-of-life." (UKGBC, 2019).

The concept of building in layers requires consideration of the lifetimes or the reference service life (RSL) of different building elements. This approach looks at the building as a series of materials and/or components with shorter to longer life spans. Buildings that incorporate spaces that are adaptable to changing needs can be renovated easily and kept sustainable over longer periods of time.

A building's potential increased longevity is linked to its inherent ability to allow for adaptation over time. Geldermans (2016) discusses the core features of flexible and adaptable buildings and surmises a building as having two primary domains to accommodate circular material flows in construction: (1) the structural support or base building, where elements are fixed with a longer life span, and (2) the changeable infill or fit-out, where building elements are more variable and responsive to change over a shorter life span (Figure 4-3). This "open building" approach is often seen as the basis for Design for Adaptability (DfA) concepts, in which a strong sense of flexibility is paramount to anticipate occupancy changes and avoid the building to become obsolete.

| BASE BUILDING | FIT-OUT |
|---|---|
| **CHARACTERISTICS** | |
| Long lifespan | Short lifespan |
| Fixed | Variable |
| Architecturally strong | Demountable |
| **SCOPE** | |
| Main structure | Partitioning walls |
| Collective spaces | Kitchen, bathroom |
| | MEP services |
| | (Possibly façade elements) |
| **DECISION SPHERE** | |
| Investor | User |
| **CIRCULARITY RELATION** | |
| Retained or increased value | Adapts to change |
| Long lifespan | Less waste |
| | Facilitates circular reuse |

Source: Geldermans, 2016

Figure 4-3. Distinction between Base Building and Fit-Out

For DfA buildings, the material inflow for the initial build is higher than the materials necessary for subsequent use cycles of various building components over the structure's life span. Vertical partitioning elements, such as flexible interior partition walls and non-load bearing façade panels, are examples of reusable building elements that play a key role in the reduction of life cycle material usage and waste generation while at the same time helping to increase the potential longevity of a building asset.

Once the first use cycle of a building component ends, it can be relocated, refurbished, and/or reused. This begins a second use cycle, and has the capacity for reuse over multiple use cycles, which allows for the elimination of construction/demolition waste and the reduction of material resource use. When a building element reaches the end of its final life cycle, many of the materials can be refurbished and reused in future projects. Any materials that cannot be reused are then recycled or sent to a landfill.

Architectural planning strategies that promote open, flexible space and façade use will be further discussed in the Discussion and Recommendations section below.

## 4.3 Background on Wall Assemblies and Literature Review

Wall assemblies (interior partitions and façade elements) are important components in a building's overall spatial makeup, its material composition, and its operational performance. Wall construction for new residential builds, along with ongoing cyclical renovations over a building's lifetime, significantly contributes to the embodied carbon and embodied energy generated from today's material resource use and CD waste that is deposited as landfill debris annually.

The Gensler Research Institute found that while "operational carbon emissions rates can be reduced over time through efficiency upgrades and grid decarbonization, embodied carbon is an up-front environmental impact. Opportunities for reducing embodied carbon as quickly as possible need to be identified in order to eliminate emissions associated with construction growth. When we extend our view of these products [and materials] over a building's life cycle—factoring in issues such as longevity, maintenance, and replacement—we found that while base materials are carbon-heavy at the outset, cyclical renovations of interiors can contribute equal or greater amounts to the total carbon of the building if no improvements are made." (Briefe et al., 2021).

The existing body of knowledge on the impacts of off-site produced wall systems has been limited. Only a few studies thought about the impact assessment for refurbishments and thus considered waste management for this only (e.g., Ghose et al., 2017). However, as building construction is now shifting from a linear to a circular paradigm, the consideration of those factors are essential for ensuring waste reduction, resources recovery, and resource-efficient construction, not to mention increasing the accuracy of such assessment, and for adopting the CE principle in the building industry (Hossain and Ng, 2018).

Despite several studies having considered "cradle-to-grave" system boundaries, some did not consider the renovation impacts (Guo et al., 2017; Roh and Tae, 2017). Most importantly, waste management scenarios during the construction and renovation stages were not taken into account in many studies (Hossain and Ng, 2018).

Buyle et al. analyzed both conventional and demountable (DfA+R) wall assemblies, which were categorized as (1) conventional (or "static") solutions, designed for a typical linear service life with a waste-generating refurbishment and end-of-life scenario, and (2) demountable and reusable (or "dynamic") solutions, designed with a high reclaim and reuse potential at the end of their functional service life (Buyle et al., 2019).

According to Buyle et al.'s final assessment, the different end-of-life scenarios affect the life cycle impact of the demountable walls more than those of the conventional alternatives. This difference can be explained by the fact that much of the used materials still have a substantial residual technical service life and reuse potential, like the steel profiles or the plywood boarding. Conventional walls on the other hand are composed of materials with less potential after treatment, resulting in a narrower range of outcomes for the different end-of-life scenarios. For example, plaster, gypsum board, and stone wool are mostly landfilled for technical reasons, while inert waste like masonry and concrete is often recycled as a low-quality substitute for gravel in road foundations (LNA - ALBON, 2014).

While the results of recent studies suggest that demountable and reusable wall alternatives have a positive environmental impact and are financially competitive with conventional wall types over a building's life cycle, there is a need to add to the existing body of knowledge that incorporates the environmental implications of reuse and optimized materials usage and waste impacts for new construction and renovations in the U.S. residential building sector.

This analysis focuses on resource use, construction and demolition waste generation, embodied carbon, and embodied energy of existing on-site constructed walls in the U.S. residential building sector, as well as the impacts of their replacement with off-site produced wall assemblies that are designed for adaptation and reuse over a 100-year building life span. The life cycle stages cover materials and component production, as well as replacement of materials and components during the use stage and EOL scenarios.

## 4.4 Methodology - Development of Residential Case Study Buildings: Primary Building Material Flow Analysis for Wall Assemblies

To analyze the potential environmental impacts of on-site wall construction with off-site produced wall assemblies, an estimate of the embodied carbon emissions and energy impacts from primary building materials used for new builds and renovations in the U.S. residential building sector was first calculated. Three prototypical residential buildings were created, and wall systems were extrapolated to analyze their environmental impact for new builds and renovations, both annually and projected out over an estimated 100-year building life span. The following steps outline our approach.

### 4.4.1 Identification of Prototype Residential Buildings

Three prototypical residential buildings were created to represent the majority of annual U.S. residential buildings and renovations. Building characteristic adjustments were made using 2018 revised Residential Energy Consumption Survey (RECS) microdata, the 2019 U.S. Census, and data from the 2019 Harvard Joint Center for Housing Studies. These adjustments were made to incorporate different building materials and frame types (two wood and one concrete) in estimating a bill of materials (BOM) on the basis of RSMeans residential building models:

- Building Type 1: Single-story residence (2,054 $ft^2$, wood frame)
- Building Type 2: Three-story apartment building (22,500 $ft^2$, wood frame)
- Building Type 3: Five-story apartment building (50,000 sq. ft, RF conc. frame)

Once the prototypical residential buildings were established, we estimated the primary BOM using our adjusted building models through RSMeans. This step categorized major building material by group, including Substructure, Shell, Interiors, Services, and Equipment.

For our building materials and waste flow analysis, major materials were further categorized by material type based on primary U.S. Environmental Protection Agency (EPA) Construction, demolition, and debris (CD&D) materials designations, including Concrete, Wood Product, Drywall and Plasters, Metal, Brick and Clay, Insulation (included in the Others designation), Asphalt Shingle, Glass, Textiles, and Plastics (Figure 4-4).

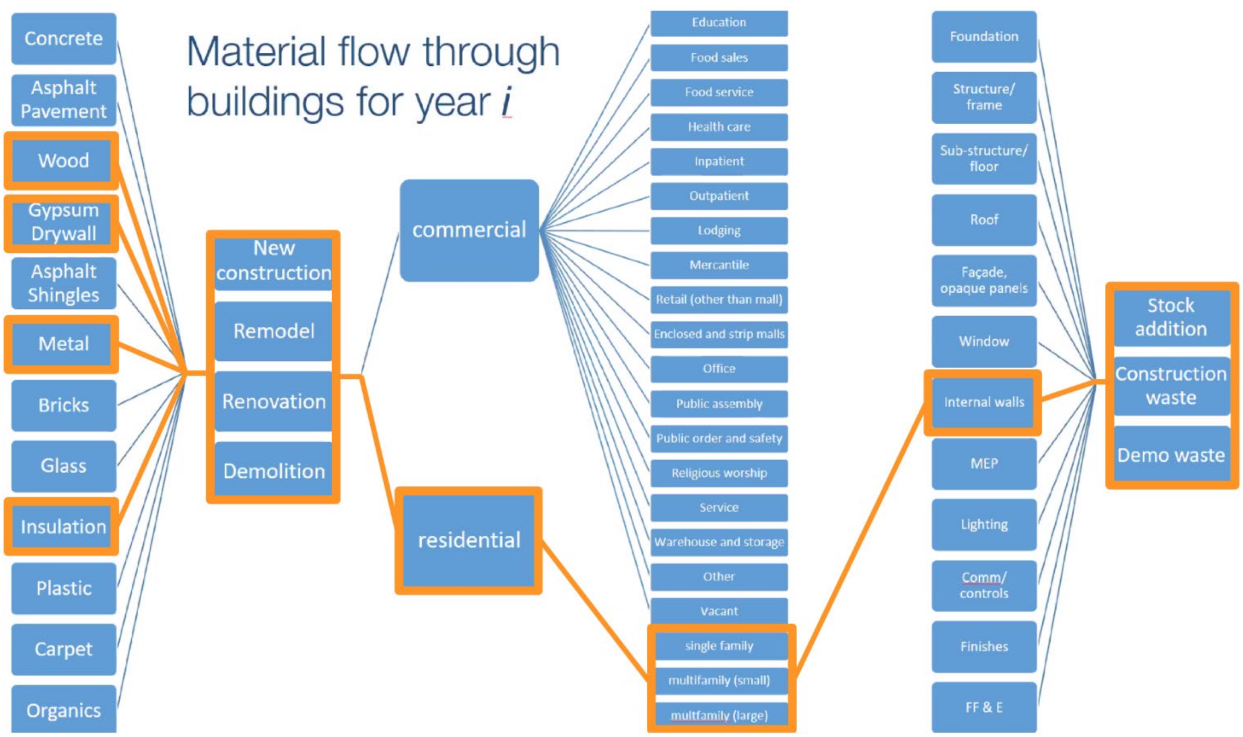



Figure 4-4. Material flow through buildings highlighting residential wall assemblies

### 4.4.2 Conversion and Quantifications of BOMs

The BOM used in building assemblies and components were converted and quantified to material quantities in units of weight and/or volume. Exterior and interior wall systems, including studs, drywall and insulation, utilized assumptions-related quantification. In addition, a conversion step of coupling units of material quantities with functional units defined in environmental product declarations (EPDs) was used for the purpose of comparing our results. While major building materials and components/assemblies were covered in this step, interior partitions were our primary focus for analysis. Major materials and assemblies include the following:

- Substructure (foundation + slab on grade): Concrete, rebar, and structural steel used in construction of footings, slab-on-grade, and foundation walls
- Structural frame (lateral and gravity system): Concrete, rebar, structural steel, and structural wood
- Exterior façade: Exterior wall materials (vary, e.g., metal panels, stucco, cement board, glass wall panels or concrete masonry unit [CMU] blocks), insulation materials (vary), studs (steel), window (aluminum, glass) and door (aluminum, steel, and/or glass) on the façade, and roof coverings (asphalt shingles, aluminum, plywood sheathing) and roof insulation.
- Interiors partitions: Partition wall systems (gypsum board, CMU), studs (wood or steel), and interior doors (aluminum or steel)
- Staircase: Wood and galvanized steel
- Interior finishes: Wall finishes (wall paint, ceramic tiles), floor finishes (carpet, vinyl tiles, ceramic tiles), and ceiling finishes (gypsum board, fiberglass for insulation)
- Service assemblies: Elevator, AC, water heater, roof drainage pipes, piping for water supply and sewage, and miscellaneous

For our three prototypical residential buildings, embodied carbon emission and energy factors to the materials used in the construction and renovation process were assigned per unit function of the materials. All factors were obtained from environmental product declarations (EPDs). Details about the building component/material definitions, related embodied carbon and energy factors, and geographical location and source of the product declarants are available in Appendix A, Table A-3.

For interior wall assemblies, the embodied impacts of materials are comprised of both construction (initial) and renovations over a 100-year period.

Interior furnishings (e.g., equipment, fixtures, furniture) are outside the scope of analysis.

### 4.4.3 Annual New Residential Builds and Renovations: Material Resource Usage and Waste Stream Generation

Using 2019 U.S. Census residential building data for new builds, we focused on three prototypical buildings. These buildings represent the 2019 annual U.S. output:

- Building Type 1: 903,000 single-family homes (2.11 billion $ft^2$ or 196 million $m^2$)
- Building Type 2: 352,000 multi-family units (391million $ft^2$ or 36.34 million $m^2$), consisting of 10,000 buildings with an average of 16.7 units per building
- Building Type 3: 3,000 buildings with an average of 41.5 units per building

Using 2019 Harvard Joint Center for Housing Studies, major U.S. renovations representing the 2019 annual output were calculated as follows:

- 335,000 kitchens (81.96 million $ft^2$ or 7.6 million $m^2$) with an average of 244.66 $ft^2$/kitchen based on 2019 cost/$ft^2$
- 445,000 baths (59.48 million $ft^2$ or 5.53 million $m^2$) with an average of 133.66 $ft^2$/bath
- 739,000 room additions (122.42 million $ft^2$ or 11.37 million $m^2$) with an average of 165.65 $ft^2$/room addition
- 338,000 garage/carport (64.79 million $ft^2$ or 6.01 million $m^2$) with an average of 191.68 $ft^2$/garage/carport
- General renovation BOM and associated wall assembly materials were estimated as a square foot percentage of single-family prototype Building Type 1.

## 4.5 On-Site versus DfA+R Wall Assembly Case Study Description and Methodology

To extrapolate on-site wall related resource use, construction and demolition waste generation, and embodied energy and embodied GHG impacts, we isolated interior wall assemblies from the BOM of our prototype residential buildings. On-site and off-site produced interior wall assemblies adopted Buyle et al. (2019) wall system definitions, which were categorized as (1) conventional (or "static") solutions, designed for a typical linear service life with a waste-generating refurbishment and end-of-life scenario (wall types 1 and 2 in Figure 4-5) and (2) demountable and reusable (or "dynamic") solutions, designed with a high reclaim and reuse potential at the end of their functional service life (wall types 3 and 4 in Figure 4-5).

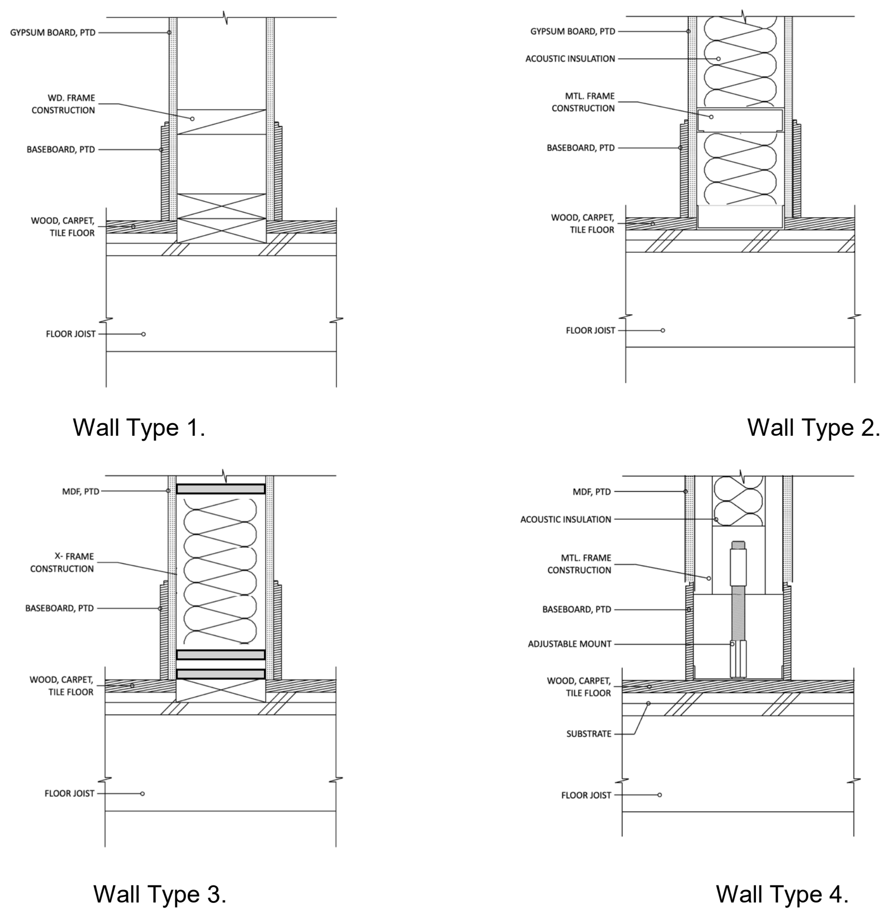



Figure 4-5. Wall types 1 and 2 (static) and 3 and 4 (dynamic)

For conventional walls: Wall Type 1, consisting of wood studs and gypsum wallboard, was used in single-family to three-story multi-family wood frame buildings. Wall Type 2, consisting of metal studs and gypsum wallboard, was used in five-story+ multi-family concrete or steel frame buildings. Fiberglass acoustic insulation was used primarily in multi-family buildings for interior wall assemblies.

For DfA+R walls: Wall Type 3 consists of a plywood substructure with medium-density fiberboard (MDF) sheathing and fiberglass acoustic insulation. Wall Type 4, consisting of an aluminum frame and MDF wallboard with denim acoustic insulation, was used for comparison. For analysis purposes, the demountable wall material composition and EPD related data were taken from representative wall products (Wall Type 3 - Manufacturer and Wall System: XFrame. Wall Type 4 - Manufacturer and Wall System: DIRTT, Chromacoat Interior Wall) (Table A3 Appendix A).

For our DfA+R wall calculations, a number of assumptions were made regarding the reuse of existing walls, both at a building's initial construction phase and during its cyclical renovations throughout its life span. For the purposes of estimating both resource use and waste generation associated with wall replacement, it was assumed that for on-site type 1 and 2 wall construction, there is a one-to-one correlation between the amount of wall surface area replaced and the amount of waste generated due to the replacement during the occupancy phase. For wall types 3 and 4, it was assumed that 50% of the walls used at a project's initial installation and at each renovation were reused, and 50% of a building's internal walls were available for reuse at a building's EOL period, and therefore reduced related to resource use and demolition waste by the correlated amount.

## 4.6 Results

Our analysis focused on the resource use, embodied carbon, embodied energy, and construction and demolition waste generated from the materials used for the construction and renovation of U.S. residential buildings and their interior wall assemblies. This analysis covers material extraction, manufacturing, transportation, building construction, renovation, demolition or deconstruction, and disposal.

### 4.6.1 Buildings, Renovations and Wall Assemblies: Material Weights, Embodied $CO_2$, and Energy, Waste Generation Results

For our building and wall embodied carbon analysis, we first calculated the overall standard material quantities of our three prototype buildings

#### *4.6.1.1 Buildings, Initial Wall Assemblies - Material Weights*

**Building Type 1** (103.56 metric tons [mt]): Interior wall assemblies comprised of gypsum board and wood framing accounted for 7 mt (6.8%) of the initial total building weight. Dimensional lumber and plywood represented 42% of the total wall assembly weight, while gypsum wallboard represented 57%.

**Building Type 2** (1,388.9 mt): Interior wall assemblies comprised of gypsum board, wood framing, and fiberglass insulation constituted 92.1 mt (6.6%) of the initial total building weight. Gypsum wallboard represented 73% of the total wall assembly weight, and wood framing represented 13%.

**Building Type 3** (3,137 mt): Interior wall assemblies were comprised of gypsum board, steel frame and furring, and fiberglass insulation that totaled 115 mt (4%) of the initial total building weight. Gypsum wallboard was 76% of the total wall assembly weight, and steel framing was 22% (Figure 4-6).

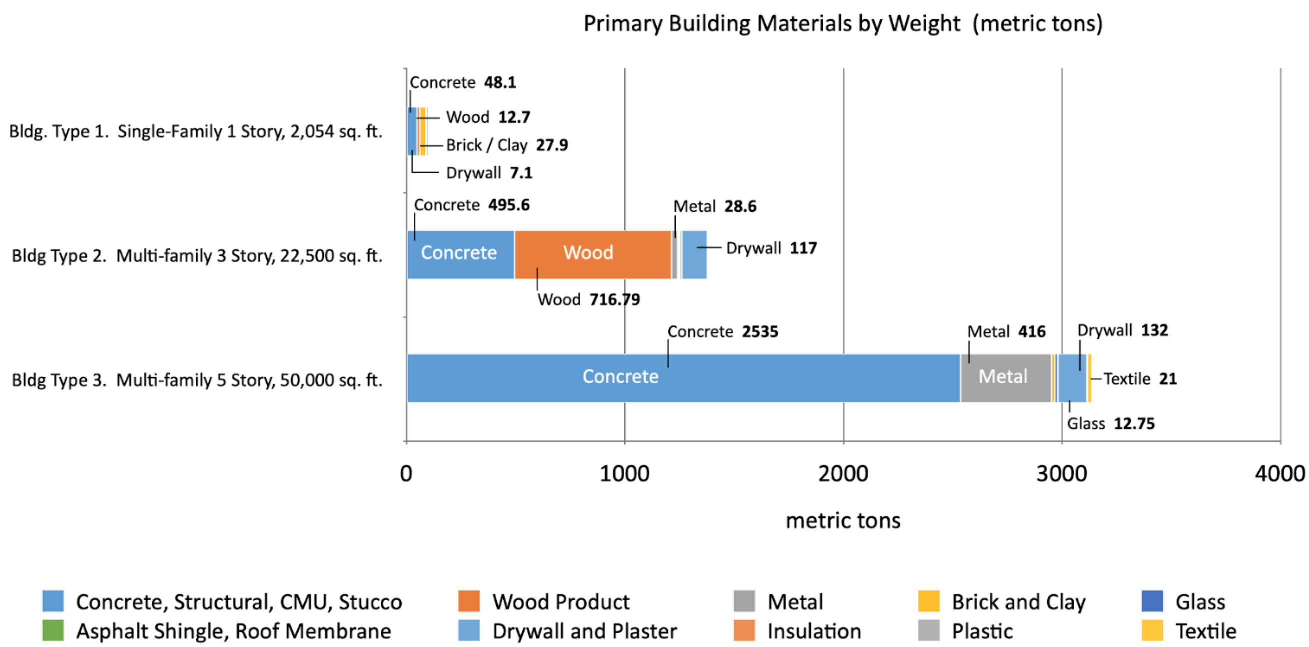



Figure 4-6. Building type 1: 103.56 mt, building type 2: 1,388.9 mt, and building type 3: 3,137 mt

#### *4.6.1.2 Wall Assemblies by CD&D Waste and Resource Use*

**Building Type 1** (Standard Wall Type 1). This type generated 10.19 mt of CD&D waste and 9.37 mt of material resource use over a weighted 100-year period. By comparison, Wall Type 4 generated 6.18 mt of CD&D waste (a 39% impact reduction) and 3.0 mt of material resource use (a 68% impact reduction) over the same period. Wall Type 3 generated 3.15 mt of CD&D waste (a 69% impact reduction) and 1.5 mt of material resource use (an 84% impact reduction) over the same period (Figure 4-7).

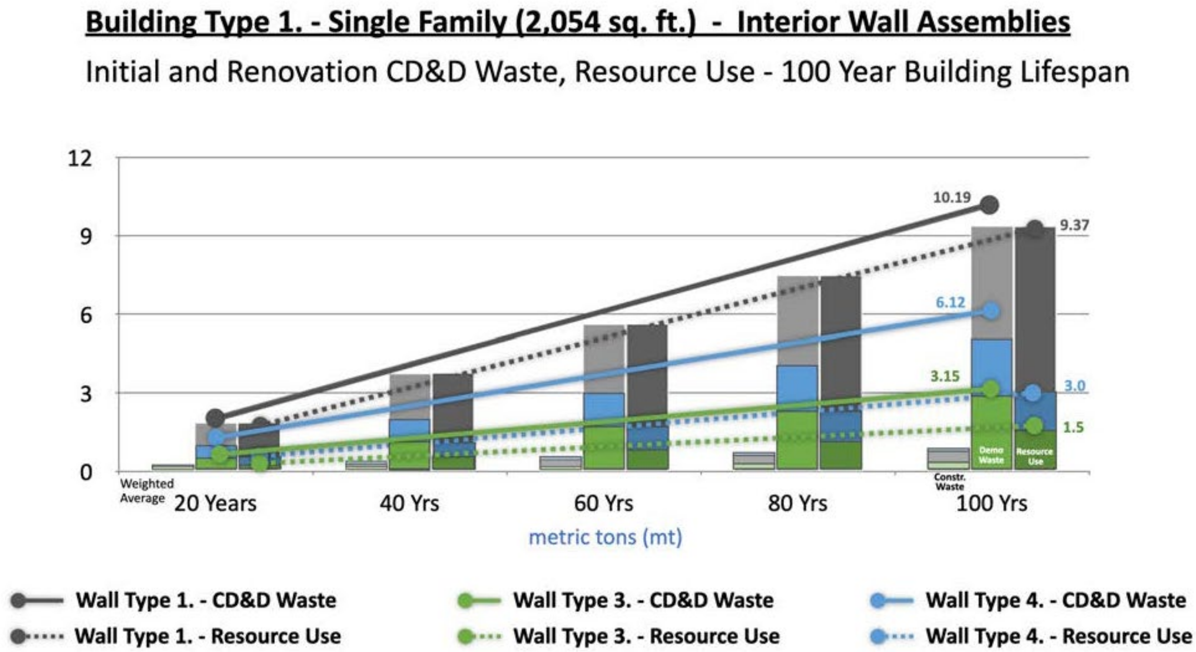



Figure 4-7. Material use and waste from conventional interior walls (Wall Type 1) compared to demountable/reusable walls (Wall Types 3 and 4) in a single-family home over the building lifetime

**Building Type 2** (Standard Wall Type 1). This type generated 157.9 mt of CD&D waste and 145.0 mt of material resource use over a weighted 100-year period. By comparison, Wall Type 4 generated 96.84 mt of CD&D waste (a 39% impact reduction) and 41.3 mt of material resource use (a 72% impact reduction) over the same period. Wall Type 3 generated 31.05 mt of CD&D waste (a 69% impact reduction) and 18.65 mt of material resource use (an 87% impact reduction) over the same period (Figure 4-8).

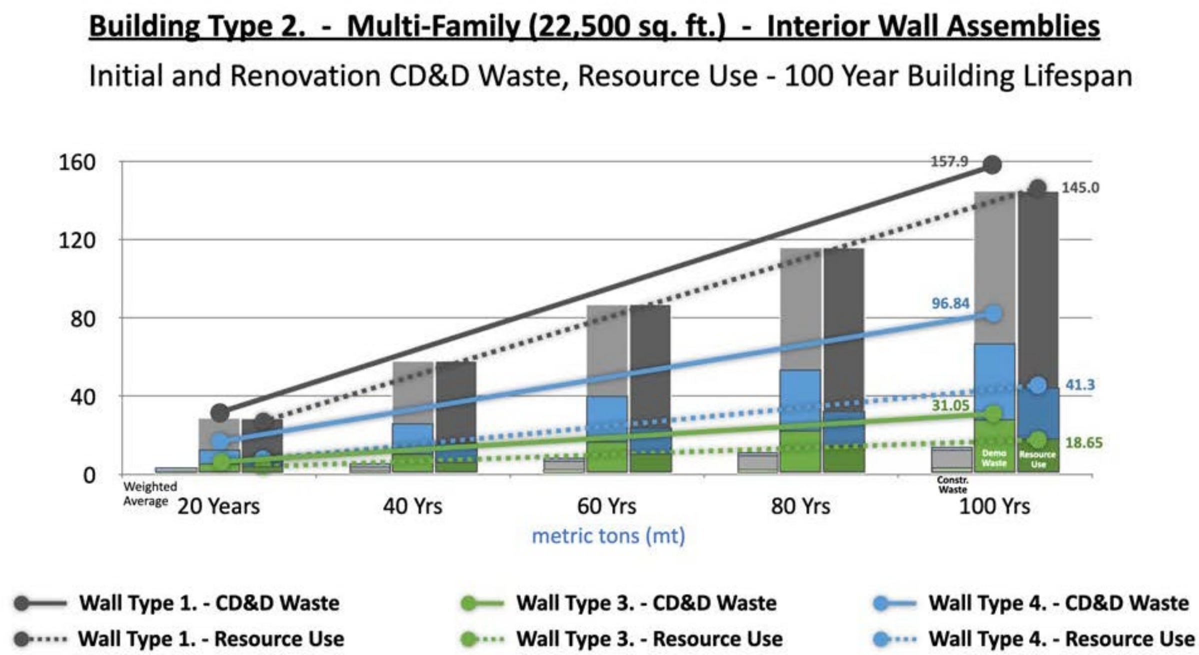



Figure 4-8. Material use and waste from conventional interior walls (Wall Type 1) compared to demountable/reusable walls (Wall Types 3 and 4) in a medium size multi-family home over the building lifetime

**Building Type 3** (Standard Wall Type 2). This type generated 234.8.9 mt of CD&D waste and 216.0 mt of material resource use over a weighted 100-year period. By comparison, Wall Type 4 generated 136.0 mt of CD&D waste (a 42% impact reduction) and 74.0 mt of material resource use (a 66% impact reduction) over the same period. Wall Type 3 generated 68.75 mt of CD&D waste (a 71% impact reduction) and 42.25 mt of material resource use (an 81% impact reduction) over the same period (Figure 4-9).

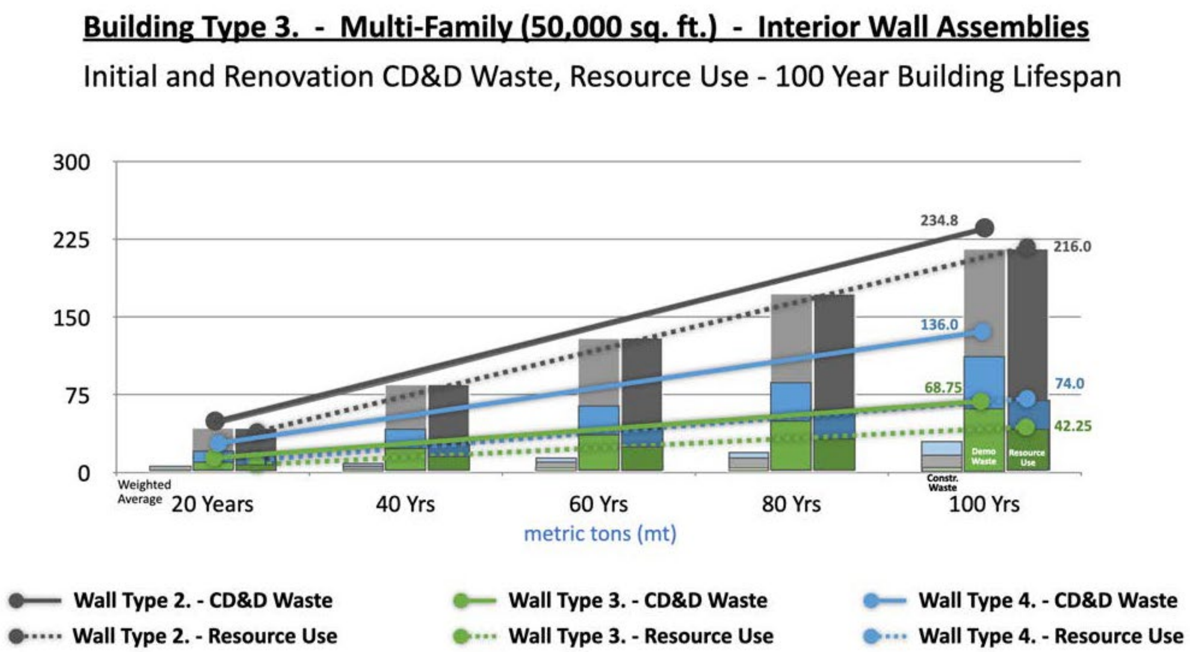



Figure 4-9. Material use and waste from conventional interior walls (Wall Type 2) compared to demountable/reusable walls (Wall Types 3 and 4) in a large multi-family home over the building lifetime

#### *4.6.1.3 Wall Assemblies - by Embodied $CO_2$*

**Building Type 1** (Standard Wall Type 1). This type (including the carbon store for wood materials) generated -3.05 mt $CO_2$-eq of embodied carbon over a weighted 100-year period. With the carbon store omitted, Wall Type 1 (as a nonreusable wall assembly) generated 2.4 mt $CO_2$-eq of embodied carbon over the same period.

By comparison, Wall Type 4 generated 4.35 mt $CO_2$-eq over the same period. Wall Type 3 generated -56 mt $CO_2$-eq over the same period. (Figure 4-10).

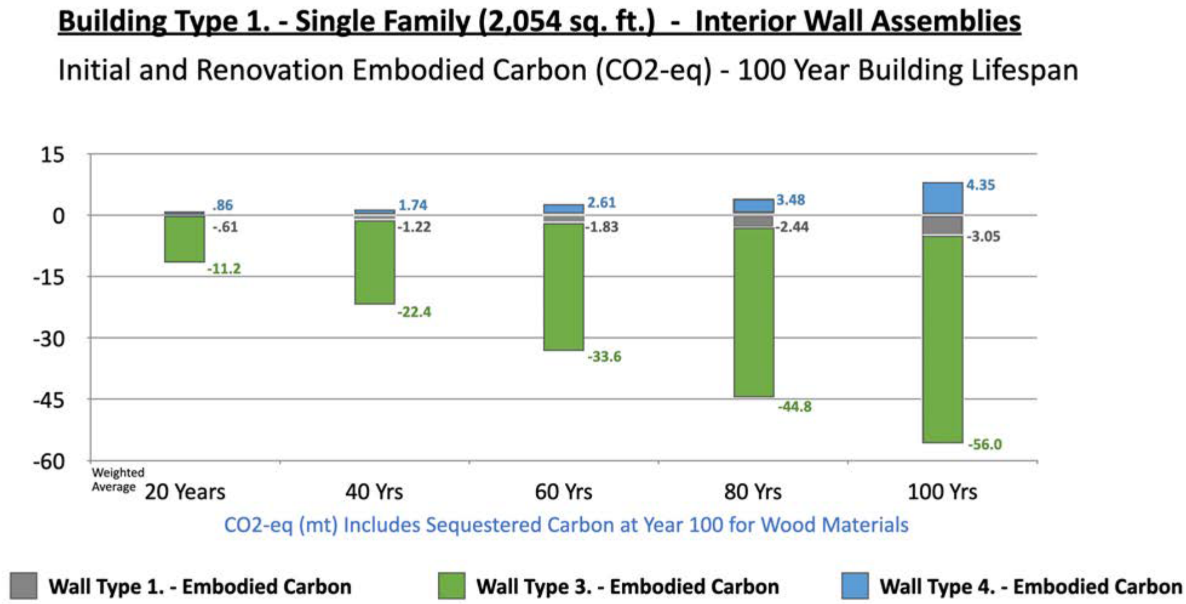



Figure 4-10. Net carbon emissions, including material sequestration, from conventional interior walls (Wall Type 1) compared to demountable/reusable walls (Wall Types 3 and 4) in a single-family home over the building lifetime

**Building Type 2** (Standard Wall Type 1). This type (including the carbon store for wood materials) generated 15.7 mt $CO_2$-eq of embodied carbon over a weighted 100-year period. With the carbon store omitted, Wall Type 1 (as a nonreusable wall assembly) generated 54.9 mt $CO_2$-eq of embodied carbon over the same period.

By comparison, Wall Type 4 generated 49.25 mt $CO_2$-eq (a 68% impact addition) over the same period. When the Wall Type 1 carbon store was omitted, Wall Type 4 generated an 11% reduction in embodied $CO_2$-eq emissions.

Wall Type 3 generated -642 mt $CO_2$-eq (a 98% impact reduction) over the same period. When the Wall Type 1 carbon store was omitted, Wall Type 3 generated an 84% reduction in embodied $CO_2$-eq emissions by comparison (Figure 4-11).

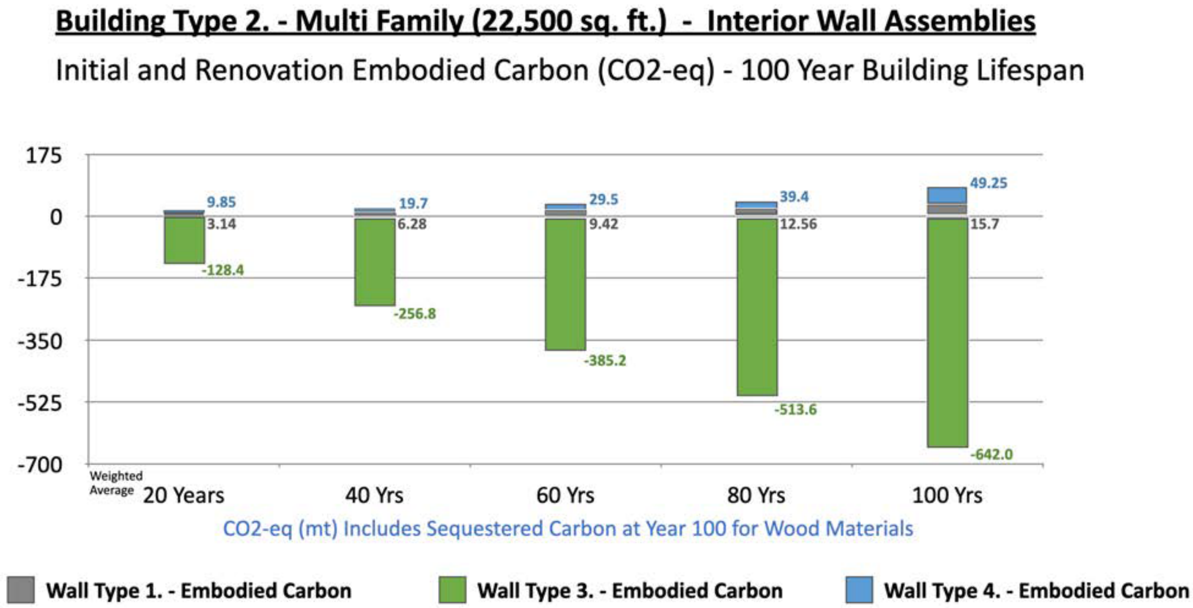



Figure 4-11. Net carbon emissions, including material sequestration, from conventional interior walls (Wall Type 1) compared to demountable/reusable walls (Wall Types 3 and 4) in a medium size multi-family home over the building lifetime

**Building Type 3** (Standard Wall Type 2). There is no carbon store for Wall Type 2. This type generated 125 mt $CO_2$-eq of embodied carbon over a weighted 100-year period. By comparison, Wall Type 4 generated 115.5 mt $CO_2$-eq (an 8% impact reduction) over the same period. Wall Type 3 generated -1,481.5 mt $CO_2$-eq (a 98% impact reduction) over the same period (Figure 4-12).

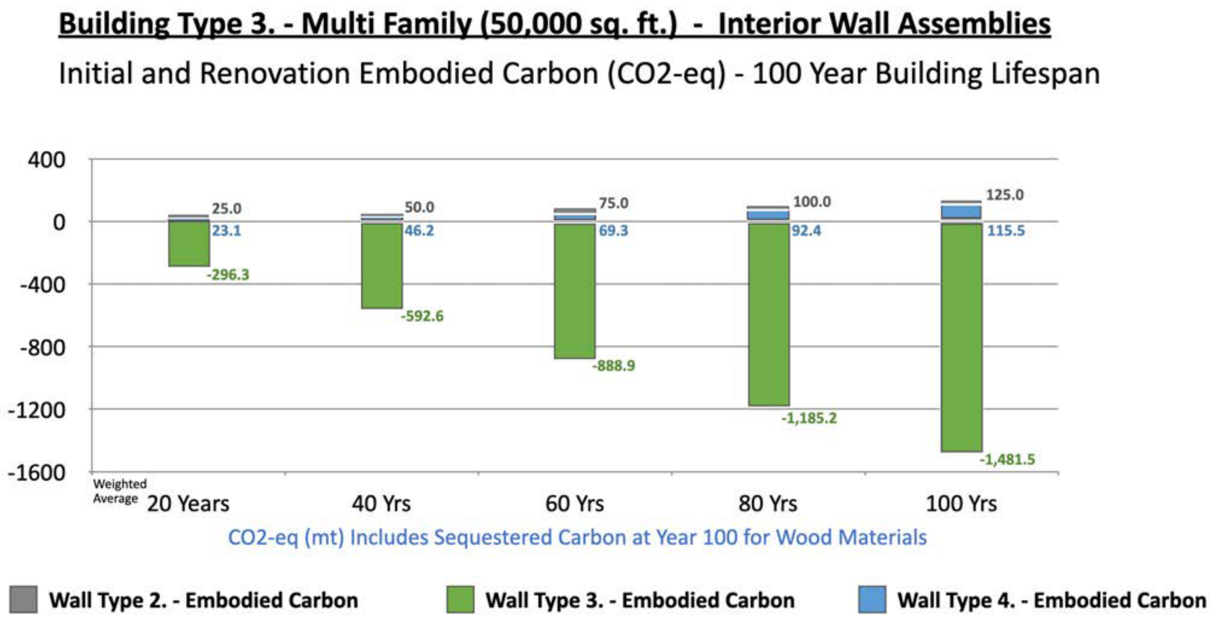



Figure 4-12. Net carbon emissions, including material sequestration, from conventional interior walls (Wall Type 2) compared to demountable/reusable walls (Wall Types 3 and 4) in a large multi-family home over the building lifetime

#### *4.6.1.4 Wall Assemblies by Embodied Energy*

**Building Type 1** (Standard Wall Type 1). This type generated 78.2 gigajoules (GJ) of embodied energy over a weighted 100-year period. By comparison, Wall Type 4 generated 292.5 GJ over the same period. Wall Type 3 generated 49.2 GJ over the same period (Figure 4-13).

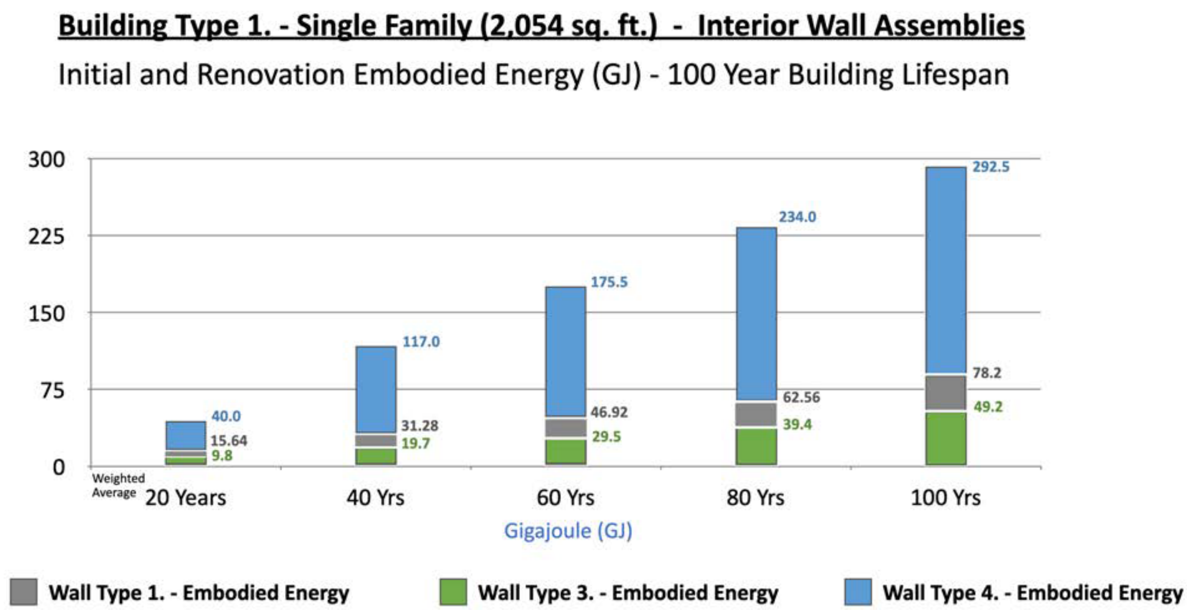



Figure 4-13. Total embodied energy from conventional interior walls (Wall Type 1) compared to demountable/reusable walls (Wall Types 3 and 4) in a single-family home over the building lifetime

**Building Type 2** (Standard Wall Type 1). This type generated 1,179 GJ of embodied energy over a weighted 100-year period. By comparison, Wall Type 4 generated 3,349 GJ over the same period. Wall Type 3 generated 563.5 GJ over the same period (Figure 4-14).

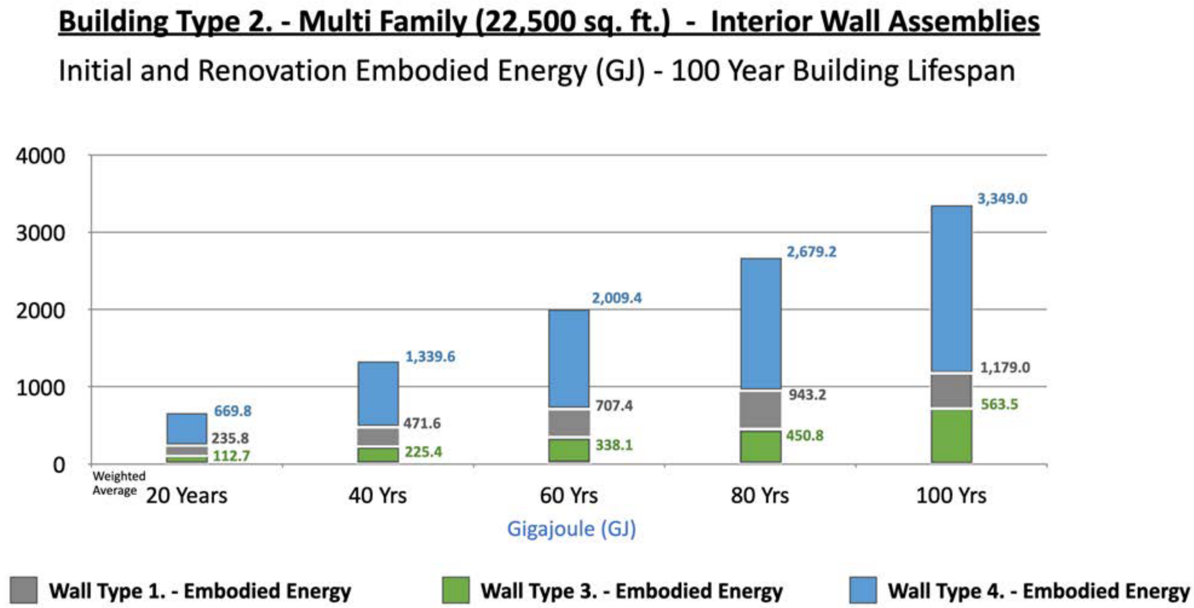



Figure 4-14. Total embodied energy from conventional interior walls (Wall Type 1) compared to demountable/reusable walls (Wall Types 3 and 4) in a medium size multi-family home over the building lifetime

**Building Type 3** (Standard Wall Type 2). This type generated 2,438 GJ of embodied energy over a weighted 100-year period. By comparison, Wall Type 4 generated 7,724 GJ over the same period. Wall Type 3 generated 1,299.5 GJ over the same period (Figure 4-15).

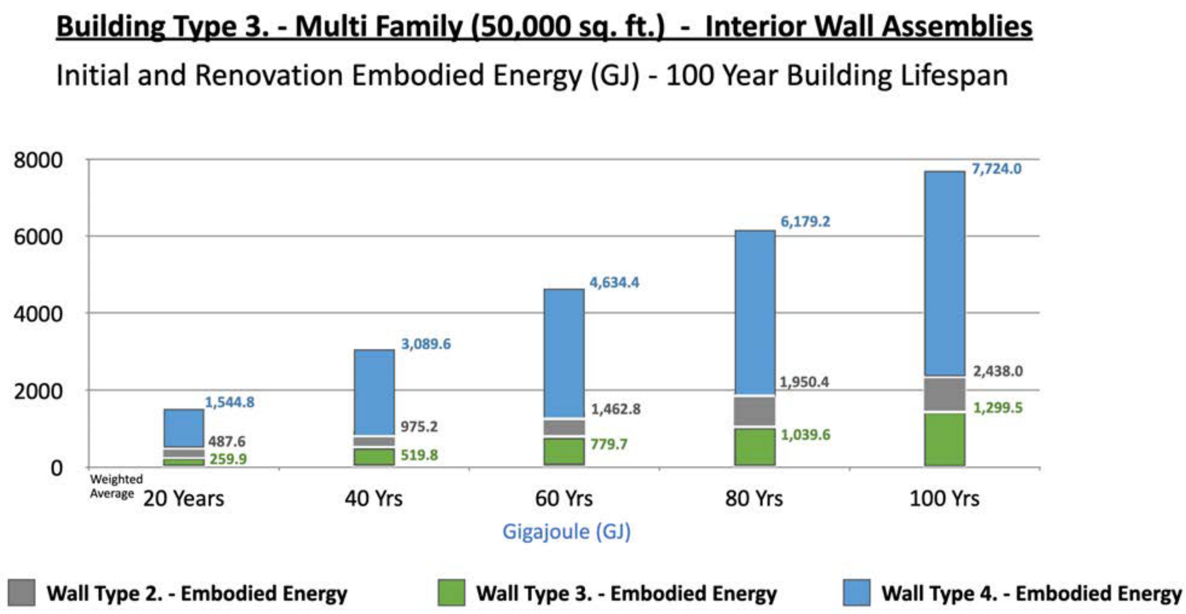



Figure 4-15. Total embodied energy from conventional interior walls (Wall Type 2) compared to demountable/reusable walls (Wall Types 3 and 4) in a large multi-family home over the building lifetime

## 4.7 Discussion: Interpretation of Results and Recommendations

Across the three building types, DfA+R wall assembly Wall Type 3 showed the greatest reduction in the overall environmental impact of interior wall elements when compared to standard wall assemblies. Compared to Wall Types 1 and 2, Wall Type 4 showed significant reductions in resource use and CD&D waste generation, but showed general increases in embodied carbon and embodied energy.

### 4.7.1 Wall Type 3 Result Summary

**Material Resource Use:** Type 3 reduced material resource use as much as 87%. Like most DfA wall assemblies, the reuse factor for Wall Type 3 was achieved through standardized modular subcomponents designed for assembly, disassembly, and reuse over multiple use cycles. The reusable nature of the DfA wall types allows for wall reconfiguration or wall replacement, and thus provides an increased benefit of material resource reduction, as well as reduced production waste associated with the manufacturing production of new walls. Wall reuse has a significant impact on diminishing demolition waste during cyclical renovations and at the EOL/disassembly stage.

**CD&D Waste:** Type 3 reduced CD&D Waste as much as 72%. Production waste of Wall Type 3's mostly wood assembly was 8% of material usage due to the computer numeric control (CNC) manufacturing process of the wall's production. Significant waste savings occur at the demolition/deconstruction phases during cyclical renovations and EOL processes during a building's life span. Reuse for reconfiguration, relocation, or general disassembly for later reuse plays a notable role in the reduction of demolition waste generation.

**Embodied Carbon:** Type 3 reduced embodied carbon as much as 98%. With extended product service life in mind, reusable wood building materials can incorporate carbon sequestration and carbon store into a product's life cycle carbon footprint. Wood products such as MDF and plywood have large carbon stores that when taken into account, often more than offsets the carbon footprint of its cradle-to-gate manufacturing process.

**Embodied Energy:** Type 3 reduced embodied energy as much as 52%. This reduction in the lifetime embodied energy of wall assembly materials that are designed specifically to enable material and component reuse significantly reduces the need for virgin material manufacturing and associated energy production.

### 4.7.2 Wall Type 4 Result Summary

**Material Resource Use:** Type 4 reduced material resource use as much as 72%. Similar to Wall Type 3, Wall Type 4 utilizes a degree of standardized subcomponents designed for assembly, disassembly, and reuse over multiple use cycles. Wall Type 4 manufacturing processes allow for customized wall sizes. These nonstandardized sizes later limit the degree of reuse beyond the wall product's initial application.

**CD&D Waste:** Type 4 reduced CD&D waste as much as 72%. Production waste of Wall Type 4's aluminum frame and MDF wall assembly was 36% of material usage due to customization of wall sizes and CNC manufacturing process for the wall's production. Similar to Wall Type 3, significant waste savings occur at the demolition/deconstruction phases during cyclical renovations and EOL processes during a building's life span.

**Embodied Carbon:** For building types 1 and 2, $CO_2$-eq emissions increased an average of 69% due to the aluminum frame composition of Wall Type 4. With carbon store included for the wall's MDF cladding, $CO_2$-eq emissions increased an average of 17%. Building Type 3 uses Wall Type 2 (metal frame wall assembly). When compared with Wall Type 2, Wall Type 4 reduced $CO_2$-eq emissions 8%. For metal frame assemblies used in high-rise and commercial buildings, a higher degree of recycled content in their steel and aluminum components will help to achieve greater embodied carbon reductions. "As steelmaking moves in the direction of 100% recycled, 100% renewable-powered electric arc furnace (EAF) production, and as emerging production methods such as molten oxide electrolysis become widely adopted, such builders would be uniquely positioned to reach the lowest possible embodied carbon from their steel-framed products." (Klammer et al., 2021).

**Embodied Energy:** Type 4 increased embodied energy as much as 73%. Although Wall Type 4 is designed specifically to enable material and component reuse to reduce the need for virgin material manufacturing and associated energy production, the assembly's 26% recycled aluminum frame still requires significant energy production. Expected higher recycled content in this and similar products will further reduce its embodied energy signature.

### 4.7.3 DfA+R Walls as a Step Toward DfA+R Buildings

Circular economy thinking places importance on the design and construction stages of buildings, to minimize resource usage and waste generation as early as possible (Honic et al., 2019). One aim of CE construction is to eliminate or at least minimize waste (Ghisellini et al., 2018) at both the construction and deconstruction stages (Akanbi et al., 2019). This provides an economically attractive model in response to the shortages of raw resources (Eray, Ekin et al., 2019). CE construction and deconstruction practices incorporate Design for Adaptability + Reuse (DfA+R) principles into all aspects of a building's design, construction, and deconstruction process, from its structural system to its building components and material.

In 2019, 1.26 million new single-family homes and multi-family units were built in the United States. About 852,000 (68%) of the new residential builds were constructed using conventional stick-frame building techniques (U.S. Census, 2022). Conventional stick-frame construction that utilizes load-bearing perimeter walls, fixed internal shear walls, and built-in-place interior walls limit a building's ability to adapt to future requirements (e.g., functional, technological, ecological) that can lengthen a building's useful life cycle.

To create flexible adaptable structures, residential building practices in the U.S. need to move away from stick-frame construction practices toward an open building approach (i.e., post and slab). Future buildings need to be planned and engineered to accommodate products that are designed for adaption and disassembly, including demountable non-load-bearing partitions and high-performance façade systems that can be updated and reconfigured at future points in time along a building's life span (Figure 4-16).

Figure 4-16. Transitioning to DfA+R Buildings that support DfA+R Building Components

### 4.7.4 Flexible Space and DfA+R Wall Systems

Although steel frame and reinforced concrete building methodologies employ open floor plan strategies for commercial and high-rise buildings, the U.S. residential architecture continues to use wood frame building techniques that have remained essentially unchanged since their introduction in the mid 1800s. Today, off-site produced mass timber and cross-laminated timber (CLT) techniques are providing a DfA+R model that brings an open building approach to the larger residential building sector.

Up until now, DfA+R wall and façade solutions have been used almost exclusively in commercial building and high rise applications. With an open building approach in the U.S. residential building sector, both wall and façade elements can take on a more significant role in the elongation of a building's useful service life, as well as the reduction of onsite construction and demolition debris.

The use of DfA+R walls will also contribute to the reduction of material resource use through reuse and reconfiguration of walls during cyclical renovations and at the end-of-life stage, where walls can be reclaimed as part of potential manufacturer take-back or lease programs (figures 4-17 and 4-18).

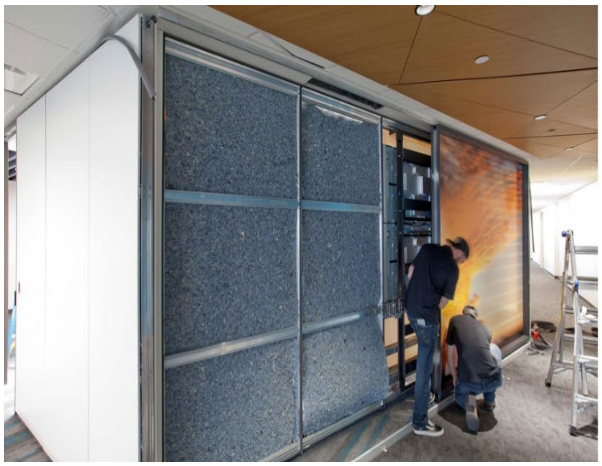


Figure 4-17. Example of off-site manufactured wall installation

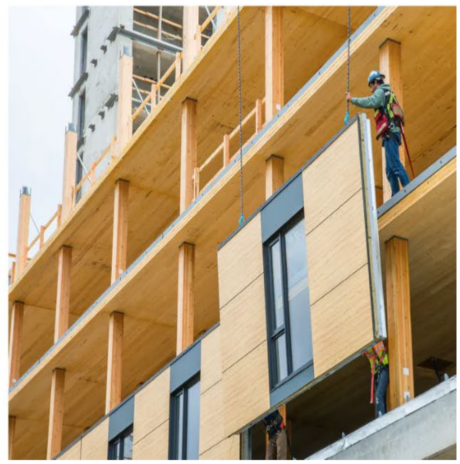


Figure 4-18. Off-site manufactured façade install

### 4.7.5 Policy Response Consideration

Policy can play a significant role in helping to spur the transition.

- Policy responses intended to reduce the life cycle impacts associated with initial installation of DfA+R wall systems could incentivize consumers through incentives, tax credits, and rebates. This policy could be expanded to encompass exterior façade systems that would also affect operational energy.
- Policy responses associated with DfA+R wall systems also could focus on construction processes that allow for open flexible interior space or flexible façade systems. For example, post and slab cross-laminated timber systems allow for non-load-bearing internal demountable walls and flexible curtainwall façade systems. Policy responses that focus on residential housing (i.e., design, construction, renovation, C&D waste management) could be an effective avenue for encouraging reductions in the impacts associated with the multiple layers of a building's composition, and their changes throughout a building asset's life span.
- Policy to incentivize wall manufacturers to offer sale and take-back or lease programs can help encourage CE practices for the building manufacturer industry.

## 4.8 Summary of Conclusion and Findings

The adoption of DfA+R walls for the U.S. residential market can assist with the transition toward a circular economy in the building industry. DfA+R wall systems facilitate the reclamation and reuse of building components, as well as help to valorize building materials to their fullest extent. When compared with conventional wall construction (wall types 1 and 2), the DfA+R wall assemblies (wall types 3 and 4) assessed in the present case study have proven to have an overall lower environmental profile over the life cycle of the building.

### 4.8.1 Potential for Avoided Impacts

There is great potential for avoided impacts, including the following:

- Material/component reuse (resource use) and demolition waste reductions considered in the analysis could result in significant reductions in material, carbon, and energy impacts associated with single-family and multi-family homes.
- Material consideration is a key driver in determining the environmental impact of a wall assembly. Consideration of the material characteristics such as weight (for shipping and installation), strength (for longevity and resilience), service life, and recyclability require critical assessment. MDF, for example, is a pre-consumer recycled product with a high embodied carbon and embodied energy footprint that also generates a significant amount of production waste for landfill. Future MDF product may be both pre- and post-consumer recyclable, which will change the material's environmental profile. It is important to note that the impact for a single material, when coupled with other materials across the spectrum of a residential building, result in more significant environmental savings over a building's life cycle.

To conclude, this study points out the potential benefits of using DfA+R wall assemblies in place of conventional interior wall construction. Further research will need to focus on the potential of DfA+R, high performance façade systems and implications of material usage effecting longevity and efficiency, and the potential for factory sensor integration with ASHRAE connectivity and compliance to optimize performance at the building's enclosure.

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# Appendix A: Supporting Information for Chapter 1

## A-1. Estimation of Embodied GHG Emissions from U.S. Building Materials

Table A-4. Calculations for estimating GHG emission from building materials in manuscript, Table 1

**Calculations: (1) Ready Mixed Concrete Use in Buildings**

| Year | Cement Production (MMT), USGS 2021 | Apparent Cement Consumption (MMT), USGS 2021 | US Ready Mix Concrete Use (MMT) | Concrete Used In Buildings | Emission Factors, CLF Baseline 2021 | EF Unit | $CO_2$ eq. (MMT) | Data Source |
|---|---|---|---|---|---|---|---|---|
| 2019 | 88 | 103 | = Apparent consumption x % used in ready mixed concrete x (Weight of concrete per 1 $m^3$ of concrete) / (Weight of cement per 1 $m^3$ of concrete)<br><br>= 103 MMT x 71% x (2,400/354) | =55% x Ready mixed concrete use (% from ERMCO 2019) | | | | U.S. Geological Survey Mineral Commodity Summaries - Cement (2021). Accessed September 10, 2021, at https://pubs.usgs.gov/periodicals/mcs2021/mcs2021-cement.pdf<br>ERMCO (2019). Ready Mixed Industry Statistics Year 2018. https://ermco.eu/wp-content/uploads/2020/08/ERMCO-Statistics-30.08.2019-R4-1.pdf |
| | | | **= 496 MMT** | **= 273 MMT** | 343 | kg $CO_2$ eq./ $m^3$ | **= 39 MMT $CO_2$ eq.** | For moderate strength ready mixed concrete, 2 400 kg/$m^3$ CLF Baseline (2021) |

**Calculations: (2) Steel Use in Buildings**

| Year | Steel Product Shipments (MMT) | Apparent Consumption (MMT), USGS 2021 | | Steel Used in Buildings | Emission Factors, CLF Baseline 2021 | EF Unit | $CO_2$ eq. (MMT) | Data Source |
|---|---|---|---|---|---|---|---|---|
| 2019 | 87.3 | 100 | | | | | | U.S. Geological Survey Iron and Steel Statistics (2021). Accessed September 10, 2021 at https://pubs.usgs.gov/periodica |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | = Apparent consumption x 46% used in buildings construction | = 100 MMT x 46% (% from AISC) | | | | ls/mcs2021/mcs2021-iron-steel.pdf AISC (2018). Structural Steel: An Industry Overview, https://www.aisc.org/globalassets/aisc/publications/white-papers/structural_steel_industry_overview_2018.pdf |
| | | | | **= 46 MMT** | 1.47 | kg $CO_2$ eq./ kg | **= 68 MMT $CO_2$ eq.** | CLF Baseline (2021) |

**Calculations: (3) Wood Use in Buildings**

| Year | Type of Wood Used in Buildings | Wood Products Consumption ($Mm^3$) | % Used in Buildings | Wood Used in Buildings ($Mm^3$) | | | | |
|---|---|---|---|---|---|---|---|---|
| 2019 | Lumber | 103 | 70% of all lumber | = 103 x 70% = 72 $Mm^3$ | 361 | kg $CO_2$ eq./ $m^3$ | **= 26 MMT $CO_2$ eq.** | Composite lumber. U.S. Department of Agriculture (USDA) (2021). Status and Trends for the U.S. Forest Products Sector 2020. |
| | Structural panel | 28.7 | 79% of total structural panels | = 29 x 79% = 22.7 $Mm^3$ | 230 | kg $CO_2$ eq./ $m^3$ | **= 5 MMT $CO_2$ eq.** | Sheathing panels (plywood, OSB sheathing). USDA (2021); CLF Baseline (2021) |
| | Non-structural panel | 19.7 | 29% of all non-structural panels | =20 x 29% = 5.7 $Mm^3$ | 63 | kg $CO_2$ eq./ $m^3$ | **= 0.36 MMT $CO_2$ eq.** | Softwood lumber. USDA (2021); CLF Baseline (2021) |

Notes:

- 55% of all U.S. ready mix concrete was used in buildings (ERMCO, 2019). Embodied carbon impacts from its use is comparably high.
- Steel construction accounted for an estimated 46% of total domestic consumption in 2019 (USGS, 2021). Structural steel has about a 46% market share (~ 100 MMT apparent consumption in 2019) in non-residential and multi-story residential buildings (AISC, 2018). Steel is already recycled at high levels.
- Construction and maintenance of wood buildings in 2019 include lumber: 70.9 $Mm^3$, structural panel: 22.3 $Mm^3$, and non-structural panels: 5.7 $Mm^3$ (USDA, 2021).

## A-2. Representative Buildings Description

The U.S. Department of Energy (DOE), in conjunction with three of its national laboratories, developed commercial reference buildings, formerly known as commercial building benchmark models and presented in the Commercial Buildings Energy Consumption Survey (CBECS). There are 16 building types that represent approximately 70% of the commercial buildings in the U.S., according to the report published by the National Renewable Energy Laboratory titled *U.S. Department of Energy Commercial Reference Building Models of the National Building Stock.*

Table A-5. Reference building types that represent most commercial buildings across 16 locations, which represent all U.S. climate zones (US DOE at https://www.energy.gov/eere/buildings/commercial-reference-buildings) and adjustments used in the prototypical building calculations based on the RSMeans model

| **Building Type Name** | **Floor Area ($ft^2$)** | **Number of Stories** | **Adjustments Based on RS Means Classification** |
|---|---|---|---|
| Large Office | 498,588 | 12 | 16 stories (11–20 story range); 400,000 $ft^2$ |
| Medium Office | 53,628 | 3 | 5 stories (5–10 story range; 50,000 $ft^2$) |
| Small Office | 5,500 | 1 | 1 story (1–3 story range; 7,000 $ft^2$) |
| Midrise Apartment | 33,740 | 4 | 5 stories (4–7 story range; 50,000 $ft^2$) |

Representation of prototypical buildings that ~ covers 60% of office buildings in the U.S.

| Number of Stories | Number of Buildings |
|---|---|
| 1 story | 544,343 |
| 5–10 stories | 21,863 |
| > 10 stories | 9,030 |
| CBECS total number of buildings | 970,000 |

## A-3. Embodied Energy and GHG Emission Factors from Environmental Product Declarations and LCAs

Table A-6. Compilation of EPDs

| Building Component/ Material | Definition | Functional Unit (FU) | Embodied Carbon (kg $CO_2$ eq.) | Embodied Energy (MJ) | Source, Year, Location | Link |
|---|---|---|---|---|---|---|
| **Substructure (Foundation + Slab on grade)** | | | | | | |
| **Concrete, structural** | 3,000 PSI concrete | $m^3$ | 268 | 2,210 | EC3, 2021 - CTI Ready Mix Elkhart Plant, Iowa, U.S. | https://buildingtransparency.org/ec3/epds/ec3r1j6k |
| **Steel, rebar** | Steel, reinforcement | mt | 979 | 13,800 | ASTM Standards, 2017 | https://pcr-epd.s3.us-east-2.amazonaws.com/360.EPD_for_Sherwood_Steel_EPD_2017-08-07.pdf |
| **Steel, structural** | Structural steel, hot-rolled, steel sections | mt | 1,220 | 18,550 | American Institute of Steel Construction (AISC), 2021 – U.S. | https://www.aisc.org/globalassets/why-steel/epd-aisc-hr-sections-2021.pdf |
| **Wood, structural** | Wood, glulam, structural. Density: 548 kg/$m^3$ | $m^3$ | 137 | 6,800 | American Wood Council, 2020 – U.S. and Canada | https://awc.org/wp-content/uploads/2021/11/AWC_EPD_NorthAmericanGluedLaminatedTimber_20200605.pdf |
| **Structural Floor and Roof, Beams & Columns + Slabs (lateral and gravity system)** | | | | | | |
| **Wood, structural** | Wood, glulam, structural | $m^3$ | 137 | 6,800 | American Wood Council, 2020 – U.S. and Canada | https://www.awc.org/pdf/greenbuilding/epd/AWC_EPD_NorthAmericanGluedLaminatedTimber_20200605.pdf |
| **Steel, structural** | Structural steel, hot-rolled, steel sections | mt | 1,220 | 18,550 | AISC, 2021 – U.S. | https://www.aisc.org/globalassets/why-steel/epd-aisc-hr-sections-2021.pdf |
| **Concrete, structural** | Structural concrete, 4,000 psi w. 15% fly ash, mix 340P75C1, | $m^3$ | 319 | 2,227 | Central Concrete, 2019 - San Francisco, CA, U.S. | EC3: https://buildingtransparency.org/ec3/epds/ec3k03x6 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Central Concrete, San Francisco, CA | | | | | |
| **Steel, galvanized** | Cold-formed steel products: Galvanized steel, studs and furring metal lath | mt | 1,710 | 21,982 | Clark Dietrich Steel, 2021 - U.S. (various plant locations, including Sacramento, CA) | https://buildingtransparency.org/ec3/material-search |
| **Steel, rebar** | Structural steel, hot-rolled, steel sections | mt | 1,220 | 18,550 | AISC, 2021 – U.S. | https://www.aisc.org/globalassets/why-steel/epd-aisc-hr-sections-2021.pdf |
| **Fiber, fireproofing** | Fiber, steel fireproofing | mt | 925 | 10,520 | Monokote fireproofing, 2017 – Massachusetts, U.S. | https://gcpat.com/sites/gcpat.com/files/2021-04/MONOKOTE_MK-6_HY_and_MK-6_Extend_Set_LEED_Package.pdf |
| **Exterior Walls** | | | | | | |
| **Cement board** | Cement board, sheathing | $m^2$ | 8 | 85 | USG Durock, 2019 - Mexico | https://api.environdec.com/api/v1/EPDLibrary/Files/8402dd7c-0b96-4f7f-b6bd-c005dc80e0d5/Data |
| **Stucco** | Stucco, for exterior façade (Product Stolit Lotusan 1.5) | $m^2$ | 17.2 | 383 | Sto Americas, 2019 - Atlanta, Georgia, U.S. | https://www.stocorp.com/wp-content/content/Systems_TechService/EPD/EPD/STO%20EPD%20Stolit%20Lotusan%20Final%20v1.1.pdf |
| **Wall - Foam insulation board** | EPS; Rigid Cellular Polyisocyanurate Thermal Insulation Board, Type I. A | $m^2$ | 4 | 100 | Polyiso wall insulation, Hunter Panels, 2017 – Portland, Maine, U.S. | https://www.hunterpanels.com/xci-technical-resources/polyiso-and-leed/1591-hunter-epd-full-doc-technical/file |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Wall - Fiberglass insulation** | Fiberglass insulation, wall R19 (See page 21 of the EPD document. Used a factor of 3.2 for R19) | $m^2$ | 2 | 28 | Owens Corning, 2018 – Toledo, Ohio, U.S. | https://www.owenscorning.com/en-us/insulation/products/png-fiberglas-insulation |
| **Metal facing panel, exterior walls** | Metal, aluminum wall panels | 100 $m^2$ | 1,860 | 34,000 | Pac-Clad Petersen - Roll form aluminum, 491 kg per 100 $m^2$, 2020 – U.S. | https://metalconstruction.org/view/download.php/online-education/education-materials/edp-educational-files/epd-for-formed-metal-sheets |
| **Galvanized steel, studs** | Cold-formed steel products: Galvanized steel, studs and furring metal lath | mt | 1,710 | 21,982 | Clark Dietrich Steel, 2021 - U.S. (various plant locations, including Sacramento, CA) | https://buildingtransparency.org/ec3/material-search |
| **Wall-glazing** | Glass, wall panels (flat) | mt | 1,400 | 21,600 | ASTM Standards and National Glass Association, 2019 – U.S. | https://www.glass.org/sites/default/files/2019-12/NGA_EPD_2019_12_16_signed.pdf |
| **Window, aluminum extrusions** | Extruded aluminum, windows, doors, roof coverings | kg | 7 | 99 | Kawneer, aluminum extrusions, 2015 –U.S. | www.kawneer.com and https://buildingtransparency.org/ec3/epds/ec35d7ka; https://aluquebec.com/ |
| **Window, glass** | Glass, Flat | mt | 1,370 | 6,686 | ASTM Standards, Cardinal Glass Industries, 2020 – U.S. | https://www.cardinalcorp.com/source/pdf/epd/535.EPD_for_Cardinal_Glass_Industries_Flat_Glass.pdf |
| **Exterior Doors, aluminum extrusions** | Extruded aluminum, windows, doors, roof coverings | kg | 7 | 99 | Kawneer, aluminum extrusions, 2015 –U.S. | www.kawneer.com and https://buildingtransparency.org/ec3/epds/ec35d7ka; https://aluquebec.com/ |
| **Exterior Doors, glass** | Glass, Flat | mt | 1,370 | 6,686 | ASTM Standards, Cardinal Glass Industries, 2020 – U.S. | https://www.cardinalcorp.com/source/pdf/epd/535.EPD_for_Cardinal_Glass_Industries_Flat_Glass.pdf |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Exterior Doors, steel** | Door, steel 18 gauge, hollow metal, 3'0" x 7'0" opening | One door | 96 | 1,597 | Steel Door Institute, 2018 - U.S. | https://steeldoor.org/wp-content/uploads/2020/04/SCS-EPD-05020_SDI_SteelDoorFrame_061418.pdf |
| **Exterior Wall- plywood** | Softwood plywood, exterior wall backing | $m^3$ | 219 | 7,463 | U.S. plywood as sheathing material - 484 $kg/m^3$, 2020 – North America | https://apawood-europe.org/wp-content/uploads/2020/06/AWC_EPD_NorthAmericanSoftwoodPlywood_20200605.pdf |
| **Roof Coverings** | | | | | | |
| **Asphalt shingles, roof** | Roof coverings, asphalt shingles | $m^2$ | 5 | 178 | Asphalt Roofing Manufacturers. 2016 – U.S. | https://www.asphaltroofing.org/wp-content/uploads/2019/10/Shingles-EPD.pdf |
| **Roof EPDM** | Roofing, single ply membrane, EPDM, 60 mils, loosely laid, stone ballast | $m^2$ | 7 | 174 | Carlisle SynTec Inc., Carlisle, 2018 – Pennsylvania, U.S. | https://www.carlislesyntec.com/dfsmedia/c9a15d476f364981b1124520f6258acf/10420-source |
| **Roof insulation, fiberglass** | Fiberglass insulation, roof R30 | $m^2$ | 3 | 47 | Owens Corning (Used a factor of 5.48 for the R30 type), 2018 – Toledo, Ohio, U.S. | https://www.owenscorning.com/en-us/insulation/products/png-fiberglas-insulation |
| **Roof - XPS, insulation** | Roofing, XPS (extruded polystyrene), 40 PSI compressive strength, 4" thick, R20 | $m^2$ | 22 | 79 | Foamular XPS, 2019 -Toledo, Ohio, U.S. | http://www.owenscorning.com/networkshare/Shared/10018928-EPD-Transparency-Brief---FOAMULAR-Insulation.pdf?id=2147487352 |
| **Roof - Aluminum extrusions** | Extruded aluminum, windows, doors, roof coverings | kg | 7 | 99 | Kawneer, aluminum extrusions, 2015 –U.S. | www.kawneer.com and https://buildingtransparency.org/ec3/epds/ec35d7ka; https://aluquebec.com/ |
| **Roof - Steel, hatch** | Cold-formed steel products: Galvanized steel, studs and furring metal lath | mt | 1,710 | 21,982 | Clark Dietrich Steel, 2021 - U.S. (various plant locations, including Sacramento, CA) | https://buildingtransparency.org/ec3/material-search |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Interiors** | | | | | | |
| **Partitions** | | | | | | |
| **Gypsum board, 5/8" fire rated** | Gypsum board, 5/8" fire rated | MSF | 308 | 6,089 | Georgia Pacific Gypsum – 1 MSF of 5/8" ToughRock® Fireguard C® Gypsum Panel, 2020 – Atlanta, Georgia, U.S. | Georgia Pacific, https://www.transparencycatalog.com/company/georgia-pacific |
| **Gypsum board, 1/2" fire rated** | Gypsum board, 1/2" fire rated | MSF | 296 | 5,775 | Georgia Pacific Gypsum - 1/2" ToughRock® Fireguard C® Gypsum Panel 1/2" Type C (Generic name), 2020 – Atlanta, Georgia, U.S. | https://buildingtransparency.org/ec3/material-search |
| **Interior wall insulation, mineral fiber** | R-15 metal wall insulation (mineral fiber) | $m^2$ | 2.92 | 47 | Owens Corning fiberglass, 2018 - Toledo, Ohio, U.S. | https://www.transparencycatalog.com/assets/uploads/pdf/EPD-Optimization-102392-4600.pdf |
| **CMU (concrete masonry unit) block, 12", medium weight** | CMU block, 12", medium weight, 2000 psi | $m^3$ | 208 | 2,550 | Angelus CMU Block, 1,954 kg/$m^3$, 2021 – CA, U.S. | https://www.angelusblock.com/assets/docs/EPD_ANGELUS_BLOCK_CMU_GARDENA_MW.pdf |
| **CMU block, 8 x 8 x 16, medium weight** | CMU block, 16", medium weight | $m^3$ | 260 | 3,076 | CMU Block, Medium weight, 2,250 kg/$m^3$, 2016 - Canada | https://ccmpa.ca/wp-content/uploads/2021/01/311.EPD_for_CCMPA_Normal-Weight_And_Light-Weight_Concrete_Masonry_Units.pdf |
| **Concrete block (CMU) partition, light weight, hollow, 6" thick** | CMU block, 6", light weight | $m^3$ | 270 | 3,094 | CMU, lightweight. 1825 kg/$m^3$, 2016 - Canada | https://ccmpa.ca/wp-content/uploads/2021/01/311.EPD_for_CCMPA_Normal-Weight_And_Light-Weight_Concrete_Masonry_Units.pdf |
| **Galvanized steel, studs** | Cold-formed steel products: Galvanized steel, studs and furring metal lath | mt | 1710 | 21,982 | Clark Dietrich Steel, 2021 - U.S. (various plant locations, including Sacramento, CA) | https://buildingtransparency.org/ec3/material-search |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Galvanized steel, furring** | Cold-formed steel products: Galvanized steel, studs and furring metal lath | mt | 1710 | 21,982 | Clark Dietrich Steel, 2021 - U.S. (various plant locations, including Sacramento, CA) | https://buildingtransparency.org/ec3/material-search |
| **Wood, studs (dimensional)** | Softwood lumber, kiln dried. 460 kg/$m^3$ | $m^3$ | 63 | 3,381 | American Wood Council and Canadian Wood Council, 2020, North America | https://awc.org/wp-content/uploads/2021/11/AWC_EPD_NorthAmericanSoftwoodLumber_20200605.pdf |
| **Interior Doors, galvanized steel** | Door, steel 18 gauge, hollow metal, 3'0" x 7'0" opening | One door | 96 | 1,597 | Steel Door Institute, 2018 - U.S. | https://steeldoor.org/wp-content/uploads/2020/04/SCS-EPD-05020_SDI_SteelDoorFrame_061418.pdf |
| **Staircase, galvanized steel** | Cold-formed steel products: Galvanized steel, studs and furring metal lath | mt | 1710 | 21,982 | Clark Dietrich Steel, 2021 - U.S. (various plant locations, including Sacramento, CA) | https://buildingtransparency.org/ec3/material-search |
| **Wall Finishes** | | | | | | |
| **Primer, interior** | Primer, interior wall | $m^2$ | 2.29 | 52 | Behr, 2018 – Santa Ana, CA | https://www.behr.com/binaries/content/assets/behrdotcom/web/pdfs/epd/113.1_behr_premium-plus-primer--epd.pdf |
| **Paint, interior** | Paint, interior wall | $m^2$ | 2.46 | 55 | Behr, 2017 – Santa Ana, CA | https://www.behr.com/binaries/content/assets/behrdotcom/web/pdfs/epd/101.1_behr_epd_premium_plus_11.18.pdf |
| **Tile, ceramic natural clay** | Ceramic tile, interior wall or floor | $m^2$ | 14.1 | 202 | Tile Council of North America: North American Ceramic Tile: Mosaic Quarry, Pressed Floor, Glazed Wall and Porcelain, 2020 – North America | https://www.arto.com/site/downloads/Environment/EPD%20-%20Ceramic%20Tile%20-%20TCNA.pdf |
| **Floor Finishes** | | | | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Carpet tile, nylon, fusion bonded, 18" x 18" or 24" x 24", 35 oz** | | m² | 16 | 263 | Mannington carpet, 2019 - U.S. | https://a.mannington.io/docs/literature/09701bc7710f43ec9f09b95d0278770a/pdf/Infinity_2_EPD_3-15-19-20190318203941.pdf |
| **Carpet tile, nylon, fusion bonded, 18" x 18" or 24" x 24", 35 oz** | | m² | 16 | 263 | Mannington carpet, 2019 -U.S. | https://a.mannington.io/docs/literature/09701bc7710f43ec9f09b95d0278770a/pdf/Infinity_2_EPD_3-15-19-20190318203941.pdf |
| **Vinyl, composition tile, maximum** | Vinyl floor tile | m² | 12 | 275 | Mannington carpet, 2019 - U.S. | https://a.mannington.io/docs/literature/a09f68a9931547c5bb8b5e94a0674c53/pdf/2019_EPD_-_Luxury_Vinyl_Tile-20190118145834.pdf |
| **Tile, ceramic natural clay** | Ceramic tile, interior wall or floor | m² | 14 | 202 | Tile Council of North America: North American Ceramic Tile: Mosaic Quarry, Pressed Floor, Glazed Wall and Porcelain, 2020 – North America | https://www.arto.com/site/downloads/Environment/EPD%20-%20Ceramic%20Tile%20-%20TCNA.pdf |
| **Ceiling Finishes** | | | | | | |
| **Ceiling - Fiberglass, acoustic insulation** | Acoustic ceilings, 3/4" fiberglass board, 24" x 48" tile, tee grid, suspended support | m² | 0.5 | 8.8 | EcoTouch® PINK® Fiberglas™ Insulation with PureFiber® Technology. For m² of unfaced insulation at RSI = 1, 2018 – North America | https://dcpd6wotaa0mb.cloudfront.net/mdms/dms/Shared/10023059/10023059-EcoTouch-Pink-Fiberglas-Batt-Roll-Insulation-Unfaced-and-Faced---EPD.pdf?v=1607530531000 |
| **Services** | | | | | | |
| **Elevator** | Elevator, Otis | tkm | 11 | 158 | EPD for Otis, 2020 - Europe | https://api.environdec.com/api/v1/EPDLibrary/Files/32b45ff9-299c-48e7-bdbd-27031b5705ff/Data |
| **Copper piping for water supply line** | Copper tube | kg | 3.37 | 52 | Copper development association, 2019 – U.S. | https://www.copper.org/environment/sustainability/pdfs/copper_life_cycle_assessment_tube_and_sheet.pdf |

| | | | | | | |
|---|---|---|---|---|---|---|
| **PVC piping** | PVC piping for sewage | 100 ft | 2,300 | 5,970 | Uni-Bell PVC Pipe, 2014 – U.S. | https://www.uni-bell.org/communication/images/environmental_product_declaration_for_water_and_sewer_piping.pdf |
| **Cast iron pipes, roof drain** | Cast iron (CI) rainwater drain pipe | linear meter | 11.4 | 205 | PAM-Global Plus. 7.46 kg per meters - CI pipe, 2020 - Germany | https://api.environdec.com/api/v1/EPDLibrary/Files/2825e2d3-30e0-4d75-afd4-e0c99f6d41db/Data |
| **Steel, wet pipe sprinkler systems** | Galvanized steel, wet pipe sprinkler systems | mt | 1710 | 21,982 | Clark Dietrich Steel, 2021 - U.S. (various plant locations, including Sacramento, CA) | https://buildingtransparency.org/ec3/material-search |
| **Wet standpipe risers** | Black steel, sch 40 - Wet standpipe risers, class III, , 4" diameter pipe | mt | 2,210 | 25,926 | Steel tube, 7800 kg/m$^3$, 2016 – U.S. | https://www.vikinggroupinc.com/sites/default/files/documents/101.1_Bull-Moose_EPD_Steel-Tube_20160928.pdf<br><br>https://api.environdec.com/api/v1/EPDLibrary/Files/eb39024d-c0f5-4068-9b30-d14ef6d5eee8/Data |
| **Central AC** | AC | per ton of cooling capacity | 43 | 530 | Centrifugal chiller AC, 2016 – U.S. | https://oslo.daikinapplied.com/api/daikindocument/DownloadDocumentByName/Doc100/101.1_Daikin_EPD_Magnitude_centrifugal_chiller_v5.pdf |
| **Internet wiring** | Internet wiring, 2 data/voice outlets per 1,000 ft$^2$ | feet | 1.62 | 24 | Fiber optical cables, Belden Company, 2016 – U.S. | https://buildingtransparency.org/ec3/material-search |
| **Joint compound for drywalls** | Drywall finishing | 4.5 gal | 29.4 | 685 | Drywall finishing council. For 4.5 gallons pail, 2017 – U.S. | https://www.certainteed.com/resources/Industry_Joint_Compound_EPD_-_Drywall_Finishing_Council_Inc_-_UL_Certifi....pdf |

Note: CA = California.

## A-4. U.S. Office Buildings by Numbers and Floor Space Distribution

Table A-7. Number of U.S. office buildings constructed by periods of construction and number of floors.

| | Years constructed (based on CBECS database) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Number of floors | Before 1946 | *1946-1959* | *1960-1969* | *1970-1979* | *1980-1989* | *1990-1999* | *2000-2012* | *2013-2018* | Number of buildings |
| 1 | 38,796 | 33,566 | 37,085 | 107,039 | 100,955 | 71,668 | 120,503 | 34,730 | **544,342** |
| 2 | 58,943 | 12,693 | 39,422 | 38,472 | 33,417 | 49,009 | 39,625 | 1,877 | **273,459** |
| 3 | 51,136 | 6,816 | 3,437 | 8,023 | 19,056 | 3,478 | 7,373 | 6,055 | **105,375** |
| 4 | 4,929 | 30 | 116 | 1,151 | 4,107 | 2,237 | 2,741 | 953 | **16,263** |
| 5 | 3,774 | 75 | 49 | 1,076 | 1,383 | 789 | 799 | 1,313 | **9,258** |
| 6 | 1,152 | 678 | 9 | 116 | 1,233 | 1,039 | 565 | 751 | **5,542** |
| 7 | 1,647 | 434 | 599 | 486 | 209 | 39 | 113 | 294 | **3,821** |
| 8 | 501 | 15 | 121 | 191 | 518 | 269 | 330 | 66 | **2,012** |
| 9 | 131 | 6 | 62 | 459 | 488 | 30 | 39 | 15 | **1,230** |
| 10-14 | 1,066 | 30 | 303 | 534 | 952 | 494 | 590 | 270 | **4,238** |
| 15 or more | 938 | 69 | 382 | 1,024 | 1,345 | 462 | 452 | 121 | **4,793** |
| Number of buildings | 163,014 | 54,412 | 81,585 | 158,569 | 163,663 | 129,514 | 173,130 | 46,445 | 970,332 |

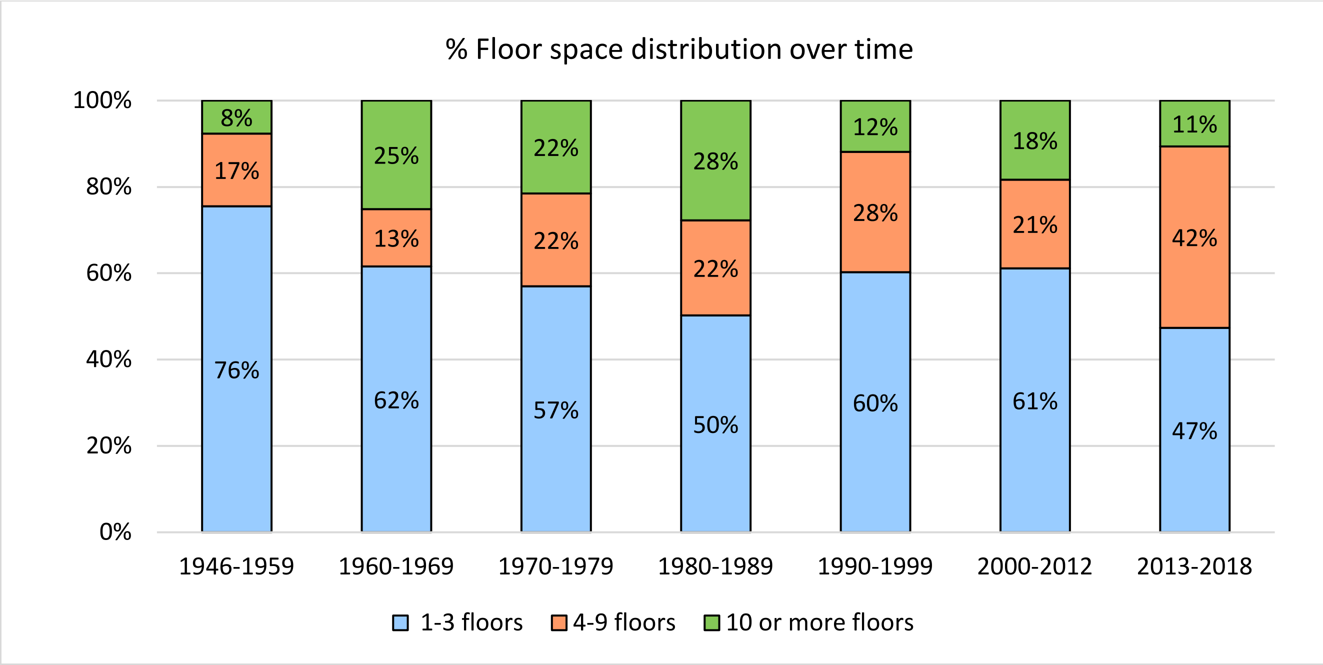



Figure A-14. Percentage distribution of floor space of office buildings over time.

## A-5. Analysis of Prototypical Office Buildings by Weight of Materials, Embodied Energy and GHG Emissions

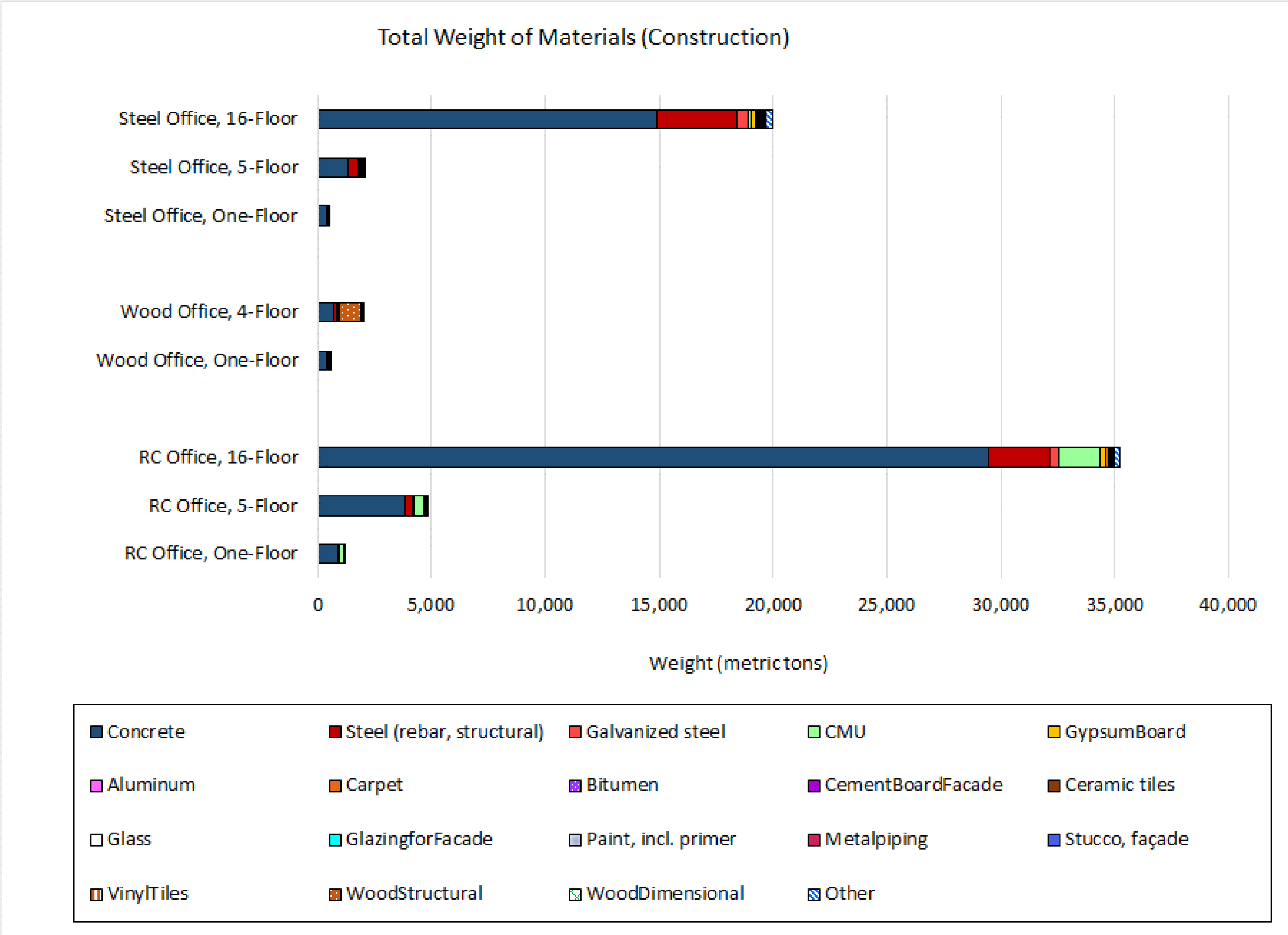



Figure A-15. Quantity of materials used for construction of prototypical office buildings

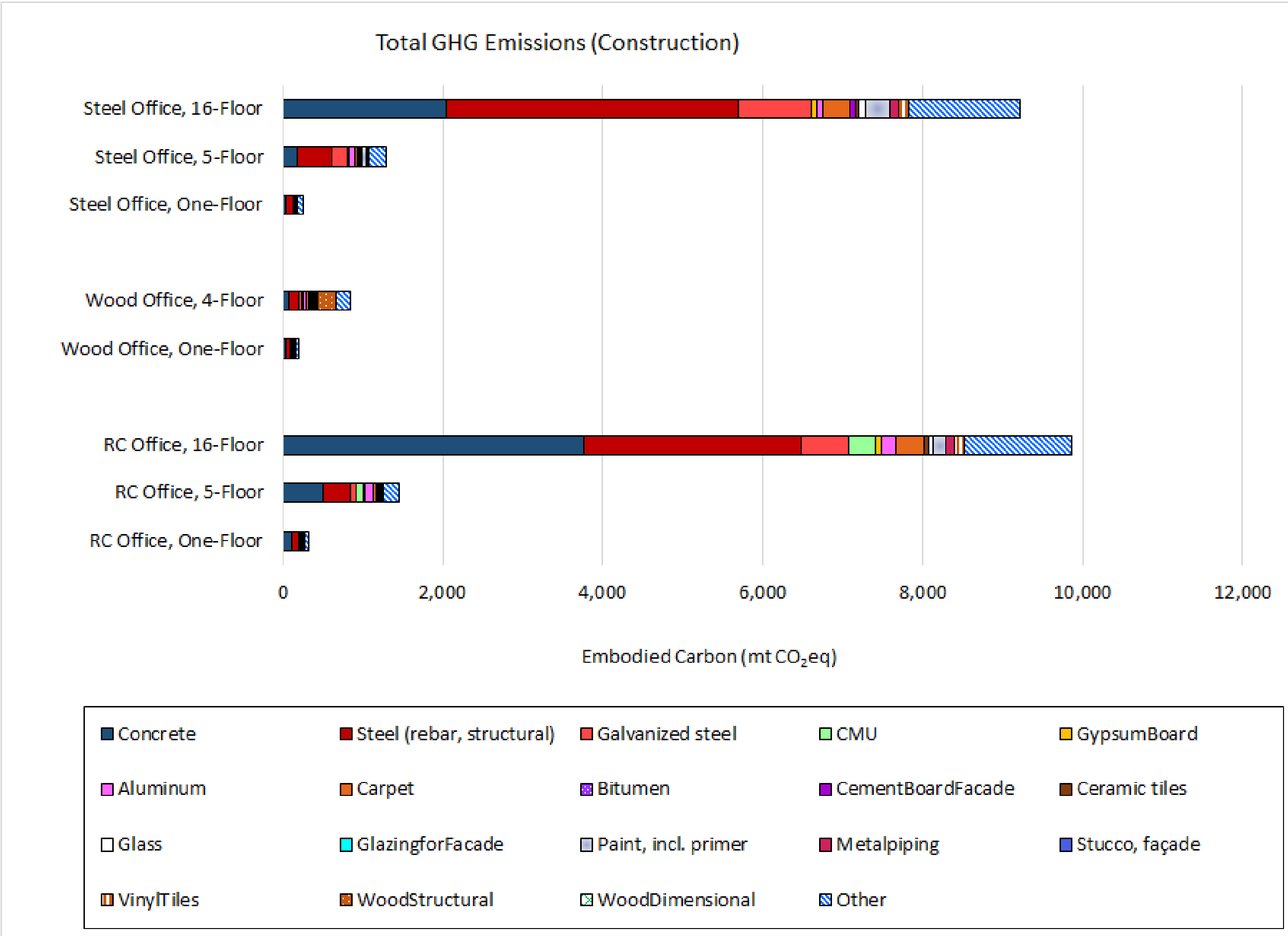



Figure A-16. Embodied GHG emissions from building materials

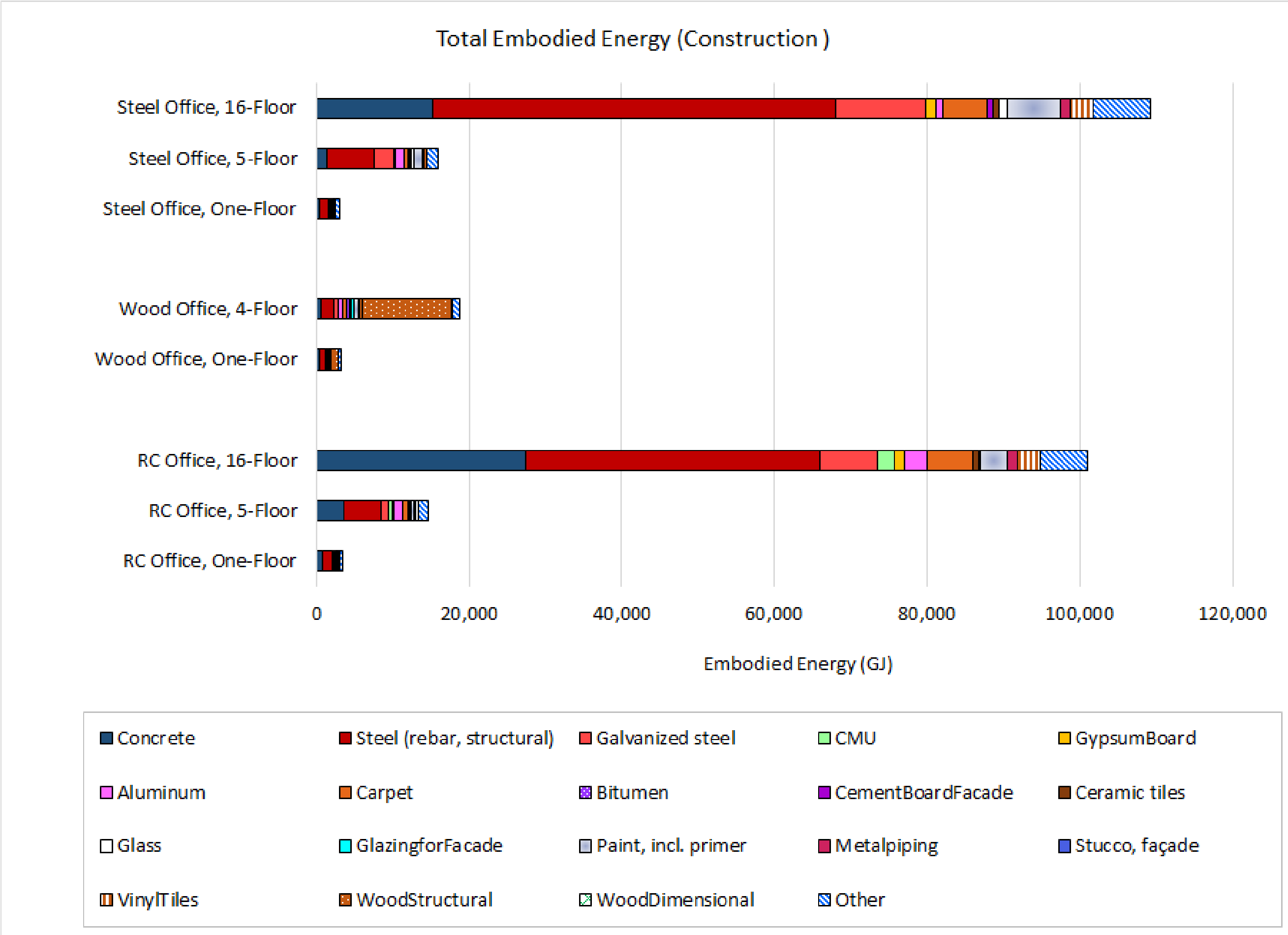
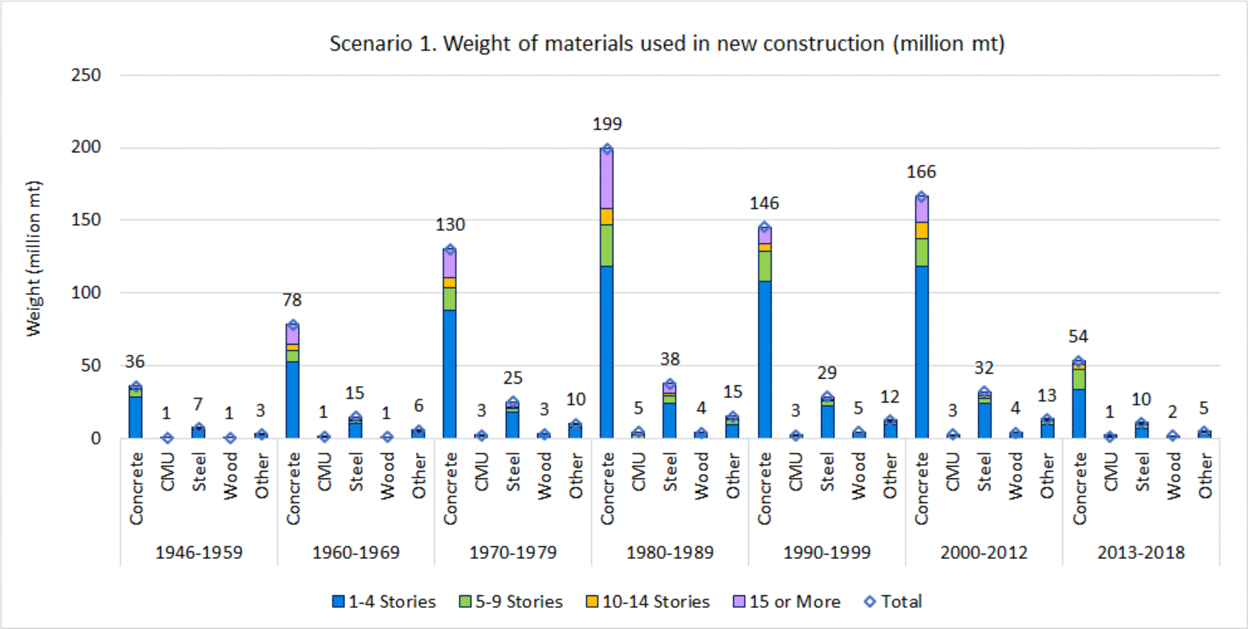
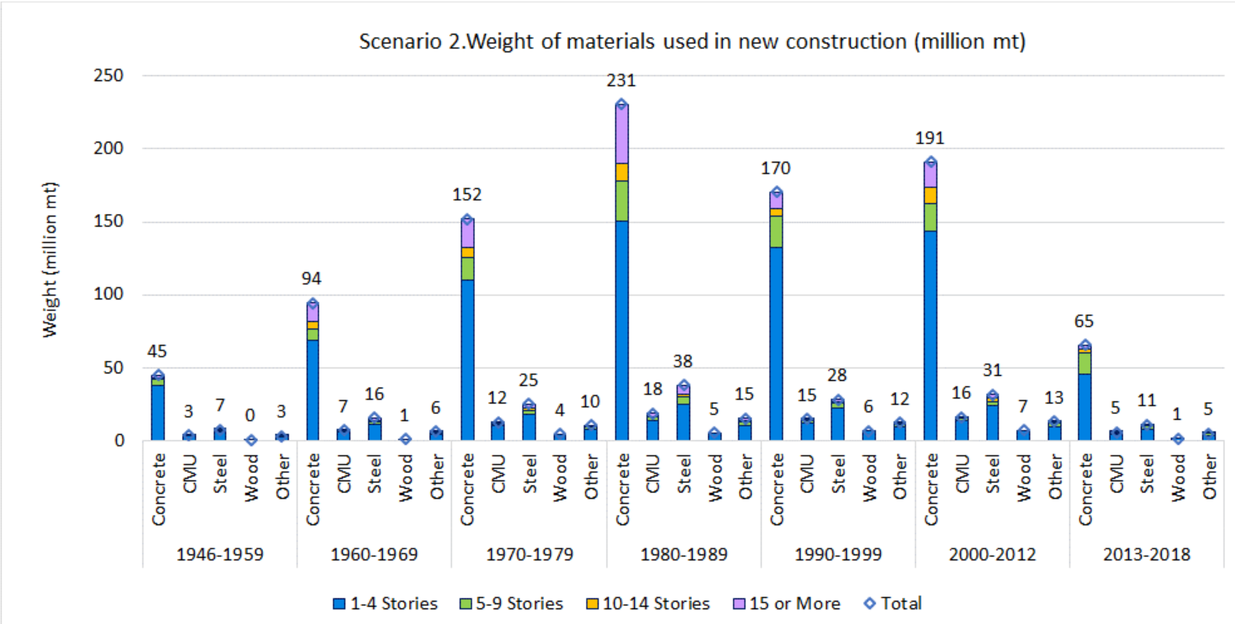



Figure A-17. Embodied energy of building materials

# A-6. Embodied Materials, Energy, and Emissions of Office Buildings Constructed After Mid-1940s




Scenario 2.Weight of materials used in new construction (million mt)
Weight (million mt)
250
200
150
100
50
0
45
3
7
0
3
94
7
16
1
6
152
12
25
4
10
231
18
38
5
15
170
15
28
6
12
191
16
31
7
13
65
5
11
1
5
Concrete
CMU
Steel
Wood
Other
1946-1959
1960-1969
1970-1979
1980-1989
1990-1999
2000-2012
2013-2018
1-4 Stories
5-9 Stories
10-14 Stories
15 or More
Total

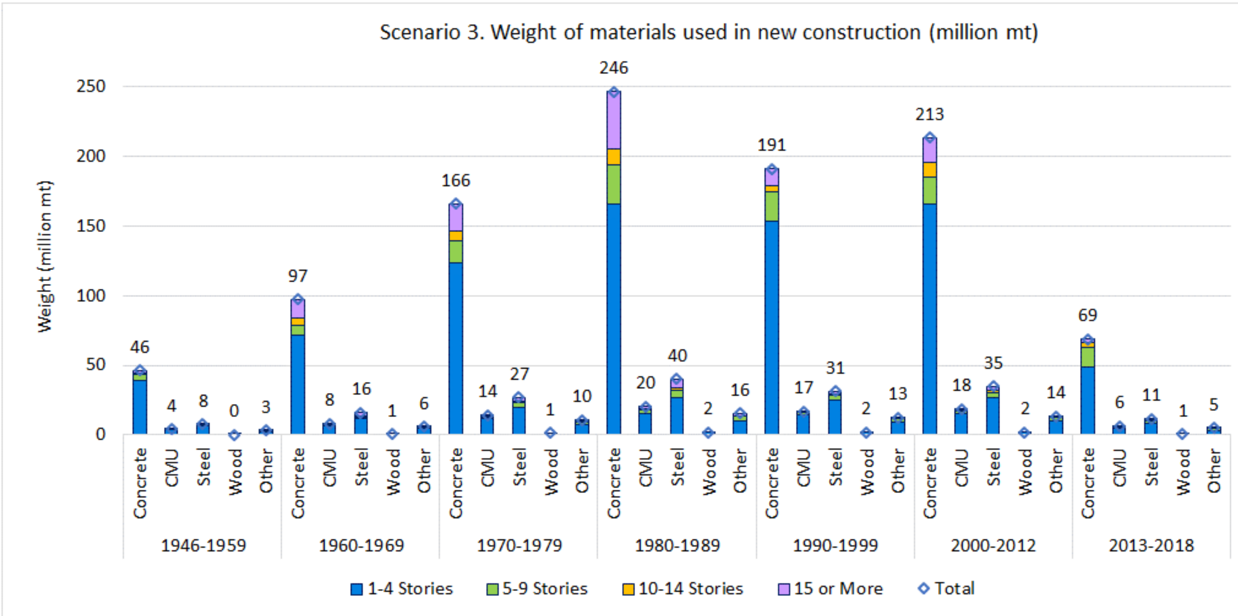
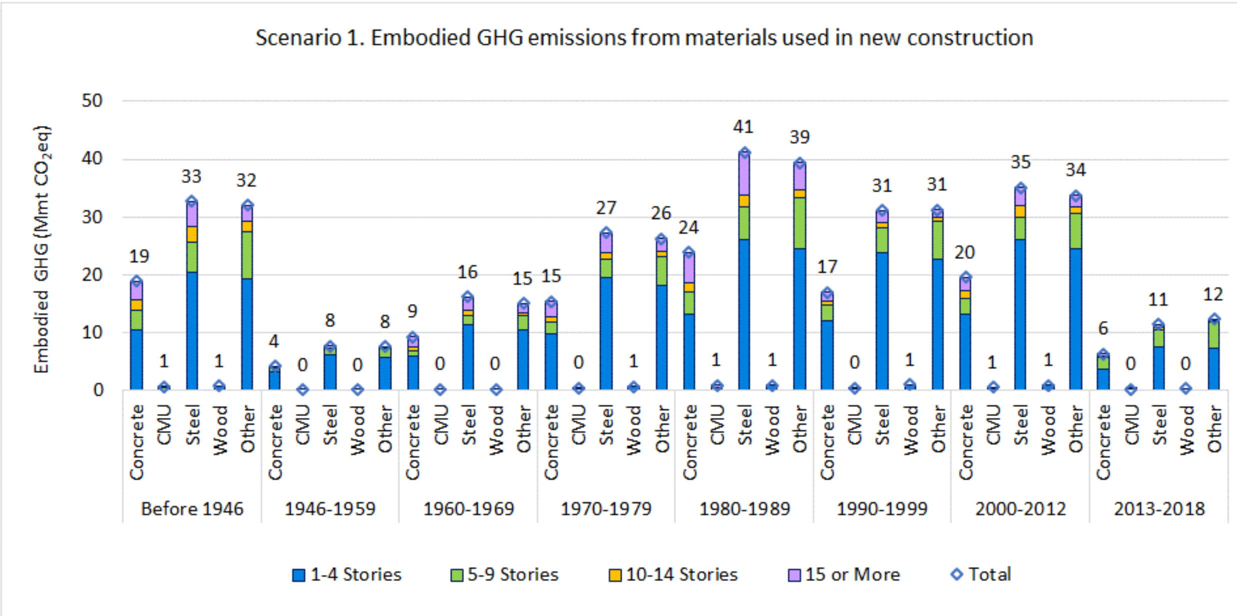



Figure A-18. Composition of major building materials used in construction of new office buildings over time (Scenario 1-3). CMU = concrete masonry unit.


Scenario 1. Embodied GHG emissions from materials used in new construction
Embodied GHG (Mmt CO2eq)
50
40
30
20
10
0
Concrete
CMU
Steel
Wood
Other
Before 1946
1946-1959
1960-1969
1970-1979
1980-1989
1990-1999
2000-2012
2013-2018
1-4 Stories
5-9 Stories
10-14 Stories
15 or More
Total

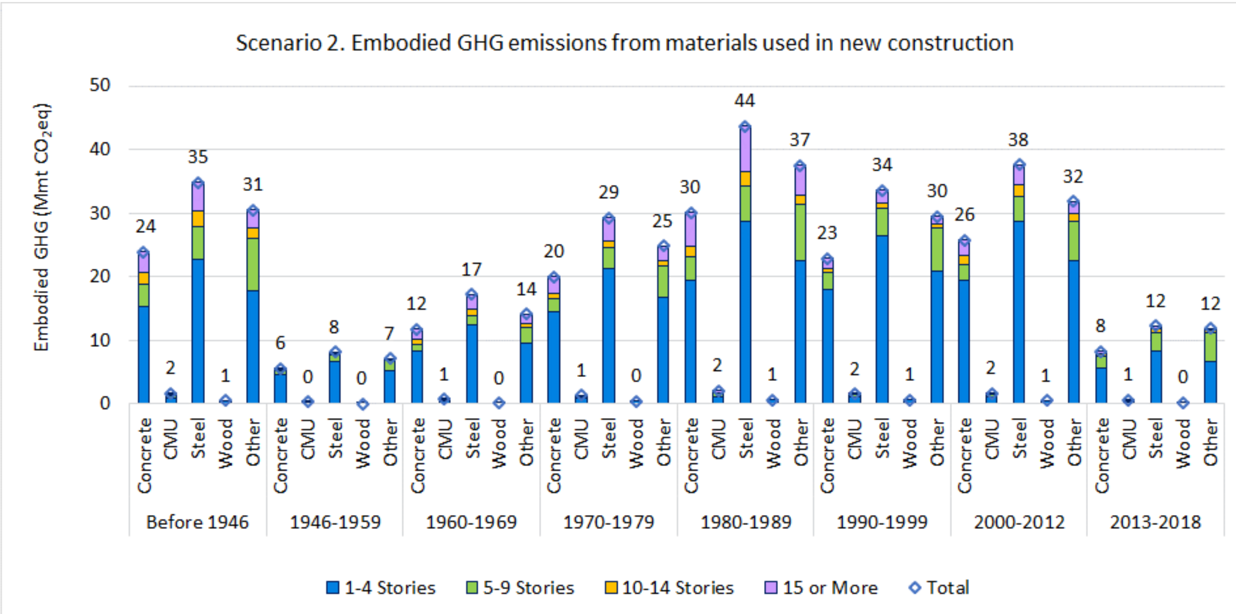
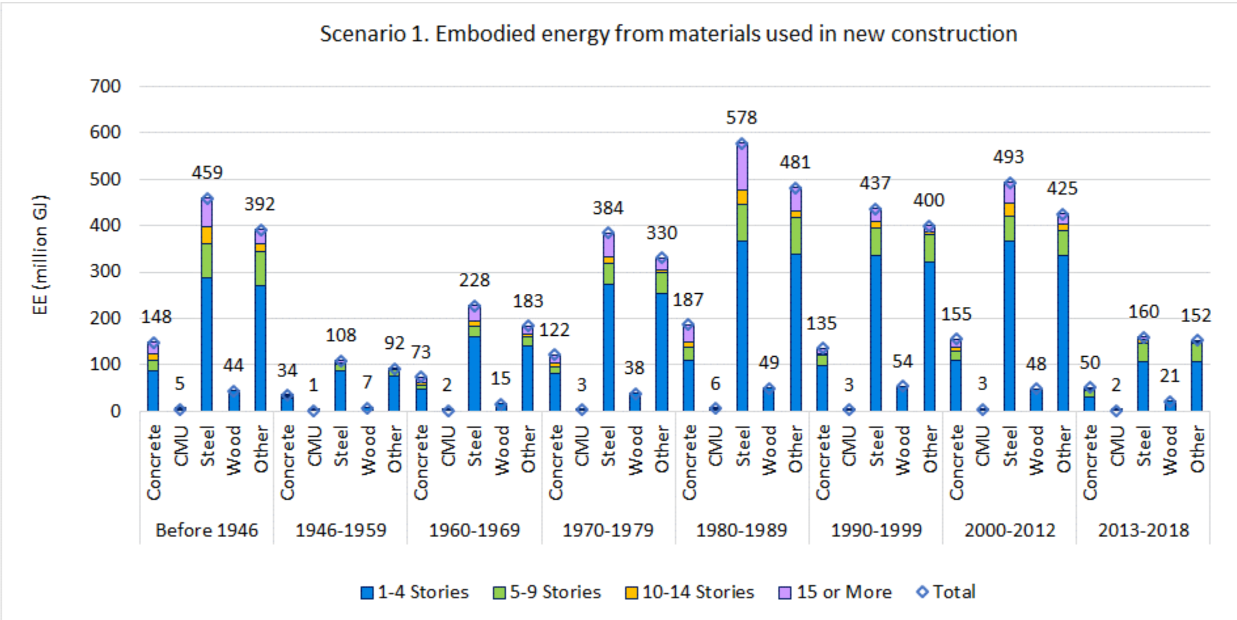
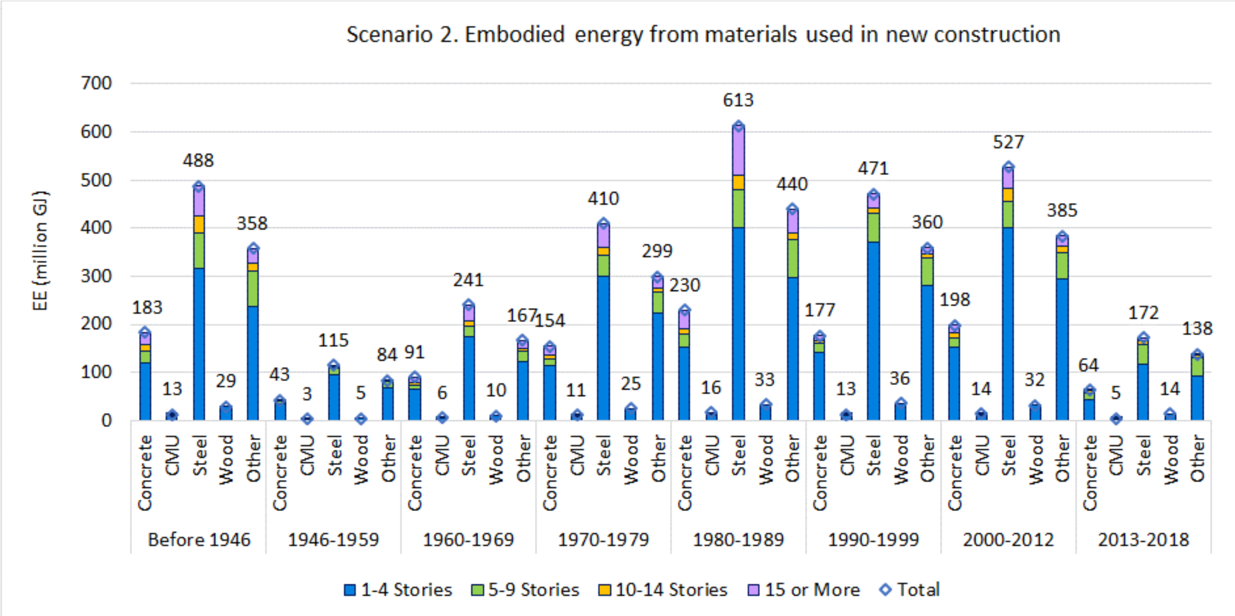



Figure A-19. Embodied GHG emissions from major building materials used in construction of new office buildings over time (Scenario 1-2).



Scenario 1. Embodied energy from materials used in new construction
EE (million GJ)
700
600
500
400
300
200
100
0
148
5
459
44
392
34
1
108
7
92
73
2
228
15
183
122
3
384
38
330
187
6
578
49
481
135
3
437
54
400
155
3
493
48
425
50
2
160
21
152
Concrete
CMU
Steel
Wood
Other
Before 1946
1946-1959
1960-1969
1970-1979
1980-1989
1990-1999
2000-2012
2013-2018
1-4 Stories
5-9 Stories
10-14 Stories
15 or More
Total



Scenario 2. Embodied energy from materials used in new construction
EE (million GJ)
700
600
500
400
300
200
100
0
183
13
488
29
358
43
3
115
5
84
91
6
241
10
167
154
11
410
25
299
230
16
613
33
440
177
13
471
36
360
198
14
527
32
385
64
5
172
14
138
Concrete
CMU
Steel
Wood
Other
Before 1946
1946-1959
1960-1969
1970-1979
1980-1989
1990-1999
2000-2012
2013-2018
1-4 Stories
5-9 Stories
10-14 Stories
15 or More
Total

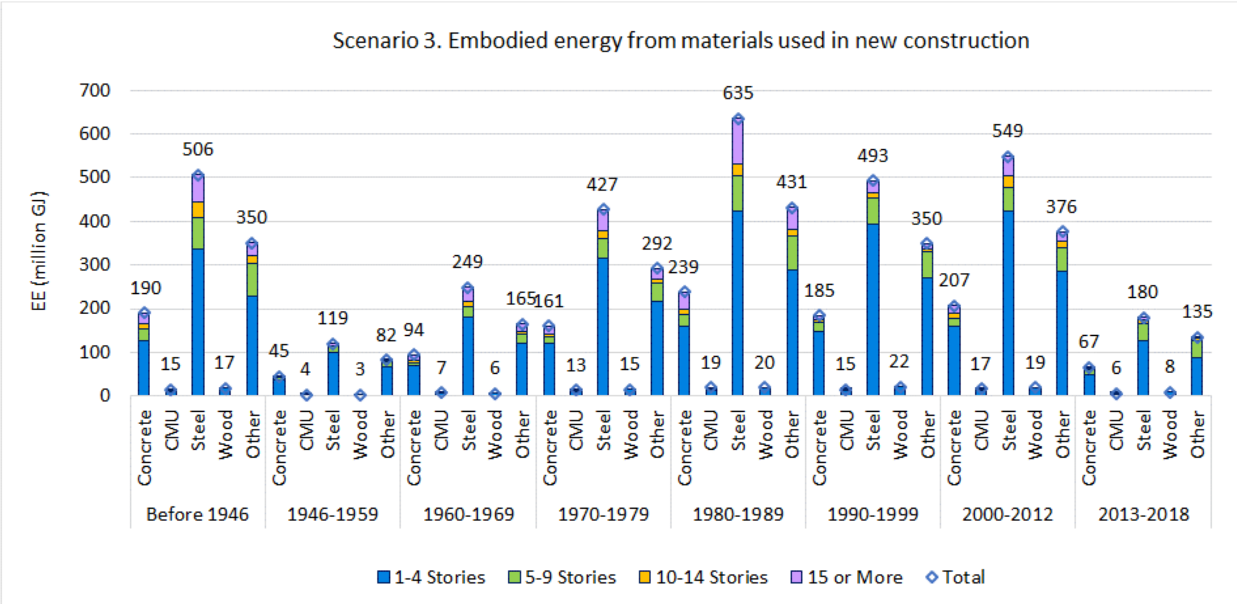



Figure A-20. Embodied energy from major building materials used in construction of new office buildings over time (Scenario 1-3)

## A-7. Embodied Energy and GHG Emissions by Structural and Non-Structural Materials used in Prototypical Office Buildings

Table A-8. Embodied energy and GHG emissions per m2 by the structural versus the non-structural materials in RC, steel, and wood-structured buildings

| | Structural materials | | | Non-structural materials |
|---|---|---|---|---|
| **Embodied GHG emissions (kg $CO_2eq/m^2$)** | **Concrete** | **Steel** | **Wood** | |
| RC Office, 1 floor | 179 | 166 | - | 154 |
| RC Office, 5 floors | 109 | 76 | - | 288 |
| RC Office, 16 floors | 101 | 73 | - | 91 |
| Wood Office, 1 floor | 88 | 129 | 5 | 119 |
| Wood Office, 4 floors | 20 | 29 | 45 | 89 |
| Steel Office, 1 floor | 66 | 143 | - | 185 |
| Steel Office, 5 floors | 42 | 108 | - | 132 |
| Steel Office, 16 floors | 55 | 113 | - | 79 |
| | | | | |
| | **Structural materials** | | | **Non-structural materials** |
| **Embodied Energy ($MJ/m^2$)** | **Concrete** | **Steel** | **Wood** | |
| RC Office, 1 floor | 1,349 | 2,338 | - | 1,757 |
| RC Office, 5 floors | 775 | 1,074 | - | 2,241 |
| RC Office, 16 floors | 734 | 1,040 | - | 943 |
| Wood Office, 1 floor | 727 | 1,817 | 251 | 1,664 |
| Wood Office, 4 floors | 165 | 412 | 2,229 | 1,066 |
| Steel Office, 1 floor | 545 | 2,031 | - | 2,032 |
| Steel Office, 5 floors | 310 | 1,538 | - | 1,637 |
| Steel Office, 16 floors | 410 | 1,613 | - | 899 |

Table A-9. Embodied energy and GHG emissions by the structural versus the non-structural materials in RC, steel, and wood-structured buildings for Scenario 3.

| ***Scenario 3*** | **Structural materials** | | | **Non-structural materials** |
|---|---|---|---|---|
| **Embodied GHG emissions (MMT $CO_2$eq)** | **Concrete** | **Steel** | **Wood** | |
| Reinforced Concrete Buildings | 218 | 176 | - | 298 |
| Steel Buildings | 91 | 203 | - | 221 |
| Wood Buildings | 18 | 26 | 8 | 35 |

| ***Scenario 3*** | **Structural materials** | | | **Non-structural materials** |
|---|---|---|---|---|
| **Embodied energy (Million GJ)** | **Concrete** | **Steel** | **Wood** | |
| Reinforced Concrete Buildings | 1,600 | 2,492 | - | 2,766 |
| Steel Buildings | 708 | 2,900 | - | 2,557 |
| Wood Buildings | 150 | 373 | 416 | 458 |

## A-8. Construction and Demolition (C&D) Waste Materials in the United States

Construction and demolition (C&D) materials consist of the debris generated during the construction, renovation and demolition of buildings, roads, bridges, and other structures. Materials included in C&D debris are steel, wood products, drywall and plaster, brick and clay tile, asphalt shingles, and concrete and asphalt concrete (asphalt pavement). 600 million short tons (544 MMT) of C&D debris were generated in the United States in 2018, which is more than twice the amount of generated municipal solid waste (292 million short tons or 265 MMT) (EPA, 2020a).

C&D concrete was the largest portion at 67.5 percent, followed by asphalt concrete at 17.8 percent. C&D wood products made up 6.8 percent, and the other products accounted for 7.9 percent combined (Figure A-8).

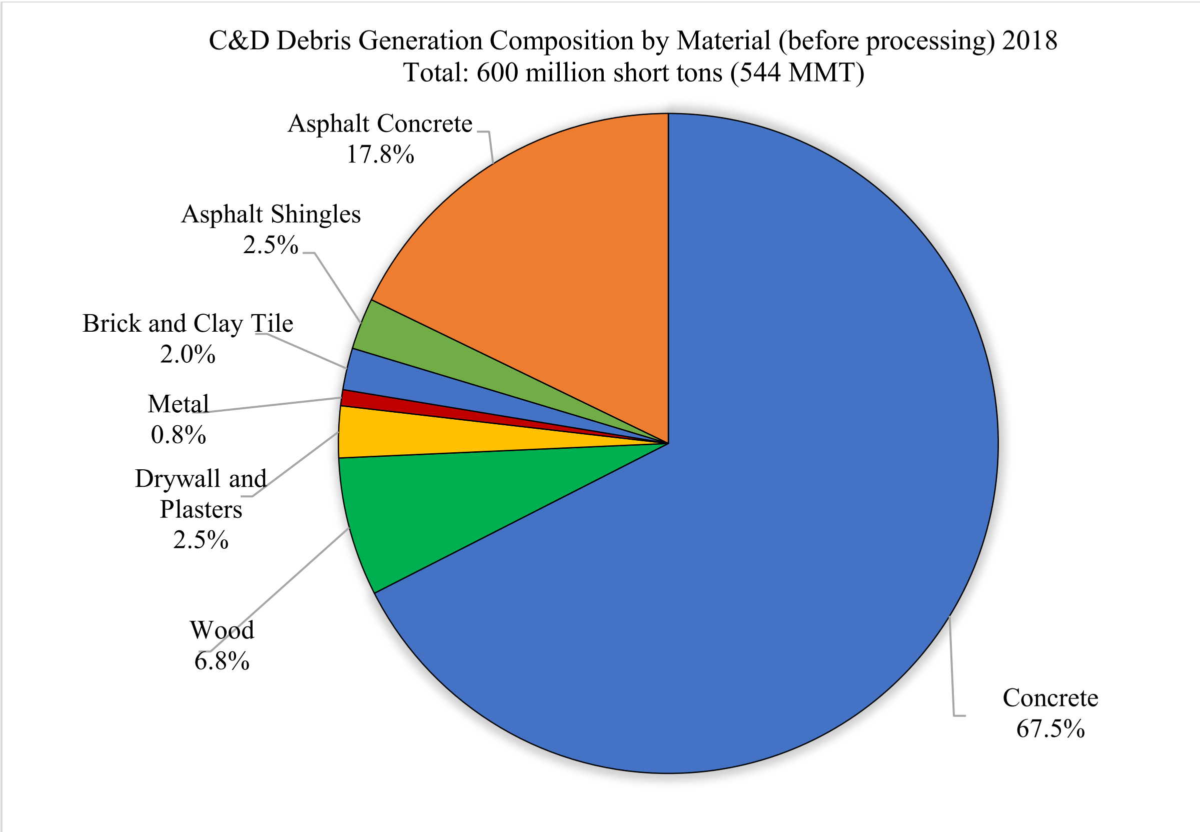



Figure A-21. C&D debris generation composition by material type for the United States, 2018 (EPA, 2020a)

Demolition represents more than 90 percent of total C&D debris generation, while construction represents less than 10 percent. This rate is more or less consistent from 2013 to 2018 (Figure A-9).

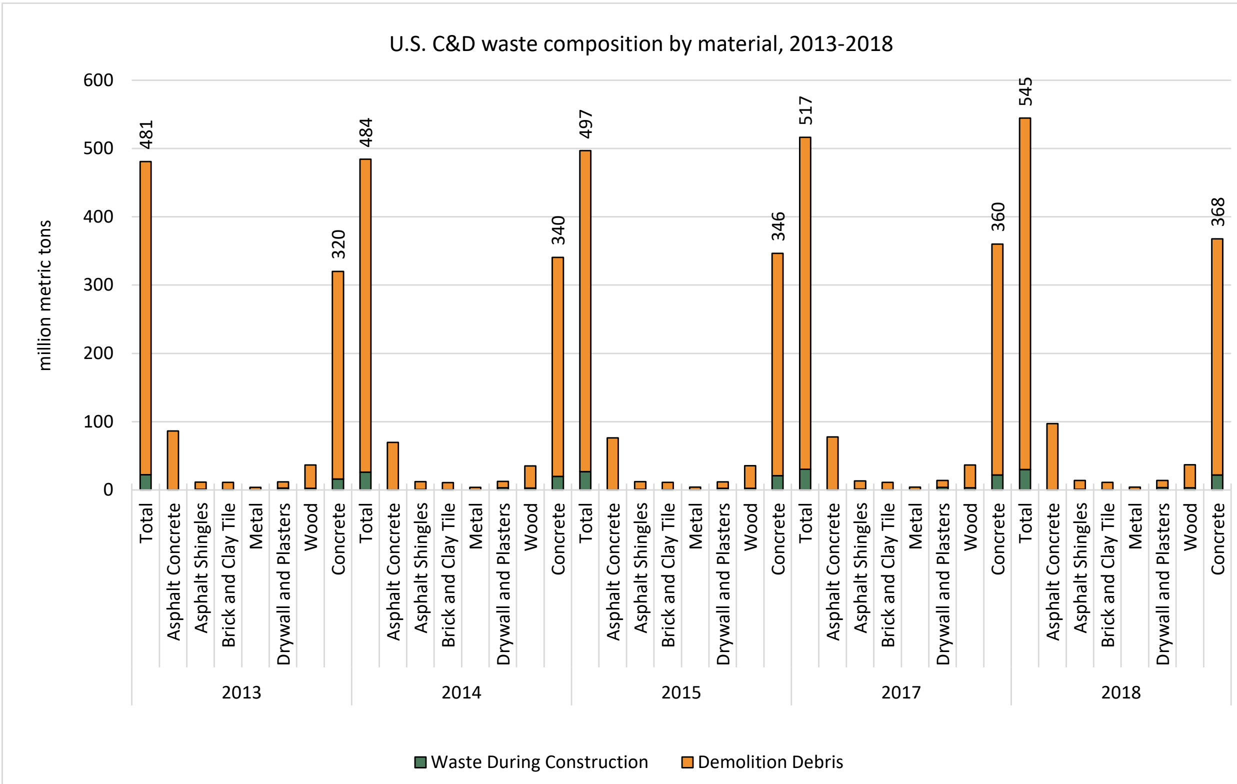



Figure A-22. C&D waste generation by material and activity from 2013 to 2018 (EPA, 2020b)

In 2018, roads and bridges contributed significantly more to the C&D waste generated than buildings and other structures, and concrete made up the largest portion for all three categories (Figure A-10 and Figure A-11).

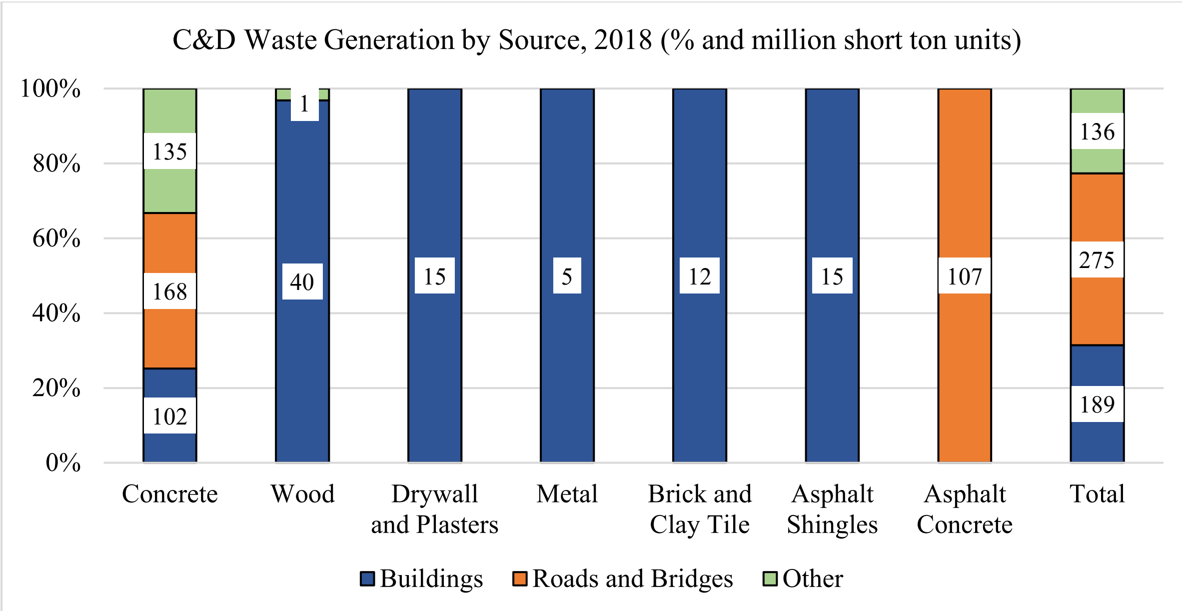



Figure A-23. C&D waste generation for all three source categories for 2018 (EPA, 2020b).

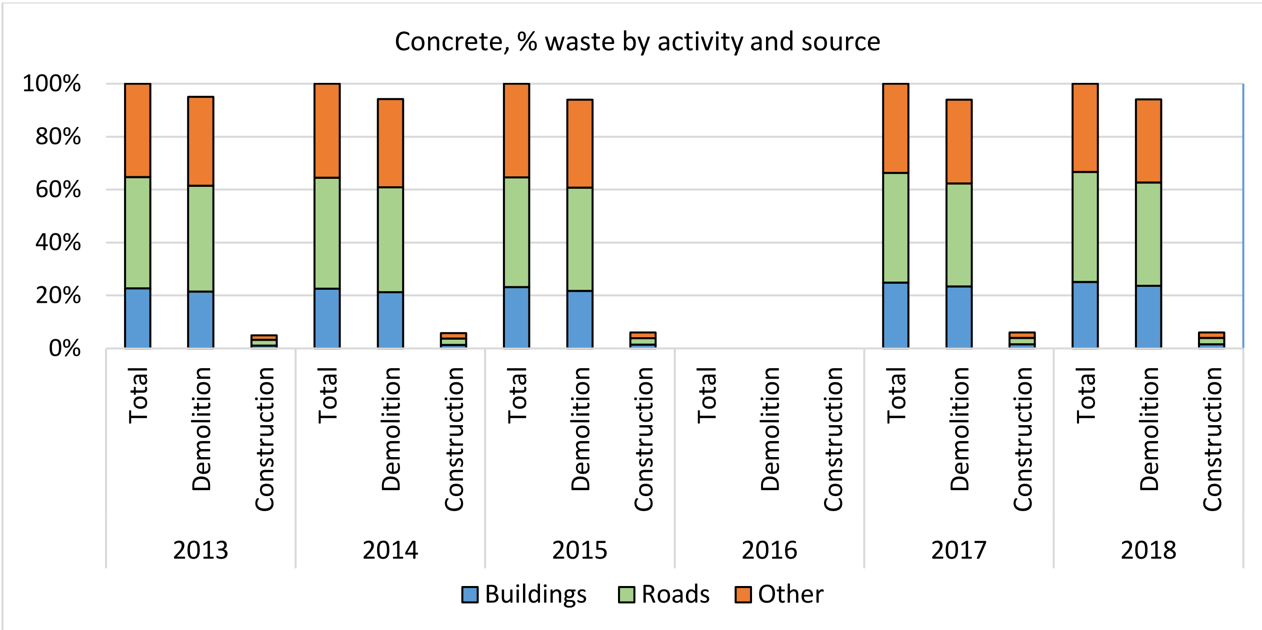



Figure A-24. Concrete waste in % by activity and source of the waste, 2013–2018 (EPA, 2020b)

C&D waste end-of-life (EOL) management includes quantities of materials going to next use or directed to landfills. "Next use" designates an intended next-use market which, depending on the material, may include fuel, manufactured products, aggregate, compost, and mulch or soil amendment. For example, about 300 million short tons of C&D concrete was processed for use in the production of aggregates. About 457 million tons of C&D debris waste directed to next use and just under 145 million tons were sent to landfills (Figure A-12 and Table A-7). Aggregate was the main next use for the materials in the C&D debris.

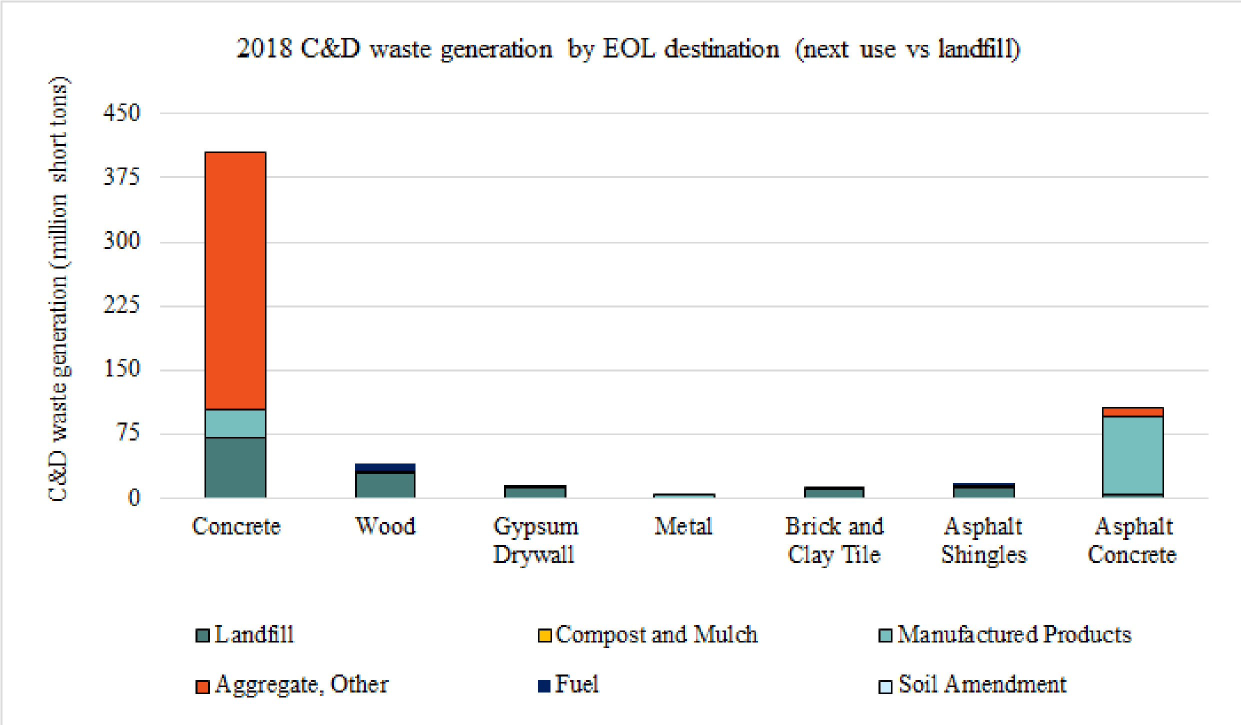



Figure A-25. C&D waste management by EOL destination, 2018 (EPA, 2020b)

Table A-7. C&D waste by material and EOL destination, 2018 (in million U.S. short tons)

| Material Type in C&D Debris | Landfill | Next Use | | | | | **Total Next Use** |
|---|---|---|---|---|---|---|---|
| | | Compost and Mulch | Manufactured Products | Aggregate, Other | Fuel | Soil Amendment | |
| Concrete | 71.2 | 0 | 32.8 | 301.2 | 0 | 0 | 334.0 |
| Wood | 29.6 | 2.5 | 1.2 | 0 | 7.5 | 0 | 11.2 |
| Gypsum Drywall | 13.2 | 0 | .2 | 0 | 0 | 1.9 | 2.1 |
| Metal | 1.1 | 0 | 3.6 | 0 | 0 | 0 | 3.6 |
| Brick and Clay Tile | 10.8 | 0 | 0 | 1.5 | 0 | 0 | 1.5 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Asphalt Shingles | 13.0 | 0 | 2.0 | .1 | .02 | 0 | 2.1 |
| Asphalt Concrete | 4.9 | 0 | 91.8 | 10.3 | 0 | 0 | 102.1 |
| **Total** | **143.8** | **2.5** | **131.6** | **313.1** | **7.5** | **1.9** | **456.6** |

EPA (2020a). Advancing Sustainable Materials Management: 2018 Fact Sheet. https://www.epa.gov/sites/default/files/2021-01/documents/2018_ff_fact_sheet_dec_2020_fnl_508.pdf. Accessed on April 8, 2022.

EPA (2020b). Sustainable Management of Construction and Demolition Materials. https://www.epa.gov/smm/sustainable-management-construction-and-demolition-materials. Accessed on April 7, 2022.

# Appendix B: Supporting Information for Chapter 2

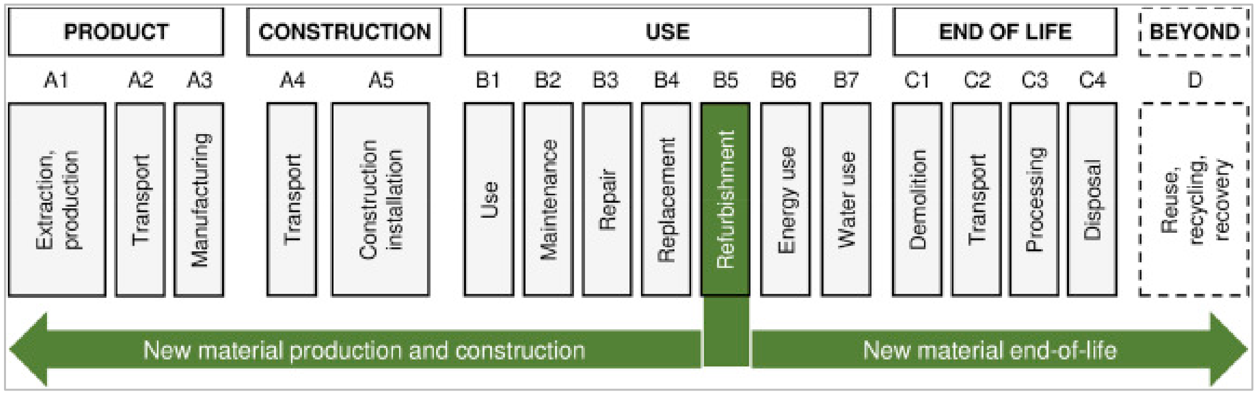



Figure B-26. Building life cycle stages and modules adapted from (European Standards, 2012). The circular economy implications over the life of buildings during various stages are presented in use, end-of-life, and beyond.

Table B-10. Description of material composition of building components for case study office and apartment buildings

| Building Component | Office Building Details | New Apartment Building Construction (After Demolition of Office Building) - Scenario 1 | Substitution in Repurposed Apartment (from Existing Office Building) - Scenario 2 |
|---|---|---|---|
| ***Substructure (Foundation + Slab on Grade)*** | Foundation wall, cast-in-place concrete, 5% rebar by weight | Same foundation system, slight increase in quantity of materials | Keep |
| | Strip footing, reinforced concrete, 5% rebar by weight | Same strip footings, slight increase in quantity of materials | Keep |
| | Spread footings, 3,000 psi concrete, 5% rebar by weight | Same spread footings, slight increase in number of footings | Keep |
| | Slab on grade, reinforced concrete, 5% rebar by weight | Same slab on grade system, same quantity of materials | Keep |
| ***Structural Frame (beam + column,*** | Columns for 12 ft. story height, cast-in-place, 4,000 psi concrete, 5% rebar by weight | Same structural frame, same quantity of materials | Keep |

| | | | |
|---|---|---|---|
| ***slab floor and roof system)*** | Beams, cast-in-place concrete, 2% rebar by weight | | Keep |
| | Slab, cast-in-place concrete, 2% rebar by weight | | Keep |
| ***Exterior Façade (Enclosure, including roof coverings)*** | Metal facing panels, textured aluminum with plywood backing on concrete masonry unit (CMU) and R-15 fiberglass insulation | Three-coat stucco on self-furring metal lath and regular CMU | Remove. Three-coat stucco on self-furring metal lath and regular CMU |
| | Studs, galvanized steel, 16" apart, for 12 ft. story height for 5 stories | Same quantity and type | Keep. |
| | Windows - Aluminum, sliding, insulated glass | Windows - Aluminum, sliding, double-panel glass. More openings in apartment building | Remove. Install aluminum, sliding, double-panel glass. More openings in apartment building |
| | Exterior doors - aluminum and glass, with transom, narrow stile, double door | Exterior doors - aluminum & glass, without transom. More openings | Remove. Install aluminum and glass, without transom. More openings |
| | Exterior doors - 18 gauge steel door frame | - | - |
| | Roofing - Single ply membrane, EPDM, stone ballast, R-20 XPS insulation + Aluminum roof edges and flashing | Same roofing system- Increased material quantity | Remove. Install similar roofing system, increased material quantity |
| ***Interior Wall System*** | CMU partition, light weight, hollow, foam insulation | - | - |
| | Metal partition, 5/8" fire rated gypsum board, sound attenuation insulation + Furring 1 side only, steel channels | Metal partition, 5/8" fire rated gypsum board + 1/4" sound deadening gypsum board | Remove. Install metal partition, 5/8" fire rated gypsum board + 1/4" sound deadening gypsum board |
| | 5/8" Gypsum board, exterior sheathing, fire resistant | 1/2" fire rated gypsum board, taped and finished, painted on metal furring | Remove. Install 1/2" fire rated gypsum board, taped |

| | | | |
|---|---|---|---|
| | | | and finished, painted on metal furring |
| | Studs, galvanized steel, 24" apart | Same quantity and type | Remove. Install same system but increased material quantity |
| | Interior doors - single leaf, steel frame, hollow metal, commercial quality | Same door frame type, more openings | Remove. Same door frame type, more openings |
| | Staircase, galvanized steel | Same | Keep. |
| ***Wall / Floor / Ceiling Finishes*** | Interior paint on plaster and drywall + primer | Same but more paint + primer | Remove. Same but more paint + primer |
| | - | Ceramic tile for walls | Add. Ceramic tile for walls |
| | Carpet floor tile, nylon | Carpet tile, nylon but larger surface coverage | Remove. Same but larger surface coverage |
| | Vinyl, composition floor tile | Vinyl, composition tile but smaller surface | Remove. Same but smaller surface coverage |
| | Ceramic natural clay floor tile | Ceramic natural clay tile, same surface area | Remove. Same type and surface coverage |
| | Acoustic ceilings, fiberglass board | 1/2" fire rated gypsum board | Remove. 1/2" fire rated gypsum board |
| ***Service Assemblies*** | Elevator; Water heater; AC; Switchgear | Same assemblies, quantities vary. | Remove. Install same assemblies. |
| | Copper piping for water supply line; PVC piping and roof drain; Steel, wet pipe sprinkler system and standpipe risers | | Quantities vary from office to apartment building |

See Appendix A, Table A-3, for a compilation of EPDs (California)

In Figure B-2, dark navy and red bars represent initial mass of materials (per $m^2$) used in construction of a new office building at year 0 and a new apartment at year 50, respectively. Green bars correspond to mass of materials replaced over the service lives of office and apartment buildings. The negative scale of the graph shows end-of-life possibilities for materials after demolishing and/or maintenance: Light blue bars represent materials recycled after demolishing the office and apartment buildings in year 50 and 100, respectively. Orange bars show aluminum recycled after maintenance over 100 years. It is assumed that 30% of the structural concrete, 100% of metals (aluminum, steel), 30% of glass, and 50% of copper from piping are recycled, while the rest of the materials are landfilled. Grey and yellow bars show landfilling after demolition and maintenance, respectively.

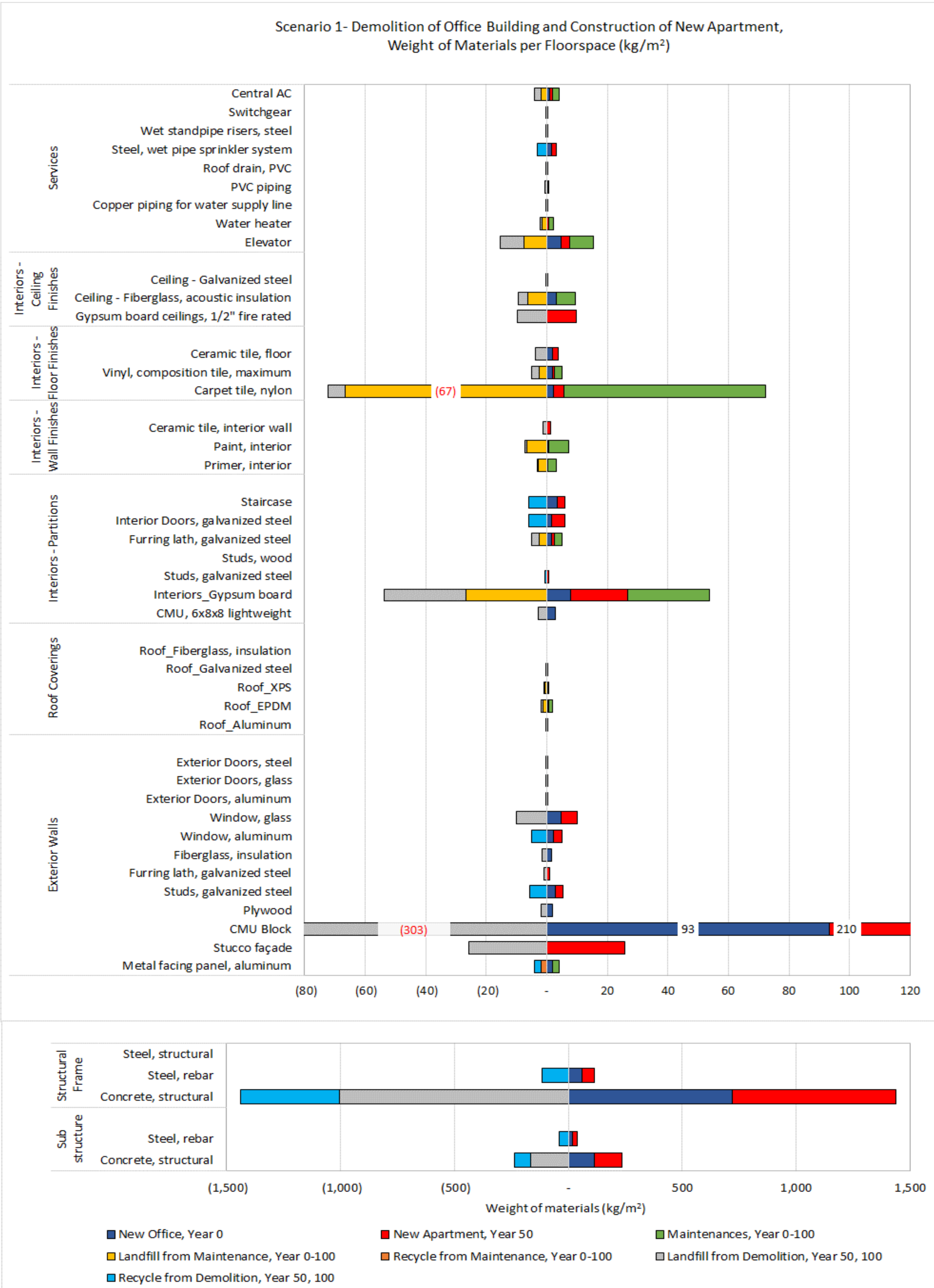



Figure B-27. Mass of materials per building area in Scenario 1

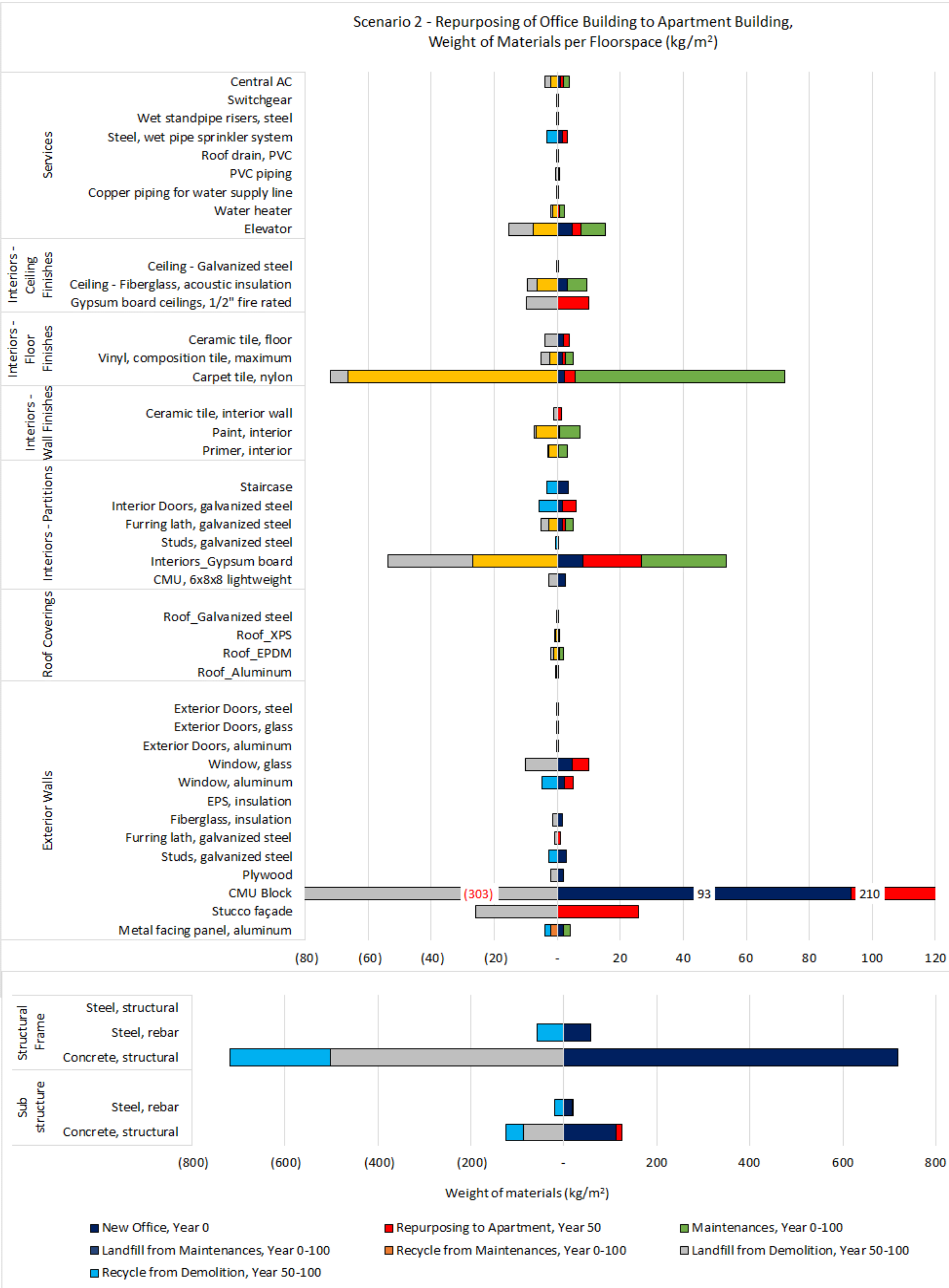



Figure B-28. Mass of materials per building area in Scenario 2

Table B-2. Maintenance schedule for materials and components (Junnila et al., 2006)

| ***Materials Replaced*** | ***Year of Replacement*** |
|---|---|
| Bitumen (roof vapor barrier) | 20 |
| Carpet | 4 |
| Elevator | 25 |
| Fiberglass (façade panels) | 20 |
| Gypsum board (interior walls) | 25 |
| Paint, incl. primer | 5 |
| Galvanized steel | 25 |
| EPDM (Ethylene propylene diene terpolymer) roof membrane | 25 |
| Vinyl floor tiles | 25 |

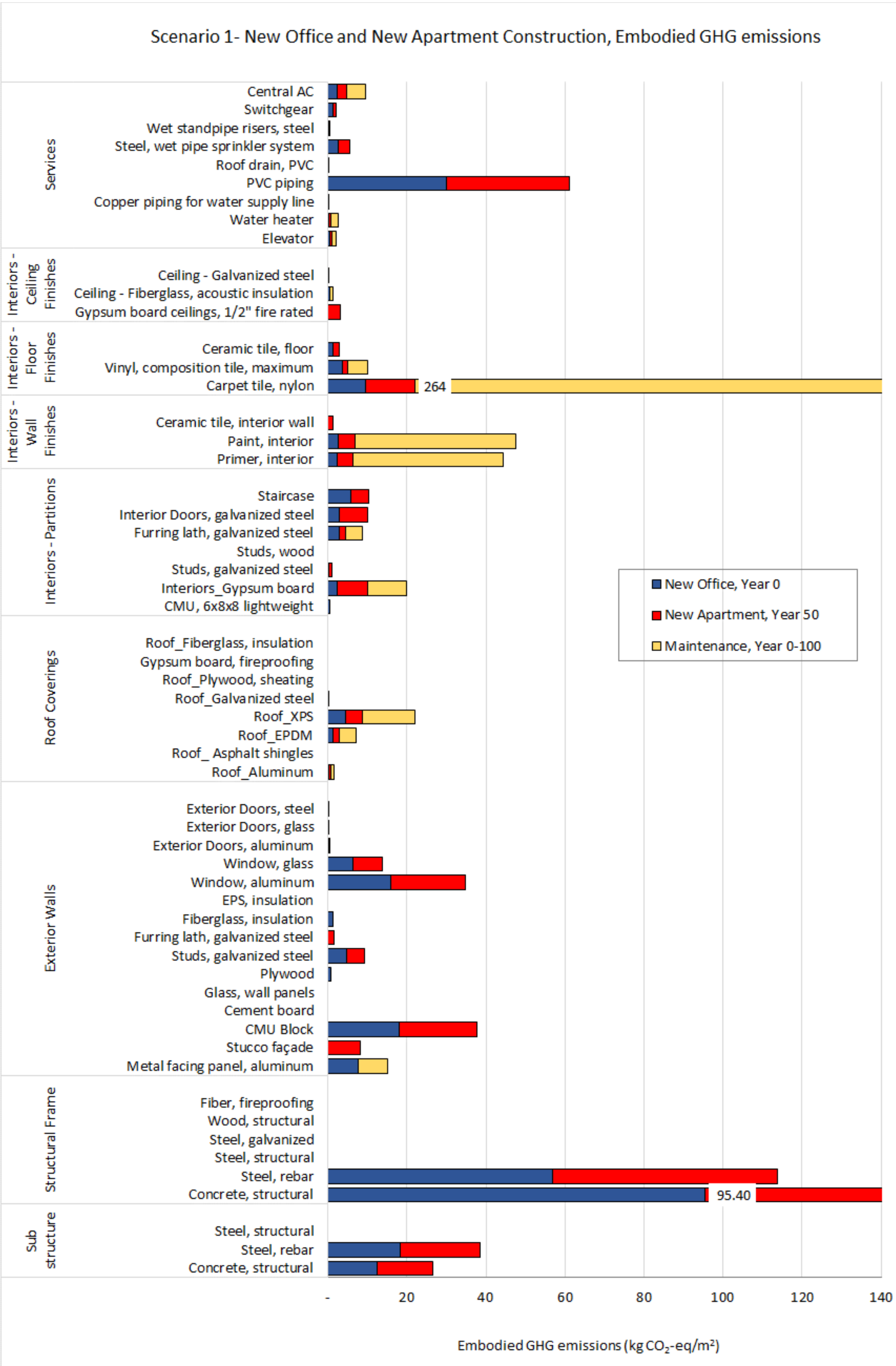



Figure B-29. Embodied GHG emissions from Scenario 1

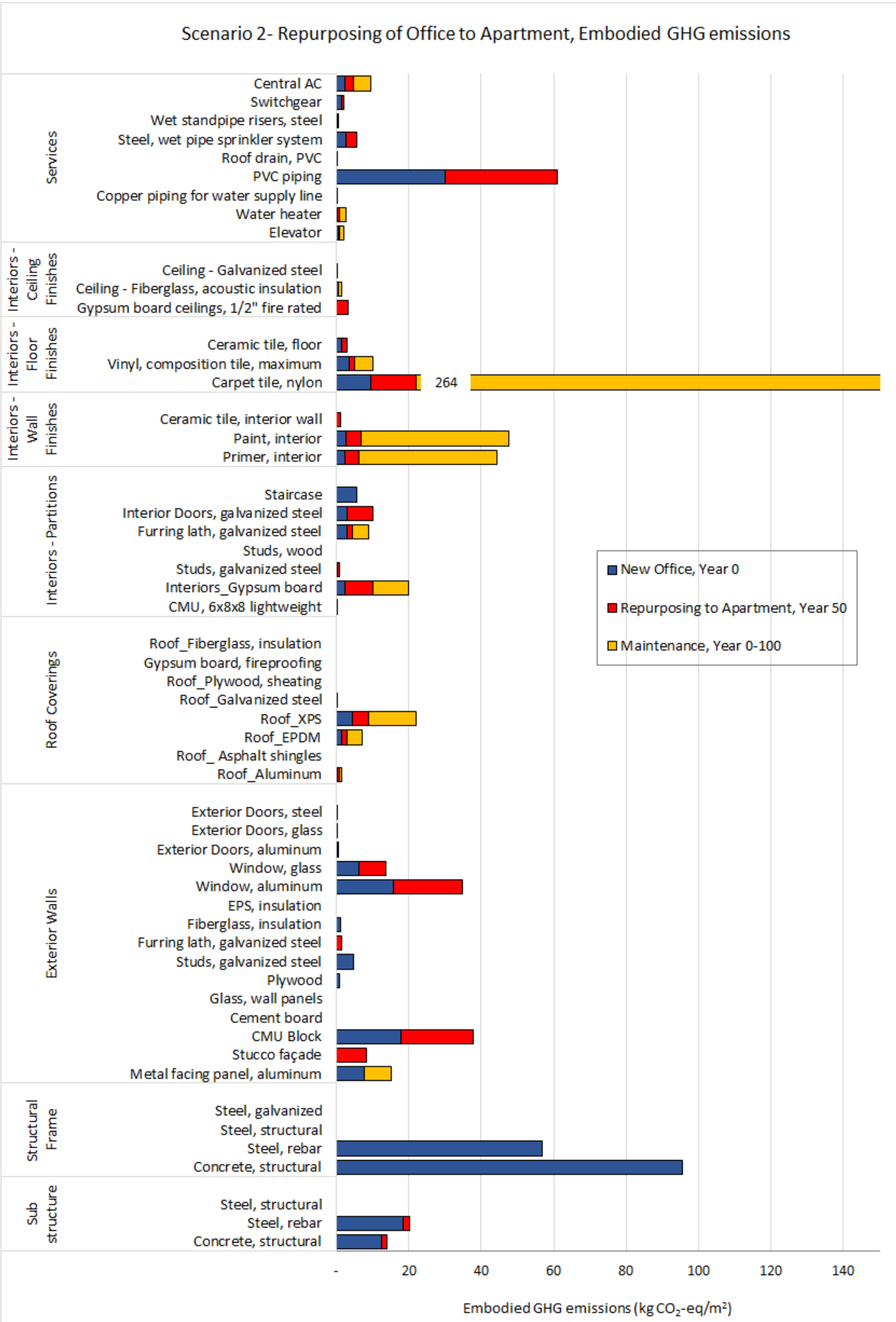



Figure B-30. Embodied GHG emissions from Scenario 2

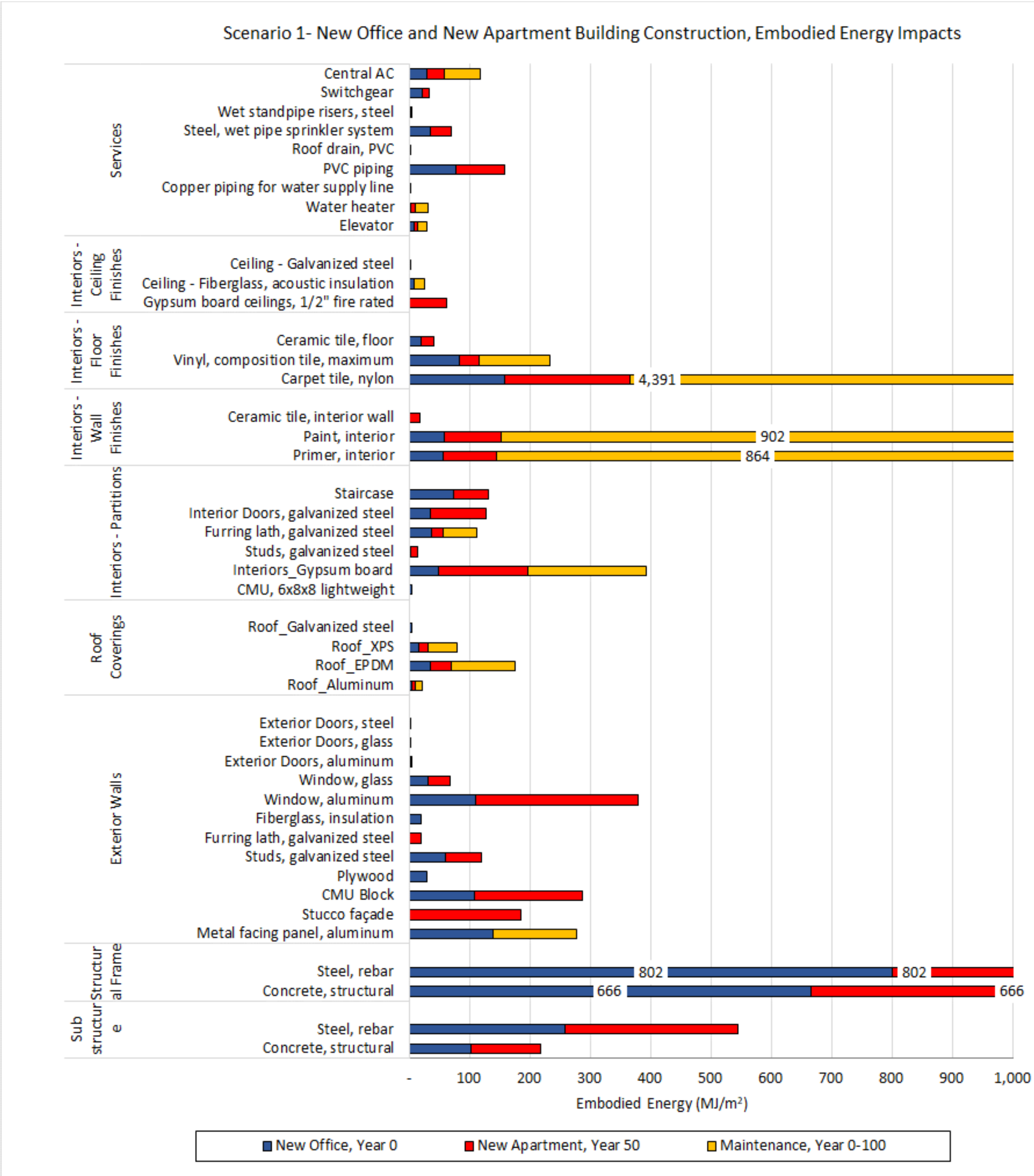



Figure B-31. Embodied energy from Scenario 1

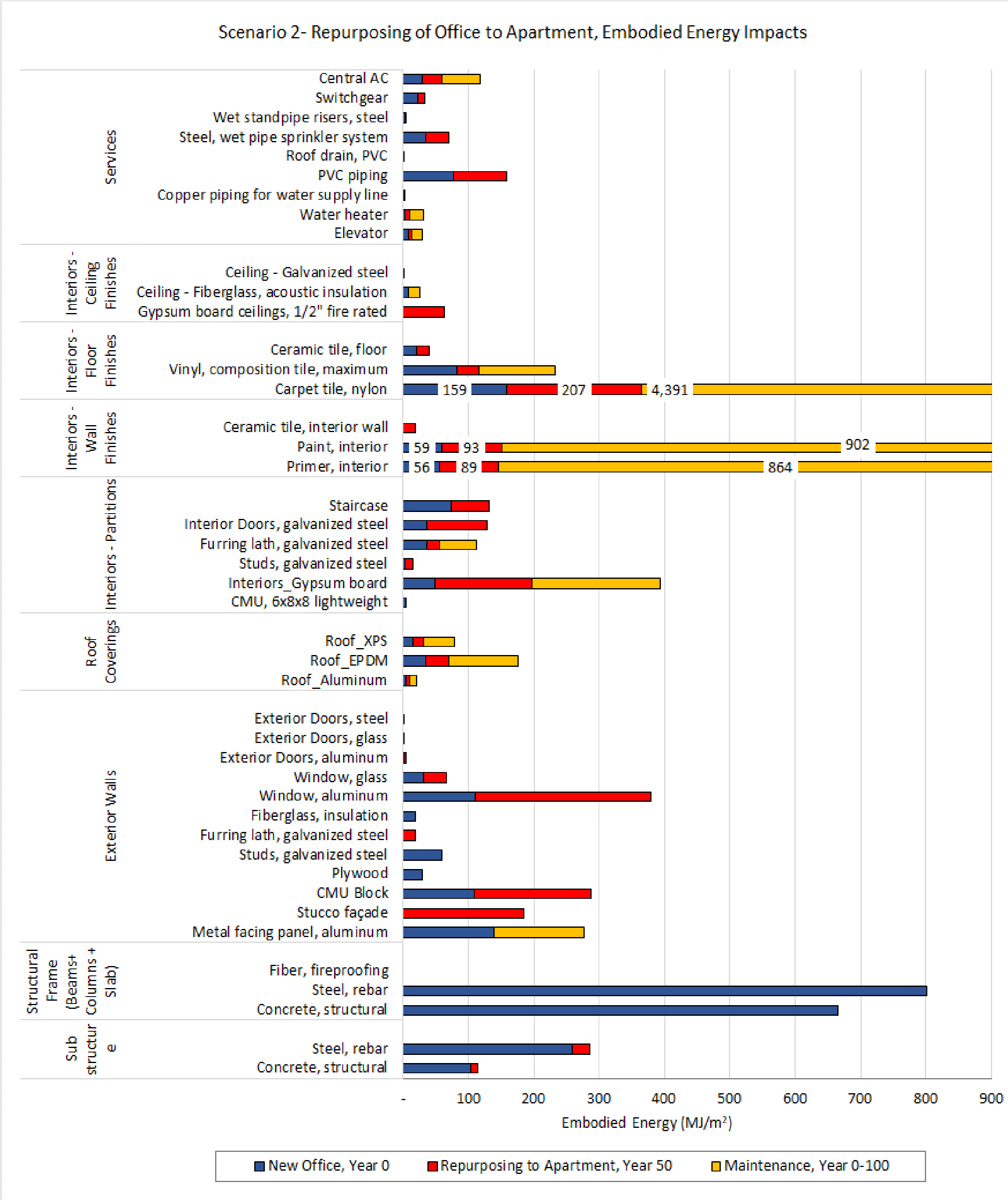



Figure B-32. Embodied energy from Scenario 2

# References

European Standards, 2012. *DIN EN 15978 Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method* [Online]. Available: https://www.en-standard.eu/din-en-15978-sustainability-of-construction-works-assessment-of-environmental-performance-of-buildings-calculation-method/ [Accessed March, 17 2022].

Junnila, S., Horvath, A. and Guggemos, A.A., 2006. Life-Cycle Assessment of Office Buildings in Europe and the United States. *Journal of Infrastructure Systems,* 12**,** 10-17.