

Environmental Performance of Green Building Code and Certification Systems

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Supporting Information – Section 1: GBCC System Comparison

GBCC system features/requirements are organized into 5 general categories

ASHRAE 189.1 was selected as the reference system. Features in IgCC and LEED that correspond with ASHRAE features are in the same line. There are several sections of the GBCC system documentation that pertain to administrative concerns and are not substantive in regard to our analysis, which are hence omitted in the following table (for example, ASHRAE Chapter 1 through Chapter 4). Features within the same rows are similar, but not necessarily identical. The exact requirements of the features may vary. Any features within IgCC and LEED that do not have a reasonably comparable feature in ASHRAE are included at the end of each category. The last column of the table indicates whether implementing the feature is likely to affect LCA results based on the current LCA scope and methodology. The criteria or requirements that are likely to affect LCA results are highlighted in red background.

Site Related Features

ASHRAE 189.1		IgCC 2012		LEED 2009		Effects on life cycle impacts
Requirement/Credit	DESCRIPTION	Requirement/Credit	DESCRIPTION	Requirement/Credit	DESCRIPTION	
5.3.1-Site Selection	Outlines areas suitable for development such as brownfields, greyfields and conditions for greenfields. Prohibits flood planes, conservation areas, etc.	402-Preservation of Natural Resources	Related to flood planes, surface water protection, wetlands, conservation areas, park land, agricultural land, greenfield sites	SS1-Site Selection SS3-Brownfield Redevelopment SS5.1-Site Development – Habitat SS5.2-Site Development – Open Spaces	Prohibits development in sensitive areas. Encourages development of brownfields, protection of conservation areas and open spaces	Would affect land use requirements for buildings.
5.3.2-Mitigation of Heat Island Effect	50% of hardscape and above grade walls must have shading. 75% of roofs must have low SRI	408-Heat Island Mitigation	50% of hardscape must have low SRI>0.3 and/or shading. Sets SRI values for roofs and green roof specifications	SS7.1-Heat Island Effect-Non-roof SS7.2-Heat Island Effect-Roofs	50% of site hardscaping needs to mitigate heat island effects in some way.	Requirements of specific materials and additional shading are not expected to affect life cycle impacts significantly.
5.3.3-Reduction of light pollution	Exterior lighting must comply with ASHRAE 90.1. Sets lighting	409-Site Lighting	Sets maximum light ratings for multiple lighting zones. Tables 409.1.1,	SS8-Light Pollution Reduction	Sets maximum illuminance ratings for exterior lighting zones.	Not expected to significantly impact life cycle impact results.

	specifications in tables 5.3.3.2A , 5.3.3.2B , 5.3.3.3		409.2, 409.3(1), 409.3(2)			
5.3.4-Plants	Stipulates that invasive plants shall be removed from building site and shall not be planted	NA		NA		While the presence of invasive plants may have an effect on the local biodiversity, this impact is not currently captured in the life cycle impact assessment models.
5.3.5-Mitigation of transportation impacts	Connective pathways from primary entrances to transit stops or public ways	407-Transportation Impact	Requires walkways, bike paths & storage, preferred vehicle parking, etc.	SS4.1-Alt.Transportation-Public Transport SS4.2-Alt. Transportation-Bike Storage SS4.3-Alt.Transportation-Preferred Vehicles SS4.4-Alt.Transportation-Parking Capacity	Features meant to encourage tenants to use low carbon emitting means of conveyance to and from building.	Likely to affect LCA results. IgCC & LEED have more requirements/credits regarding transport than ASHRAE, and transportation is currently included in the system boundary of the occupancy phase.
5.4.1-Site Development: Prescriptive Option	Minimum of 40% of site shall incorporate vegetation, green roofs, permeable pavement, etc.	NA- The means of ASHRAE 5.4.1 are meant to produce ends comparable to 5.5.1		NA		LCA-relevant effects on energy consumption are reflected in other criteria. Other than that, the current LCA is unlikely to capture the effect.

5.5.1-Site Development: Performance Option	>50% of annual rainfall must be managed via infiltration	403- Stormwater Management	Site must maintain pre-development natural runoff	SS6-Stormwater Design	3 options, essentially equivalent to IgCC 403	The feature may reduce some of the runoff emissions, but due to the data limitation it is unlikely to affect the LCA result significantly.
Relevant requirements not in ASHRAE 189.1		405- Management of Vegetation, Soils and Erosion Control		SS Pre 1- Construction Activity Pollution Prevention	Limits impacts of soil erosion, sedimentation, etc.	Due to the data limitation it is unlikely to affect the LCA result significantly.
		406- Building Site Waste Management	>75% of clearing debris diverted	NA		Differs from Construction & Demolition waste management (See "Materials" section). Relates to land clearing and earth moving residues.
		Relevant requirements not in IgCC 2012		SS2-Development Density and Community Connectivity	Encourages construction in high density areas	Could affect land use requirements for buildings. However, current database does not include land as inputs to building types.

Water Related Features

ASHRAE 189.1		IgCC 2012		LEED 2009		Effects on life cycle impacts
Requirement/Credit	DESCRIPTION	Requirement/Credit	DESCRIPTION	Requirement/Credit	DESCRIPTION	
6.3.1-Site Water Use Reduction	Landscape design: 60% native plants. Irrigation: hydrozoning, no spray near building. Controls: smart	404-Landscape Irrigation	Irrigation system requirements. Reduce potable water by 50% from summer baseline	WE1-Water Efficient Landscaping	Reduce potable water by 50%	Current study excludes exterior water use.
6.3.2-Building Water Use Reduction	Plumbing fixture, toilet, maximum flow rates. Table 6.3.2.1. HVAC systems cannot use potable water. Specs for cooling method.	702-Fixtures, Fittings, Equip. & Appliances 703-HVAC Systems & Equipment	Maximum flow rates. Table 702.1. Appliances must be Energy Star water factor <6. More detailed than ASHRAE. Detailed HVAC specifications	WE Pre1-20% Building Water Use Reduction WE3-Further Water Use Reduction	Employ 20% less water than baseline building. Additional points for 30,35, 40% reduction	Efficiency requirements and specifications for plumbing fixtures, HVAC, appliances, etc. Determining impacts on use phase water use will require baseline building specs and consumption data. Water use reduction has been modeled in life cycle impact results.
6.3.3-Water Consumption Management	Requires installation of metering devices, data collection and storage	705-Metering	Requirement states that water consumed from any source associated with the building or building site shall be metered	NA		These requirements will not directly affect life cycle results. Reduction in water consumption is captured from other criteria.
6.4.1-Site Water Use – Prescriptive	Max 1/3 landscape area will use potable water	404-Landscape Irrigation	Irrigation system requirements. Reduce potable water by 50% from summer baseline	WE1-Water Efficient Landscaping	Reduce potable water by 50%	Not expected to significantly impact life cycle impact results. Reduction in water consumption

						is captured from other criteria.
6.4.2-Building Water Use – Prescriptive	Concerns quality of water discharged from HVAC systems (i.e. hardness)	NA		NA		Not expected to significantly affect life cycle impacts due to the fact that water quality emissions are not taken into consideration.
6.5.1-Site Water Use - Performance Option	Potable water used in irrigation limited to 35% of water demand, based on ET	404- Landscape Irrigation	Irrigation system requirements. Reduce potable water by 50% from summer baseline	WE1-Water Efficient Landscaping	Reduce potable water by 50%	Not expected to significantly impact life cycle impact results.
6.5.2-Building Water Use - Performance	Water use must be equal or better than that obtained from adhering to 6.3.2,6.4.2,6.4.3	702-Fixtures, Fittings, Equip. & Appliances 703-HVAC Systems & Equipment	Maximum flow rates. Table 702.1. Appliances must be Energy Star water factor <6. More detailed than ASHRAE. Detailed HVAC specifications	WE Pre1-20% Building Water Use Reduction WE3-Further Water Use Reduction	Employ 20% less water than baseline building. Calcs based on Tables provided. Additional points for 30,35, 40% reduction	Efficiency requirements and specifications for plumbing fixtures, HVAC, appliances, etc. Determining impacts on use phase water use will require baseline building specs and consumption data. Water use reduction has been modeled in life cycle impact results.
Relevant requirements not in ASHRAE 189.1						

Energy Related Features

ASHRAE 189.1		IgCC 2012		LEED 2009		Effects on life cycle impacts
Requirement/Credit	DESCRIPTION	Requirement/Credit	DESCRIPTION	Requirement/Credit	DESCRIPTION	
7.3.1-General	Designed in compliance with ANSI/ASHRAE/IES Standard 90.1	NA		NA		No effect: the baseline building is already compliant with ANSI/ASHRAE/IES Standard 90.1
7.3.2-On-site renewable energy systems	Allow Future installation of at least 20kWh/m2 of generation capacity	610- Building Renewable Energy Systems	Provide at least 2% total building energy use from on-site renewables	EA2- On-site Renewable Energy	Points based on percentage renewables (increments of 2% from 1)	Will reduce energy purchased from grid with clean alternative. ASHRAE requirement covered in section 7.4.1.
7.3.3-Energy Consumption Management	Metering, data collection and storage	603- Energy Metering, Monitoring and Reporting	Requirements concerning meters and energy management systems	EA5- Measurement & Verification	ongoing accountability of building energy consumption	Will not have a direct effect on building life cycle impact results. Energy reduction captured in other criteria.
7.4.1-On-site renewable-prescriptive	Not less than 32 kWh/m2	610- Building Renewable Energy Systems	Provide at least 2% total building energy use from on-site renewables	EA2- On-site Renewable Energy	Points based on percentage renewables (increments of 2% from 1)	Will reduce energy purchased from grid with clean alternative. ASHRAE requirement covered in section 7.4.1
7.4.2-Building envelope	Efficiency requirements superseding ASHRAE 90.1 Table A-1 and A-8	605- Building Envelope Systems	Building envelope insulation specifications	EA Pre2- Minimum Energy Performance EA1- Optimize Energy Performance		Insulation, fenestration, roofs, etc. Will reduce whole building energy requirements for heating/cooling during occupancy.

						Will require re-running energy model with new specifications.
7.4.3-HVAC	Minimum HVAC equipment efficiencies	606- Building Mechanical Systems	Minimum HVAC equipment efficiencies			Energy efficiency requirements. Will reduce occupancy energy consumption. Requires comparison to baseline scenario
7.4.4-Service Water Heating	Minimum water heating equipment efficiencies	607- Building Service Water Heating Systems	Minimum water heating equipment efficiencies			Energy efficiency requirements. Will reduce occupancy energy consumption. Requires comparison to baseline scenario
7.4.5-Power	Minimum power system equipment efficiencies	608- Building Electrical Power and Lighting Systems	Minimum power system equipment efficiencies			Energy efficiency requirements. Will reduce occupancy energy consumption. Requires comparison to baseline scenario
7.4.6-Lighting	Minimum lighting efficiencies	608- Building Electrical Power and Lighting Systems	Minimum power system equipment efficiencies			Energy efficiency requirements. Will reduce occupancy energy consumption. Requires comparison to baseline scenario
7.4.7-Other Equipment	Minimum appliance efficiencies	609- Specific Appliances and Equipment	Minimum appliance efficiencies			Energy efficiency requirements. Will reduce occupancy energy consumption. Requires comparison to baseline scenario
7.5-Performance options	Performance must be equivalent to that from measures	NA		NA		Comparisons between ASHRAE and IgCC prescriptive

	in 7.4. Utilize Normative Appendix D for calculations					measure must be performed to test if ASHRAE performance is appropriate estimate for IgCC performance.
Relevant requirements not in ASHRAE 189.1						

Indoor Environment Related Features

ASHRAE 189.1		IgCC 2012		LEED 2009		Effects on life cycle impacts
Requirement/Credit	DESCRIPTION	Requirement/Credit	DESCRIPTION	Requirement/Credit	DESCRIPTION	
8.3.1- Indoor Air Quality	Minimum air quality standards (ASHRAE/ANSI 62.1)	804- Specific Indoor Air Quality 803- Pollutant Control Measures	Prescribes requirements for fireplaces and appliances, and post-construction and pre-occupancy baseline IAQ testing	IEQ Pre 1- Minimum Indoor Air Quality IEQ Pre 2- Tobacco Smoke (ETS) Control (IEQ 1) (IEQ 2)	Indoor air quality related points	None of the requirements in this category are expected to affect the life cycle impacts significantly.
8.3.2- Thermal Conditions	ANSI/ASHRAE Standard 55, section 6.1	803- HVAC Systems	Prescribes requirements during the construction phase of the building for duct openings, indoor air quality during construction, thermal environmental conditions for human occupancy, environmental tobacco smoke control, isolation of pollutant sources and filters.	IEQ 7- Thermal Comfort		
8.3.3- Acoustic Controls	Minimum sound ratings, etc.	807- Acoustics	Requirements stated for sound transmission and sound levels	NA		
8.3.4- Daylighting	Minimum daylighting and skylight specs	808- Daylighting	Requirement states that interior spaces be planned to benefit from exposure to natural	IEQ 8- Daylight & Views		

			light			
8.3.5- Isolation of building from pollutants in soil	Only applies to brownfield development	NA		NA		Does not apply to this study due to application only in case of brownfields
Relevant requirements not in ASHRAE 189.1		806- Material Emissions and Pollutant Controls	VOC emissions limits for various building materials	IEQ 4-Low-emitting materials	Low VOC adhesives, paints, flooring, composites	Will affect life cycle results to the extent that VOCs are included in occupancy phase emissions however they have not been included in the current model due to lack of data.

Materials Related Features

ASHRAE 189.1		IgCC 2012		LEED 2009		Effects on life cycle impacts
Requirement/Credit	DESCRIPTION	Requirement/Credit	DESCRIPTION	Requirement/Credit	DESCRIPTION	
9.3.1- Construction waste management	Minimum of 50% NON-HAZ C&D waste shall be diverted. Excavated soil and land-clearing does not count.	503- Construction Waste Management	Requires establishing waste management plan. % diverted decided by jurisdiction (Sec 302)	MR2- Construction Waste Management	1 credit for 50%, 2 credits for 75%	These will reduce the waste generated during the pre-occupancy phase
9.3.2- Extracting, harvesting and manufacturing.	Nothing illegal can be used	NA		NA		Will not affect life cycle results
9.3.3- Refrigerants	No CFCs in HVAC. No CFCs, HFCs, Halons in fire suppression	NA		EA Pre2 - Fundamental Refrigerant Management EA 4 - Enhances Refrigerant Management	Option 1: No refrigerants = 2 points	No CFCs, HFCs, Halons, etc. Will reduce emissions of these substances during occupancy however they have not been included in the current model due to lack of data.
9.3.4- Recycling	Provision of recycling facilities	504- Waste Management & Recycling	Provision of recycling facilities	MR Pre 1- Storage and Collection of Recyclables	Provision of recycling facilities	Recycling facilities within building. Not likely to affect LCA results due to lack of occupancy phase waste data.
9.4- Prescriptive option - Recycled content, etc.		505- Material Selection		MR4- Recycled content MR5- Regional materials MR6- Renewable materials MR7- Certified Wood		Input material recycled content, regional, biobased, etc. Would be difficult to incorporate this into model.

Supporting Information – Section 2

Use phase energy consumption (purchased electricity and natural gas) estimates were generated using the NREL OpenStudio application with an EnergyPlus plug-in. Due to the regional variability in heating and cooling requirements the baseline building energy model was run eight times, once for each climate zone. The table below shows the annual energy consumption results for the baseline office building in cities that are representative of each climate zone.

Baseline Annual Energy Consumption by Climate Zone

Climate Zone	Representative City	Electricity (kWh)	Natural Gas (MJ)
1	Miami, FL	313,750	30,080
2	Houston, TX	292,442	249,150
3	Los Angeles, CA	218,236	165,160
4	Nashville, TN	254,706	772,170
5	Reno, NV	233,889	1,065,250
6	Madison, WI	243,386	1,873,650
7	Caribou, ME	233,631	2,468,940
8	Fairbanks, AK	249,325	4,166,540

Source: NREL *OpenStudio*; National Renewable Energy Laboratory: Golden, Colo.

The results above were used to generate an estimate of national average energy use for the baseline building using weighting factors for each climate zone (SI section 3).

Supporting Information – Section 3

Climate Zone Weighting Factors

Climate Zone	Weight Factor
1	0.015
2	0.241
3	0.270
4	0.197
5	0.221
6	0.048
7	0.006
8	0.001

Source: Baechler, M. C.; Williamson, J. L.; Gilbride, T. L.; Cole, P. C.; Hefty, M. G.; Love, P. M. Building America Best Practices Series: Volume 7.1: Guide to Determining Climate Regions by County; Pacific Northwest National Laboratory (PNNL), Richland, WA (US), 2010.

Supporting Information – Section 4

The table below shows the sensitivity coefficients (SC) for major model parameters and each impact category. The sensitivity analysis was performed by adjusting a parameter by a certain amount and observing the change in total impact results that occur. Specifically, the SC is calculated by $\delta c_{ij}/\delta p_j$, where c_{ij} is i th characterized impact with an alternative value for the j th assumption or parameter, and p_j is j th assumption or parameter. Sensitivity coefficient of 0.52, for example, means that 10 % change of the parameter in question results in 5.2% change in the characterized impact analyzed.

Life Cycle Phase	Model Component	GW	AC	HHR	EUT	OD	SMG	ET	HHC	HHN	PE	LU	WU
Construction	Gasoline Use	0.01	0.01	0	0.02	0	0.01	0	0	0	0.03	0	0
	Purchased Electricity	0.01	0.01	0	0	0	0.01	0	0	0	0	0	0.03
	Natural Gas Use	0	0	0	0	0	0	0	0	0	0	0	0
	Inputs from Bill of Materials (BoM)	0.06	0.04	0.04	0.03	0.23	0.04	0.1	0	0.05	0.03	0.49	0.16
	Estimated missing inputs from the BoM	0.02	0.02	0.02	0.02	0.06	0.03	0.02	0	0.02	0.02	0.14	0.06
	Direct Construction Impacts	0.03	0.02	0.17	0.03	0	0.04	0	0	0	0.05	0	0.05
Maintenance & Repair (M&R)	Materials obtained from Whitestone Report	0.1	0.08	0.05	0.05	0.51	0.07	0.15	0	0.11	0.05	0.3	0.23
	Estimated missing inputs from the BoM	0.12	0.1	0.06	0.08	0.53	0.1	0.16	0	0.12	0.09	0.32	0.27
	Direct M&R Impacts	0.01	0.01	0.01	0.01	0	0.01	0	0	0	0.03	0	0.02
Occupancy/Use	Water Use	0	0	0	0	0	0	0	0	0	0	0	0.27

	Purchased Electricity	0.41	0.53	0.5	0.37	0.04	0.33	0.27	0.26	0.34	0.37	0.02	0
	Natural Gas Use	0.1	0.02	0.01	0.03	0.04	0.03	0.02	0.04	0.03	0.12	0	0.08
	Employee Transportation	0.22	0.21	0.16	0.37	0.09	0.36	0.39	0.64	0.39	0.24	0.02	0.05
End of Life	All End-of-Life Processes	0.03	0.01	0.03	0.05	0	0.03	0.04	0.04	0.04	0.01	0	0