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GREEN FOOTSTEP: CALCULATIONS AND DATA SOURCES

GREEN FOOTSTEP
YOUR BUILDING, YOUR CARBON, AND WHAT YOU CAN DO ABOUT IT

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Abstract

Green Footstep is an online assessment tool for reducing carbon emissions from building construction projects and is publicly available at greenfootstep.org. The Green Footstep tool guides the user through the process of life cycle carbon assessment, and then reveals how users can theoretically reduce the net carbon emissions. Some description of the calculation method is provided on the website; however the calculations and data sources are not provided in detail. This paper provides these calculations and data sources in order to make the Green Footstep methodology completely accessible to the general public.

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Overview of Method

Green Footstep estimates net carbon flow from the earth to the atmosphere, or vice versa, as a result of a building project. The analysis period extends from initial construction (or renovation) through a user-specified number of years of building operation. Green Footstep assesses the building project with regard to carrying capacity, a concept used by biologists to describe how many animals a given habitat could support but, in contrast, used in Green Footstep to denote the amount of carbon stored on the building project site in its native state. By the end of the project analysis period, the net amount of carbon stored on the building project site must be equal to or greater than the native amount in order for the project to be considered "carbon neutral."

Why use such a definition of carbon neutrality? If we think back to a time when there were no buildings, the amount of carbon stored in the native vegetation and soil on the current building sites helped to maintain a global carbon balance between the earth and atmosphere. Any vegetation that is removed from the site or any carbon emissions that are emitted from the site (such as to operate a building) creates an increase in atmospheric carbon. It is worthwhile thinking of these emissions as an ecological mortgage that needs to be repaid in order to achieve net zero impact, or carbon neutrality (Olgyay and Herdt 2004).

Green Footstep accounts for the carbon emissions (also known as carbon dioxide equivalent, CO2e, and green house gas (GHG)) from three aspects: site development, construction, and operation. "Site development" accounts for the removal or addition of vegetation and other carbon storing elements to the project site. "Construction" accounts for the carbon emissions from the raw material extraction, manufacture, transport and on-site assembly of building materials. "Operation" accounts for the GHG Protocol Scope 1 and 2 carbon emissions resulting from consumption of electricity, natural gas, fuel oil and other fuels used on site. Users can also account for other (Scope 3) emissions sources such as commuter transport in the Operation category. (GHG Protocol)

Figure 1 below is a representation of the "Overview Chart" that Green Footstep generates. As illustrated, the emissions from site development and building construction occur during only the first year of the building project. Figure 1 also illustrates three separate scenarios for the operation phase of the building. The scenario represented by the red line shows how the building continues to emit carbon and goes into greater carbon "debt" (if we continue with the ecological mortgage analogy). The orange line represents a net zero operational carbon emissions scenario and the blue line represents a building that has negative operational carbon emissions. The dips in the lines represent possible retrofits that would each carry an amount of embodied carbon emissions (these dips are currently not possible to chart in Green Footstep).

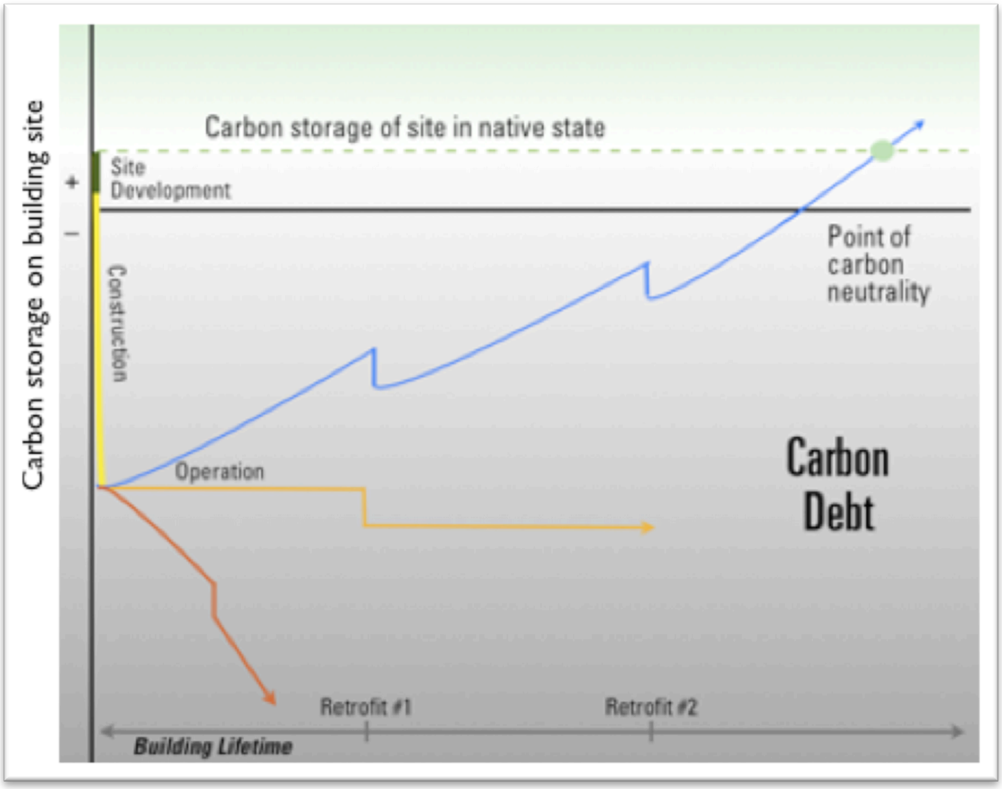

Figure 1. Green Footstep's Overview Chart. The carbon stored on the building site (y-axis) goes up or down with the threes aspects of the building project: site development, construction, and operation. If during the operation phase a building can reach back up to the amount of carbon stored on the site in the native state, the building project is considered "carbon neutral."

As shown in Figure 2 below, the carbon model shows whether or not the building project is contributing to a net increase or decrease in atmospheric concentration of carbon based on the location of the end point. Above the dotted line indicates a net decrease in concentration and vice versa.

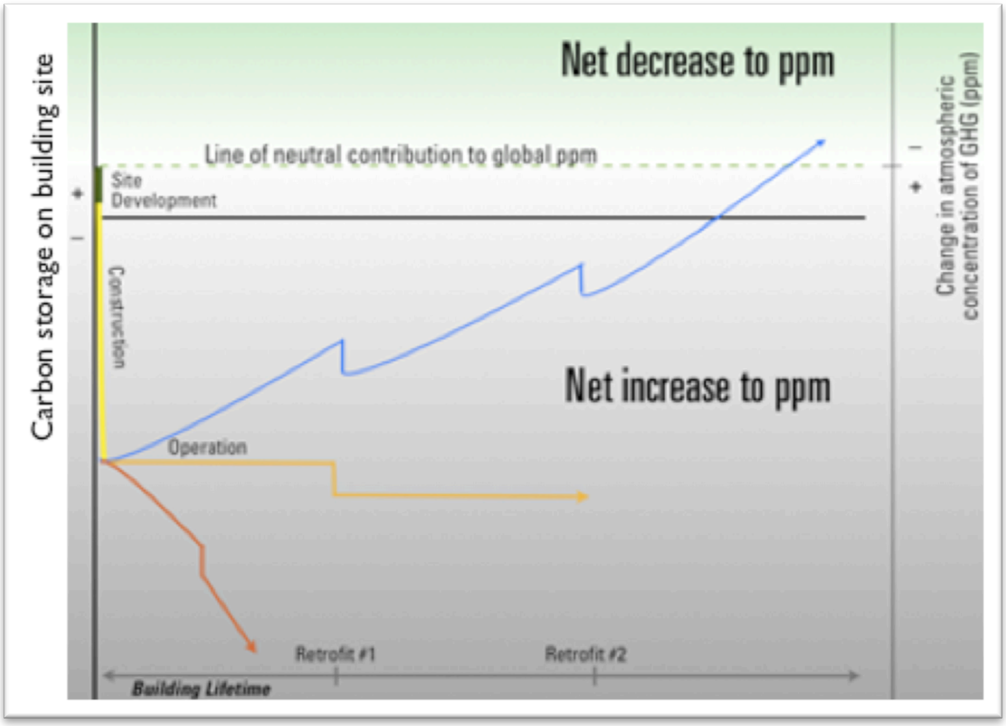

Figure 2. Atmospheric concentration of GHGs. Green Footstep shows a net increase or decrease to parts-per-million (ppm) of carbon in the atmosphere. If the carbon storage on the building site increases to a point above the native site carbon storage, or the "line of neutral contribution to global ppm," the project will result in a net decrease in concentration of greenhouse gasses.

The Green Footstep formula behind the Overview Chart is as follows:

$$CS(t) = NSCS - SD - C - O(t)$$

Equation 1. Overview Chart

Where:

CS = Carbon storage on the building site (kg CO_2e)

t = Time (years)

NSCS = Native-site carbon storage (kg CO_2e)

SD = Emissions from site development (kg CO_2e)

C = Emissions from building construction (kg CO_2e)

O = Emissions from building operation (kg CO_2e/year)

Establishing the native site carbon storage

The IPCC has gathered several studies of carbon storage specific to land types including forests and grassland, as shown in Table 1. New studies continued to be conducted (Powell et al 2006, Alexis et al 2006); unfortunately, there is no available data for land types other than forest or grassland. In addition, the studies do not account for underground biomass, which can be as high as 80 percent of the total biomass (Swain 2008).

Table 1. Biomass of various ecological zones. The IPCC recommends multiplying the biomass by a carbon fraction of 0.5 to obtain the carbon (C) content, which will then have to be multiplied by a factor 44/12 to obtain CO_2 mass. See Appendix A for the complete list of stored carbon values for different land types from the IPCC.

Above-ground biomass in forests			
Domain	**Ecological zone**	**Continent**	**Above-ground biomass (tonnes d.m. ha^{-1})**
Temperate	Temperate oceanic forest	Europe	120
		North America	660 (80-1200)
		New Zealand	360 (210-430)
		South America	180 (90-310)
	Temperate continental forest	Asia, Europe (≤20 y)	20
		Asia, Europe (>20 y)	120 (20-320)
		North and South America (≤20 y)	60 (10-130)
		North and South America (>20 y)	130 (50-200)
	Temperate mountain systems	Asia, Europe (≤20 y)	100 (20-180)
		Asia, Europe (>20 y)	130 (20-600)
		North and South America (≤20 y)	50 (20-110)
		North and South America (>20 y)	130 (40-280)

$$NSCS = CI \times SA$$

Equation 2. Native site carbon storage

Where:
NSCS = native site carbon storage (kg CO_2e)
CI = Carbon intensity of the native ecological zone (kg CO_2e/sq ft)
SA = Site area (sq ft)

Estimating carbon emissions from site development

Site development is perhaps most well known as forest depletion, which represents nearly 20 percent of global carbon emissions. Using the same method developed by the IPCC to account for this depletion in carbon storage and resultant carbon emissions, it is possible to calculate the emissions associated with land or site development for buildings and urbanization (IPCC 2006).

The amount of emissions from site development is calculated by comparing the design-case carbon storage with the native-state carbon storage, as shown in Equation 3. The design case carbon storage may include some percentage of the site that has native vegetation, in which case that percentage should be multiplied with the native-state carbon storage. On areas with no native vegetation the number of trees can be estimated, and converted to stored carbon using Table 2. The Green Footstep carbon storage value per tree is based on an average tree growth rate over 20 years, or a total of 0.2 metric tons (t) of carbon (or 0.73 t CO2e[1]) per tree.

$$SD = NSCS - (\%Native \times NSCS) - (Trees \times CR \times Yrs)$$

Equation 3. Emissions from site development

Where:
SD = Emissions from site development (kg CO_2e)
NSCS = Native site carbon storage (kg CO_2e)
%Native = Percent of building site that will have native vegetation in its design state
Trees = Number of trees expected on the site in non-native areas
CR = Rate at which the trees sequester carbon during growth period (kg CO_2e/yr)
Yrs = Length of trees growth period (yr)

[1] The mass of C (carbon) is converted to CO2e (carbon dioxide equivalent) by multiply by 44, the molecular weight of carbon dioxide, and dividing by 12, the molecular weight of Carbon.

Table 2. Annual carbon accumulation per tree per year (developed from IPCC 2006).

Species	Annual carbon accumulation per tree (T C/yr)
Aspen	0.0096
Soft Maple	0.0118
Mixed Hardwood	0.01
Hardwood Maple	0.0142
Juniper	0.0033
Cedar/Larch	0.0072
Douglas Fir	0.0122
Pine	0.0087
Spruce	0.0092
Average Carbon Stored per Tree per Year	0.01

Estimating emissions from building construction

The emissions from the building construction include all site work (earth moving, assembling, etc.) and the embodied carbon emissions of materials (from the extraction of raw materials through transportation to site). Since assessment of carbon emissions from these sources for building projects is a relatively nascent practice and several methods and tools exist, Green Footstep enables users either to enter their own estimate (using their own tool or method) or use economic input-output life cycle assessment (EIO LCA) data that is embedded in Green Footstep.

$$C = \text{UserValue}$$

Equation 4a. User option for estimating construction emissions

Where:
C = Emissions from building construction (kg CO_2e)
UserValue = Value entered by user

$$C = EIOLCA$$

Equation 4b. Green Footstep EIOLCA option for estimating construction emissions

Where:
C = Emissions from building construction (kg CO_2e)
EIOLCA = The total carbon emissions from building construction based on 1997 EIO LCA carbon intensity values (kg CO_2e)

The EIO LCA option for estimating construction emissions

As part of the EIO LCA option summarized by Equation 4b above, Green Footstep enables users to determine the EIOLCA variable used in Equation 4 in two ways. One approach is valid for both new and renovation construction and the other works for new construction only. This section will describe both approaches.

Approach #1: New and renovation construction

Approach #1 for determining the EIOLCA variable is to use data that comes directly from the Carnegie Mellon EIO LCA calculator, the 1997 National Purchaser Price model.[2] The data from this model is the amount of carbon emissions per US dollar of construction activity in a particular construction sector of the US economy, as shown below in Table 3. Users simply enter the amount of dollars in the project budget to determine the amount of emitted carbon.

[2] www.eiolca.net. For building construction sectors, there is no difference between the Producer and National Purchaser price models.

Table 3. EIO LCA coefficients for new and renovation construction based on the US economy in 1997.

EIO LCA Sector		Energy intensity (TJ/million USD)	Carbon intensity (t CO_2e/million USD)
23011	1-unit Residential	6.8	563
23012	Multifamily	7.9	640
23021	Manufacturing and industrial buildings	7.63	588
23022	Commercial and institutional buildings	7.72	599
Source:	Carnegie Mellon University Green Design Institute. (2008) Economic Input-Output Life Cycle Assessment (EIO-LCA), US 1997 Industry Benchmark model [Internet], Available from: <http://www.eiolca.net> Accessed 1 January, 2008.		

Approach #2: New construction only

Approach #2 for determining the EIOLCA variable is to use the data in Table 3 above converted to the amount of carbon emissions per square feet of new construction. Users simply enter the amount of square feet of new construction in order to determine the amount of emitted carbon. This section will describe how the carbon per square foot data was derived.

First, the total amount of carbon emitted in 1997 was determined for each of the building sectors in Table 3. Second, the total square feet of construction starts in 1997 was determined. Finally, the total carbon emitted was divided by the total square feet of constructions starts in order to determine the carbon emissions per square feet of new construction.

In order to calculate the total amount of carbon emissions in 1997 for each of the building types, the total economic outputs of each construction sector were multiplied by the appropriate carbon emissions coefficients in Table 3. The total economic outputs were determined from the BEA's 1997 Benchmark IO Item Output table and are listed in Table 4 below.

Construction starts in 1997 were provided by the McGraw-Hill Companies, Inc. The categories of this data were several and required mapping to one of the four EIO LCA sectors of Table 3. For example, the McGraw-Hill categories "Offices and Bank Buildings" as well as "Hotels and Motels" were both included in EIO LCA sector 23022, "Commercial and Institutional Buildings." The entire map can be found in Appendix B. Results are shown in Table 4.

Table 4. 1997 characteristics of EIO LCA sectors in the US economy.

EIO LCA Sector		Total industry output (million USD)	Area of Construction Starts (1000 ft^2)
23011	1-unit Residential	172,489	2,182,072
23012	Multifamily	26,234	403,362
23021	Manufacturing and industrial buildings	27,487	327,815
23022	Commercial and institutional buildings	190,818	958,231
Source:		Bureau of Economic Analysis, 1997 IO Item Output	McGraw-Hill Construction

Table 5 below shows the results of dividing the total carbon emitted by the total square feet of constructions starts for each EIO LCA Sector. While these coefficients are only accurate to one or two significant digits, they can be trusted since they are similar to coefficients produced by other studies, as discussed in Appendix C.

Table 5. Energy and carbon intensity coefficients for building construction sectors

EIO LCA Sector		Energy intensity ($kBtu/ft^2$)	Carbon Intensity ($kg\ CO_2e/ft^2$)
23011	1-unit Residential	510	45
23012	Multifamily	490	42
23021	Manufacturing and industrial buildings	610	49
23022	Commercial and institutional buildings	1500	120

Estimating emissions from building operation

During the operation of the building, the flow of carbon can move either into or out of the atmosphere. In order to determine the direction and magnitude of this net flow, the magnitude of each flow must be determined. Thus, the calculation of net emissions from building operation requires two steps.

The first step is to estimate the amount and type (electricity, natural gas, etc.) of energy the building will use. It is straightforward to calculate the emissions of this mix of energy with emissions coefficients for each energy source. The electricity coefficients in Green Footstep come from the US Environmental Protection Agency's eGRID Subregion Emission Rates, Output Emission Rates, covering carbon dioxide, methane and nitrous oxide.[3] Natural gas and other coefficients come from the US Energy Information Administration.[4]

The second step is to estimate the emissions offset through generating renewable energy onsite or purchasing off-site renewable energy and carbon offsets. The carbon intensity (kg CO2e/kBtu) of on-site electricity should equal that of the purchased electricity. The carbon intensity of energy produced by a solar thermal system should equal that of

3 http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html
4 http://www.eia.doe.gov/oiaf/1605/coefficients.html#tbl1

whatever the auxiliary energy source is (in most cases, natural gas). The amount of carbon offset by purchasing off-site renewable energy or other carbon offsets should be measured by dollars per metric ton of carbon offset. Typically, the seller of off-site renewable energy or carbon offsets will calculate this number for the purchaser. Strategies to offset emissions are provided in the Green Footstep website section titled "Footstep Logic."

A third optional step is to calculation other operational emissions that were not included in the above steps, such as employee commuting.

$$O\ (t) = (E - EG)EI + (N - TG)NGI + (OF - TG)OFI + OR$$

Equation 5. Emissions from building operation

Where:

O	=	Carbon emissions from building operation (kg CO_2e)
E	=	Electricity used (kBtu)
EG	=	Electricity generated on-site (kBtu)
EI	=	Electricity carbon emissions intensity (kg CO_2e/kBtu)
N	=	Natural gas used (kBtu)
TG	=	Renewable thermal energy from on-site (kBtu)
NGI	=	Natural gas carbon emissions intensity (kg CO_2e/kBtu)
OF	=	Other fuel used (kBtu)
OFI	=	Other fuel carbon emissions intensity (kg CO_2e/kBtu)
OR	=	Other operational emissions (kg CO2e)

References

Greenhouse Gas Protocol Initiative. http://www.ghgprotocol.org/

Intergovernmental Panel on Climate Change (2006) "Guidelines for National Greenhouse Gas Inventories Volume 4: Agriculture, Forestry, and Other Land Use" http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html

Olgyay, Victor W. and Julee Herdt (2004) "The application of ecosystems services criteria for green building assessment," Solar Energy, 77, 389–398

Powell, Thomas L., Rosvel Bracho, Jiahong Li, Sabina Dore, C. Ross Hinkle, Bert G. Drake. (2006) "Environmental controls over net ecosystem carbon exchange of scrub oak in central Florida" *Agricultural and Forest Meteorology* 141 19-34

Swain, Hilary. Director, Archbold Biological Station. (2008), Personal communication

Appendix A: Carbon storage for forest and grassland types

The IPCC (2006) recommends multiplying the dry mass by a fraction of 0.5 to determine the mass of the carbon stored in the biomass.

ABOVE-GROUND BIOMASS IN FORESTS

Domain	Ecological zone	Continent	Above-ground biomass (tonnes d.m. ha^{-1})
Tropical	Tropical rain forest	Africa	310 (130-510)
		North and South America	300 (120-400)
		Asia (continental)	280 (120-680)
		Asia (insular)	350 (280-520)
	Tropical moist deciduous forest	Africa	260 (160-430)
		North and South America	220 (210-280)
		Asia (continental)	180 (10-560)
		Asia (insular)	290
	Tropical dry forest	Africa	120 (120-130)
		North and South America	210 (200-410)
		Asia (continental)	130 (100-160)
		Asia (insular)	160
	Tropical shrubland	Africa	70 (20-200)
		North and South America	80 (40-90)
		Asia (continental)	60
		Asia (insular)	70
	Tropical mountain systems	Africa	40-190
		North and South America	60-230
		Asia (continental)	50-220
		Asia (insular)	50-360
Subtropical	Subtropical humid forest	North and South America	220 (210-280)
		Asia (continental)	180 (10-560)
		Asia (insular)	290
	Subtropical dry forest	Africa	140
		North and South America	210 (200-410)
		Asia (continental)	130 (100-160)
		Asia (insular)	160
	Subtropical steppe	Africa	70 (20-200)
		North and South America	80 (40-90)
		Asia (continental)	60
		Asia (insular)	70
	Subtropical mountain systems	Africa	50
		North and South America	60-230
		Asia (continental)	50-220
		Asia (insular)	50-360

ABOVE-GROUND BIOMASS IN FORESTS			
Domain	**Ecological zone**	**Continent**	**Above-ground biomass (tonnes d.m. ha^{-1})**
Temperate	Temperate oceanic forest	Europe	120
		North America	660 (80-1200)
		New Zealand	360 (210-430)
		South America	180 (90-310)
	Temperate continental forest	Asia, Europe (≤20 y)	20
		Asia, Europe (>20 y)	120 (20-320)
		North and South America (≤20 y)	60 (10-130)
		North and South America (>20 y)	130 (50-200)
	Temperate mountain systems	Asia, Europe (≤20 y)	100 (20-180)
		Asia, Europe (>20 y)	130 (20-600)
		North and South America (≤20 y)	50 (20-110)
		North and South America (>20 y)	130 (40-280)
Boreal	Boreal coniferous forest	Asia, Europe, North America	10-90
	Boreal tundra woodland	Asia, Europe, North America (≤20 y)	3-4
		Asia, Europe, North America (>20 y)	15-20
	Boreal mountain systems	Asia, Europe, North America (≤20 y)	12-15
		Asia, Europe, North America (>20 y)	40-50

DEFAULT BIOMASS STOCKS PRESENT ON GRASSLAND , AFTER CONVERSION FROM OTHER LAND USE			
IPCC climate zone	**Peak above-ground biomass[1] (tonnes d.m. ha^{-1})**	**Total (above-ground and below-ground) non-woody biomass[2] (tonnes d.m. ha^{-1})**	**Error [3]**
Boreal – Dry & Wet[4]	1.7	8.5	± 75%
Cold Temperate – Dry	1.7	6.5	± 75%
Cold Temperate –Wet	2.4	13.6	± 75%
Warm Temperate – Dry	1.6	6.1	± 75%
Warm Temperate –Wet	2.7	13.5	± 75%
Tropical – Dry	2.3	8.7	± 75%
Tropical - Moist & Wet	6.2	16.1	± 75%

[1] Data for standing biomass are compiled from multi-year averages reported at grassland sites registered in the ORNL DAAC NPP database [http://www.daacsti.ornl.gov/NPP/].

[2] Total above-ground and below-ground biomass values are based on the peak above-ground biomass values, and the below-ground biomass to aboveground biomass ratios (Table 6.1).

[3] Represents a nominal estimate of error, equivalent to two times standard deviation, as a percentage of the mean.

[4] Due to limited data, dry and moist zones for the boreal temperature regime and moist and wet zones for the tropical temperature regime were combined.

Appendix B: Map between McGraw Hill construction data and EIO LCA Sectors

	EIO LCA Sectors				
McGraw Hill data (1997)	New residential 1-unit structures	New multifamily housing structures	Commercial and institutional buildings	Manufacturing and industrial buildings	
Space type	Sector 23011	Sector 23012	Sector 23021	Sector 23022	Total new construction starts
	(1000 ft²)				(1000 ft²)
Stores and Restaurants			220,151		220,151
Warehouses (excl. manufacturer owned)				180,980	180,980
Office and Bank Buildings			178,570		178,570
Parking Garages and Automotive Services			109,611		109,611
Manufacturing Plants, Warehouses, Labs				146,835	146,835
Schools, Libraries, and Labs (nonmfg)			130,653		130,653
Hospitals and Other Health Treatment			66,488		66,488
Government Service Buildings			39,337		39,337
Religious Buildings			24,272		24,272
Amusement, Social and Recreational Bldgs			61,043		61,043
Miscellaneous Nonresidential Buildings			30,661		30,661
Hotels and Motels			86,821		86,821
Dormitories			10,624		10,624
One-family Houses	2,182,072				2,182,072
Two-family Houses		51,857			51,857
Apartments		351,505			351,505
Total new construction starts	2,182,072	403,362	958,231	327,815	3,871,480

Appendix C: Validating the derived 1997 EIO LCA coefficients

It is worthwhile to validate the derived energy and carbon intensity coefficients presented in Table 5. The energy intensity coefficients can be compared to the results of the only other EIO LCA study of a US economy, conducted of the 1967 US economy and presented in the "Handbook of Energy Use for Building Construction" by Stein et al (1981). This comparison concludes that the two sets of coefficients are within 30 percent of each other.

The Department of Energy "Handbook of Energy Use for Building Construction" (Stein et al 1981) utilized an EIO LCA method to produce estimates of the embodied energy of building construction (embodied energy of materials and energy used on site) per square feet of new construction starts, based on 1967 data. The results of this analysis are shown in Table 6.

In order to compare the 1967 coefficients to the 1997 energy intensities, building construction sectors of the 1967 US economy (the "Handbook sectors") were aggregated into the four 1997 EIO LCA sectors, as shown in Table 7.

		Total energy	Total new construction starts
Handbook sector number	Building Type	Btu/ft^2	1000 ft^2
23	Residential , one family	715,611	1,122,169
24	Residential, two family	635,638	55,708
25	Residential, garden apartments	664,482	227,787
26	Residential, high-rise apartments	744,703	160,225
27	Residential, alterations and additions	NA	NA
28	Hotel and motel	1,145,337	61,187
29	Dormitories	1,466,399	40,426
30	Industrial buildings	983,697	476,468
31	Office buildings	1,667,111	157,578
32	Warehouses	566,071	103,468
33	Garages and service stations	788,024	41,801
34	Stores and restaurants	960,050	209,333
35	Religious buildings	1,273,540	54,564
36	Educational buildings	1,404,249	315,485
37	Hospital buildings	1,742,549	67,979
38	Other non-farm buildings	147,192	159,483
48	Farm residences	561,914	54,457
49	Farm service buildings	147,799	392,763

Table 6. Results from the Stein et al (1981) study.

		IO Sectors			
Stein et al (1981)		New residential 1-unit structures	New multifamily housing structures	Commercial and institutional buildings	Manufacturing and industrial buildings
Handbook sector number	Building Type	Sector 23011	Sector 23012	Sector 23021	Sector 23022
23	Residential , one family	X			
24	Residential, two family		X		
25	Residential, garden apartments		X		
26	Residential, high-rise apartments		X		
27	Residential, alterations and additions*				
28	Hotel and motel			X	
29	Dormitories			X	
30	Industrial buildings				X
31	Office buildings			X	
32	Warehouses				X
33	Garages and service stations			X	
34	Stores and restaurants			X	
35	Religious buildings			X	
36	Educational buildings			X	
37	Hospital buildings			X	
38	Other non-farm buildings*				
48	Farm residences*				
49	Farm service buildings*				

* These sectors do not belong to any of the four EIO LCA sectors

Table 7. Map between Handbook sectors and EIO LCA sectors

The total energy consumed in 1967 within each of the four EIO LCA sectors was divided by the total square footage to obtain the energy intensity, as shown in Table 8. For example, EIO sector 23021 "Manufacturing and industrial buildings" included two Handbook sectors: Industrial buildings (Sector 30) and Warehouses (Sector 32), each of which have an energy intensity (983,697 and 566,071 Btu/ft^2, respectively) and an amount of 1967 construction starts (476,468,000 and 103,468,000 ft^2, respectively). The energy intensity for Sector 23021 is the averaged energy intensity of Sectors 30 and 32, weighted by the construction starts, which equals 909,000 Btu/ft^2.

	New residential 1-unit structures	New multifamily housing structures	Commercial and institutional buildings	Manufacturing and industrial buildings
Total new construction (1000 ft^2)	1,122,169	443,720	948,353	579,936
Total energy (Billion Btu)	803,036	306,091	1,256,936	527,270
Total energy intensity (kBtu/ft^2)	**716**	**690**	**1325**	**909**

Table 8. Energy intensities of EIO LCA Sectors in 1967.

According to the results displayed by Figure 3, the energy intensity of building construction has decreased since 1967 for three of the four analyzed sectors. New residential 1-unit, new multifamily, and manufacturing and industrial structures each decreased by 30 +/- 3 percent. The outlier was "Commercial and institutional buildings," which actually increased by 15 percent.

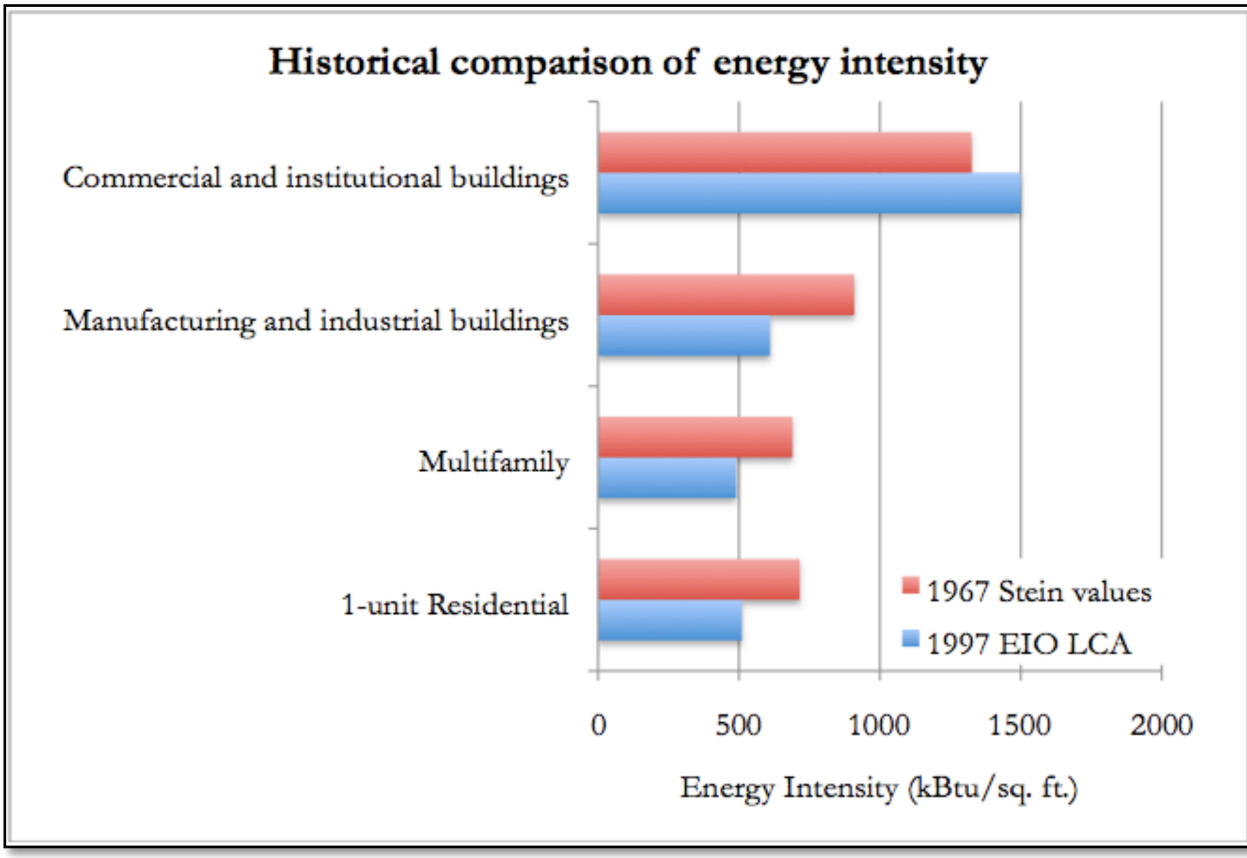

Figure 3. Historical comparison between Stein et al (1981) and 1997 construction energy intensity.

Given a general trend of decreasing carbon emissions per GDP in the US, it is expected that the energy of building construction would decrease over the three decades between the 1967 Stein and the 1997 EIO LCA studies. Since 1980, the energy and emissions intensity has been cut almost in half, as shown in Figure 4. Thus, it is somewhat surprising that the commercial and institutional building sector would not decrease about 30 percent like the other sectors. A different mix of materials going into those buildings could explain the disparity. For instance, there was likely a large increase in energy-intensive glazing (including double-skinned facades) between 1967 and 1997. In addition, highly energy-intensive concrete as opposed to wood or stone structural materials has become more common.

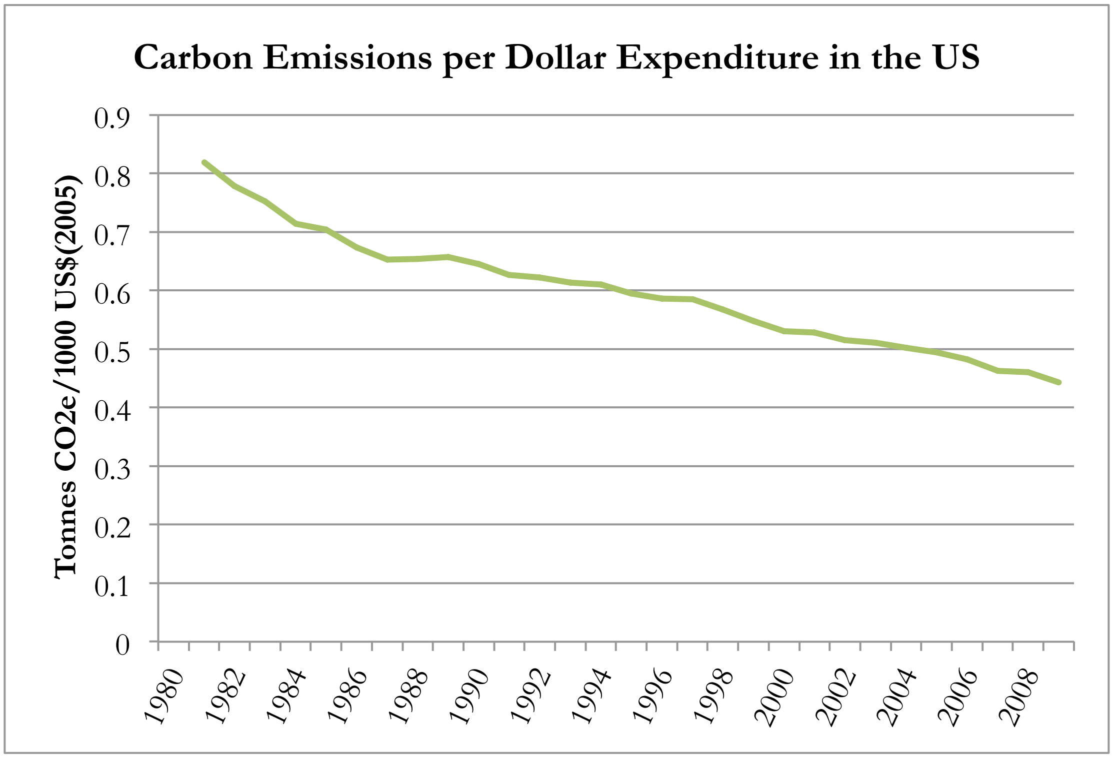

Figure 4. The carbon intensity of the GDP has been steadily decreasing. Source: US Energy Information Administration

There was a small source of error in aggregating the 1967 Handbook sectors into the four 1997 EIO LCA sectors. One sector, Handbook Sector 38 "Other non-farm buildings," could have been included in either EIO LCA sectors 23021 (Manufacturing and industrial buildings) or 23022 (Commercial and institutional buildings). In fact, it is possible that a percentage of Sector 38 (159,483,000 ft^2 of construction starts at 147 $kBtu/ft^2$) belongs in each one.

The errors of the 1967 energy intensity estimates for 23021 and 23022 can be estimated by calculating the range between including and not including the entire Sector 38. A mid-point value and the percent increase or decrease to reach the high and low values were calculated. This simple analysis indicates that including 100 percent of Sector 38 in either 23022 or 23021 would not change the fundamental conclusion displayed in Figure 3;

that is, the 1967 estimate of 23022 would remain smaller than the 1997 estimate, and the 1967 estimate of sector 23021 would remain larger than the 1997 estimate.

EIO LCA Sector		1967 EIO LCA sector "mid" estimate (kBtu/ft^2)	Absolute Value of Error (+/–)	Percent difference from 1997 EIO LCA sector estimate
23022	Commercial and institutional buildings	1240	7%	–21%
23021	Manufacturing and industrial buildings	827	10%	+26%

Table 4-9. Error analysis of 1967 and 1997 EIO LCA comparison. Half of the Handbook sector 38 was added to sectors 23022 and 23021 to produce the "mid" estimate. Since the absolute value of the error is less than the percent difference from 1997 EIO LCA sector, the main conclusion of the analysis does not change.