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Embodied energy and greenhouse gas emission trends from major construction materials of U.S. office buildings constructed after the mid-1940s

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ABSTRACT

While recognized as important, calculation of embodied energy and greenhouse gas (GHG) emissions associated with buildings, especially at a large scale, has scant literature. A model has been created for estimating the inventory of structural and non-structural materials and building components and their associated embodied energy and GHG emissions for the approximately 807,400 office buildings constructed in the United States between 1946 and 2018. The buildings were modeled using eight prototypical designs. We estimate that 1100–1300 million metric tons of materials are embodied in these 807,000 buildings (90% of which have just 1–3 floors), as well as 6–7 years' worth of national construction and demolition waste. In total, 6.5 billion Gigajoules of primary energy use (~6% of the U.S.'s 2021 energy consumption) and 0.5 billion metric tons of carbon dioxide equivalent emissions (~8% of the U.S.'s 2020 total GHG emissions) are estimated to be embodied in these buildings. One-floor steel and wood buildings were about equally GHG intensive from structural materials as well as combined structural and non-structural materials perspectives, while reinforced concrete (RC) buildings were 50% and 27%–47% more GHG intensive, respectively. From the all-materials-use perspective, 5-floor steel buildings were 54% more GHG intensive to construct than wood buildings, and in turn RC buildings were 68% more GHG intensive than steel buildings. Non-structural material contributions were significant. Increasing economies of scale in embodied impacts can be observed as the number of floors increases. Results constitute points of reference for those who seek to find ways of reducing the carbon footprint of buildings.

1. 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 [1]. Between 2020 and 2050, it is predicted that about 50% of emissions associated with new buildings will be embodied [2]. The embodied GHG emissions are attributed to the materials and energy required to construct the building, and they result primarily from the burning of fossil fuels (for electricity, transportation, and on-site manufacturing energy) and chemical reactions (of carbon dioxide [CO_2] during the calcination of limestone to produce cement) [3]. 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 due to cement) [4]. The fraction due to all construction materials and activities has been estimated at 6% of the U.S. total [3]. 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 total U.S. GHG emissions (6572 Mmt of CO_2 eq.) (Supporting Information (SI), Section 1 -Table 1 and Fig. 1)[7].

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 [8]. According to the U.S. Environmental Protection Agency (US EPA), 544 Mmt of construction and demolition (C&D) debris were generated in 2018 in the United States (SI, Section 2 - Fig. 2). This is more than twice the amount of generated municipal solid waste: 265 Mmt [10]. C&D debris consists of waste generated during construction, renovation and demolition of buildings, roads, bridges, and other structures. More than 90% of the C&D waste was from demolition, while the share of waste from on-site construction activities was less than 10% (SI, Section 2 - Figs. 3 and 4). About one-third of C&D waste in 2018, 189 Mmt, was from buildings (SI, Section 2 - Figs. 5 and 6). Concrete made up the largest portion of C&D waste at 68% (368 Mmt) and 54% (102 Mmt) of total and buildings-related C&D waste, respectively, in 2018 (SI, Section 2 - Figs. 2-6). Concrete waste grew

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consistently between 2013 and 2018, adding about 412 Mmt to the buildings-related C&D waste stream in the period [11] (SI, Section, Fig. 6).

With the increasing manifestations of climate change, the depletion of natural resources used in the construction industry, and increasing volumes of C&D waste, sustainability has gained wide importance, and the term circular economy (CE) has emerged as one of the most important factors leading to sustainable development [12]. As opposed to the prevailing traditional economic system, which is based on the trifecta of “make, use, and finally, dispose of,” CE aims for continuous use of products by recycling and reusing instead of disposing them to create a closed-loop system and reduce resource consumption [13]. CE 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 [14]. However, buildings are often one-of-a-kind projects where designs are based, importantly, on geography, climate, purpose, building codes, and available technologies. Moreover, buildings are characterized by their long lifetimes and accompanied by thousands of tons of materials embedded in them. Therefore, implementation of CE strategies is a complicated task that requires extensive data and information about the building stocks, materials and waste flows through buildings, and their embodied impacts.

In this article, we describe an approach 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 m^2 of floor space. The scope of the analysis is limited to the product stage (A1-A3 as shown in Fig. 1). The construction, use, and end-of-life (EOL) stages are outside the scope of this analysis because the focus is on estimating the embodied energy and GHG emissions from building materials. 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 (Fig. 1).

The purpose of this analysis is to provide detailed information on material quantity and composition and embodied impacts of the existing U.S. building stock, which are likely to be demolished in the near future. A detailed understanding of the building stock today is critical to informing the stakeholders and supporting the circular economy, sustainability applications, and future planning in the construction industry.

2. 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 CO_2 eq.), i.e., emissions arising from manufacturing and processing of building materials or their contribution to life-cycle GHG emissions [3]. Only a few studies have investigated a larger number of buildings that represent a given region, a city, or a nation [15]. In an early research study, Reyna and Chester [16] 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, and GHG emission 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. The analysis was based on only three materials (concrete, steel, and aluminum) due to scarce literature on 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. [17] 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 building information modeling (BIM) examples of existing projects or published results. The results showed a wide range of variability as structural material quantities varied between 200 kg per m^2 and 1800 kg per m^2 and total-building embodied CO_2 eq. between 150 and 600 kg CO_2 eq. per m^2. Morsi et al. [18] analyzed the contribution of different design scenarios of a residential building’s structural system using the latest One-Click LCA plugin in the BIM platform (BIM-LCA integration). Their methodology facilitated data processing to overcome the associated challenges of LCA complexity. Röck et al. [19] 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 [19]. De Wolf et al. [20]

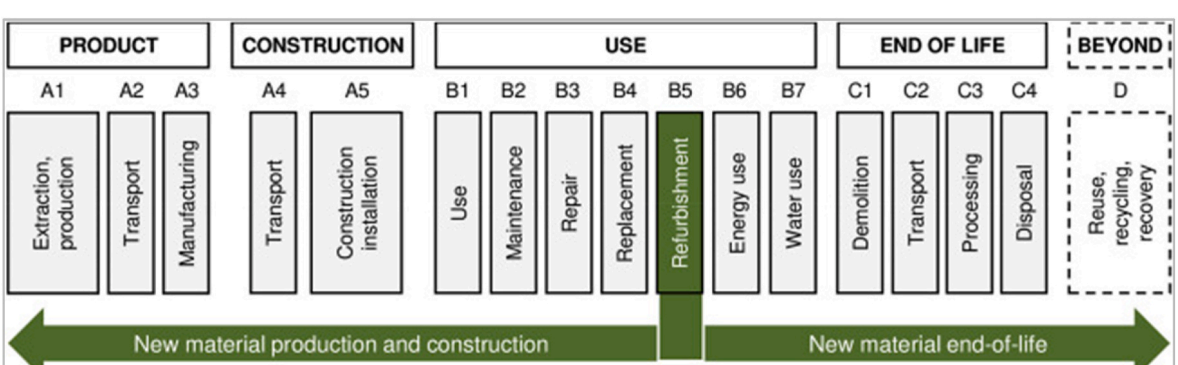

Fig. 1. Building life-cycle stages and modules adapted in the analysis are A1-A3 [6].

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. [21] 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., 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 could be considered in optimising embodied carbon-intensive components and materials based on their different design- and location-specific contexts. Recently, Lanau and Liu [22] quantified the total amount and spatial (including vertical) distribution of 46 construction materials stocked in buildings (residential and nonresidential), roads, and pipe networks (wastewater, water supply and natural gas) for the city of Odense, Denmark. They estimated the material stocks through integration of a GIS-based bottom-up approach with primary data on building material intensity coefficients. In total, 329 mt per capita of construction materials were stocked in Odense.

Only a handful of studies in the available literature have investigated a larger number of buildings, and they focused only on a limited number of building characteristics. There is no multi-building or large-scale building stock study from the United States. Therefore, there is a need for an insightful and practical approach for 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.

3. Materials and methods

Embodied impacts of the U.S. office building stock (at material and component level) from 1946 to 2018 are estimated methodologically in three major steps. The first step constitutes the compilation and extraction of the U.S. office building data in terms of their characteristics and year of construction from the Commercial Buildings Energy Consumption Survey (CBECS) database. The second step is the identification and creation of prototypical office buildings that represent the building stock. In this step, bill of materials (BOM) compiled for each prototype were converted into material quantities used in building assemblies and components. Quantities of materials used in the U.S. office building stock were then estimated by the integration of CBECS data with the prototypical office building data to estimate stock-level bill of quantities of materials. In the last step, embodied energy and GHG (CO_2 eq.) emission factors extracted from the compiled environmental product declarations (EPDs) were assigned to the materials used in the construction of U.S. office buildings to quantify the embodied energy (in GJ) and GHG emissions (in Mmt of CO_2 eq).

3.1. Estimation of the office building stock in the United States

There is no central database of all office buildings in the United States. Therefore, we estimated their number and floor space from publicly available surveys, using a systematic approach. The U.S. Department of Energy's (DOE) CBECS microdata [9] have provided information about the location, floor space, number of floors, and year of construction of the office buildings in our study. The microdata file contains 6436 records, 1332 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 m^2) in the United States, 970,000 (1.54 billion m^2) of which are office buildings (Fig. 2). The floor area was scaled up to the national level using the multipliers provided for each office building type in the microdata.

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. Only 163,000 buildings were built before 1946, the year building data were first being recorded by DOE in CBECS (SI, Table 5). 56% of the 807,400 office buildings are one-floor high, 28% have two floors, 11% have three floors, 4.5% have between four and 14 floors, and only 0.5% are high-rises with 15 floors or more, thus nearly all (95%) of U.S. office buildings are low-rise with just one to three floors. The total floor space in such buildings constructed between 1946 and 2018 constitutes 57% of the total (SI, Section 5 – Fig. 8).

3.2. Estimation of bill of materials for office buildings

In contrast to the De Wolf et al. [17] 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 [5]. RSMeans is a U.S. industry-standard, pay-per-use building information database that provides cost information on material and construction activities, but also, usefully, BOMs for prototypical building designs of many sizes and uses, including residential, commercial, and industrial. The data are representative of how buildings are currently 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 that constitutes the basis for prototypical building analysis.

To characterize the U.S. office building stock, we first identified eight types of prototype office building designs, with variations of structural frame options (reinforced concrete (RC), 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 [5] (Table 1).

The BOM obtained from RSMeans for the eight building types were then converted into material quantities in units of mass 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 mass of these buildings. Other building components that needed substantial assumptions were related to the quantification of exterior and interior wall systems, studs, and piping for water supply and sewage located throughout the buildings. Table 2 provides a list of the major building materials and components/subcomponents included in the prototypical buildings.

As previously noted, one of the key pieces of missing information is the distribution of office buildings by their structural frame type which is crucial in estimating embodied energy and GHG emissions from the construction of office building stock at national level. Since there is no publicly available dataset, we had to make assumptions based on professional judgment together with the information from CBECS microdata to capture the variation in structural systems across three different scenarios (Table 3):

- o Large office buildings are composed of 50% high-rise (10 or more floors) and 50% mid-rise (5–9 floors) buildings by floor space.

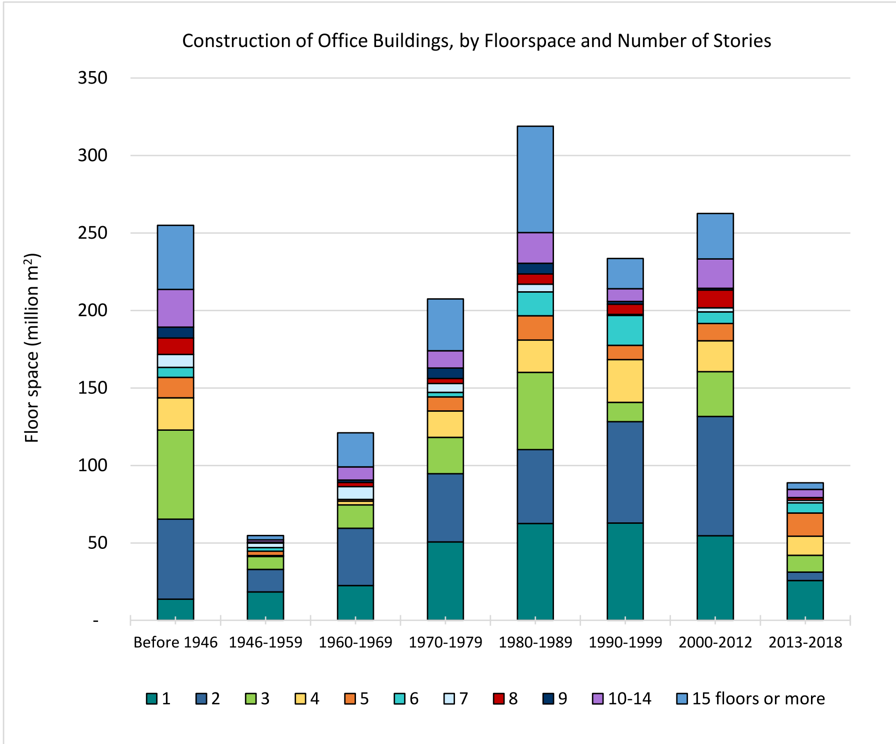

Fig. 2. U.S. office building construction statistics, based on CBECS data [9].

Table 1
Characteristics of prototype office buildings (note floor height is 12 ft. (3.65 m). Data based on RSMeans [5].

Building Type	Floor Count	Floor Area, ft^2 (m^2)
Office, 1 floor with Exterior Insulation and Finish Systems (E.I.F.S) (Cement board); Steel frame	1	7000 (650)
Office, 5–10 floors, with E.I.F.S.; Steel frame	5	50,000 (4600)
Office, 11–20 floors with E.I.F.S.; Steel frame	16	400,000 (37,160)
Office, 1 floor with glazing facade; Wood frame	1	7000 (650)
Office, 2–4 floors with glazing facade; Wood frame	4	50,000 (4600)
Office, 1 floor with stucco façade; Reinforced concrete frame	1	7000 (650)
Office, 5–10 floors with metal panel façade; Reinforced concrete frame	5	50,000 (4600)
Office, 11–20 floors with metal panel façade; Reinforced concrete frame	16	400,000 (37,161)

- o Large office buildings are 50% RC and 50% steel frame by floor space.
- o 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% RC, 33% steel, and 33% wood frame by floor space.
  - Scenario 3: 40% RC, 40% steel, and 20% wood frame by floor space.

Table 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: • Footings • Slab-on-grade • Foundation walls • Piles and grade beams (only for tall buildings)
Structural Frame (reinforced concrete – steel – wood)	• Concrete • Rebar • Structural steel • Structural wood • 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) • Windows (aluminum, glass) and door (aluminum, steel, and/or glass) on the façade • Roof coverings (asphalt shingles, aluminum, plywood sheathing) • Roof insulation (vary)
Interiors Partitions	• Partition wall systems (gypsum board, CMU) • Studs (wood or steel) • Interior doors (aluminum, glass, wood, 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	• Elevator • Air handling, cooling, heating, ventilation systems • Water heater • Roof drainage pipes • Piping for water supply and sewage • Miscellaneous

Table 3
Distribution of office buildings by floor space (million m^2), estimated on the basis of CBECS microdata and aforementioned assumptions. Note that 5 plus 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 and 50% steel; 33% RC, 33% steel, and 33% wood; 40% RC, 40% steel, and 20% wood by floor space for Scenarios 1, 2, and 3, respectively.

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

3.3. Estimation of embodied energy and GHG emissions

Publicly available, LCA-based EPDs constitute the source of energy use and emission factors for embodied energy (in GJ) and GHG emission (CO_2 eq.) calculations, respectively, based on the functional unit of the materials used in the construction of office buildings. The selected EPDs are specific to U.S.-made or U.S.-used building materials, are the latest available (completed in years between 2015 and 2021), and represent transparent and trackable sources of data for a consistent analysis that can be verified because they are publicly available. The scope of the analysis is limited to the product stage (Fig. 1). Construction, use (maintenance and operation) and EOL stages are outside the scope of this analysis because the focus is on estimating the embodied energy and GHG emissions from building materials.

One of the limitations of using the most recent EPDs is to assume that the designs for prototypical buildings stayed constant from 1946 to 2018 due to lack of historical environmental impact data. However, we used embodied energy and GHG emission factors to adjust our current EPDs to pre-1990 conditions. Factors are adopted from Reyna and Chester [16] and cover three time periods: Before 1950, between 1950 and 1990, and after 1990s for low-rise (1–4 floors) and high-rise (5 and higher) office buildings (SI-Table 5).

Coupling units of material quantities from BOMs with functional units defined in EPDs has been a critical step in our analysis, specifically for the representation of our results and their comparison to other building LCA studies. Details about the material and building component definitions and the EPD-derived data are available in SI - Table 4. Fig. 3 depicts the overview of our methodological approach and percent GHG emissions by building components for eight prototypical buildings.

4. Results

4.1. Embodied energy use and GHG emission results for prototypical buildings

Embodied energy and GHG emissions from prototypical buildings are first quantified by coupling the mass of materials used in construction of prototypical buildings (SI Fig. 9) with their associated embodied energy and GHG emissions (SI Figs. 10-11).

RC office buildings represent 1800–3700 MJ/m^2, steel buildings 1800–2600 MJ/m^2, and wood buildings about 2800 MJ/m^2 of embodied energy for structural materials (depending on the number of floors and structural and façade configurations) (Table 4).

Non-structural materials added another 940–2200 MJ/m^2 for RC, 900–2000 MJ/m^2 for steel, and 1100–1700 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 5-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 perspective, 5-floor RC and wood buildings were 10–15% more energy intensive than steel buildings. 16-floor RC and steel building materials needed about

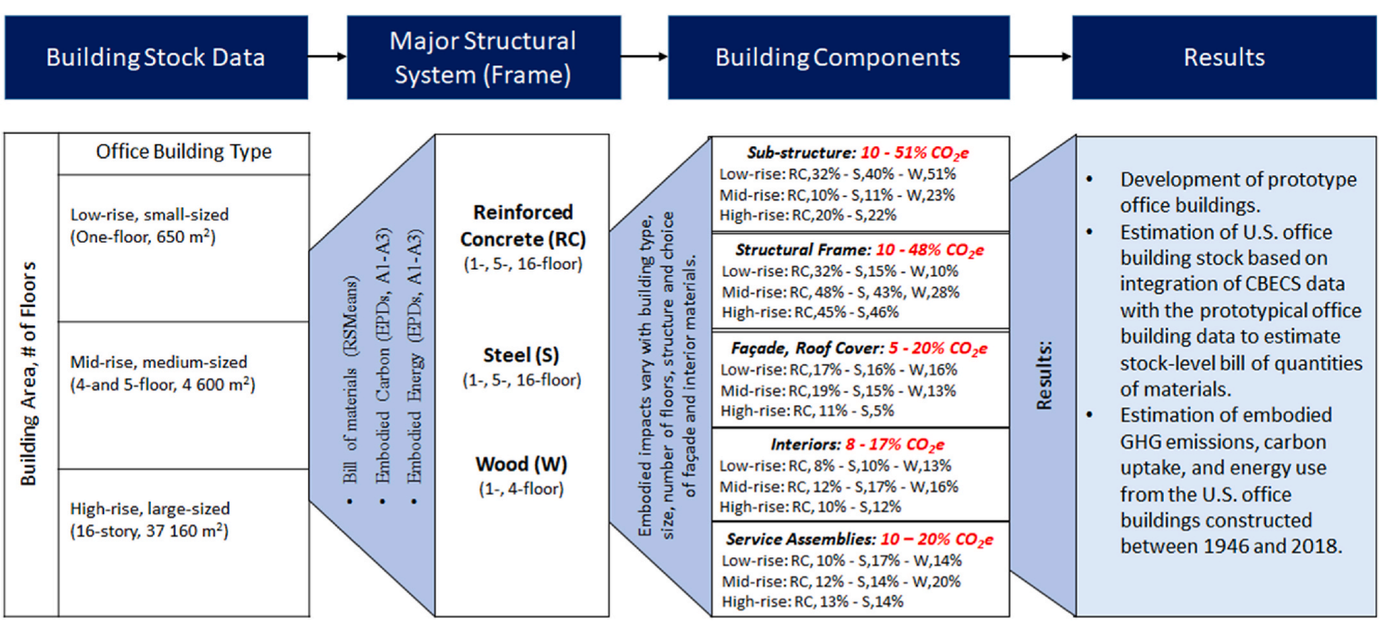

Fig. 3. Methodological approach and percent CO_2 equivalent estimates from the prototypical building conceptualization and formation analysis.
Note: The office building stock was represented by eight prototypical buildings with variations in structural frame options (reinforced concrete–RC, steel–S, and wood–W), number of floors, floor area, façade system, and interior components. Material quantities were taken from BOM on the basis of estimations from the RSMeans 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 for each component type for eight prototypical buildings are shown under "Building Components". 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.

Table 4
Embodied energy per m^2 by the structural versus the non-structural materials in RC, steel, and wood-structured buildings.

Embodied Energy (MJ/m^2)	Structural materials			Non-structural materials	Total
	Concrete	Steel	Wood		
RC Office, 1 floor	1349	2338	–	1757	5444
RC Office, 5 floors	775	1074	–	2241	4090
RC Office, 16 floors	734	1040	–	943	2717
Wood Office, 1 floor	727	1817	251	1664	4459
Wood Office, 4 floors	165	412	2229	1066	3872
Steel Office, 1 floor	545	2031	–	2032	4608
Steel Office, 5 floors	310	1538	–	1637	3485
Steel Office, 16 floors	410	1613	–	899	2922

the same amount of embodied energy.

Increasing returns to scale (economies of scale) was observed for RC buildings with increasing number of floors with respect to their embodied energy use: 5- and 16-floor buildings took half of the embodied energy to construct per m^2 of floorspace than 1-floor buildings for structural materials. However, there was no significant difference between 5- and 16-floor RC buildings. 16-floor RC buildings took half of energy to construct compared to the non-structural materials needs of 1- and 5-floor buildings, per m^2 of floorspace. Scale economies were less dramatic for steel buildings: 25%–30% reduction was observed between 16-floor and 1- or 5-floor buildings for structural materials, but 50% reduction for non-structural materials. It is important to note that there were no 16-floor wood buildings in our analysis, and while there were no significant scale economies between 1- and 5-floor buildings for structural materials, there was a 40% reduction in energy use for non-structural materials as the buildings got larger. From the perspective of combined structural and non-structural materials use per m^2, 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%. 5-floor wood buildings needed 87% of the embodied energy of 1-floor building materials per m^2 of floorspace.

The embodied GHG emissions due to structural materials were found to be 180–350, 150–210, and 94–220 kg CO_2 eq./m^2 for RC, steel-, and wood-structured buildings, respectively (depending on the number of floors and structural and façade configurations) (Table 5).

For non-structural materials, the respective numbers were 91–290, 79–190, and 89–120 kg CO_2 eq./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 emissions of office buildings, in some cases as or even more significant 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 from a structural as well as combined structural and non-structural materials perspectives, while RC buildings were about 50% and 27%–47% more GHG intensive, respectively. From the all-materials-use perspective, 5-floor steel buildings were 54% more GHG intensive than wood buildings, and in turn RC buildings were 68% more GHG intensive than steel buildings (i.e., wood buildings were responsible for only 39% of the embodied GHG of RC buildings). 16-floor RC and steel buildings resulted in about the same amount of embodied GHG.

Table 5
Embodied GHG emissions per m^2 floorspace by the structural versus the non-structural materials in RC, steel, and wood-structured buildings.

Embodied GHG emissions (kg CO_2eq/ m^2)	Structural materials			Non-structural materials	Total
	Concrete	Steel	Wood		
RC Office, 1 floor	179	166	–	154	499
RC Office, 5 floors	109	76	–	288	473
RC Office, 16 floors	101	73	–	91	265
Wood Office, 1 floor	88	129	5	119	341
Wood Office, 4 floors	20	29	45	89	183
Steel Office, 1 floor	66	143	–	185	394
Steel Office, 5 floors	42	108	–	132	282
Steel Office, 16 floors	55	113	–	79	247

Again, economies of scale was observed in embodied GHG emissions with the increasing number of floors. 5- and 16-floor RC buildings took half of the embodied GHG per m^2 floor space than 1-floor buildings for structural materials. (There is no significant difference between 5- and 16-floor RC buildings). 16-floor RC buildings took about one-half of embodied GHG to construct compared to the non-structural materials needs of 1- and 5-floor buildings. Scale economies were less dramatic for steel buildings: 20%–25% reduction was observed between 5- and 16-floor buildings compared to 1-floor buildings for structural materials, but 50% reduction for non-structural materials between 16-floor and 1-floor buildings. There are no 16-floor wood buildings. While 5-floor wood buildings have only about one-half of embodied GHG from structural materials, compared to 1-floor wood buildings, there was no significant reduction from non-structural materials as the buildings got larger. From the perspective of combined structural and non-structural materials use per m^2, 16-floor RC buildings had just about half of the embodied GHG emissions of 5-floor and 1-floor buildings per m^2 of floorspace. 5-floor and 16-floor steel buildings had about 60% of the GHG emissions of 1-floor steel buildings per m^2 of floorspace. 5-floor wood buildings needed half of the embodied GHG of 1-floor wood buildings per m^2 of floorspace.

Comparisons of our results to previous studies are inherently difficult because past studies may not have shared the details of their data and analyses, and data have changed in the interim. Reyna and Chester [16] 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 6690 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 (3500–5400 MJ/m^2, including accounting for 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 (around 2800 MJ/m^2, including more types of materials) were 3–4 times higher and embodied GHG emissions (around 250 kg CO_2 eq/m^2) about twice higher. We are not sure where the differences came from because we do not have complete information about mass of materials from the Reyna and Chester study, and also their research had to contend with scarce LCA data availability when it was written 8 years ago. We were able to use EPDs (which have proliferated in the meantime) specific to the United States in our study, which is an advantage unavailable to most previously published studies.

De Wolf et al. [17] 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. [3] study, embodied GHG emissions varied between 200 and 500 kg CO_2 eq/m^2 for the few analyzed office buildings. These numbers are about twice the magnitude of our numbers. The office building analyzed by Malabi Eberhardt et al. [21] resulted in 250 kg CO_2 eq/m^2 of total embodied GHG, which is in our range. Except for the Reyna and Chester study [16], the other studies did not provide the embodied energy in their results.

4.2. Embodied energy and GHG emissions results for the U.S. office building stock

Based on the U.S. commercial building construction statistics from CBECS (Fig. 2), 30% of the current building stock by floor space was constructed before 1970, 50% between 1970 and 1999, and 20% after 2000 [9]. Coupling the CBECS's office building data (floor space, number of floors) with the BOM (RSMeans) for the eight building types and related material EPDs, we estimated that 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 (Fig. 4). Among the three scenarios described in Table 3, 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 as a result of a higher number of RC and steel structural frames. From 1946 to 2018, it was estimated that office building materials were responsible for around 0.5 billion mt of CO_2 eq emissions (Scenario 1: 0.43 billion mt, Scenario 2: 0.49 billion mt, and Scenario 3: 0.51 billion mt).

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 (Fig. 5). Scenarios deviate less with embodied energy use than with GHG emissions (Fig. 4 versus Fig. 5). This can be explained by 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 mass. Overall, 6.5 billion GJ of energy (Scenario1: 6.4 billion and Scenario 3: 6.6 billion) was embodied in office buildings over 73 years from 1946 to 2018.

Higher spikes in office building material uses have occurred in the 1980–1989 period in parallel with the growth in non-residential building demand (SI - - Fig. 12). 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 attributed 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 sequestered in buildings that are now 22 to 52 years old and expected to be demolished soon. (SI - Fig. 12).

In the 73-year period, steel contributed to 15% of material use. It is mainly used in structural systems in the form of structural steel profiles and reinforcing in concrete, in wall systems as studs, and in metal staircases and doors. Its use by mass corresponds to about 4%, 7%, and 3% of the total amount of steel used over the above-stated three time intervals, respectively. Meanwhile, 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) (SI Fig. 13).

Steel has been the largest source of embodied GHG emissions in the 1946–2018 period, being responsible for 39% of the total (11%, 19%, and 9% of total GHG from steel for the periods before the 1970s, between 1970 and 1999, and after 2000, respectively), while concrete's total contribution was 22% (6%, 11%, and 5% of total GHG from concrete over the respective time periods). Fig. 6 shows the embodied GHG emissions from the materials used in construction of office buildings over time for Scenario 3 only (Refer to SI Fig. 14 for results from Scenarios 1 and 2.).

When current buildings reach functional obsolescence (when they are no longer needed as office space), their demolition (if they are not repurposed) is inevitable. As shown in Fig. 2, construction of new office buildings peaked in the 1980–1989 period and the growth has slowed since then. 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, portending an increase in annual construction debris. Replacing them will have significant implications for demolition waste, EOL options, and demand for new building materials and components.

One possible reason for the increase in concrete waste could be the

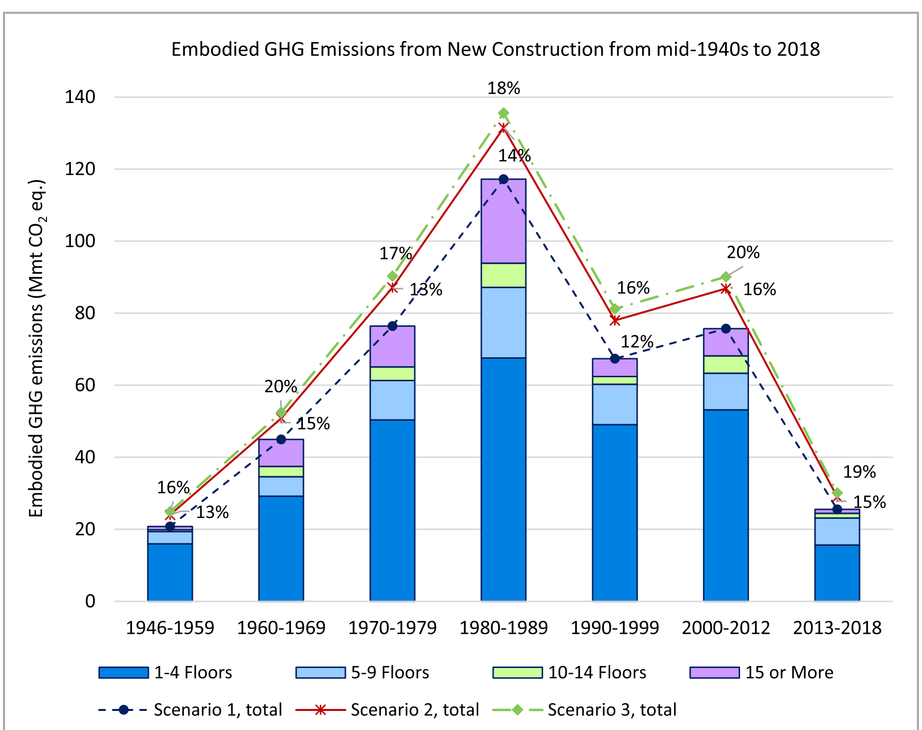

Fig. 4. Embodied GHG emissions from construction of new office buildings from 1946 to 2018. Percentages next to red solid line and green dash line show deviation of Scenario 2 and Scenario 3 from Scenario 1, respectively (Refer to Table 3 for description of scenarios.). Mmt: million metric tons. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

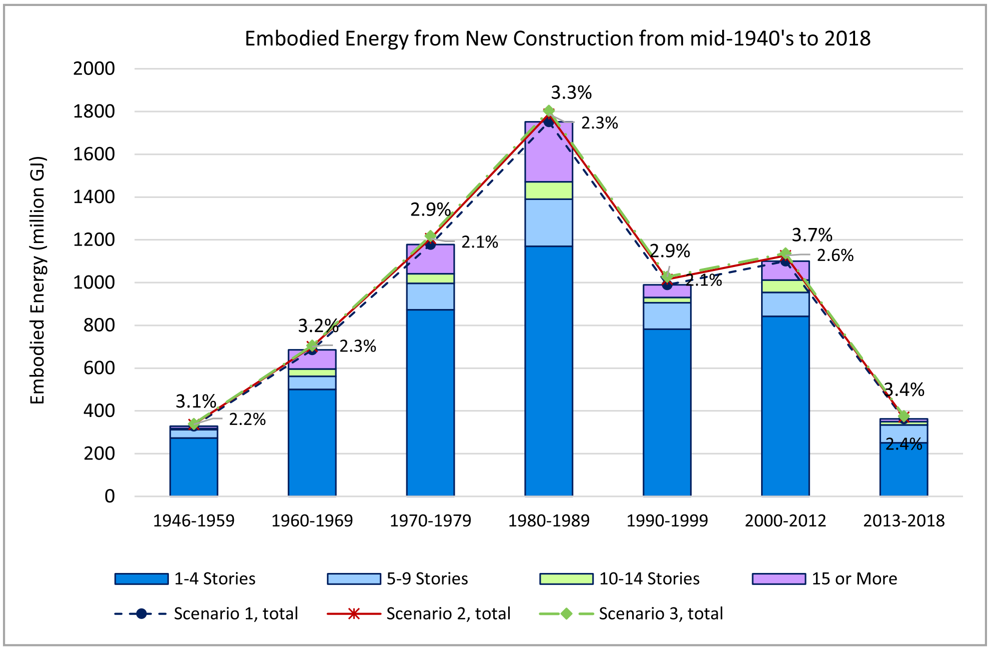

Fig. 5. Embodied energy use of U.S. office building stock constructed from 1946 to 2018 (based on CBECS and EPD data).

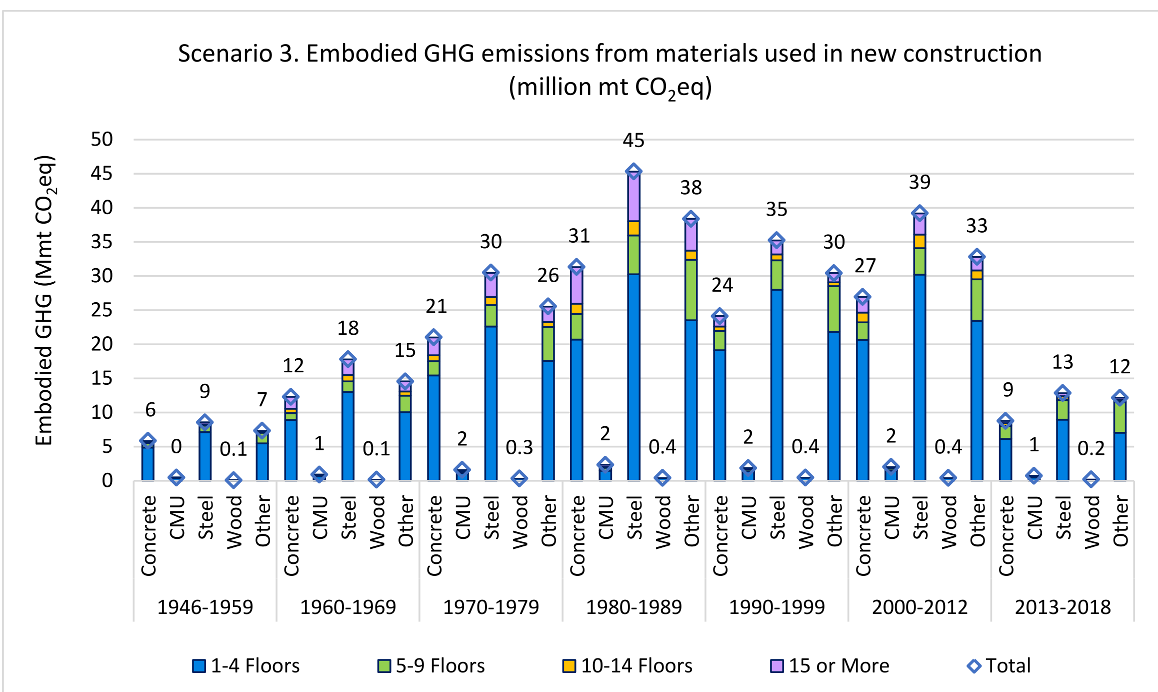

Fig. 6. Embodied GHG emissions from major building materials used in construction of office buildings over time (Scenario 3).

increase in demolition of office buildings constructed before 1980 (a boom time for such construction, see Fig. 2), which are reaching their end of life. For context, if all such office buildings were demolished (Fig. 7), concrete waste would amount to 245 Mmt for Scenario 1, 291 Mmt for Scenario 2, and 309 Mmt for Scenario 3, respectively. While steel is mainly recycled and wood can be used as a source of fuel or landscaping material following the demolition of buildings, waste concrete uses are very limited. It is typically disposed of in a landfill, used as a landfill daily cover, sometimes recycled into aggregates in new concrete-mix applications, or used as a non-structural fill (SI Table 2) [11]. Although it is outside the scope of this paper, building EOL strategies after obsolescence and carbon uptake beyond demolition of buildings should be analyzed to better understand the carbon implications of millions of tons of materials embedded in those buildings [26–28].

4.3. Sources of uncertainties

In our approach, data sources can be 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:

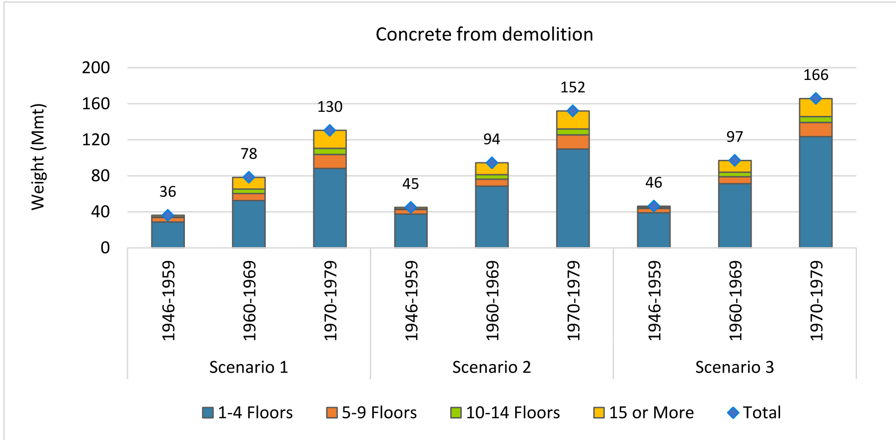

Fig. 7. Estimated amount of concrete from the demolition of the current stock of buildings built prior to 1980.

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 mass units for the purpose of coupling them with declared units in the EPDs. Such conversions required the use of unit mass factors (e.g., mass/surface area, mass/volume, mass/piece, mass/length) as described in EPDs and/or product description labels.
3. The BOM was then converted into material quantities in units of mass 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. The BOM for buildings in 1946–1959 are assumed to be the same for the same type of buildings (size, structure, height) as in 2013–2018 due to lack of historical data.
5. Material quantities are for current building designs. Older buildings could be different, especially for façade, insulation, and interior wall systems.
6. The embodied energy and GHG emission factors for unit of only structural materials (concrete and steel) for buildings of same type (low-rise (1–4 floors) and high-rise (5 or more)) are adjusted for three construction time periods, namely before-1950, 1950–1990, and post-1990, based on factors from Reyna and Chester [16]. In this way, changes in embodied energy and GHG emission factors (for concrete and steel buildings, but not for wood) over time are factored into our analysis.
7. 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.
8. 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 [29–31]. 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 [23].

The case buildings that form the basis for this article 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 to 1–2 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, and the results provide an acceptable basis for information about the building stock and decisions one might want to make.

5. Discussion and conclusion

We quantified embodied energy and GHG emissions associated with U.S. office buildings constructed between 1946 and 2018 based on RSMeans data, CBECS statistics, and recent EPDs created for U.S. building materials and components. Buildings were modeled using eight prototypical, representative 1-, 5-, and 16-floor designs with reinforced concrete (RC), steel, or wood structures and various façade systems and interior configurations. Interior furnishings such as fixtures and furniture were left outside the scope of the analysis since these portable components are traditionally not part of the analysis of embodied energy and emissions.

The scope of the analysis was limited to the manufacturing of materials and building components (including any recycled content) for the initial construction stage, focus being on the embodied impacts.

From the all-materials-use perspective, 5-floor RC and wood buildings are 10–15% more energy intensive than steel buildings. 16-floor RC and steel buildings need about the same amount of embodied energy. With respect to GHG emissions, 5-floor steel buildings are 54% more CO_2 eq.-intensive 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). 16-floor RC and steel building materials represent about the same amount of embodied GHG.

Based on the CBECS microdata, it was estimated that 807,400 office buildings were built during the 1946-2018 period. These buildings, plus the ones constructed 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 [24]). About 6.4 billion GJ of primary energy use (Fig. 6, Scenario 1), 6.2% of the U.S.'s 2021 consumption (102.7 billion GJ; EIA [25]), and 430 Mmt of CO_2 eq. emissions (Fig. 5, Scenario 1), 8.2% of the U.S.'s 2020 total GHG emissions (5222 million; US EPA [7]), are estimated to be embodied in them.

The key materials that drive the embodied numbers are found to be mainly concrete and steel. About 76% and 15% of construction material use by mass in the 1946–2018 period was due to concrete and steel, respectively. More than 75% of concrete and steel by mass are contained in the buildings that are now 22- 52 years old and may be demolished soon as a result of their expected obsolescence. Since metals are readily recycled after demolition, concrete stands out as the single most important C&D waste from buildings. It has substantial implications either if it is disposed of and laid over a landfill as a daily cover or recycled into aggregates in new concrete-mix applications. We estimated the amount of concrete from the demolition of buildings to range from 245 Mmt for Scenario 1 to 291 Mmt for Scenario 2 and 309 Mmt for Scenario 3 from buildings constructed before 1980 that are reaching their end of life.

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, as well as service life and EOL strategies in estimation of embodied energy and GHG emissions of buildings. These results also indicate that future work should analyze the energy use and GHG emissions from EOL strategies and carbon uptake from building materials after demolition. Moreover, additional material accounting of building components in the current and future building stock can inform a variety of stakeholders to better plan for materials and component recovery, smart waste management, and opportunities for adaptive reuse in a circular economy.

CRediT authorship contribution statement

Aysegul Petek Gursel: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Arman Shehabi:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **Arpad Horvath:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

We have shared data and supporting information in the SI section.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2023.110196.

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