A Whole Building Life-Cycle Assessment Methodology and its Application for Carbon Footprint Analysis of U.S. Commercial Buildings

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Abstract:
Buildings account for nearly 40% of the greenhouse gas emissions in the U.S. Although emerging energy efficient technologies can bring improved energy efficiency with lower environmental impact in the operation phase, their performances over the whole life cycles may have been overlooked. This paper presents a holistic building life-cycle assessment methodology that estimates the embodied and operational global warming potentials (GWPs) of a building covering the envelope, mechanical and lighting systems. The proposed methodology relies on EnergyPlus to generate the use-phase energy consumption for any given building and incorporates a streamlined procedure to extract construction material information from EnergyPlus, which is used for building envelope GWP analysis. Embodied GWP accounting was performed for a representative packaged electric cooling and gas heating system and three types of lighting technologies, namely incandescent, compact fluorescent (CFL) and light-emitting diode (LED). The methodology was applied for carbon footprint analysis of five U.S. Department of Energy commercial building prototypes across seven climate locations. The results show that the operation phase has a dominant impact on the overall building environmental impact and the embodied GWP contribution is less than 26% for all of the studied building prototypes. Buildings in California have the lowest life-cycle GWP because of the low air-conditioning demand and greener local electricity generation. LED and CFL lighting result in almost a 45% whole-building energy consumption reduction compared to incandescent lights,

which projects to up to a 35% reduction in the whole-building life-cycle GWP. The embodied and use-phase GWP tradeoff is anticipated to change dramatically with the emerging energy efficient technologies and deeper utilization of renewable energy. The methodology presented in this paper could be used to continuously evaluate these evolutions and support sustainable decision making.

Keywords: life-cycle assessment, commercial buildings, carbon footprint, HVAC, lighting.

1. Introduction

The building sector accounts for approximately 39% of the greenhouse gas (GHG) emissions and 40% of the total energy consumption in the U.S. [1]. As building owners are increasingly aspiring towards more environment-friendly products, energy efficient technologies have seen significant advancements over the past few years, such as light emitting diode (LED) lights, variable-speed heat pumps, district heating/cooling equipment, etc. In addition, national/regional renewable portfolio regulations (e.g., the California rooftop solar photovoltaic mandate [2]) have led to the emergence of net-zero or near net-zero energy buildings [3] that can achieve energy neutrality through combinations of efficient end-use equipment and on-site renewable generation. Although advanced technologies can be effective in reducing building site energy uses, studies have shown that some energy efficient features rely on materials that have significant embodied carbon and in some cases, it can require tens of years' operation before the reduction of CO_2 emissions in the operation phase surpass the embodied carbon [4]. Thus, there is a need for a comprehensive life-cycle environmental impact assessment methodology for building efficiency measures.

Life-cycle assessment (LCA) is a widely adopted analysis technique to evaluate environmental impacts associated with several stages of a product's life including raw material extraction, processing, manufacturing, distribution, use, and demolition [5]. It represents a systematic approach to quantify the energy and material flows through the whole life of a product, process or service, and has been applied for building carbon footprint analysis since the 1990s [6]. A majority of the previous efforts focused on analysis of the life-cycle carbon footprint associated with building construction (e.g., [7] [8] [9] [10] [11] [12]). For instance, Asif et al. [13] performed a LCA study of five main construction materials (wood, aluminum, glass, concrete and ceramic tiles) for a dwelling in Scotland to determine their respective environmental impacts. The study found that concrete alone contributed over 65% of the total embodied energy and carbon of the building under study. Citherlet et al. presented a LCA approach to estimate the environmental performance of various window and glazing systems used in commercial buildings [14]. Advanced glazing technologies, e.g., low-emissivity glass, were found to have greater life-cycle environmental impacts compared to conventional windows. However, the resultant savings of the air-conditioning energy consumption outweighed the increase of the embodied energy. Ochsendorf et al. [15] evaluated and compared the environmental impacts of concrete and steel for commercial buildings and found similar embodied emissions; however, the use-phase environmental impacts associated with concrete buildings were found to be 7% to 9% lower, due to the higher thermal inertia.

Heating, ventilation and air-conditioning (HVAC) and lighting together are responsible for about 42% of the total building electricity use in the U.S. [16]; but few studies can be found for characterizing the life-cycle carbon footprint of mechanical and lighting equipment in buildings. Shah et al. [17] evaluated the life-cycle environmental performance of three combinations of residential heating and cooling systems, including warm-air furnaces and air-conditioners (AC), hot water boilers and ACs, and air-to-air heat pumps, across four different climate locations in the U.S. The analysis accounted for both the embodied and operational carbon footprint, which were shown to be highly dependent on the climate location and regional energy mixes. Heikkila [18] assessed the environmental impacts of two types of AC systems, an all-air system in combination with a chiller cooling unit and a desiccant and evaporative cooling system, used in Sweden buildings. Although the environmental impacts of the various life stages have noticeable differences between the two AC systems, the dominant impact for both systems was associated with the energy consumption in the use phase (over 75% of the total life-cycle impact). Blom et al. [19] presented a LCA methodology for assessment of multiple heating and ventilation systems in Dutch dwellings. Electric heat pumps were shown to contribute the highest environmental burden compared to condensing and non-condensing boilers, mainly because of the high emissions associated with local electricity generation. Gagnon et al. [20] compared and evaluated life-cycle carbon footprints of two space heating systems, namely electric radiators and heat pumps. A design tradeoff was identified: designs with an electric radiator have the lowest embodied carbon but the highest use-phase carbon; selection of a heat pump reduces the energy consumption and thus use-phase impact, but heat pumps tend to have higher embodied carbon.

In most of the aforementioned studies, national average electricity generation mixes were used for estimating the environmental impacts associated with the electricity consumed during the operation phase. However, the mix of electrical power sources could vary significantly from one location to another, which makes the GWP per kWh of electricity highly dependent on the location. Blom et al. compared the environmental impacts associated with the 2004 electricity mixes in Belgium, Germany, France, Netherlands, Norway and the United Kingdom; the results show that the Norwegian electricity generation, which is mostly hydropower-based, led to the minimum emissions among the six countries. Blom et al. also showed that a 14% reduction on GWP could be achieved by changing the electricity mix in Netherlands of 2004 to the 35% renewable target in 2020 [21]. Shifting the energy mix towards renewable sources would lead to a significant reduction in the electricity GWP, which consequentially impacts a building's life-cycle carbon footprint. The influence of local electricity generation infrastructure on the building environmental performance has been recently studied. For instance, Rossi et al. [22] compared the carbon footprint of two residential houses in three European towns, and the results confirmed the strong influence of local electricity mix on building environmental impacts. The total life-cycle carbon footprint of a masonry house located in Belgium, Portugal and Sweden were found to be 28.71 kg CO_2/m^2-yr, 43.34 kg CO_2/m^2-yr and 7.68 kg CO_2/m^2-yr, respectively [22]. Kneifel considered 12 prototypical buildings located in 16 U.S. cities, and compared life-cycle carbon emission reduction and life-cycle cost savings for three different building design options for each building-location combination [23].

The literature has indicated that the operation phase contributes the most environmental impact, representing 80% to 90% of a building's overall life-cycle GWP, while the manufacturing/construction phase only accounts for 10% to 20% of the total building carbon footprint [24]. However, this pattern is expected to change dramatically over the next few decades as more energy efficient technologies are adopted to achieve net-zero energy or even net-zero carbon buildings. In order to continually assess buildings' life-cycle environmental impacts with the emerging building technologies and the transforming electrical infrastructure, there is a need for a holistic building environmental impact assessment methodology that considers the various life-cycle stages and integrates the disparate building technologies [25]. This is a challenging task and very limited work can be found for whole-building LCA studies due to difficulties in integrating the various construction, mechanical and electrical components for complete carbon accounting. The lack of interoperability between building energy simulation tools and LCA databases presents another major obstacle for a streamlined building LCA procedure [26].

This paper fills the void and presents a holistic LCA methodology to enable streamlined building environmental performance assessments. The approach covers various life stages of building components including raw material extraction, manufacturing, construction, operation and maintenance, and incorporates comprehensive carbon accounting for the HVAC equipment, lighting systems and building envelope. The whole building energy simulation suite, EnergyPlus and OpenStudio[1] [27], is leveraged to calculate a building's use-phase energy consumption. The LCA framework includes a material extraction routine to automatically collect construction material information from EnergyPlus models, which is used in combination with mainstream LCA databases to estimate the embodied carbon of building envelope. In addition, embodied carbon analyses were performed for a packaged air-conditioning unit with an internal gas furnace and three lighting technologies: incandescent, compact fluorescent light (CFL) and LED, using

[1] OpenStudio, developed and maintained by the National Renewable Energy Laboratory, is an upfront graphical user interface for EnergyPlus.

material data collected from laboratory dissembling or public literature. The two major differentiating features of the presented methodology are (1) a streamlined LCA procedure that allows automated carbon footprint reporting for any given EnergyPlus building model and (2) a holistic LCA framework capturing the carbon interdependence between building envelope, HVAC equipment and lighting systems. The proposed LCA methodology has been applied for environmental performance assessment of five Department of Energy (DOE) commercial building prototypes across seven U.S. climate locations. Key environmental performance metrics are presented and analyzed. Results presented in this paper can be used as a reference to facilitate decision making from an environmental perspective.

2. Goal and Scope

2.1 Case study building description

In this study, the proposed methodology was applied for assessments of five DOE prototypical commercial buildings (small office, medium office, sit-down restaurant, stand-alone retail, and primary school) across seven climate locations in the U.S. Key information of the considered prototypical buildings is presented in Table 1. The analysis was based on the Pacific Northwest National Laboratory (PNNL) Standard 90.1-2010 prototype building models [28].This study focused on analyses of buildings constructed in 2010 as opposed to new constructions since 88% of U.S. commercial buildings are over a decade old [29]. These five building prototypes have floor areas ranging from 511m^2 to 6871m^2, and are representative of small- to medium-sized commercial buildings in the U.S. The small office relies on air-source heat pumps for space cooling and heating with gas furnaces as back-up heat sources. All the other four building prototypes are served by packaged air-conditioning units with gas furnaces inside. For the retail store and primary school, additional heating is provided by standalone gas furnaces or gas boilers to a subset of the conditioned zones. Energy uses of these additional heat sources are relatively small and therefore, embodied carbon of the standalone furnaces and boilers was not considered in the overall analysis.

Table 1. General information on the five building prototypes under study [30]

Building type	Number of floors	Floor area (m^2)	Number of conditioned zones	Space cooling equipment	Space heating equipment
Small office	1	511	5	Air-source heat pump	Air-source heat pump with gas furnace as back up
Medium office	3	4982	18	Packaged AC unit	Gas furnace inside the package AC unit
Sit-down restaurant	1	511	2	Packaged AC unit	Gas furnace inside the package AC unit
Stand-alone retail	1	2294	5	Packaged AC unit	Gas furnace inside the package AC unit + standalone furnace
Primary school	1	6871	25	Packaged AC unit	Gas furnace inside the package AC unit + gas boiler

For each prototypical building, energy simulations were carried out for seven U.S. cities located in different climate zones[2], as shown in Table 2. Climate zone 8 for Alaska was not included in this study since it represents a less populated area with a small number of buildings. Climate zone 1 corresponds to the hottest climate while climate zone 7 represents the coldest region.

Table 2. ASHRAE 90.1-2010 climate zones and cities for the analysis [32]

Climate zone	Climate type	Representative city
1A	Very hot	Miami, FL
2A	Hot	Houston, TX
3C	Warm	San Francisco, CA
4A	Mixed	Baltimore, MD
5A	Cool	Chicago, IL
6A	Cold	Minneapolis, MN
7A	Very cold	Duluth, MN

In this study, a lighting requirement of 500 lumens/m^2 was assumed for all building spaces. The incandescent, CFL, and LED lights have quite different characteristics as shown in Table 3. Incandescent has the lowest efficacy (lumens/watt) of about 15 lumens/watt, while the efficacy of LED is the highest (64 lumens/watt). Detailed embodied and use-phase carbon analyses were carried out with the key results presented in Section 3.

[2] Climate zones are categorized from 1 to 8, with increasing heating degree days and decreasing cooling degree days; these climate zone are further divided into moist (A), dry (B), and marine (C) region [31]

Table 3. Characteristics of the three lighting options [33]

Lamp Type	Watts	Lumens	Lifespan (hrs)
Incandescent	60	860	1,000
CFL	14	900	10,000
LED	12.5	850	25,000

2.2 Goal and definitions

2.2.1 Goal

This study aims to evaluate the environmental impacts of five DOE commercial building prototypes across seven locations in U.S. considering three different lighting systems.

2.2.2 Functional unit

The functional unit, "usable floor space per unit life of the building in m^2-year", is widely used for quantification of building environmental impacts [34] [35]. It is adopted in this study as it allows direct performance comparisons across different building prototypes, which have quite different lifespan and floor areas. The life times of the various building prototypes recommended by Kneifel et al. [23] are used: 41 years for the primary school, small and medium offices, 38 years for a stand-alone retail store, and 27 years for a sit-down restaurant.

2.2.3 System boundaries

The proposed LCA methodology considers environmental impacts associated with raw material extraction, manufacturing, construction, operation and maintenance phases, while the demolition-phase impact is neglected. The system boundaries of this LCA study are explicitly listed in Table 4. Two main categories of carbon emissions are considered: embodied and operation-phase carbon. The embodied carbon accounts for the carbon emissions associated with raw material extraction and manufacturing, building construction and maintenance phases. The construction phase analysis estimates the emissions associated with transportation and energy uses involved in construction activities. Equipment replacements for HVAC equipment and light bulbs are considered in the maintenance phase based on the presumed life times of the different buildings and equipment. The operation carbon analysis accounts for the energy uses for heating (both gas and electrical), cooling, ventilation, interior or exterior lighting, and other electricity requirements. Electricity and natural gas are the only site energy sources considered.

Table 4. System boundaries for the present building LCA study

Life-cycle carbon	Life-cycle phases	Main assumptions
Embodied carbon	• Raw material extraction and manufacturing phases • Construction phase • Maintenance phase	• Building envelope • HVAC system • Lighting system
Operation carbon	• Operation phase	• Gas heating for indoor spaces • Electricity usage associated with space cooling, heating and ventilation • Interior lighting electricity use • Electrical energy uses for domestic hot water, interior equipment, and exterior lighting

2.2.4 Data origins and life-cycle inventory

Materials used in the building envelope were obtained from the prototypical building information models. Material data for HVAC and lighting systems were collected via laboratory dissembling or from public literature. Building energy end uses during the operation phase were estimated with whole building energy simulations in EnergyPlus.

Different locations could have very different mixes of energy sources for electricity generation, depending on local regulations, available resources, etc. The 2019 electricity supply mix published by the U.S. Environmental Protection Agency (EPA) [36] was used for the case studies and the combined GWPs per kWh of electrical energy for the considered locations are shown in Table 5. Electricity in FL, TX and MN has the highest carbon intensity as coal and natural gas are the dominant generation sources. MD and IL have cleaner electricity as nuclear contributes a significant portion of the overall generation. CA is aggressive in adopting clean and renewable energy resources and more than 55% of its electricity is generated from clean energy sources such as hydro, geothermal and nuclear [36]. That is why the electricity GWP in CA is significantly lower than the other locations.

Table 5. Average GWP for electricity in the case study locations

Climate zone	City	Global warming potential (kg CO2 eq./kWh)
1A	Miami, FL	0.40
2A	Houston, TX	0.41
3C	San Francisco, CA	0.18
4A	Baltimore, MD	0.34
5A	Chicago, IL	0.33
6A	Minneapolis, MN	0.40
7A	Duluth, MN	0.40

Natural gas is the primary site energy source for space heating and domestic hot water in most of the considered building prototypes. The U.S. national average data "Natural gas, at production/RNA S" from Ecoinvent database is used for estimation of the natural gas GWP (0.311 kg CO2 equivalent per 1 m^3 of natural gas). The approach presented in this paper assumes that the energy mixes and supplement systems are kept unchanged over a building's life time.

2.3 Life-cycle assessment methodology

A whole building LCA methodology is proposed which accounts for the embodied and operation phases separately as shown in Figure 1. The overall process starts with acquisition of detailed building construction information. The construction information is fed to a whole building energy simulation tool to generate building energy uses in the operation phase. In this study, the EnergyPlus and OpenStudio suite was used to demonstrate the proposed procedure. OpenStudio takes the construction information (geometries and materials used) for a given building and calls EnergyPlus to execute whole building energy simulations. To facilitate automatic extraction of material information, a material extraction routine was developed that takes an OpenStudio/EnergyPlus model and automatically generates the bill of materials for a given building.

Based on the collected material information, the embodied carbon associated with the building construction materials is estimated via queries to LCA databases. The U.S. Life Cycle Inventory

(USLCI) [37] and Ecoinvent databases [38] are used as main LCA data sources in the current framework. The USLCI database is used to model the impacts of energy and material input and output flow. Only for cases where relevant data is not available in USLCI, the Ecoinvent database is used. In this study, the databases were downloaded as local Excel spreadsheets and a script was used to automatically extract carbon intensity of a given material from the spreadsheets. However, materials in EnergyPlus and LCA databases have different naming conventions and a given material may link to multiple entries in the same database with minor differences. To ensure accurate transfer, a mapping between EnergyPlus construction materials and unit processes in LCA databases was manually created (e.g., concrete was mapped to the unit process "Concrete, normal, at plant/CH S" of the Ecoinvent database). Detailed LCA analyses for HVAC and lighting systems relied on both data collected in the laboratory and publicly available literature. With the simulated operation phase energy consumption and estimated embodied carbon, whole building LCA analysis is performed. Detailed discussions are given in the following subsections.

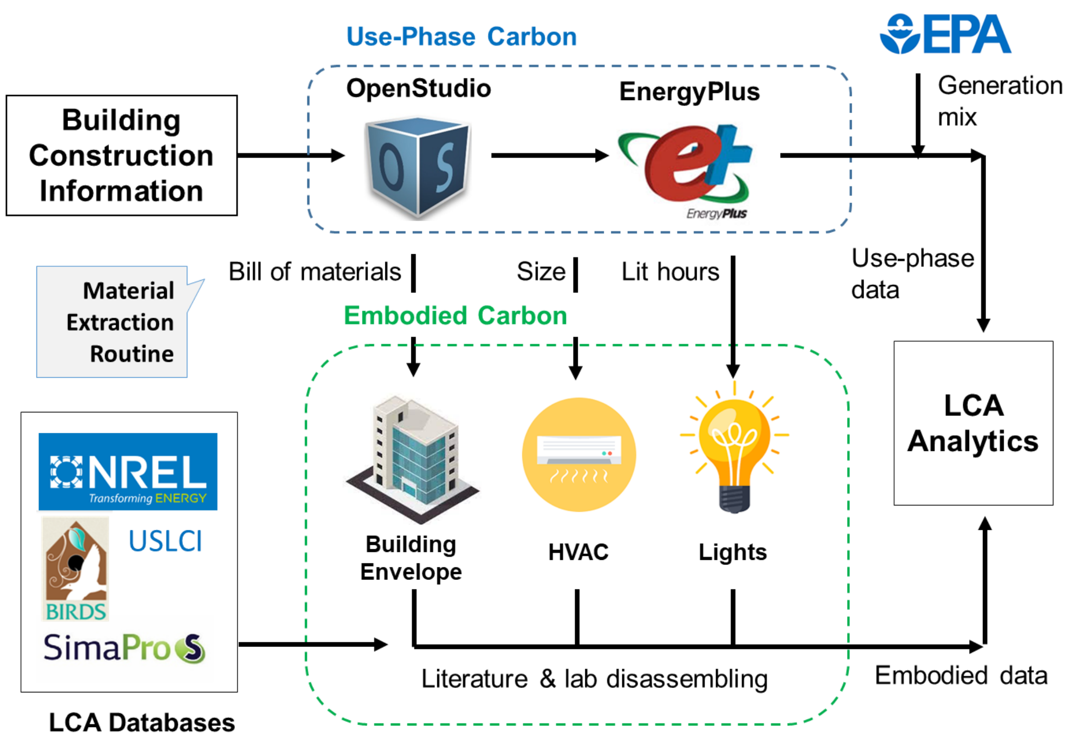

Figure 1. Proposed building LCA methodology

2.3.1 Raw materials and manufacturing

Estimation of the GWPs associated with raw materials and manufacturing of the key building components, including building envelope, HVAC equipment and lighting systems, are discussed as follows.

(1) Building envelope

The building construction information can be used to estimate the quantities of different construction materials used in building envelope. The LCA databases provide environmental impacts per unit weight of construction materials. The total embodied carbon of the envelope for each building prototype can be calculated through addition and multiplication of the total material weights extracted from the construction information and the respective environmental impacts collected from the LCA databases. The material extraction routine automatically searches through the EnergyPlus/OpenStudio model file and extracts a tree structure of the building construction elements, which includes construction nodes such as zones, surface types, walls and layers; each node contains geometric and physical parameters such as area of a wall, density of a specific material and thickness of a construction layer.

Table 6 shows the surface area of each wall type for all five case study buildings in San Francisco, CA as an illustrating example. Buildings of the same type but located in different climate zones may use different construction materials. For instance, all the considered building prototypes located in San Francisco, CA use “8-inch normal-weight concrete floor”, but buildings in the other six climate zones assume “6-inch normal-weight concrete floor” for the same floor type. It should be noted that the prototypical R-value of insulation varies significantly from one climate location to another. In the case study buildings, the insulation used in “exterior mass walls” has R-values ranging from R-4.23 in hot climates to R-8.72 in cool climates to as high as R-11.7 in very cold locations. Steel framed exterior walls have the insulation range from R-5.89 in very hot climates to R-13.45 in very cold climate zones. For exterior mass floors, insulation levels can be R-6.78 in hot climates, R-13.06 in very cold climates and R-10.94 in cool climates.

Table 6. Materials used for the prototypical buildings at San Francisco, CA (90.1-2010-ASHRAE)

Surface type	Construction type	Surface (m^2)					Layer name	Thickness (m)
		Medium office	Small office	Sit-down restaurant	Stand-alone retail	Primary school		
Window	Window	653	56	47	108	879	Glazing	-
							Frame	-
Ceiling	Interior ceiling	8304	511	511	-	-	100 mm Normal-weight concrete floor	0.1016
Floor	Slab floor	1661	511	511	1099	6871	8 in. Normal-weight concrete floor	0.2032
	Interior floor	8304	511	511	-	-	100 mm Normal-weight concrete floor	0.1016
	Exterior mass floor	-	57	-	-	-	Insulation R-6.78	-
							4 in. Normal-weight concrete floor	0.1016
Wall	Interior wall	2562	492	138	1470	5864	13mm Gypsum board	0.0127
							13mm Gypsum board	0.0127
	Exterior mass wall	1325	226	-	1069	-	1 in. Stucco	0.0253
							8 in. Concrete HW RefBldg	0.2032
							Insulation R-5.74	-
							1/2 in. Gypsum	0.0127
	Steel framed exterior wall	-	-	229	-	2512	25mm Stucco	0.0254
							5/8 in. Gypsum board	0.0159
							Insulation R-9.73	-
							5/8 in. Gypsum board	0.0159
							Frame	-
Roof	IEAD roof	1661	599	-	1099	6871	Roof membrane	0.0095
							Insulation R-19.72	-
							Metal roof surface	0.0008
	Wood joist attic floor	-	-	570	-	-	5/8 in. Gypsum board	0.0159
							Insulation R-35.4	-

							Frame	-

Table 7 lists the collected construction materials and the associated LCA unit processes used for all building prototypes and across all climate locations. A variety of insulation materials are used in buildings, such as fiberglass, mineral wool, polyisocyanurate, polyurethane etc. In this study, we assume that polyurethane rigid foam is used for all building prototypes. The thickness of the insulation foam can be calculated based on the required R-value for each wall type and the nominal R-value per unit thickness of polyurethane rigid foam (R-7 per inch). The GWP per 1kg of polyurethane rigid foam is 6.788 kg CO_2 eq. [39].

Table 7. LCI databases for building envelope LCA analysis

Component category	Building element	Building component	Building material	Unit process name
Floor	Slab floor	8 in. normal-weight concrete floor	Concrete	Concrete, normal, at plant/CH S
	Interior floor	100 mm normal-weight concrete floor	Concrete	Concrete, normal, at plant/CH S
	Exterior floor	Insulation R-6.78	Polyurethane rigid foam	Literature
		4 in. normal-weight concrete floor	Concrete	Concrete, normal, at plant/CH S
Wall	Interior wall	13mm gypsum board	Gypsum	Gypsum fibre board, at plant/CH S
		13mm gypsum board	Gypsum	Gypsum fibre board, at plant/CH S
	Exterior wall	1 in. stucco	Stucco	Stucco, at plant/CH S
		8 in. concrete HW RefBldg	Concrete	Concrete, normal, at plant/CH S
		Insulation R-5.74	Polyurethane rigid foam	Literature
		1/2 in. gypsum	Gypsum	Gypsum fibre board, at plant/CH S
	Steel framed exterior wall	25 mm stucco	Stucco	Stucco, at plant/CH S
		5/8 in. gypsum board	Gypsum	Gypsum fibre board, at plant/CH S
		Insulation R-9.73	Polyurethane rigid foam	-
		5/8 in. gypsum board	Gypsum	Gypsum fibre board, at plant/CH S
Window	Window	Glazing	Glazing	Literature
		Frame	Aluminum	Literature
Roof	IEAD roof	Roof membrane	Roof	Single-ply, white, polyester reinforced

				PVC roofing membrane, 48 mils (1.219 mm)
		Insulation R-19.72	Polyurethane rigid foam	Literature
		Metal roof surface	Metal panel	Metal panels, roof, at plant
	Wood joist attic floor	5/8 in. gypsum board	Gypsum	Gypsum fibre board, at plant/CH S
		Insulation R-35.4	Polyurethane rigid foam	Literature
Ceiling	Interior ceiling	100 mm normal-weight concrete floor	Concrete	Concrete, normal, at plant/CH S

Embodied carbon for windows is estimated assuming that all windows for the case study buildings are of fixed storefront type. A major window manufacturer in the U.S. has made the GWP data of their window products publicly available, which is fairly comprehensive and accounts for the environmental impacts associated with the various life stages from raw materials to final products. The published data is normalized with respect to the window area (128 kg CO_2 eq. per m^2 of glazing, and 49.5 kg CO_2 eq. per m^2 window for the aluminum frame) [40]. The total embodied carbon contributed by windows in a given building is estimated by multiplying the total window area and the published global warning potential per window area.

(2) HVAC system

As shown in Table 1, all the considered building prototypes are served by packaged air-conditioning units with gas furnaces as the primary space heating equipment, except for the small office building. Therefore, a representative 4-ton packaged gas heat and electric cooling unit was identified and assumed to serve all the prototypical buildings considered in this study. The number of units required for each building and location is determined based on the nominal cooling capacity automatically calculated in EnergyPlus. A detailed LCA was carried out for this unit that considers the environmental impacts associated with the major components including the condenser coil, blower motor, evaporator coil, compressor, etc. The material information was collected from different sources including public literature, manufacturer specification sheets and laboratory dissembling. A 4-ton packaged unit was torn down in the laboratory and key components such as the evaporator coil, indoor blower and control board were weighed (see

Figure 2). The condenser coil and compressor were too heavy to be taken out from the casing and their material composition was estimated from manufacturer drawing and literature. Table 8 lists the individual components and the corresponding material information. Both the condenser and evaporator coils are made of copper tubes and aluminum fins. The weights of copper and aluminum were calculated based on their geometric parameters such as face area, fin height, fin thickness, tube diameter, tube wall thickness, etc. that are available in the manufacturer specification sheet. The material weights were verified through comparisons to the total evaporator coil weight obtained in the laboratory. For components that lack adequate details for the materials being used, data published in the open literature was utilized. For instance, the weight fractions (magnet 3%, copper wires 11%, lamination steel 86%) reported in reference [41] were leveraged to estimate the different material quantities for the supply fan motor whose total weight is available from the manufacturer data (weight verified by laboratory tear-down). A similar approach was adopted for the compressor material accounting; the material breakdowns by weight for a typical compressor are 9% steel, 4% copper, 2% Aluminum, and 84% cast iron [42]. It may be noted that all considered prototypical buildings use gas furnaces as the primary space heating equipment except for the small office building, which is served by packaged air-source heat pumps with gas furnaces as backup heat sources. The embodied carbon of a heat pump of the same thermal capacity should be similar to that of an air-conditioning unit. Therefore, the estimated embodied carbon for the representative packaged unit was used directly for the heat pump equipment serving small offices.

(a) (b) (c)

Figure 2. HVAC unit tear-down in the laboratory: (a) evaporator coil, (b) supply fan and (3) main control board.

Table 8. Materials for a representative 4-ton packaged gas heat and electric cooling unit [42] [43] [44] [45] [46] [47] [48].

Component	Materials	Mass (kg)
Casing	Steel	53.66
Condenser coil	Aluminum	23.47
	Copper tub	5.89
Blower motor	Magnet	0.33
	Copper wire	1.26
	Laminated steel	9.59
Blower wheel	Galvanized steel	2.99
Evaporator coil	Copper tube	3.79
	Aluminum	8.37
Condenser motor	Magnet	0.27
	Copper wire	1.03
	Laminated steel	7.84
Condenser fan	Galvanized steel	5.28
Gas furnace	Galvanized steel	16.53
Compressor	Galvanized steel	3.18
	Copper	1.42
	Aluminum	0.71
	Cast iron	29.72

Table 9 lists the adopted LCA unit processes and GWPs for the materials associated with the packaged air-conditioning unit. It may be noted that environmental impacts for different copper products (e.g., copper tube versus copper wire) are quite different. High percentages of scrap materials with minor impurities can be reused as input materials for the semi-production of copper tubes and sheets. However, high-grade copper wires are produced with 100% copper cathode [49], resulting in higher GWPs in the production phase compared to those in manufacturing of copper sheets and tubes [50]. The GWP of laminated steel, galvanized steel, and magnet were obtained from references [41] and [51]. Since the specific manufacturing processes for the case study unit are largely unknown, the generic "metal product manufacturing, average metal working/RER S" in the Ecoinvent database was used for estimation of the manufacturing-phase environmental impact. Based on the data collected in Table 8 and Table 9, the GWP of the 4-ton packaged gas heat and electric cooling unit was estimated to be 1057.20 kg CO_2 eq. considering both raw material extraction and manufacturing phases.

Table 9. Unit processes for the packaged gas heat & electric cooling unit.

Component	Description /material	Mass (kg)	Unit process name
Casing	Steel	53.66	Steel, low-alloyed, at plant/kg/RER
Condenser coil	Aluminum	23.47	Aluminum, primary, ingot, at plant
	Copper	5.89	Copper, primary, at refinery/RER S
Blower	NdFeB motor	11.18	Literature [41]
	Galvanized steel	2.99	Literature[51]
Evaporator coil	Copper	3.79	Copper, primary, at refinery/RER S
	Aluminum	8.37	Aluminum, primary, ingot, at plant
Condenser fan and motor	NdFeB motor	9.14	Literature [41]
	Galvanized steel	5.28	Literature [51]
Compressor	Galvanized steel	3.18	Literature [51]
	Copper	1.42	Copper, primary, at refinery/RER S
	Aluminum	0.71	Aluminum, primary, ingot, at plant
	Cast iron	29.72	Cast iron, at plant/RER S
Heat exchanger	Galvanized steel	16.53	Literature [51]

Ductwork is used in buildings to distribute conditioned air to the indoor spaces. HVAC ducts are typically hollow metal pipes made of galvanized steel. We assumed that 0.56 kg of galvanized steel is used for ductwork per square meter of floor area based on the prototypical air distribution layout provided by Mechanical, Electrical, and Plumbing (MEP) consulting engineers [52]. The total weight of ductwork for each building type was estimated according to the total floor area. All the five building prototypes considered in this study utilize constant air volume distribution except for the medium office in which variable-air-volume terminal boxes are present. The embodied carbon of terminal delivery devices is expected to be small and neglected in this study.

(3) Lighting systems

Lighting consumes 20~45% of the total site energy in commercial buildings [53]. This section presents embodied carbon analysis results for three representative light bulbs, one for each lighting technology: 12.5 W LED, 14 W CFL, and 60 W incandescent bulbs. Material inputs were collected from [54] [55] [56] and Table 10 presents the weights, materials, unit processes, and GWPs for the three types of lights. It is assumed that the major electronic components in the ballast include the printed circuit board, capacitors, resistors and transistors [57].

Table 10. Material inputs and corresponding Ecoinvent datasets for the three light bulbs.

Component	Material	Mass (g)	Ecoinvent unit process
14-W CFL			
Electronics	Printed circuit board, capacitors, resistors, transistors	14.1	Capacitor, unspecified, at plant, GLO S Resistor, unspecified, at plant, GLO S Transistor, unspecified, at plant, GLO S Inductor, unspecified, at plant, GLO S Printed wiring board, mixed mounted, unspec., solder mix, at plant/kg/GLO S
Bulb	Glass	18.2	Glass tube, borosilicate, at plant/DE S
Basement	Copper	5.3	Copper, primary, at refinery/GLO S
Lamp holder	Plastic	11.9	Polycarbonate at plant/RER S
12.5-W LED			
Metal	Aluminum	68.2	Aluminum alloy AlMg3, at plant/RER S
Lamp holder	Copper	15.3	Copper, primary, at refinery/GLO S
Plastic	Plastic	16.1	Polycarbonate at plant/RER S
LED aluminum board	Aluminum	6.9	Aluminum alloy AlMg3, at plant/RER S
Electronics	printed circuit board, capacitors, resistors, transistors, diodes	43.7	Production efforts, capacitors/GLO S Production efforts, resistors/GLO S Production efforts, inductors/GLO S Production efforts, transistors/GLO S Production efforts, diodes/GLO S
Rubber	Rubber	25.2	Synthetic rubber, at plant/RER S
60-W Incandescent			
Lamp holder	Copper	7.5	Copper, primary, at refinery/RER S
Wire	Copper	3.2	Copper, at regional storage/RER S
Metal base	Tin plate	1.5	Tin, at regional storage/RER S
Filament	Tungsten	0.02	Rhodium, at regional storage
Bulb glass	Glass	16.4	Glass tube, borosilicate, at plant

Table 11 shows the main manufacturing processes for the three lighting options. Since the specific manufacturing processes for metal components are not completely known, the generic "metal product manufacturing, average metal working/RER S" in the Ecoinvent database was used for all metal materials.

Table 11. Manufacturing processes assumed for the three light bulbs.

Component	Mass (g)	Ecoinvent unit process

14-W CFL		
Electronics	14.1	Production efforts, capacitors/GLO S Production efforts, resistors/GLO S Production efforts, inductors/GLO S Production efforts, transistors/GLO S
Bulb	18.2	Tempering, flat glass/RER S
Basement	5.3	Metal product manufacturing, average metal working/RER S
Lamp holder	11.9	Injection molding/RER S
12.5-W LED		
Metal	68.2	Metal product manufacturing, average metal working/RER S
Lamp holder	15.3	Metal product manufacturing, average metal working/RER S
Plastic	16.1	Injection molding/RER S
LED aluminum board	6.9	Metal product manufacturing, average metal working/RER S
Power driver: power supply devices: printed circuit board, capacitors, resistors, transistors, diodes	43.7	Production efforts, capacitors/GLO S Production efforts, resistors/GLO S Production efforts, inductors/GLO S Production efforts, transistors/GLO S Production efforts, diodes/GLO S
Rubber	25.2	Injection molding/RER S
60-W Incandescent		
Lamp holder	7.5	Metal product manufacturing, average metal working/RER S
Wire	3.2	Wire drawing, copper/RER S
Metal base	1.5	Metal product manufacturing, average metal working/RER S
Filament	0.02	Metal product manufacturing, average metal working/RER S
Bulb glass	16.4	Tempering, flat glass/RER S

2.3.2 Construction

The construction-phase environmental impact stems from the energy and materials consumed in transportation and construction activities. In this study, the construction-related GWP is assumed to be 20% of the embodied carbon of the building envelope [58].

2.3.3 Maintenance

The maintenance-phase environmental impact associated with the replacements of HVAC and lighting systems over a building's service life is estimated. It is assumed that each prototypical building is served by multiple 4-ton packaged air-conditioning units and the number of units required for each building type-and-location combination is determined based on the nominal cooling capacity calculated by EnergyPlus. The indoor temperature setpoints assume 21℃ for heating and 24℃ for cooling. The lifespan of the HVAC system is assumed to be 10 years and therefore, HVAC equipment needs to be replaced multiple times over a building’s life time [59].

The number of light bulbs required for each building type over the respective building life time is estimated based on the floor area, lamps' physical parameters (i.e., lifespan, luminous flux) and annual lit hours. The annual lit hours can be calculated from the lighting schedules specified in the EnergyPlus prototypical building models. As an example, Table 12 shows the total numbers of CFL bulbs required for each building over a one-year period of time and over a building's entire life time.

Table 12. Total numbers of CFL bulbs required for all building prototypes

Building type	Number of CFL bulbs needed for one year	Number of CFL bulbs needed over a building's life time
Small office	103	4,223
Medium office	737	30,217
Retail stand alone	410	15,580
Sit-down restaurant	134	3,618
Primary school	1256	51,496

2.3.4 Operation

EnergyPlus simulations were carried out to generate annual electricity and natural gas uses for the considered building types and climate locations. HVAC systems are auto-sized (number of packaged AC units) in EnergyPlus based on the peak cooling/heating demand during design days. As previously mentioned, the lighting requirement was assumed to be 500 lumens/m^2 for all indoor spaces. Based on this lighting requirement and the lamps' lighting efficacies (lumens/watt), the interior lighting power densities were configured in EnergyPlus.

2.4 Impact assessment

The EPA TRACI method in SimaPro is used for impact assessment [56] and the impact category considered is the GWP in kg CO_2 equivalent.

3. Case Study Results and Discussions

3.1 Embodied GWP results

3.1.1 Component-level embodied GWP

HVAC embodied GWP: Figure 3 shows the GWP of the 4-ton packaged air-conditioning unit by component. The estimated GWP of the whole unit is 1057.20 kg CO_2 eq. Among the various components, the condenser coil contributes the most embodied carbon, representing 34% of the total unit carbon footprint. The unit casing is the next most significant carbon contributors responsible for 15% of the unit carbon footprint, while the evaporator coil and blower each accounts for 13% of the unit GWP. Although regular steel has a relatively low carbon density compared to other involved metal materials, the large volume used in the unit casing makes it stand out. Copper and aluminum are extensively used in fin-tube heat exchangers and the material production processes involve significant carbon emissions. As a result, copper and aluminum used in the evaporator and condenser coils are responsible for almost half of the unit GWP. It may be noted that the U.S. HVAC industry is shifting from copper to aluminum tubes for evaporator coils as a means to lower the manufacturing cost. This change adversely impacts the equipment embodied GWP and further studies are needed to re-evaluate this market change from the environmental perspective.

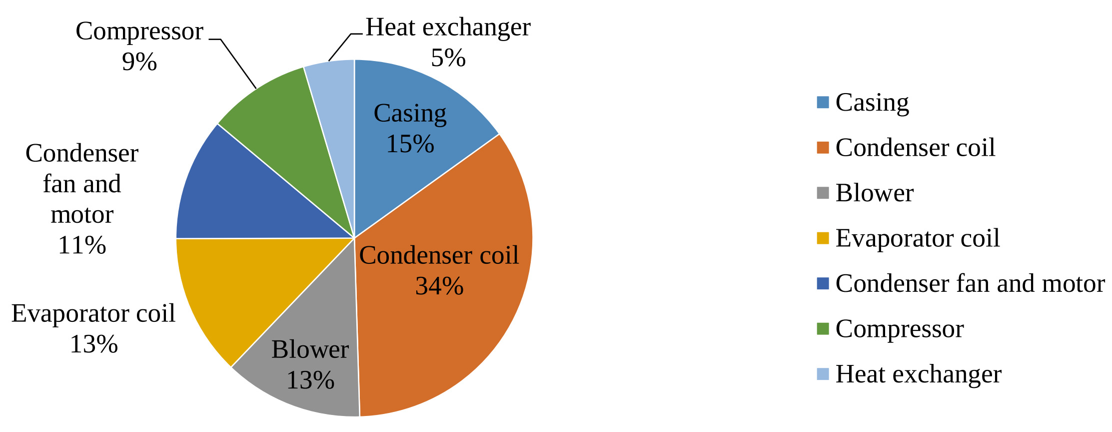

Figure 3. The global warming potential for the packaged air-conditioning unit by components

Embodied carbon per lamp: Based on the raw material inputs and manufacturing processes shown in Table 10 and Table 11, the GWPs of the 60 W incandescent, 14 W CFL, and 12.5 W

LED bulbs were estimated to be 0.73 kg CO2/eq., 2.29 kg CO2/eq., and 9.81 kg CO2/eq., respectively, considering both raw material extraction and manufacturing phases. The embodied carbon of the LED bulb is the highest while the incandescent bulb has the lowest carbon footprint. However, LED lights have much longer life spans, 25 times the life span of an incandescent bulb of the same lumens; thus, fewer LED light bulbs are needed for a given operation period. As a result, the long-term embodied carbon footprint of LED bulbs is the lowest.

Embodied GWP for building envelope: Figure 4 shows the estimated embodied GWPs for a medium office building envelope across different locations. It can be seen that concrete used in the "100 mm normal weight concrete floor" contributes the most significant environmental impact among all the construction materials. Construction differs from one location to another, to meet local codes. The medium office prototype located in San Francisco uses "8 in. concrete block basement wall" for the floor, while a medium office located in other climate zones uses "6 in. normal-weight concrete floor". The insulation level is highly dependent on the climate location, and the contribution of wall insulation to the total building envelope embodied carbon varies significantly across different regions. Windows make noticeable contributions, close to 15% of the total material carbon footprint. Due to space limitations, only the medium office results are presented to illustrate the relative significance of the various construction elements, while similar patterns can be observed across all other building prototypes:

- Concrete makes the most significant contribution to the total embodied carbon of building envelope;
- The impact associated with wall insulation is significant and highly variable with the climate location;
- Windows constitute a noticeable portion of the total embodied carbon for all considered building types.

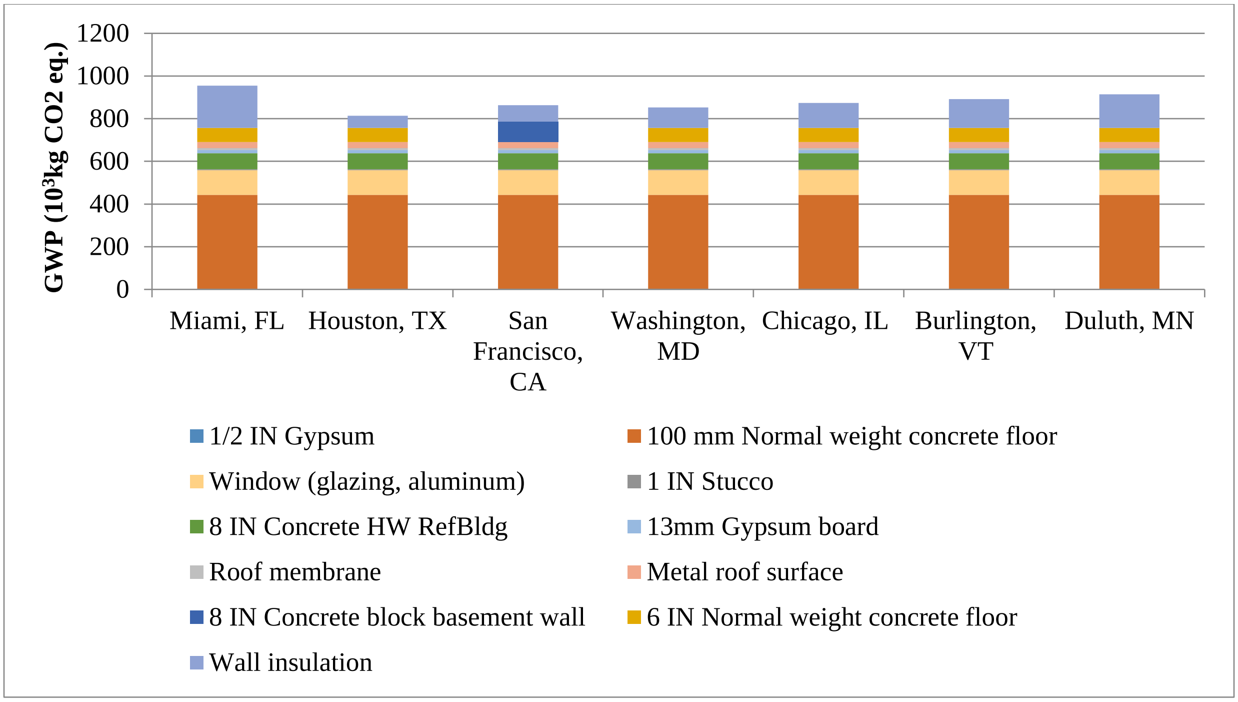

Figure 4. Building envelope GWP by material for the medium office.

3.1.2 Whole building embodied GWP

Embodied GWPs for the envelope, HVAC and lighting systems over the respective building life times are compared and shown in Figure 5. The presented GWPs for lighting and HVAC equipment have already accounted for replacements required during a building's life time. It can be seen that building envelope has the most significant contribution to the total embodied GWP (74% to 89%). The impacts from lighting systems are relatively small, but cannot be neglected (5% to 11%). HVAC equipment makes a noticeable GWP contribution for restaurants (11% to 15%) and retail stores (9-13%), mainly due to the high densities of cooling/heating demand; however, the HVAC embodied carbon contribution is relatively minor for the other building types (less than 10%). It should be noted that these results were obtained for a representative AC unit having a minimum standard SEER (seasonal energy efficiency ratio) of 13. As the efficiency regulations become more stringent, the embodied carbon of HVAC equipment is expected to increase attributed to adoption of higher efficiency components, such as larger-sized or micro-channel heat exchangers.

From Figure 5, it can be seen that small offices and sit-down restaurants, having the smallest floor areas, involve the highest embodied GWP density due to high wall-to-floor area ratios. The primary school is the largest building considered in this study and has the minimum embodied GWP per unit floor area. The stand-alone retail store is of big-box type with very few internal walls, which makes the embodied GWP density comparable to that of the primary school, although the total floor area is much smaller.

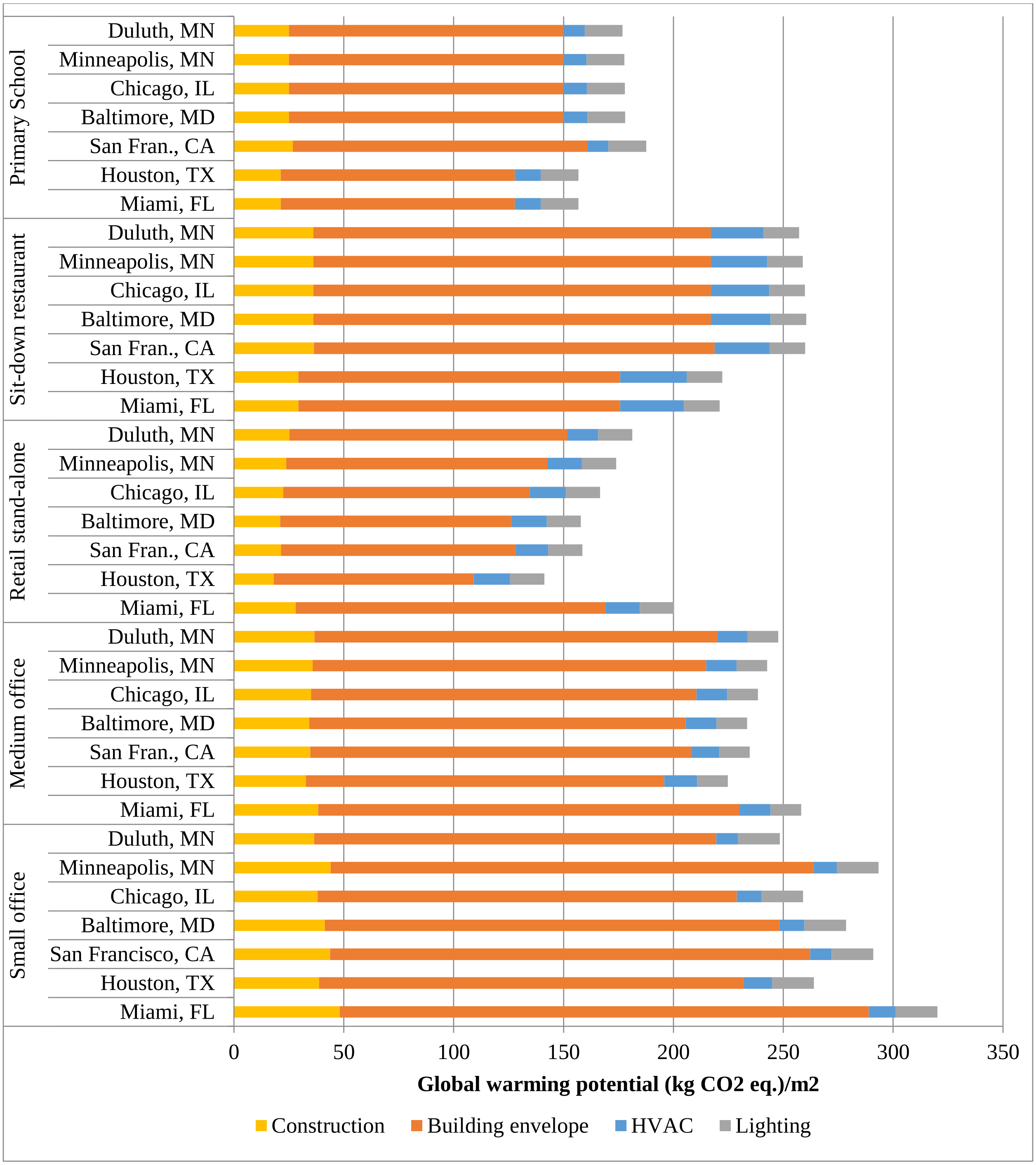

Figure 5. Embodied GWP over the lifespans of the case study buildings

3.1.3 Impact of lighting technology on building embodied GWP

Figure 6 compares the building embodied GWPs for the medium office building adopting different lighting technologies. It can be clearly seen that the lighting technology affects the embodied GWPs for both the lighting system itself and the HVAC equipment, as the heat gains from different light bulbs are quite different leading to different sizes of the HVAC system for a given building. To better illustrate this effect, Figure 7 compares the cooling system sizes for different lighting technologies for a medium office at Miami, FL. LED lights lead to the minimum HVAC equipment size (61.99 ton), while incandescent lighting results in the largest cooling system requirement (100.14 ton). Incandescent lights have the lowest embodied carbon per lamp among the three light bulbs under study. However, the total embodied carbon for incandescent lights is the highest as shown in Figure 6, because of the shortest lifespan and more frequent replacements throughout a building's life time. Although the LED bulb has the longest lifespan, 2.5 times the lifespan of CFL, the total embodied GWP of LED lights is still higher because of the higher embodied carbon per lamp, which is almost 4 times the embodied GWP of a CFL bulb. Due to the highest efficacy and lowest heat gains, LED lights lead to the minimum size requirement for the space cooling system.

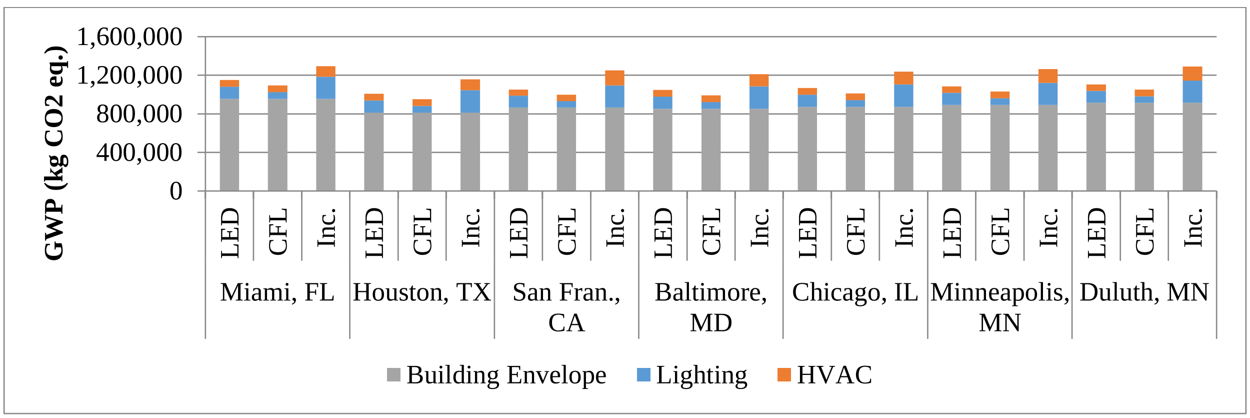

Figure 6. Embodied GWPs for the medium office adopting different lighting technologies.

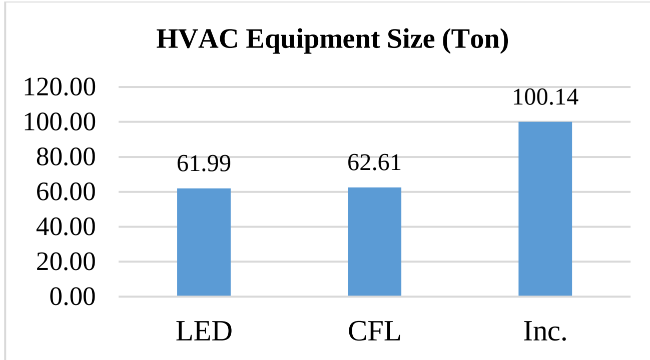

Figure 7. HVAC equipment size (in cooling ton) for different lighting technologies for a medium office at Miami, FL.

3.2 Operation-phase GWP

3.2.1 Building energy end uses

Figure 8 presents the annual site energy end uses, i.e., electrical heating, cooling, internal lighting (CFL) and gas heating, per square meter of floor area for all building types. It can be observed that energy use patterns are very different from one building type to another. Interior lighting is responsible for a significant portion of the total energy use in office buildings (21-31% and 12-21% in small and medium offices, respectively). However, lighting's share of energy usage in the sit-down restaurant is very small, from 2% to 4%. Location and climate are also influencing factors for building energy uses. For the primary school and stand-alone retail store, more than 30% of the site energy use is attributed to gas heating in the cold areas, e.g., Duluth, Minneapolis and Chicago, while in the hot climate locations such as Houston and Miami, HVAC cooling energy use is more significant. For the medium office, both electricity and natural gas are used for space heating although the electrical portion is more significant, because heat pumps are used as the primary heating source with the gas furnace as backup. Among the five building prototypes, the sit-down restaurant is the most energy-intensive, using 5~11 times more energy per square meter than the other four building types.

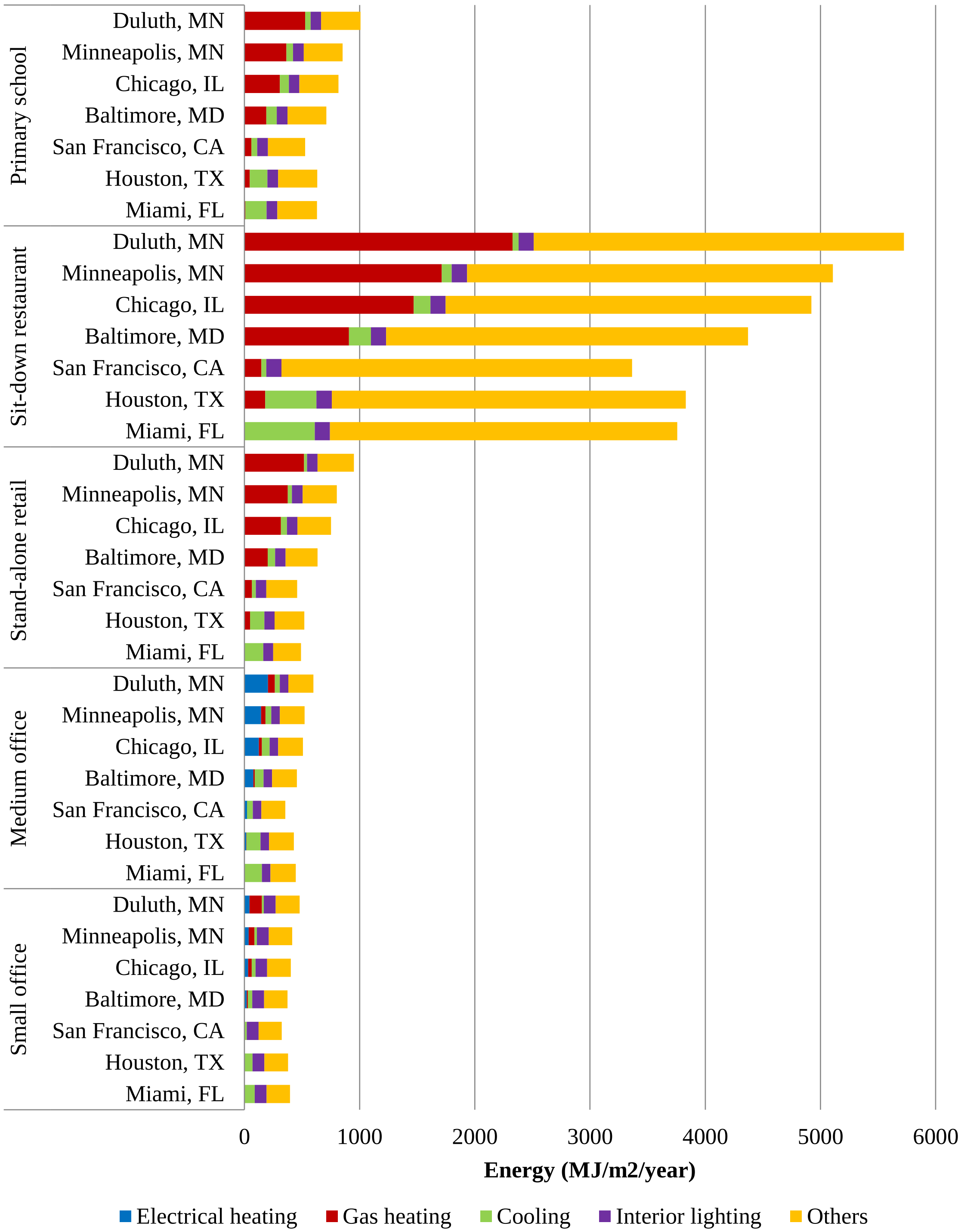

Figure 8. Site energy end uses for the case study buildings.

3.2.2 Impact of lighting technology on building energy uses

To illustrate the impact of lighting technology on the whole building energy use, Figure 9 shows the annual energy end uses for the medium office building adopting the three different types of lights. Simulations of the different lighting systems were achieved by setting different lighting power densities in EnergyPlus. Among the three lighting options, incandescent has the highest lighting energy consumption and the lowest efficacy. On the other hand, LED lights are the most energy efficient. The heat released from light bulbs also affects the energy consumption of HVAC systems. It can be observed that less efficient lights, e.g., incandescent, lead to noticeable reduction in heating energy uses for cold climate locations such as Duluth and Minneapolis; however, these lights result in higher cooling energy use for hot climate locations such as Miami and Houston. Therefore, applications of energy efficient lighting technologies could provide both lighting and HVAC energy savings for hot climate locations.

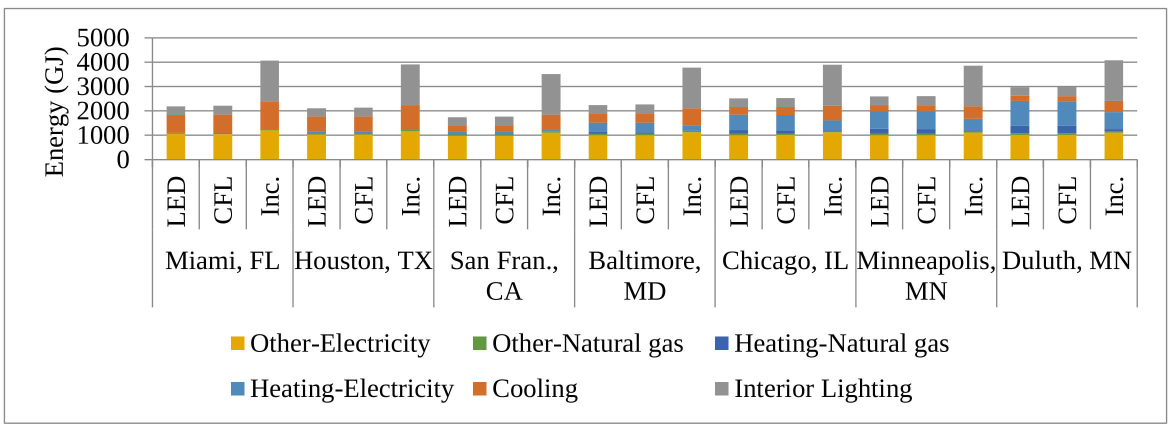

Figure 9. Annual energy end uses for the medium office.

3.2 Building life-cycle GWP

The annual electricity and natural gas uses estimated through the whole building energy simulations were combined with the estimated embodied GWP for a complete life-cycle environmental impact analysis. Figure 10 presents the obtained life-cycle GWP results for different combinations of building prototype and location; the presented results are associated with CFL, which has very similar environmental performance to that of LED lights. The life-cycle GWP density of a sit-down restaurant is 2 to 4 times the GWP density of the other four case study buildings, because of its high internal energy density (see Figure 8). Embodied carbon contribution to the overall life-cycle GWP is small in general (11-27% for the small office, 9-25% for medium office, 5-13% for stand-alone retail, 2-8% for sit-down restaurant, and 5-16% for primary school) and the use-phase GWP is dominant. Buildings in CA have the lowest use-phase GWP relative to the life-cycle GWP as (1) their HVAC energy consumption is the lowest due to the mild weather and (2) electricity is the cleanest in CA. As more building energy efficient technologies and renewable energy resources are adopted, the tradeoffs could change dramatically. For net-zero energy or carbon buildings, it is anticipated that the embodied carbon would be more significant compared to the operation-related GWP. The proposed methodology can be used to analyze the evolutions of whole-building environmental performance with the emergence of new technologies and decarbonization of the electric infrastructure.

Fuel type also impacts the overall building GWP. Duluth is located in a cold climate region where gas heating is responsible for a significant portion of a building's site energy use. Miami is in a hot climate zone where electricity used for space cooling is dominant. As can be seen from Figure 8, although the annual site energy use per square meter of building floor area in Duluth is greater than that in Miami, the life-cycle GWP density in Duluth is smaller for most of the building prototypes (see Figure 10). This is because the GWP per joule of natural gas is much smaller than that of electricity.

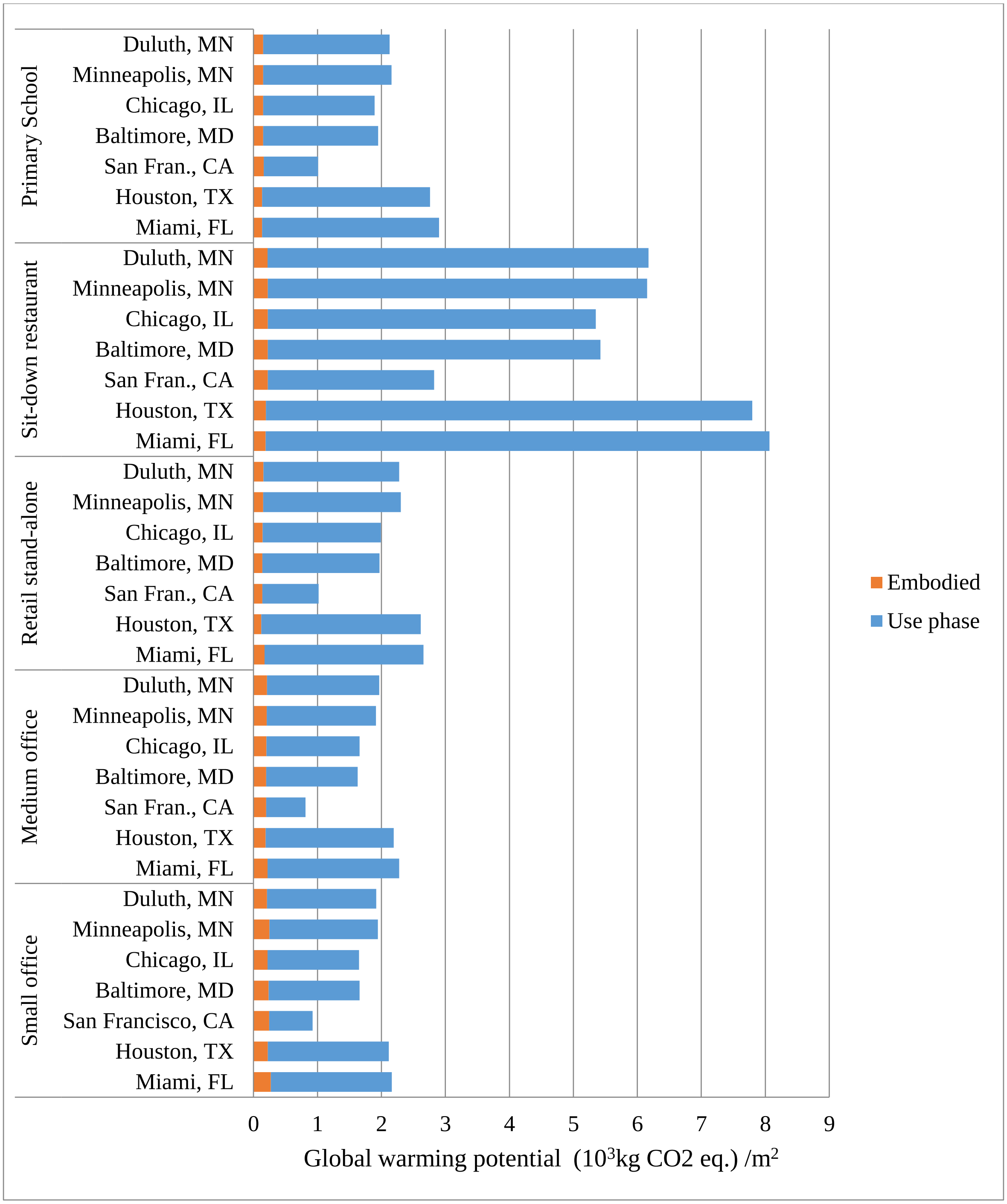

Figure 10. Embodied and operation-phase GWP for the case study buildings over their entire lifespans.

4. Conclusions

This paper presented a holistic building LCA methodology, which leverages whole building energy simulations and comprehensive embodied carbon accounting for major building components to provide a streamlined procedure for building life-cycle environmental analysis. The methodology uses EnergyPlus to generate building energy end uses in the operation phase. A variety of LCA databases are utilized in conjunction with laboratory collected data and results from the literature to estimate the embodied carbon for the different components. The methodology has been applied for life-cycle environmental performance assessment of five DOE prototypical commercial buildings across seven different climate locations in the U.S. and covering three different lighting technologies. The following conclusions can be drawn from the case study results:

- The sit-down restaurant is the most energy-intensive building prototype considered in this study and has the highest life-cycle GWP among the five building prototypes;
- Lighting makes a relatively small contribution to the total building embodied carbon for all considered cases (5% to 11 %);
- HVAC embodied carbon constitutes a small but appreciable fraction of the overall building embodied carbon, especially for sit-down restaurants (11% to 15%) and stand-alone retail stores (9% to 13%) which have higher cooling/heating densities;
- Building location influences both the energy consumption and construction materials. Construction materials of buildings located in San Francisco differ significantly from buildings located in other regions;
- HVAC energy uses contribute small environmental impacts for buildings in cold climate locations and with natural gas as the primary heating source, since natural gas has a much smaller carbon intensity compared to electricity;
- Operation-related GWPs are dominant in a building's life-cycle environmental impact; the tradeoffs could change dramatically as building energy efficiency increases and more renewable energy resources are employed;

- Incandescent lights have the lowest embodied carbon per lamp; but the overall embodied carbon is the highest due to the short lifespan and more bulb replacements over a building's life time;
- Efficient lights such as CFL and LED have reduced lighting energy use and use-phase environmental impact;
- Efficient lights also lead to reduced cooling energy use for hot climate locations (further reducing use-phase environmental impact); although they cause higher heating energy use for cold climate locations, the lighting electricity savings outweigh the heating energy increase, resulting in reduced overall use-phase environmental impact.

Although this study aimed to be comprehensive, there were limitations in the system boundaries that could affect accuracy of the results. The methodology only focused on the embodied and operation phases of a building's life time while the impact associated with the demolition phase was neglected. Although previously published results show that the end-of-life impact is small, this could change as new construction technologies are adopted. There is also a growing demand for accurate U.S. manufacturing data, for both mechanical/lighting equipment and building construction materials. The developed methodology can be improved in future work by incorporating more precise manufacturing data and including the environmental impact associated with the end-of-life phase.

The embodied carbon of construction materials, especially concrete, can vary significantly by the origin and the supplier. This study estimated the environmental impacts of construction materials based on industry averages recorded by relevant LCA databases such as Ecoinvent and USLCI. However, recent technological advances have led to significant emission reductions associated with concrete manufacturing processes (e.g., increasing use of green cement). The lower embodied carbon of concrete can substantially affect the tradeoff between the embodied and operational carbon footprint, which should be re-visited in future work.

The presented LCA procedure allows automated carbon footprint reporting for any given EnergyPlus/OpenStudio building model, although minor modifications may need to be made when other types of HVAC equipment are in place. For instance, chilled-water cooling systems which are more common in larger commercial buildings could have very different embodied and operational carbon footprint compared to direct-expansion cooling systems analyzed in this study. The methodology can support sustainable decision making in the building design phase if a building information model (BIM) can be translated flawlessly to an EnergyPlus model. Although data transfer from a BIM to a building energy model (e.g., EnergyPlus) has attracted growing research interests in recent years, reliable and accurate model translation is still a challenging task [60][61]. A promising alternative is to incorporate the presented methodology to BIM-based energy analysis features, such as the Autodesk Insight 360 plug-in for Revit. Insight 360 utilizes the EnergyPlus simulation engine with prototypical HVAC equipment, for which the integration of the presented LCA methodology seems straightforward. This is a topic worth pursuing in future work.

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