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A Whole Building Life-Cycle Assessment Approach to Support Decision-Making for Sustainable Buildings

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ABSTRACT

Buildings account for 39% of the CO_2 emissions in the U.S. Although emerging building energy-efficient technologies lead to improved energy efficiency and lower environmental impact in the operational phase, not much attention has been paid to the environmental impact associated with the materials and manufacturing of the building mechanical systems. This paper presents an integrated life-cycle assessment method for buildings that accounts for the embodied and use phase carbon impacts of the building and its mechanical systems. The proposed methodology relies on EnergyPlus to generate the use-phase energy consumption for any given building. A material 'grabber' routine was developed to automatically extract building envelope material information from EnergyPlus models, which is then used for envelope embodied carbon analysis. For the mechanical equipment, embodied carbon accounting was performed for two representative air-conditioning and heat pump units: a 4-ton packaged unit and a 4-ton split heat pump. The different elements were incorporated in the overall life-cycle assessment tool along with lighting embodied data to allow generation of a whole building environmental performance report. Five Department of Energy commercial building prototypes were used as case studies and analysis results for seven U.S. climate locations are presented in this paper. The results show that for the investigated prototypical buildings, the use phase energy consumption has a dominant impact on the overall building environmental performance: the embodied carbon contribution is less than 9% for all considered cases. However, the tradeoffs could change dramatically as the U.S. moves towards net-zero buildings and the tool presented in this paper could be used to consider these tradeoffs.

1. INTRODUCTION

The building sector accounts for 39% of total CO_2 emissions in U.S. (EIA 2018). The life cycle assessment (LCA) approach has been applied by researchers to investigate the environmental performance of buildings since 1990s (Wang et al., 2011). However, most of the previous work focused on building construction materials, e.g., (Su and Zhang, 2010); (Monteiro and Freire, 2012); (Lemay, 2011). Very limited research can be found that performed LCA studies on a whole building level due to difficulties in integrating the various construction, mechanical and electrical elements within a building. In addition, energy efficient technologies, such as light-emitting diode (LED) lights, solar- or geothermal-assisted heating/cooling equipment, are widely implemented in buildings with the purpose to reduce energy usage and the associated environmental impacts (Bribian et al., 2009). However, the embodied carbon emission of building systems could be increased by using these new technologies. Thus, there is a need to evaluate different energy efficient technologies in terms of environmental impact considering both manufacturing/construction and operation phases.

This paper fills a research gap by presenting a whole building LCA methodology that covers both embodied and use phases and the integration of building envelope and mechanical system design. The method utilizes EnergyPlus (National Renewable Energy Laboratory, 2017), a flagship building energy simulation software developed and maintained by the U.S. Department of Energy (DOE), to generate building energy uses in the operation phase. LCA, e.g., BEES,(National Institute of Standards and Technology, 2016), U.S.LCI, (National Renewable Energy Labratory, 2010), etc., databases are employed to estimate the building environmental impacts associated with the raw material acquisition, building material production and operation stages. Five DOE prototypical commercial buildings were considered as case studies to demonstrate the analysis approach. In-depth analysis was carried out for three types of lighting technologies: incandescent, compact fluorescent (CFL) and LED lights. Detailed embodied carbon analysis was carried out for a representative packaged rooftop air-conditioning unit and a split heat pump. Parametric analysis was performed for the different lighting options, building types and climate locations. As building owners or contractors are increasingly aspiring towards healthier and more environment-friendly products in the building design and retrofit phases, results presented in this paper can be used as a reference to facilitate decision making from an environmental perspective.

2. METHODOLOGY

Figure 1 describes the methodology proposed for whole-building LCA analysis. The overall process starts with a building information model (BIM), which contains detailed building construction information. The BIM is fed to a whole building energy simulation tool to generate building energy uses in the operation phase. OpenStudio (Guglielmetti et al., 2011), developed and maintained by the National Renewable Energy Laboratory, is an upfront graphical user interface for EnergyPlus. OpenStudio takes the BIM for a given building and calls EnergyPlus to execute whole building energy simulations. A “Material Grabber” routine was developed that can take an OpenStudio/EnergyPlus model and automatically generate the bill of materials for a given building. Based on the collected material information, the embodied carbon associated with the construction materials are estimated via queries to LCA databases. The U.S. LCI and ecoinvent databases (Wernet et al., 2016) were used as main LCA data sources for the material life-cycle stages. Building-specific databases, BEES and BIRDS (Lippiatt et al., 2013), were also used when pertinent data was not available in the U.S. LCI or ecoinvent databases. With the simulated operation phase energy uses and estimated embodied carbon, whole building LCA analysis is performed. Detailed LCA analysis for HVAC equipment and lighting systems relied on both laboratory collected data or publicly available literature. As summarized in Table 1, embodied carbon and carbon emissions associated with building operation were estimated in this study. Carbon emissions for the transportation and building construction were not considered as these effects are believed to be small relative to the other impacts.

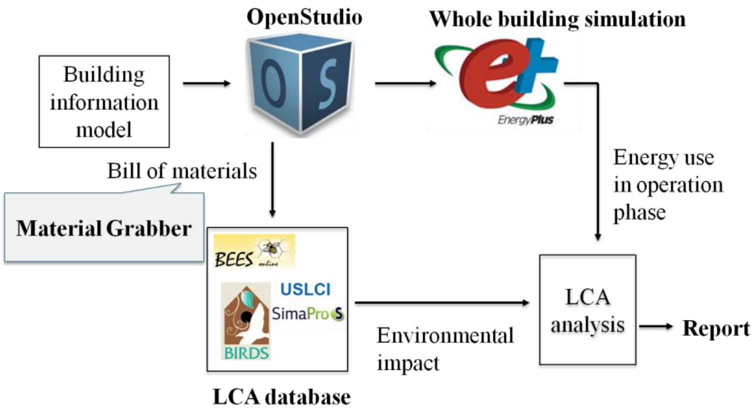

Figure 1. Proposed building LCA methodology.

Table 1. System boundary

Life cycle phases	Main assumptions for calculation
Embodied	Building envelope HVAC system Lighting system
Use phase	Operation (electricity and nature gas consumption)

Five DOE prototypical commercial buildings were used (small office, medium office, sit-down restaurant, standalone retail, and primary school) as case studies to demonstrate the processes in the proposed LCA approach. Detailed descriptions of these prototypical buildings can be found on the DOE website (U.S. Department of Energy, 2016). The LCA case studies considered seven locations with one representative location from each of the seven climate zones in the US: Miami, FL (1A), Houston, TX (2A), San Francisco, CA (3C), Washington, MD (4A), Chicago, IL (5A), Burlington, VT (6A), and Duluth, MN (7A). Parametric analysis covering different climate locations was performed to investigate the impact of climate conditions on the building environmental performance.

3. EMBODIED CARBON ANALYSIS

3.1 Building Envelope Embodied Carbon Analysis

Construction material carbon analysis for a medium office case study is presented in this section as an example to illustrate the process. Construction materials vary with respect to building location and the presented example is associated with San Francisco. The bill of materials for this prototype building was obtained using the “Material Grabber” routine. The global warming potential (GWP) per unit of construction material were mainly obtained from ecoinvent and U.S.LCI databases. The GWP values of storefront window materials were downloaded from a major manufacturer’ website, which is 128 kg CO_2 eq. per m2 of glazing and 49.5 kg CO_2 eq. per m2 of frame (Kawneer Company, n.d.).The GWP of wall insulation (fiberglass) was calculated based on constituents and manufacturing energy requirements from BEES. Table 2 gives the collected material information and the corresponding carbon densities.

Table 2. Material inputs and corresponding GWP for the medium office at San Francisco

Building product	**Mass (or area)**	**Material**	**GWP (kg CO_2 eq.) /kg material**
½ IN Gypsum	13.2 Tonnes	Gypsum fiber	0.292
100 mm Normal weight concrete floor	3920 Tonnes	Concrete	0.112
1 IN Stucco	62.3 Tonnes	Stucco	0.074
8 IN Concrete block basement wall	784 Tonnes	Concrete block	0.123
8 IN HW Concrete	603 Tonnes	Concrete block	0.123
13 mm Gypsum board	52.1 Tonnes	Gypsum fiber	0.292
Metal roof surface	10.4 Tonnes	Metal panel	2.722
Roof membrane - highly reflective	17.7 Tonnes	Roofing membrane	0.488
Windows	652.83 m^2	Fixed storefront window	-
Wall insulation (2.54 cm thickness)	0.408 Tonnes	Fiberglass	0.806

Figure 2 shows the estimated embodied GWP associated with all the materials in a medium office across different locations. It can be seen that the material “100 mm Normal weight concrete floor” has the largest impact on the global warming compared with other materials. The medium office located in San Francisco (climate zone 3C) uses “8 IN Concrete block basement wall”, while a medium office located in other climate zones uses “6 IN Normal weight concrete floor”. That is one main difference in construction materials between different locations. The insulation level also differs significantly from one location to another, but the relative contribution of wall insulation to the total building envelope embodied carbon is very small, which makes it difficult to see the insulation variation for different locations. Windows contribute a significant portion of the total embodied carbon in the case study building. Materials associated with interior furnishings were not considered in this embodied carbon analysis. Similar patterns can be observed across all the other building types:

- Concrete makes the most significant contribution to the total embodied carbon;
- The impact coming from wall insulation is very small and probably can be neglected in the overall building LCA analysis;

- Windows contribute a noticeable portion of the total embodied carbon for all considered building types.

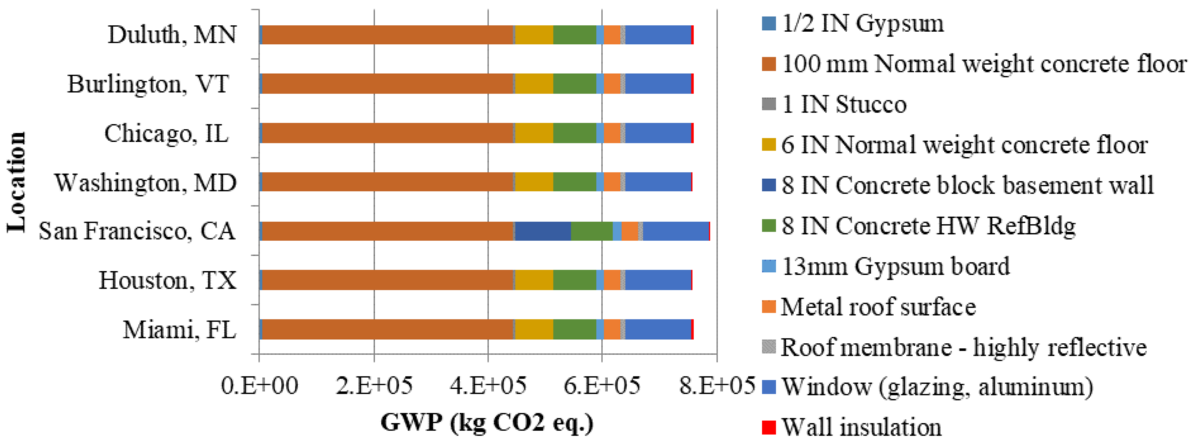

Figure 2. GWP by embodied materials for a medium office.

3.2 Lighting Embodied Carbon Analysis

Embodied carbon for three types of commonly used lighting systems (incandescent, CFL and LED) was analyzed as part of the overall building analysis. Carbon emissions associated with raw material extraction and manufacturing were considered. Material inputs for 12.5-W LED, 14-W CFL, and 60-W incandescent light bulbs were collected from (Scholand and Dillon, 2012), (Tuenge et al., 2013), (Zhang et al., 2017), respectively. Table 3 lists all the major material inputs for the three types of light bulbs. 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 components.

Table 3. Material inputs for lighting systems

Component	**Mass (g)**	**Material**
12.5-W LED		
Metal	68.2	Aluminum
Lamp holder	15.3	Copper
Plastic	16.1	Plastic
LED aluminum board	6.9	Aluminum
Power supply devices	43.7	Printed circuit board, capacitors, resistors, transistors
Rubber	25.2	Rubber
14-W CFL		
Power supply devices	14.1	Printed circuit board, capacitors, resistors, transistors
Bulb glass	18.2	Glass
Lamp holder	5.3	Copper
Plastic	11.9	Plastic
60-W Incandescent		
Lamp holder	7.5	Copper
Wire	3.2	Copper
Metal base	1.5	Tin plate
Filament	0.02	Tungsten
Bulb glass	16.4	Glass

Based on the collected raw material inputs shown in Table 3 and manufacturing process information, the total GWPs per lamp were calculated and the results are given in Table 4. It can be seen that the embodied carbon for a LED bulb is the highest while an incandescent bulb has the lowest embodied carbon. However, incandescent lights have much shorter life time and lower efficacy; thus, more light bulbs are needed for a given operation period.

Table 4. Characteristics of the three lighting options

Lamp type	**Lumens**	**Lifespan (hrs)**	**GWP (kg CO_2 eq.) per lamp**
60 W-Incandescent	860	1,000	0.726
14 W-CFL	900	10,000	2.29
12.5 W-LED	850	25,000	9.81

3.3 HVAC System Embodied Carbon Analysis

A 4-ton packaged gas heat & electric cooling unit and a 4-ton split heat pump unit with similar rated efficiency were identified and detailed embodied carbon analysis was carried out for these two representative HVAC units based on laboratory collected data and publicly available literature(Carrier Enterprise, 2018). The estimated GWPs for the two units are very close and only the results for the packaged unit are presented in this paper due to space limitations. Table 5 shows the collected material information and the corresponding carbon densities collected from the various LCA databases.

Table 5. Material inputs and corresponding GWP for the packaged unit

Components	**Mass (kg)**	**Materials**	**GWP (kg CO_2 eq.) per kg material**
Casing	53.66	Steel	1.81
Condenser coil	23.47	Aluminum	8.94
	5.89	Copper	1.99
Blower motor	9.43	NdFeB magnet motor (Navarro et al., 2014)	6.79
Blower wheel	2.99	Galvanized steel (American Galvanizers Association, 2017)	1.79
Evaporator coil	3.79	Copper	1.99
	8.37	Aluminum	8.94
Condenser motor	9.14	NdFeB magnet motor	6.79
Condenser fan	5.28	Galvanized steel	1.79
Heat exchanger	16.53	Galvanized steel	1.79
Compressor	3.18	Galvanized steel	1.79
	1.42	Copper	1.99
	0.71	Aluminum	8.94
	29.72	Cast iron	1.52

Figure 3 shows the GWP for the packaged system by materials. The results show that aluminum has the largest impact (46%) on the overall unit environmental impact, due to the high carbon density of aluminum and the significant amount of aluminum used in the fin-tube evaporator and condenser coils.

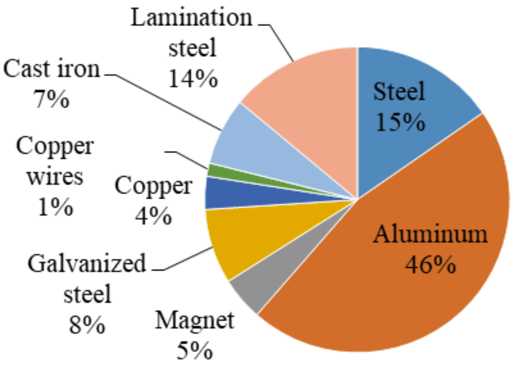

Figure 3. Packaged unit GWP (kg CO_2 eq.) by materials.

3.4 Use Phase Analysis: Simulation Results

In this section, simulation results in the use phase analysis are presented for the different building types and locations. The incandescent, CFL, and LED lights have quite different characteristics as shown in Table 4. Incandescent has the lowest efficacy (lumens/watt) of about 14 lumens/watt, while the efficacy of LED is the highest (68 lumens/watt) among the three lighting options. In the whole building simulations, a lighting requirement of 500 lumens/m2 was assumed for all building spaces. Based on lighting efficacies, the lighting power densities (LPD) for the different lighting options were configured accordingly in EnergyPlus.

EnergyPlus simulations were carried out to generate annual electricity and natural gas uses for all considered building types, lighting options and climate locations. Multiple 4-ton packaged units were assumed to serve all the building types and the numbers of units required were selected automatically in EnergyPlus based on the annual peak cooling demands. All building prototypes use gas furnaces for space heating except for the small and medium offices. The small office prototype is served by packaged air-source heat pumps with gas furnaces as back up. Although the analyzed packaged unit is not a heat pump, the embodied carbon of a heat pump should be similar and the estimated embodied carbon for the packaged unit was used directly for heat pump equipment in the prototype buildings. In the medium office, electrical heating is only used for variable air-volume (VAV) terminal boxes while the packaged unit uses gas as the primary heating source. Embodied carbon for VAV boxes and electrical heaters were not studied in this paper as they only show up in the medium office case studies and the impact should be small.

The different lighting systems (LED, incandescent, CFL) were applied to all the prototype buildings by setting the lighting power densities appropriately in EnergyPlus. As an example, Figure 4 shows the simulated annual energy end uses for the medium office. Among the three lighting options, incandescent has the highest lighting energy consumption due to the low efficacy. LED lights, which have highest efficacy, consume the least energy. 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 bulbs, lead to noticeable reduction in heating energy uses for cold climate locations such as Duluth and Minneapolis; these lights result in higher cooling energy use for hot climate locations such as Miami and Houston. So applications of energy efficient lighting technologies could provide both lighting and HVAC energy savings for hot climates. Although LED and CFL lights lead to increased heating energy use, the lighting energy savings is much greater than the marginal heating energy increase leading to reduced total energy use.

Energy use patterns are very different from one building type to another. For small and medium offices, interior lighting and HVAC equipment are responsible for a significant portion of the total energy use. For a sit-down restaurant, the lighting energy contribution is very small while miscellaneous and HVAC loads are more significant. The distribution of energy use for the primary school and retail store have a stronger dependence on location and lighting type than for the other buildings. However, both HVAC and lighting energy uses are significant for these two building types.

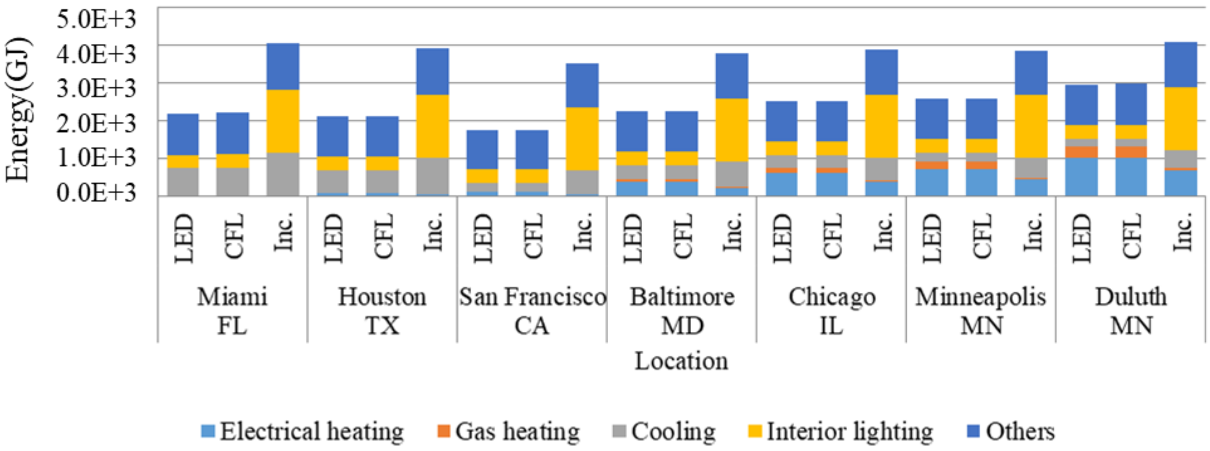

Figure 41. Annual energy uses for medium office.

3.5 Life-Cycle Environmental Analysis

3.5.1 Embodied GWP (50 years)

This study assumed a building life of 50 years for all case study buildings and life cycle assessment was carried out for the same period of time. Again, a lighting requirement of 500 lumens/m2 was assumed for all building spaces. The number of light bulbs required for each building type was calculated based on the design lighting power, efficacies, and the floor area. Different light bulbs have different lifespans (also listed in Table 4). LED bulbs have much longer life time and thus, need less frequent replacements. To calculate the total number of light bulbs needed for the analysis period, lighting schedules were extracted from the EnergyPlus prototypical building models and annual lit hours were calculated. In EnergyPlus, HVAC systems were auto-sized based on the peak cooling/heating demand during design days. All buildings were assumed to be served by identical 4-ton units and the number of units needed for each building was determined by the auto-sized cooling capacity. The lifespan of a HVAC system was assumed to be 10 years. Thus, HVAC equipment needs to be replaced 5 times during a building's life cycle.

The embodied GWP for building envelope, lighting, and HVAC equipment are compared for all considered building types. Figure 5 shows an example of the embodied carbon analysis for the medium office building. It can be clearly seen that the building envelope has the most significant contribution to the total embodied GWP. The impact from lighting systems is also significant and cannot be neglected. It should be highlighted that the embodied carbon per lamp is lowest for incandescent lights. But the total embodied carbon for incandescent lights is highest. That is because an incandescent bulb has a much shorter life time compared to LED and CFL and more bulbs are needed during a building's life cycle. HVAC equipment makes a noticeable contribution to the embodied carbon for restaurants (10%~18%) and retail stores (7%~12%) (results not presented in this paper), mainly due to the high cooling/heating densities; but the HVAC embodied contribution is negligible for the other building types.

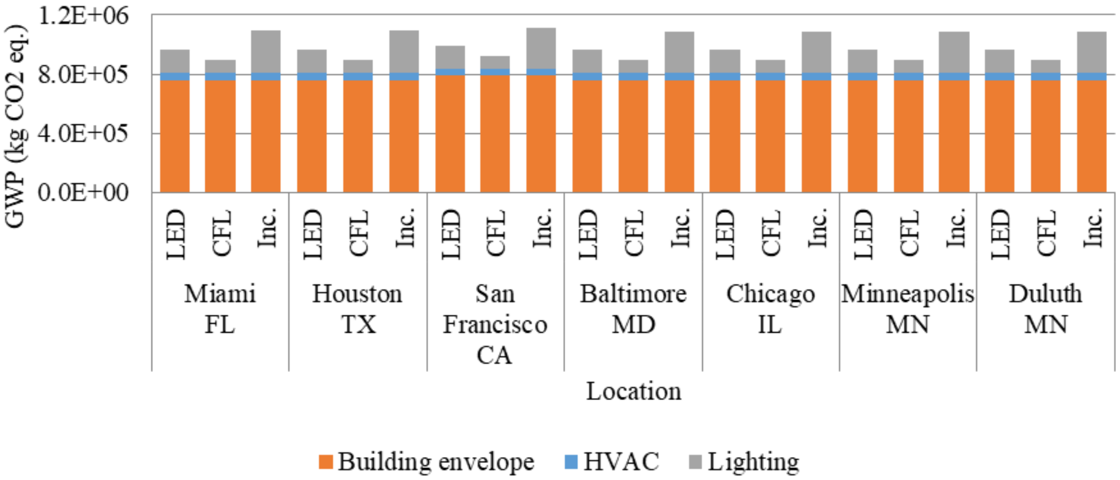

Figure 5. Embodied GWP for medium office.

3.5.2 Embodied and use phase GWP (50 years)

The whole building life-cycle analysis was performed for a 50-year building life time considering embodied and use phase GWP. Figure 6 shows example LCA results for the medium office buildings for different locations and lighting options.

The results show that the embodied carbon contribution to the life-cycle GWP is in general very small and can be neglected (2.5~8.2% for small office, 2.3%~6.4% for medium office, 1.3%~4.0% for standalone retail, 0.6%~1.4% for sit-down restaurant, and 1.4%~4.4% for primary school). However, the results were associated with typical building descriptions in 2010. As more energy efficient technologies are adopted and net-zero buildings are developed, the tradeoffs could change dramatically and the proposed methodology will be able to capture the tradeoffs.

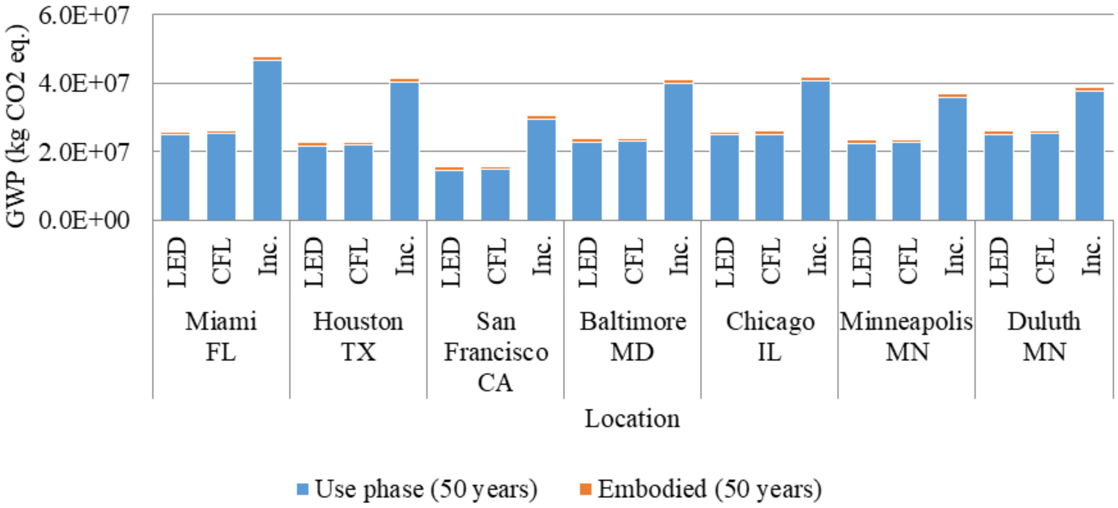

Figure 6. Embodied and use phase (50 years) global warming potential for medium office.

4. CONCLUSIONS

In this paper, a holistic building LCA methodology was developed and applied to 5 prototypical commercial buildings for different climate locations in the U.S. The overall methodology integrates whole building energy simulation and LCA together, providing a streamlined process for building life-cycle environmental analysis. In this paper, EnergyPlus was used to generate building energy end uses in the operation phase. A variety of LCA databases were utilized to estimate the building environmental impact in the construction phase. Then an overall analysis was carried out based on the collected information for the use and construction phases.

High-granularity environmental data are not available for HVAC systems in the existing LCA databases. To fill the gap, detailed embodied carbon analysis was performed for two representative HVAC systems, based on laboratory collected material data and manufacturer literature. In-depth analysis was carried out for three types of lights that are mostly used: incandescent, CFL, and LED. Parametric analysis was performed for the different lighting options, building types and climate locations. Based on the analysis results, the following conclusions can be drawn:

- Wall insulation differs significantly for buildings in different climate locations; but its embodied carbon contribution is negligible compared to the other construction materials;
- Windows make a noticeable contribution to the total building envelope embodied carbon;
- Lighting makes a significant contribution to the total building embodied carbon for all considered cases;
- Incandescent lights have lower embodied carbon per lamp; but their long term embodied carbon is highest due to the short lifespan and more bulb replacements;
- HVAC embodied carbon constitutes a small fraction of the overall building embodied carbon, except for restaurants (10%~18%) and retail stores (7%~12%) which have higher cooling/heating densities;
- Efficient lights such as CFL and LED lead to reduced cooling energy use for hot climate locations (further reducing use phase environmental impact); but they cause higher heating energy use for cold climate locations (lighting electricity savings are greater than heating energy increases resulting in reduced use phase environmental impact);
- HVAC energy use contributes small environmental impacts for cold climate locations and for buildings with natural gas as the primary heating source, as natural gas has much smaller environmental impact compared to electricity;
- Building use phase GWP are dominant in the total life-cycle GWP; the tradeoffs could change dramatically as building energy efficiency increases and as the U.S. moves towards net-zero buildings and renewable power generation.

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