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Environmental Performance of Green Building Code and Certification Systems

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Supporting Information

ABSTRACT: We examined the potential life-cycle environmental impact reduction of three green building code and certification (GBCC) systems: LEED, ASHRAE 189.1, and IgCC. A recently completed whole-building life cycle assessment (LCA) database of NIST was applied to a prototype building model specification by NREL. TRACI 2.0 of EPA was used for life cycle impact assessment (LCIA). The results showed that the baseline building model generates about 18 thousand metric tons CO_2-equiv. of greenhouse gases (GHGs) and consumes 6 terajoule (TJ) of primary energy and 328 million liter of water over its life-cycle. Overall, GBCC-compliant building models generated 0% to 25% less environmental impacts than the baseline case (average 14% reduction). The largest reductions were associated with acidification (25%), human health—respiratory (24%), and global warming (GW) (22%), while no reductions were observed for ozone layer depletion (OD) and land use (LU). The performances of the three GBCC-compliant building models measured in life-cycle impact reduction were comparable. A sensitivity analysis showed that the comparative results were reasonably robust, although some results were relatively sensitive to the behavioral parameters, including employee transportation and purchased electricity during the occupancy phase (average sensitivity coefficients 0.26–0.29).

INTRODUCTION

Buildings generate substantial environmental and natural-resource impacts on modern society. Estimates show that about 40 exajoules (EJ) or 40% of total energy consumed in the US is associated with residential and commercial buildings.[1−3] Given the importance of energy consumption in climate change, acidification, tropospheric oxidant formation, and toxic impacts, the significance of buildings in many air-pollutant-induced impacts is obvious. In addition, buildings are an important conduit for water consumption, land conversion, and land occupation,[1] and building materials constitute the most significant end-use category of material consumption by mass.[4]

Various approaches including, but not limited to, material choices,[5,6] thermal insulation,[7,8] local sourcing,[9] passive thermal storage and alternative envelope designs,[10−13] and energy efficient designs[14−16] have been developed and applied in an attempt to reduce environmental and resources footprints of buildings. Since the 1990s, lessons learned from such efforts have informed industry standards, model building codes, rating systems, and green building certifications,[14,17,18] which are collectively referred to as green building code and certification (GBCC) systems in this paper.

Over a dozen GBCC systems and their combinations are reported in the literature,[19−24] among which some of the most frequently discussed include LEED (Leadership in Energy and Environmental Design), BREEAM (Building Research Establishment's Environmental Assessment Method), Green Globes, Living Building Challenge (LBC), ISO/TS 21929-1:2006, ASHRAE (American Society of Heating, Refrigeration, and Air-Conditioning Engineers) 189.1 and 90.1, and IgCC (International Green Construction Code). Some of these GBCC systems have achieved remarkable market penetration over the past decade. For example, according to the U.S. Green Building Council (USGBC), as of August 2013 there are 44,270 LEED-certified projects in the U.S. alone.[25]

A natural question is whether these GBCC systems mitigate environmental impacts. If so, which environmental impacts are better addressed, and how much impact can they mitigate?

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Empirical studies that attempt to answer such questions focus mainly on direct energy and water consumption.[24,26−28] Many such studies show modest to significant benefits of GBCC systems but not without exceptions. For example, Turner and Franckel (2008)[26] concluded that LEED-certified buildings use 26−44% less energy than average buildings reported in the Commercial Buildings Energy Consumption Survey (CBECS).[29] Newsham et al. (2009)[30] confirmed that LEED-certified buildings use less energy on average but also showed that 28−35% of LEED-certified buildings use more energy than non-LEED-certified counterparts. Scofield (2009)[28] re-examined Newsham's analysis and came to the conclusion that there is no evidence that LEED-certified buildings collectively show lower energy consumption than comparable non-LEED buildings. These empirical analyses frequently use cross-sectional data from the Commercial Buildings Energy Consumption Survey (CBECS)[29] of the U.S. Energy Information Administration (EIA) to derive energy and water consumption profiles of comparable buildings. One of the challenges, which in part contributed to the mixed results in the literature, lies in the difficulties of establishing counterfactuals: each building is, to a certain extent, unique with respect to the design, materials, location, climate, purpose, and occupants, which in concert influence the building's energy and water consumption profiles.

A few studies approached the question using life cycle assessment (LCA) and went beyond direct energy and water consumption. In their pioneering work on an earlier version of LEED, Scheuer and Keoleian (2002)[31] applied LCA and showed that the lack of comparability between LEED credits creates disparities in quantitative environmental outcomes across buildings with the same level of LEED rating. Humbert et al. (2007)[32] quantified life-cycle environmental costs and benefits of LEED credits and concluded that the life-cycle environmental benefits of a LEED credit can be negative or positive, the credit that provides the highest environmental benefits being the requirement of at least 50% renewable energy.

Building upon the previous studies, we attempt to approach the question using a recently completed whole-building LCA database of the National Institute of Standard and Technology (NIST)[33] and a prototype model building specification by the National Renewable Energy Laboratory (NREL).[34] The objective of our study is to quantify the potential life-cycle environmental impact reduction of three GBCC systems: LEED, ASHRAE 189.1, and IgCC, covering a wide range of environmental impact categories. Our intention is neither to generalize the environmental performance of the three GBCC systems nor to provide a rank between them. Rather, we intend to gauge the potential environmental benefits of GBCC systems from a life-cycle point of view using a typical small office building and the three GBCC systems as a case study.

■ METHOD AND DATA

In this study, we first mapped the criteria for compliance by the three GBCC systems in terms of their potential influence, either on inputs (e.g., material, services, energy, and water) or on outputs (e.g., waste, greenhouse gas emissions, toxic pollutant emissions). Using a prototypical small office building model as a baseline,[34] we quantified inputs to and outputs from each of the three GBCC-compliant building models. The inputs and outputs quantified were used to generate life cycle inventories (LCIs) for the baseline and the three GBCC-compliant building models. Building lifetime was assumed to be 40 years following previous literature and data available for our analysis.[35,36] We applied a life cycle impact assessment (LCIA) model and interpreted the results. The overall procedure of our analysis is illustrated in Figure 1.

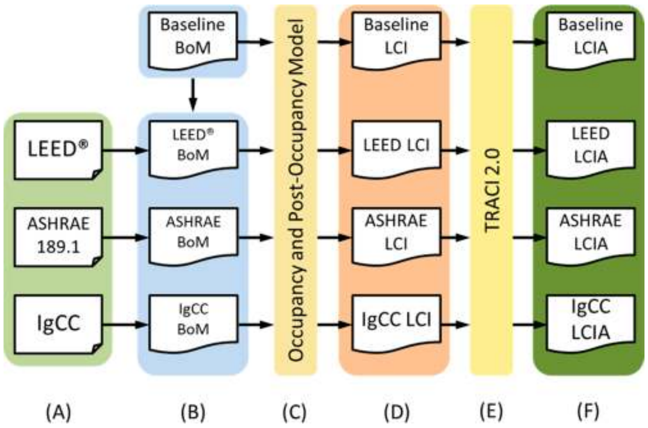

Figure 1. Procedure for LCA of Green Building Standard, Code and Certification Systems: (A) Key features matrix for LEED, ASHRAE 189.1 and IgCC; (B) Bill of Materials (BoM) for the baseline and three alternative building models to conform three GBCC systems; (C) Quantification of occupancy and postoccupancy inputs and outputs; (D) Mapping the BoM and the occupancy and postoccupancy inputs and outputs data with LCI databases; resulting Life Cycle Inventory (LCI); (E) Application of TRACI 2.0 for impact assessment; (F) Characterized impact results for interpretation and sensitivity analysis.

The three GBCC systems selected in this study are briefly reviewed in the next subsection. The analytical approach is further elaborated in the next five subsections.

Scope of the GBCC Systems Analyzed. In this study we selected three GBCC systems: LEED, ASHRAE 189.1, and IgCC. These GBCC systems were chosen because they have been widely adopted by local authorities and architects and were developed in a close coordination, so that the topical areas covered are closely aligned.

LEED is a voluntary, third-party, verified green building rating and certification system led by the U.S. Green Building Council.[37] LEED criteria are regularly updated through an open, participatory process. The most recent, officially released version of the LEED rating system is version 3 published in 2009. The next version is expected to be released later in 2013. The remaining description of LEED is based on LEED version 3. LEED employs credit points as well as prerequisites, which are mandatory for any level of LEED certification. Depending on the type of project in question, LEED uses a point scale ranging from 100 to 125, covering 5 major topical areas including (a) sustainable sites; (b) water efficiency; (c) energy and atmosphere; (d) materials and resources; and (e) indoor environmental quality. In addition, up to 11 additional points can be added in the areas of design innovations and regional priorities.

LEED contains Global Alternative Compliance Paths (ACPs) that allow project teams outside the U.S. to select local equivalents to the prescribed U.S. codes and regulations for select credits. The ACPs are substitute credit and prerequisite requirements that establish a new and different way to demonstrate compliance with the stated intent of a credit or prerequisite. This is applicable only for certain credits such as for credit 1, 'water efficient landscaping' under the Water Efficiency requirement.[38] We used 'certified' level rating for our analysis, which requires 40 or higher credit points.

ASHRAE 189.1 of 2009[39] is an ANSI (American National Standards Institute) standard in a model code format that intends to set the minimum requirements for the design of high-performance green buildings. Model building codes are designed to be applicable to a wide range of local governments and municipalities, which help reduce redundant efforts to develop them by individual entities. ASHRAE 189.1 was developed jointly by the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE), the Illuminating Engineering Society (IES), and the US Green Building Council (USGBC). ASHRAE 189.1 uses ASHRAE 90.1[40] as the baseline case, targeting 30% additional energy savings compared to the baseline.[41] ASHRAE 189.1 codes consist of mandatory provisions and prescriptive recommendations over six topical areas, which correspond well with those in LEED.

International Green Construction Code (IgCC)[42] is also designed as a model building code by the International Code Council (ICC). Local governments can adopt IgCC either as a mandatory or voluntary requirement. IgCC recognizes ASHRAE 189.1 as an alternative compliance path. The topical areas that IgCC covers are similar to ASHRAE 189.1 and LEED, with a notable exception on the commissioning, operation, and maintenance sections. IgCC provides both mandatory and elective provisions and allows alternative compliance paths on a number of specific requirements. For instance, a whole-building LCA is recognized as an alternative to material selection requirements (section 505). In this study, we used the mandatory requirements as the basis of modeling the effect of adopting IgCC to the baseline building model.

The three GBCC systems described in this section have been developed in close consultation with each other, cover similar topical areas, and in part employ comparable requirements. Nevertheless, the three systems utilize different modalities of implementation: LEED is a voluntary certification system based on credit points, while ASHRAE 189.1 and IgCC are developed as a model building code designed to be adopted as building codes by local authorities, which set normative requirements. As such, a direct comparison between them may not be relevant. Instead, the close coordination between the three GBCC systems and the participatory nature of their development processes provide a point of reference to contemporary GBCC systems, the potential implications to the environment of which are examined in this study for the case of a small office building.

Key Feature Mapping. In this study we first mapped the criteria for compliance with LEED (for 'new office buildings'), ASHRAE 189.1, and IgCC to a list of 15−30 key features for each that affect the life-cycle environmental performance through changes in the inputs (e.g., material, services, energy, and water), outputs (e.g., waste, greenhouse gas emissions, toxic pollutant emissions), or both (see Supporting Information (SI) section 1).

First, we analyzed each criterion of the three GBCC systems and determined whether implementing a criterion is likely to affect the life-cycle environmental impacts quantified using current LCA methodology and data available. For example, ASHRAE 189.1's section 5.3.3, IgCC's clause 409, and LEED's SS 8 set exterior lighting specifications to reduce light pollution. While light pollution is becoming an increasingly important issue, the methodology to characterize the impact has yet to be developed and incorporated in LCA. Therefore implementing the requirement is unlikely to affect LCA results. On the other hand, ASHRAE 189.1's section 5.3.5, IgCC's clause 407, and LEED's SS4.1, SS4.2, SS4.3, and SS4.4 set specifications to reduce transportation needs, the impact of which can be easily quantified using current LCA methodology (see section 1 of the SI).

Second, the effects of implementing the criteria that are likely to affect life-cycle environmental performance are quantified in terms of the changes in inputs and outputs throughout the preoccupancy, occupancy, and postoccupancy phases. For ASHRAE 189.1 and IgCC, this was done by simply changing the parameters of the baseline building model in accordance with the requirements set by these two building codes. For LEED, however, an architect can choose different combinations of credits to achieve the same, certification-level compliance. Therefore, we adjusted the parameters of the baseline building model under three scenarios: (a) ASHRAE 189.1-comparable case, (b) 'LCA-relevant credits first' case, and (c) 'no LCA-relevant credits' case. Some local authorities recognize a certification-level LEED rating as well as ASHRAE 189.1 and IgCC as an alternative compliance path for their building codes, and therefore, the ASHRAE 189.1-comparable case was set as a default for the certification-level LEED case. Under the 'LCA-relevant credits first' case, the credit points of which the environmental benefits can be quantified using LCA were incorporated as much as possible, while the 'no LCA-relevant credits' case draws credit points from the requirements of which the environmental benefits cannot be quantified by the current LCA methodology. The allocation of LEED credit points for these three scenarios is shown in Table 1.

As shown in Table 1, there were 38 credits, of which the environmental benefits of implementation can be measured using LCA, for the 'LCA-relevant credits first' case.

Table 1. Allocation of LEED Credit Points for ASHRAE 189.1-Comparable Case, Best Case, and Worse Case Scenarios Used in This Study

		LEED credits for		
	credit	'no LCA-relevant credits' case	ASHRAE-compliant case	'LCA-relevant credits first' case
measurable using LCA	alternative transportation - public transportation access[a]	0	1	6
	water use reduction[b]	0	2	4
	optimize energy performance[c]	0	13	19
	on-site renewable energy[d]	0	4	7
	construction waste management[e]	0	1	2
unmeasurable using LCA (remaining credits)		≥40	≥19	≥2
total (minimum 40 for certification-level)		≥40	≥40	≥40

[a] Sustainable Sites (SS Credit 4.1). [b] Water Efficiency (WE Credit 3). [c] Energy and Atmosphere (EA Credit 1). [d] Energy and Atmosphere (EA Credit 2). [e] Materials and Resources (MR Credit 2).

Estimation of Bill of Materials (BoM). After the key features of the three GBCC systems were analyzed, Bills of Materials (BoM) for a baseline building model and those for GBCC-compliant alterations to the baseline were developed. We used the BoM for a 3-story office building (national average) compiled by the National Institute of Standards and Technology (NIST),[35,43−45] which is based on the specifications of the National Renewable Energy Laboratory (NREL)'s ASHRAE 90.1-compliant prototype for a 3-story small office building.[34] Table 2 lists the specifications for the NREL prototype small office building.

Table 2. Prototype 3-Story Office Building Specifications

parameter	specification
CBECS type	office
% U.S. floor space	17%
number of floors	3
floor height	3.66 m
floor area	1858 m^2
roof type	IEAD
wall type	mass (masonry)
% glazing	20%
max occupancy	72 people or 1 person per 25.5 m^2
density	25.5 m^2/occupant
lighting	8.6−14.0 W/m^2
elec. equipment load	8.07 W/m^2
cooling equipment	rooftop packaged unit
heating equipment	furnace
infiltration (ACH)	0.3 or 0.189 m^3/s per floor
ventilation (ACH)	0.4 or 0.246 m^3/s per floor

The BoM data from NIST contains information on the cost of inputs for a prototypical, 3-story office building in a UNIFORMAT II third-level breakdown organized into 7 general categories: (i) Substructure, (ii) Shell, (iii) Interiors, (iv) Services, (v) Equipment & Furnishings, (vi) Special Construction, and (vii) Building Sitework.[36] For each general category, a total cost is provided along with a list of assemblies that contribute to the total costs. A building assembly may be comprised of multiple components. For example, the assembly category, 'Spread Footings' consists of wooden concrete forms, steel reinforcements, and concrete. The building-assembly level BoM was not granular enough for constructing an LCI and was therefore further disaggregated into subcomponents using the RSmeans database.[46] For example, the BoM data that NIST provided shows $49,000 worth of input for the category, "A1010 Standard Foundation". RSMeans data allowed us to further disaggregate the BoM, first to three assembly categories: (1) "Strip footing, concrete, reinforced, load 11.1 KLF, soil bearing capacity 6 KSF, 30.48 cm deep, 60.96 cm wide", (2) "Spread footings, 20,684 kPa concrete, load 200K, soil bearing capacity 6 KSF, 1.82 m−0 square cm, 50.8 cm deep", and (3) "Spread footings, 20,684 kPa concrete, load 300K, soil bearing capacity 6 KSF, 2.13 m−38.70 cm^2, 63.5 cm deep". These three assembly level components were further disaggregated into 16 subassembly components, including "concrete form, plywood", "rebar, footings", and "concrete, ready mix".

The key features of each of the three GBCC systems were then mapped into potential BoM changes needed to satisfy each GBCC system. There can be a one-to-many correspondence between a GBCC requirement and potential BoM changes to satisfy the requirement. For example, the building envelope section of the ASHRAE 189.1 specifies, for each climate zone, energy efficiency requirements for building envelope components including roof and wall. Such a requirement can be achieved by (a) increasing the thickness of the materials for the envelope specified in the baseline building model or by (b) adding new materials. Given the wide variety of envelope materials, there can be near infinite combinations of materials that can achieve the same requirements. In this case, we used two criteria to select one representative option for a BoM change: (i) whether the option can be commonly and easily applied to all three GBCC systems and (ii) whether the option can be easily translated into quantifiable changes. For example, improvements in the roof and wall thermal performance were obtained by increasing the thickness of the insulation modeled using EnergyPlus[47] software tool, because this option is straightforward and can be easily applied to all GBCC systems.

In many cases, the level of change required in a BoM to satisfy certain GBCC criteria needs to be calculated using engineering estimations. For example, the baseline building model following ASHRAE 90.1 requires the coefficient of performance (COP) of packaged air conditioning systems of 19 kW to 70 kW capacity to be a minimum of 3.0, whereas ASHRAE 189.1 requires a 3.7. In this case, we used the regression model of Kneifel (2012),[35] which shows the relationship between an increase in HVAC efficiency and percent increase in HVAC purchase cost, to estimate the change in BoMs to meet the higher efficiency standard in air conditioning systems of ASHRAE 189.1.

As a result, four BoMs were obtained, one for the baseline building and three for the GBCC-compliant modifications. We further examined the completeness of these BoMs by comparing them against the input structures of relevant building sectors in the U.S. national input-output table by the Bureau of Economic Analysis (BEA).[48] We identified a number of missing inputs such as transportation and on-site fuel consumption, which were estimated and incorporated into respective BoMs.

Occupancy and Postoccupancy Phases. Occupancy and postoccupancy phase materials, energy, water requirements, on-site emissions, and end-of-life waste were estimated for each of the four building models obtained in the previous step.

Occupancy Phase. For the occupancy phase, energy and water consumption as well as occupants' commuting, maintenance, and repair were included in the scope. Data on annual electricity and natural gas use for the prototype small office building were generated using EnergyPlus[47] and NREL's OpenStudio software package.[49]

Compliance to ASHRAE 189.1 and IgCC under 'Energy' category can be achieved either through prescriptive compliance path or performance compliance path. The performance option generally involves a model-based calculation and does not specify specific improvements from the baseline. Therefore, for the sake of simplicity in modeling energy reductions, the prescriptive option was chosen for the ASHRAE 189.1 and IgCC 2012.

The annual energy consumption of the office building will vary depending on its geographic location and climate zone. To account for this variability, the building energy simulations were run 8 times, one for each of the major climate zones within the U.S. following Baechler et al. (2010).[50] The representative cities for each of the climate zones and the electricity and natural gas consumption results are shown in SI section 2. Baseline energy consumption results for each climate zone were combined into a single value using weighting factors obtained from Baechler et al (2010),[50] which is based on the statistics of new construction that starts in each climate zone by building type over a period of several years (see SI section 3).

For water use during the occupancy phase, data from the Federal Water Use Indices[51] were used, where the typical water use in an office per employee is reported to be 57 L per day. Consistent with the approach used by Kneifel (2011), we assumed that the baseline building is occupied by 72 employees.[44]

Impacts arising out of worker commutes to and from work were also calculated since the GBCC systems generally include requirements and credits for it. A baseline model for transportation phase impacts was created using the following assumptions for the baseline and GBCC building designs:

- Average transport distance for an employee to and from the work site (mean distance to and from work was assumed to be 30km based on a U.S. Census Bureau study[52]).
- Transportation mode was assumed to be a 4-door sedan per each employee. Number of working days per year was assumed to be 250.[53] Later in the analysis, some of these assumptions were revisited for sensitivity analysis.

A maintenance and repair (M&R) cost schedule for small office buildings was obtained from the Whitestone Facility Maintenance and Repair Cost Reference.[54] This report provides annual costs per square foot for 12 building system categories: Exterior Closure, Roofing, Interior Construction, Stairways, Conveying Systems, Plumbing, HVAC systems, Fire Protection, Electrical, Equipment, and Site Improvements. The M&R data aggregate all costs associated with each system. Therefore, each Whitestone building system was linked to corresponding building assembly components from the bill of materials. Similar to BoM, the input structure of 'Nonresidential Maintenance and Repair' sector of the U.S. input-output table was used to examine the completeness of the M&R costs, and data gaps identified were estimated. These estimates were tested during the sensitivity analysis.

Postoccupancy Phase. The postoccupancy phase mainly focused on end-of-life (EoL) processes associated with demolition of a building. All material inputs during the preoccupancy and occupancy phases, including those for M&Rs, are assumed to be generated either as waste or as recyclable materials output at the EoL. For the baseline model, all EoL materials are assumed to be landfilled (ca. 80%) or incinerated in the case of combustibles (ca. 20%). For GBCC-compliant building designs, alternative EoL treatment processes were chosen following appropriate EoL requirements of respective GBCC systems.

Life Cycle Inventory Analysis and Impact Assessment. The BoM and inputs and outputs during the occupancy and postoccupancy phases quantified in the previous steps contain direct materials and energy consumption, water consumption, and direct emissions from the construction and occupancy phases. However, none of the supply chain emissions embodied in the material and energy inputs and those in EoL waste treatment processes were included. To quantify the embodied environmental exchanges, the BoM and EoL output data were mapped with the recently updated BEES database.[55] The BEES database offers LCI and Life Cycle Costing data for major building materials following the ASTM standard classification for building elements, UNIFORMAT II. Recently, NIST extended and updated BEES v4 to support a whole-building analysis using a hybrid LCA approach, and these updated data from BEES were used as the main LCI data source for this study.[33] In cases where appropriate data were not available from the BEES database, various LCI databases including the ecoinvent v3,[56] the US LCI,[57] and the CEDA v4[58,59] databases were used instead. When combining LCI results from multiple data sources, comparability between the databases in terms of the underlying data quality and completeness were taken into account.[60] For example, some of the unit process data may have systematically omitted capital goods as an input, while other data may have consistently included them. Likewise, data age and coverage of substances in LCI also vary within and between these databases. In this case, potential input data gaps are filled by comparing the input structures of unit process data and corresponding input-output data,[33] and the LCIs that are similarly recent and comprehensive were selectively chosen for the analysis.[60] Aggregating the environmental exchanges from preoccupancy, occupancy, and postoccupancy phases, we obtained LCIs for the four building models.

We then applied the TRACI 2.0 of U.S. EPA[61] to translate the LCIs to characterize environmental impact results. The results were derived for the following 12 impact categories: global warming; acidification; human health-criteria pollutants; eutrophication; ozone layer depletion; smog formation; ecological toxicity; human health−cancer; human health−noncancer; primary energy; land use and water consumption.

Interpretation. Finally, the results were interpreted, and a series of sensitivity analyses were performed on major assumptions and key parameters. The relative impact magnitudes of the baseline office building and the alternative designs derived from the three GBCC systems were compared for each impact category, and major impact contributors were identified.

Due to the large number of assumptions made and parameters used, we had to prioritize the target for sensitivity analysis. We conducted a qualitative assessment of the parameters (such as purchased electricity) and assumptions (such as average power loads) in terms of the level of variability and the potential to materially change the overall results when the parameter is altered. As a result, 14 major assumptions and parameters were identified, and sensitivity analyses were conducted for each (see section 4 in the SI).

For each of these assumptions and parameters, an alternative value, which is generally 10% higher than the original value, was drawn, and the results were recalculated. The results are expressed in the form of a sensitivity coefficient (SC), which is defined as $\partial c_{ij}/\partial p_j$, where c_{ij} is the ith characterized impact with an alternative value for the jth assumption or parameter, and p_j is the jth assumption or parameter.[62,63] A sensitivity coefficient of 0.52, for example, means that a 10% change of the parameter in question results in a 5.2% change in the characterized impact analyzed.

■ RESULTS

Baseline Results. The life-cycle greenhouse gas (GHG) emissions of the baseline building model were estimated to be 18.3 thousand metric tons CO_2-equiv. measured in global warming potential (GWP) 100, which is 9.9 tons of CO_2-equiv./m^2. This result is about 38% and 12% lower than recent estimates for comparable office buildings in China[64] and the U.S. midwest,[65] respectively, when the differences in building lifetime are adjusted. Such discrepancies can be ascribed to the differences in underlying electricity grid-mix, heating and cooling degree days, fuel mix, and material choices, among

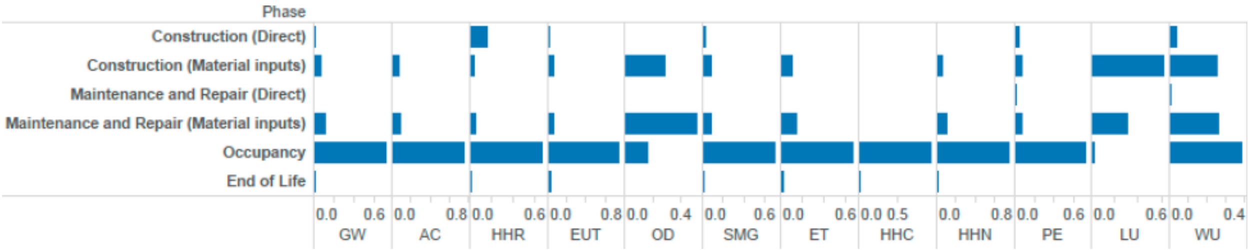

Figure 2. Key life-cycle phases and their relative contribution to each impact category (the case of baseline building model). GW: global warming; AC: acidification; HHR: human health respiratory (criteria pollutants); EUT: eutrophication; OD: ozone layer depletion; SMG: smog formation; ET: ecological toxicity; HHC: human health—cancer; HHN: human health—noncancer; PE: primary energy; LU: land use; WU: water consumption. Each column sums to 1.

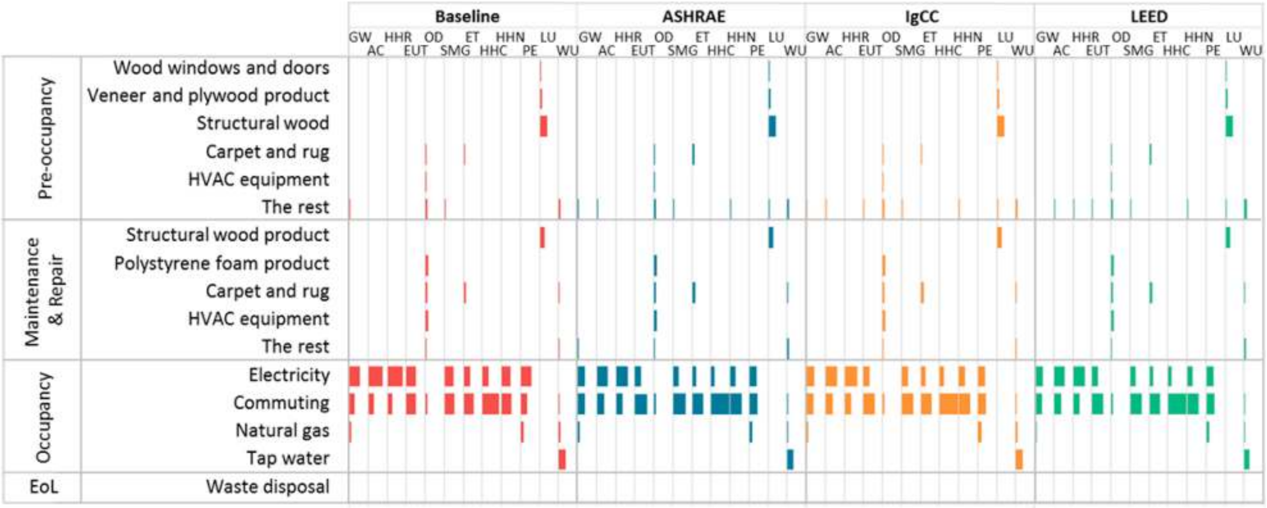

Figure 3. Significant inputs in terms of their relative contributions to each environmental impact (range of each column: 0−70% of total characterized impact). GW: global warming; AC: acidification; HHR: human health respiratory (criteria pollutants); EUT: eutrophication; OD: ozone layer depletion; SMG: smog formation; ET: ecological toxicity; HHC: human health—cancer; HHN: human health—noncancer; PE: primary energy; LU: land use; WU: water consumption. Each column ranges from 0 to 70% of total.

others. Primary energy use and water consumption of the baseline building model were about 6.0 terajoule (TJ) and 328 million liter (or 177 m^3/m^2), respectively.

Figure 2 shows the main life-cycle stages that contribute the most to the environmental impacts of the baseline building model; occupancy (excluding M&R) phase dominated in all but two impact categories, namely ozone layer depletion (OD) and land use (LU). In particular, occupancy phase was responsible for 80% or more of the overall impact for acidification (AC), eutrophication (EUT), human health—cancer (HHC), and human health—noncancer (HHN). Construction and M&R phases (both direct and supply chain impacts) generated relatively significant impact to OD, LU, and water consumption (WU).

Contribution Analysis Results. There were 380 direct inputs to the baseline building model throughout the life-cycle that contributed nonzero impacts (167 inputs for construction, 180 for M&R, 4 for occupancy, and 29 for EoL). In general, the embodiment of impacts in direct inputs to a product system is positively skewed in a unimodal probability density function. In other words, few inputs embody a large portion of the overall life-cycle impacts, while a large number of direct inputs embody a relatively small portion of the overall impacts. Sorting these inputs in a decreasing order of embodied impact reveals the skewness or inhomogeneity in the distribution of impacts among them. HHC category displayed the highest degree of inhomogeneity, where only the top 13 inputs (including passenger car transportation and electricity during the occupancy phase) contributed to over 99% of the total life-cycle HHC impact. Impacts embodied in the inputs were most homogeneous for the WU category, where making up 99% of the WU impact of the baseline building model needed the top 153 inputs. In general, high inhomogeneity in the impacts embodied in inputs help prioritize and target mitigation efforts such as input reduction or alternative input selection. Focusing on these key inputs can also benefit knowledge mining[66] and the development of product categories rules (PCRs) in whole building LCA.

Aggregating small contributors into "the rest", Figure 3 summarizes the major inputs that embody significant impacts on the four building models. Electricity and commuting from the occupancy phase clearly stood out. Within the construction and M&R phases, wood and wood products-related inputs had significant LU impact. Some of the inputs that use synthetic chemicals such as polystyrene foam, carpet, and rugs as well as HVAC-equipment that use coolants showed relatively large contribution to OD.

EoL phase displayed relatively small impacts as compared to other phases.

Overall Comparison. GBCC-compliant building models under the specifications and assumptions employed in this study generated 0% to 25% less environmental impacts than the

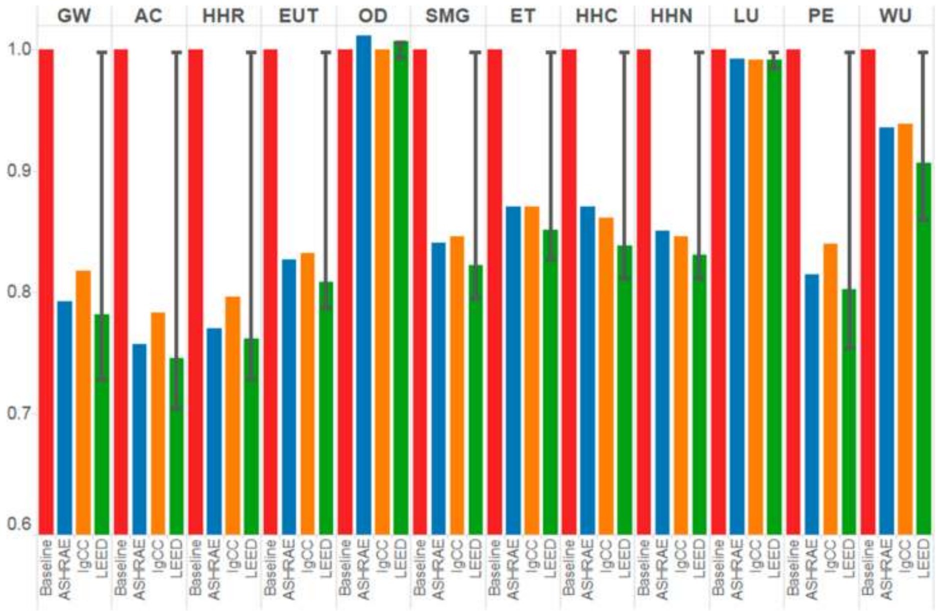

Figure 4. Relative magnitude of impact between baseline (= 1), ASHRAE, IgCC, and LEED modeling buildings based on the NREL's prototypical small office building. GW: global warming; AC: acidification; HHR: human health respiratory (criteria pollutants); EUT: eutrophication; OD: ozone layer depletion; SMG: smog formation; ET: ecological toxicity; HHC: human health—cancer; HHN: human health—noncancer; LU: land use; PE: primary energy; WU: water consumption. The whiskers represent upper and lower bounds based on different combinations of LEED credit.

baseline case (average 14% reduction) (Figure 4). The largest reductions were associated with AC (25%), human health—respiratory (HHR) (24%), and global warming (GW) (22%), while no reductions were observed for OD and LU. The degrees by which environmental impacts were reduced by the three GBCC-compliant building models were comparable due largely to the way GBCC-compliant buildings were modeled in this study, where comparable options were employed for requirements under the same topical area among the three GBCC systems. Therefore, the results say little about the relative magnitude of life-cycle environmental benefits between the three GBCC systems.

The whiskers for the LEED results show the range of LCA results for the certification-level LEED building model. As shown in Table 1, all 40 credits required for the certification-level LEED model could be drawn all from the requirements of which the benefits of implementation cannot be adequately quantified by the current LCA method and data. Therefore the upper bounds are close to the baseline case for all impact categories. Lower bound LEED results were calculated by applying as many LCA-relevant LEED criteria as possible, in which case up to about 5% reduction in impacts can be further achieved in addition to the ASHRAE 189.1-comparable case.

Connecting the results to the key feature mapping exercise, the requirements related to occupancy phase energy consumption showed the greatest capacity for impact reduction. ASHRAE Section 7 and IgCC Section 6 have subsections concerning the thermal properties of the building envelope, lighting, power, HVAC, and other systems as well as on-site renewable energy. LEED Energy and Atmosphere Credit 1 (Optimize Energy Performance) also provides a performance based criterion.

Within the energy sections of ASHRAE and IgCC, the most effective subsections were those concerning building envelope and HVAC performance. These sections contained detailed requirements that resulted in a reduction in the heating and cooling loads of the building throughout the year and an improvement in the efficiency of the building's ability to serve those loads.

Our results concur with the previous findings by Scheuer and Keoleian (2002)[31] and Humbert et al. (2007)[32] that the environmental impact reduction potentials are not homogenously distributed across GBCC criteria.

Nevertheless, the results showed that potential environmental impact reduction through the adoption of GBCC systems can be significant. As compared to the baseline building, GBCC-compliant building models showed 15% to 25% less environmental impacts in most impact categories including GW, AC, HHR, EUT, SMG, ET, HHC, HHN, and PE (assuming that ASHRAE 189.1-comparable options were taken for LEED-compliant building model). If none of the LCA-relevant credits were taken, environmental benefits of certification-level LEED building model could not, obviously, be measured using LCA.

Uncertainty and Sensitivity analysis. Quantitative uncertainty characterization was lacking in the raw data used in this study, and therefore we qualitatively assessed the uncertainties in the results followed by a sensitivity analysis for major assumptions.

Potential sources of uncertainty include the following:

- BoM data for prototypical small office building (for construction and M&R)
- Occupancy phase energy and utility consumption data
- Changes in BoM and occupancy phase energy and utility consumption in GBCC-compliant building models
- LCI data used (hybrid BEES and ecoinvent)
- Characterization factors for LCIA (TRACI version 2)

Initial BoM data produced by NIST using NREL's technical specifications represents a typical office building in the U.S. While changes to BoM in GBCC-compliant building models were made based on a comprehensive analysis of the key features of three GBCCs (see SI section 1), they inevitably involve subjective choices and assumptions. Therefore major choices and assumptions were tested using sensitivity analysis.

In this study, we employed a recently updated, hybrid BEES database. The original BEES database employs process LCA approach, which is detailed but potentially truncated.[67] The hybrid BEES database used in this study combines the strengths of process and input-output approach, where potentially truncated far-upstream processes are estimated using input-output LCA, while granular, process-level information are preserved for the foreground processes.[33,67−70] Furthermore, due to the random nature of parametric uncertainty, relative magnitude of impacts between the building models are more robust than the absolute results. Although in general upstream supply chain impacts associated with construction and R&M inputs are more uncertain, their contributions to overall impacts are relatively small, and therefore it is unlikely for them to cause any major shift in conclusions.

As shown in the result, the majority of the life-cycle impacts of the building model were associated with energy and utility consumption during the use phase, which are based on national statistics and thus relatively well-defined. Changes in energy and utility consumption in GBCC-compliant building models are dominant sources of impact reduction, and they are relatively straightforward as compared to the changes in BoM. Nevertheless, occupancy phase energy and utility consumption figures were also tested using sensitivity analysis.

Characterization factors are developed using a variety of assumptions, models, and estimates, and therefore uncertainties in characterization factors especially those for human health and ecotoxicity are reported to be high.[71,72] TRACI version 2 is a recently updated characterization data set developed by U.S. EPA, and it incorporates the most up-to-date characterization modeling techniques for the U.S. Characterization of uncertainties in TRACI, however, was beyond the scope of this study, and therefore it was left unaddressed.

Sensitivity analysis results showed that two assumptions associated with tenants' behavior, which are electricity consumption and commuting during the occupancy phase, were particularly sensitive ($0 \leq SC \leq 0.64$, average 0.27) to the overall results. GW, AD, HHR, EUT, SMG, HHC, HHN, and PE were the most significantly affected by the occupancy-phase assumptions (see section 4 in SI). These assumptions are, however, based on national average data that are reasonably robust. Assumptions on M&R inputs drawn from the Whitestone report and estimated missing inputs, which are more uncertain, were highly sensitive for a limited number of impact categories including OD ($SC > 0.5$) and LU ($SC > 0.3$). Increasing BoM for the construction phase by 10% resulted in a 4.9% increase in LU category ($SC = 0.49$). Overall, the results were considered to be reasonably robust against the assumptions and parameters used in this study, while future refinements on the employee commuting (for HHC), M&R material requirements (for OD), and wood-related BoM (for LU) would be the most rewarding.

■ DISCUSSION

Our analysis showed that the building model designs following the three GBCC systems have around 15% to 25% less life-cycle environmental impacts throughout the environmental impact categories considered. For LEED, however, the potential to reduce life-cycle environmental impacts can be none existing or larger than 15−25% depending on which LEED criteria are selected for implementation. The influence of the three GBCC systems on OD and LU was, however, not significant in all cases.

Given the significance of the role that buildings play in materializing various environmental impacts, 15% to 25% of the impact reduction cannot be taken lightly. A wide adoption of GBCC systems, therefore, deserves encouragement. What is not clear, however, is whether the criteria and requirements set by these GBCC systems are the most cost-effective ones. In other words, will there be less costly options that can achieve the same level of impact reduction? Or are there options with comparable costs that achieve higher reduction in the environmental impacts? Such questions can help guide future development of GBCC systems that maximize their cost-effectiveness.

Our results also confirm the earlier findings that the potential to reduce environmental impacts by satisfying a requirement or a credit point of a GBCC system is not uniform. We found that the provisions for occupancy phase energy use including those on thermal properties of the building envelope, lighting, power, HVAC, and on-site renewable energy in ASHRAE Section 7, IgCC Section 6, and LEED Energy and Atmosphere Credit 1 (Optimize Energy Performance) are critical in achieving substantial reductions across various impact categories. In particular, the life-cycle environmental performances of buildings that conform to the same level of LEED rating or certification may vary significantly depending on whether such high-impact criterion or requirement is chosen by an architect.

It is also notable that there are often significant discrepancies between model predictions and actual performance of a building.[28,30] Buildings may not be operated as originally designed, and tenants' behavioral aspects also play an important role in determining a building's environmental performance. Our analysis that uses model results cannot address such discrepancies.

Lastly, there are limitations in the current analysis: it is notable that LCA alone cannot address all the issues around the environment and human health. There were various potential benefits of the GBCC systems analyzed that could not be adequately quantified using LCA. For example, some of the provisions that address the indoor air pollutants, heat island, and light pollution issues were not adequately reflected in the results partly due to the limited scope in current LCIA methodologies. In addition, improvements in occupants' comfort and productivity, which are essential for office buildings, were not considered in this study.

Although the current analysis employed a prototypical, small office building based on national average values, the results should not be interpreted as a measure of absolute performance of the GBCC systems in general. Depending on the choice of options and local conditions under which individual projects are implemented, the potential for these GBCC systems to achieve environmental impact reductions can vary significantly. Nevertheless, we believe that our results are indicative of the potential that green building codes and certification systems have on reducing the environmental impacts of buildings, and provide a point of reference in the effort of quantifying it.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

GBCC system comparison, use phase energy consumption (purchased electricity and natural gas) estimates, climate zone weighting factors, and sensitivity coefficients (SC) for major model parameters and each impact category. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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