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Partial Environmental Life Cycle Inventory of a Lightweight Concrete Masonry House Compared to a Wood Frame House

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KEYWORDS

Block, cement, concrete, concrete masonry unit, CMU, emissions, embodied energy, energy, housing, LCA, LCI, life cycle assessment, life cycle inventory, lightweight concrete, lightweight concrete block, modeling, residential, wood frame

ABSTRACT

A partial life cycle inventory (LCI) of a wood frame house and a lightweight concrete masonry unit (CMU) house has been carried out according to the Society of Environmental Toxicology and Chemistry (SETAC) guidelines and the International Organization for Standardization (ISO) standards 14040 and 14041. The house was modeled in five cities, representing a range of U.S. climates: Tampa, El Paso, Knoxville, Providence, and Detroit.

The house is a two-story single-family building with a contemporary design. The house life cycle system boundary includes the energy and material inputs and outputs of excavation; construction; occupancy; maintenance, repair, and replacement; demolition; and disposal. It also includes (i) the upstream profile of concrete, lightweight concrete masonry units, mortar, grout, and stucco, (ii) the mass of other building materials used, (iii) occupant energy-use, and (iv) transportation energy. Lightweight CMUs are made with lightweight aggregate, which consists of expanded shale, clay, and slate. The partial LCI is presented in terms of energy use, material use, emissions to air, and solid waste generation over a 100-year life.

The LCI is partial because it does not include the embodied energy or emissions from the production of other non-cementitious building materials, such as wood, steel, and plastics. It also does not include the upstream profiles of fuel and electricity production and distribution.

The results show that occupant energy-use accounts for 99% of the life cycle energy-use of the lightweight CMU house and the wood frame house. Approximately 1% of the life cycle energy is due to cement manufacturing and concrete production. The house life cycle energy is primarily a function of climate and occupant behavior, not concrete content. In the four cities representing the colder climates (El Paso, Knoxville, Providence, and Detroit), the lightweight CMU house has a lower life cycle energy-use than the wood frame house. Furthermore, although the lightweight CMU house contains more embodied energy than the wood frame house, after 11 years in Detroit, for example, the cumulative energy use of the wood frame house surpasses that of the lightweight CMU house.

Most of the house life cycle emissions to air are from the two natural gas burning appliances (furnace and water heater). Most of the emissions of CO_2 (95%), NO_x (85%), CO (90%), VOC (75%), and CH_4 (90%) are from the combustion of household natural gas for heating and hot water. Most of the particulate matter (60%) and SO_2 emissions (95%) are from the production of concrete, lightweight CMUs, mortar, grout, and stucco.

REFERENCE

Marceau, Medgar L., Gajda, John, VanGeem, Martha G., Gentry, Thomas, and Nisbet, Michael A., “Partial Environmental Life Cycle Inventory of a Concrete Masonry House Compared to a Wood Frame House”, PCA R&D Serial No. 2466, Portland Cement Association, Skokie, IL, September 2000, 53 pages.

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PARTIAL ENVIRONMENTAL LIFE CYCLE INVENTORY OF A CONCRETE MASONRY HOUSE COMPARED TO A WOOD FRAME HOUSE

by Medgar L. Marceau, John Gajda, Martha G. VanGeem,
Thomas Gentry, and Michael A. Nisbet*

1. INTRODUCTION

The Portland Cement Association (PCA) is currently developing environmental life cycle inventory (LCI) data for use in evaluating environmental aspects of concrete products. An LCI is the compilation and quantification of energy and material inputs and outputs of a product system. The ultimate goal of this endeavor is to use the LCI data to conduct a life cycle *assessment* (LCA) of concrete products. The LCA will quantify the *impacts* of concrete products on the environment, such as climate change, acidification, nutrification, natural resource depletion, risks to human health, and other ecological consequences. An LCA can be used to compare the environmental impact of concrete products with competing construction products. The LCI data will also be available for incorporation into existing and future LCA models, which are designed to compare construction material and system alternatives and to improve construction material production processes. The purpose of this report is to compare the partial LCI of a wood frame house with that of a house with walls constructed of lightweight concrete masonry units. Further information on the target audiences for this report and other project reports is provided in Appendix A.

The methodology for conducting an LCI has been documented by the United States Environmental Protection Agency,[1] the Society of Environmental Toxicology and Chemistry (SETAC),[2] and the International Organization for Standardization (ISO).[3] The partial LCI in this report follows the guidelines proposed by SETAC. These guidelines parallel the standards proposed by ISO in ISO14040, "Environmental Management - Life Cycle Assessment - Principles and Framework," ISO 14041, "Environmental Management - Life Cycle Assessment - Goal and Scope Definition and Inventory Analysis," and other ISO documents.

The house life cycle comprises the energy and material inputs and outputs of excavation; construction; occupancy; maintenance, repair, and replacement; demolition; and disposal. The partial LCI in this report includes the upstream profile of ready-mixed concrete, lightweight concrete masonry units (CMUs), mortar, grout, and stucco.[4,5] The PCA intends to include the upstream profiles of other materials (such as wood and steel) and fuels (such as coal and

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electricity) once a suitable database is found. Furthermore, water usage from upstream profiles and from household occupants will also be included. Figure 1-1 shows the materials and energy inputs that are included in this partial LCI.

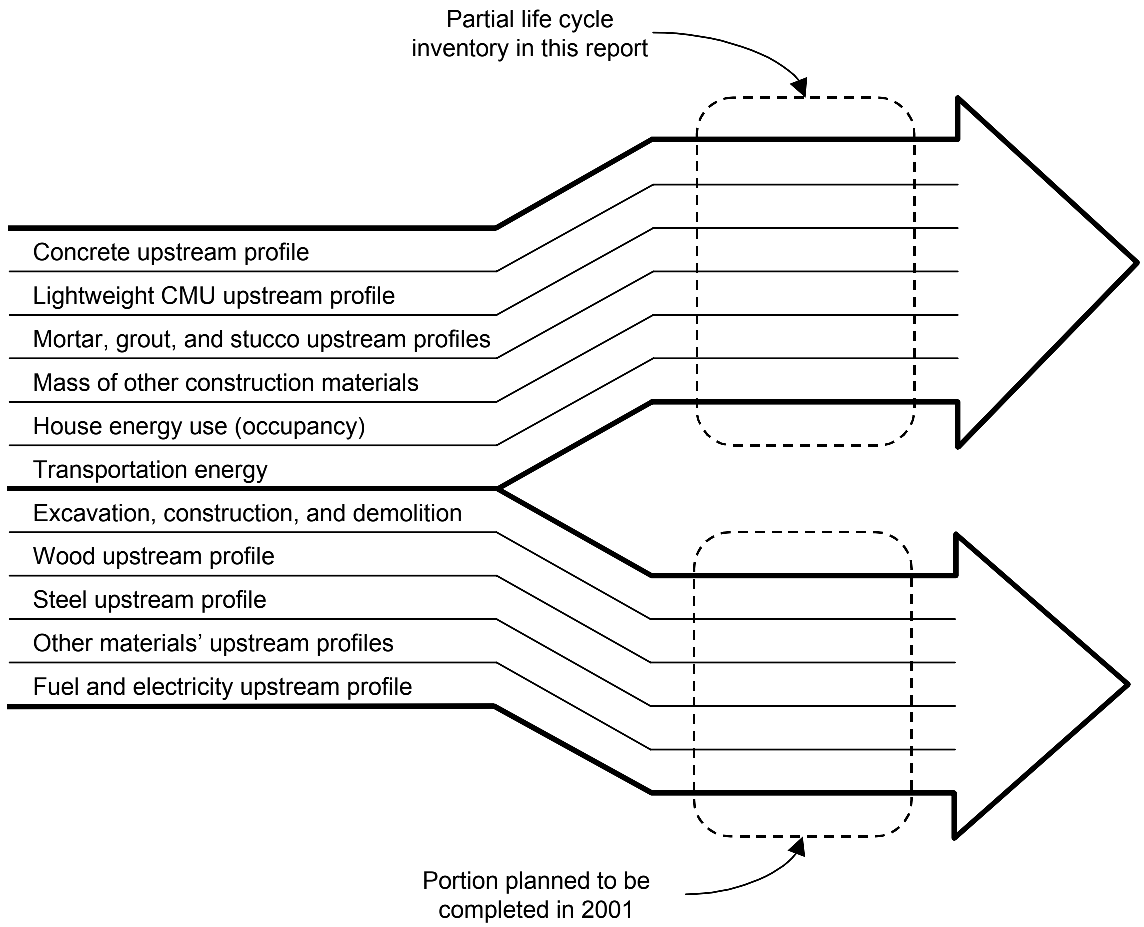

Figure 1-1. Material and energy inputs included in the partial LCI.

The partial LCI is presented in terms of energy use, material use, emissions to air, and solid waste generation; and it includes the upstream profile of concrete, lightweight CMUs, mortar, grout, and stucco. The masses of other building materials used in the house are included, and they can be used as inputs in existing and future LCA models.

The same layout is used for both the wood frame house and the lightweight CMU house. The houses are designed to meet the requirements of the 1998 International Energy Conservation Code (IECC)[6] because it is the most current and most widely used energy code in the United States. The long-term energy consumption of a building depends on local climate, so the houses are modeled in a variety of regions. Five cities were chosen that represent the range of climates in the United States: Tampa, Florida; El Paso, Texas; Providence, Rhode Island; Knoxville, Tennessee; and Detroit, Michigan.[7] House energy consumption is modeled on an hourly basis with building energy simulation software that uses the DOE 2.1E calculation engine.[8]

2. SYSTEM BOUNDARY

The house life-cycle system-boundary, shown in Figure 2-1, defines the limit of the partial LCI. It includes the energy and material inputs and outputs of excavation; construction; occupancy; maintenance, repair, and replacement; demolition; and disposal. The system boundary also

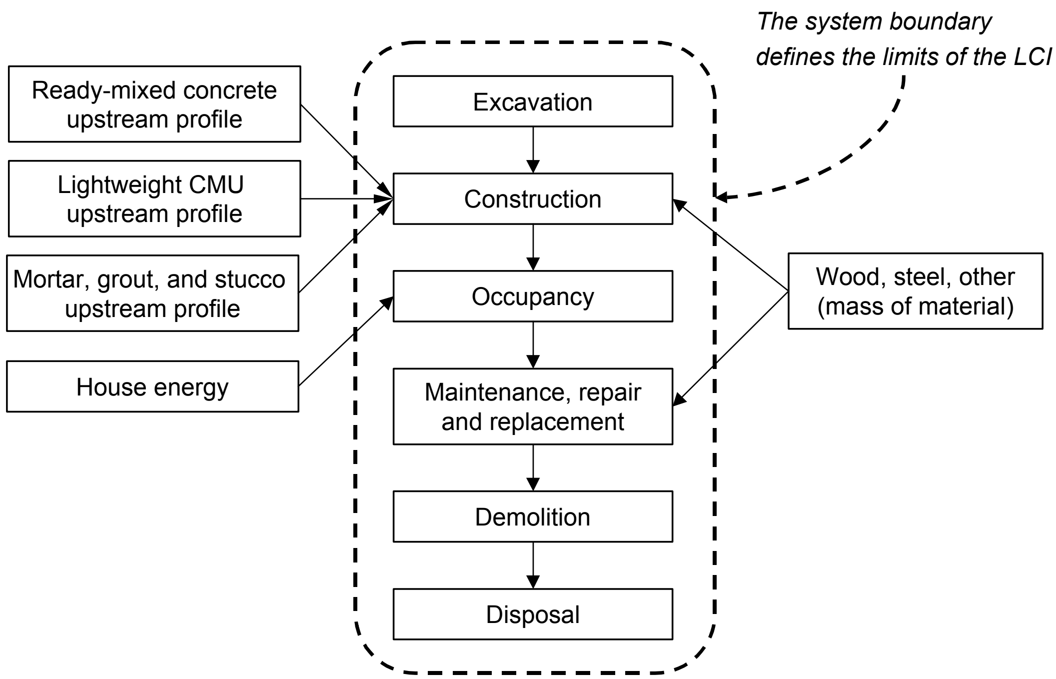

Figure 2-1. System boundary for house environmental life cycle inventory.

includes (i) the upstream profiles of concrete, lightweight CMUs, mortar, grout, and stucco[5], (ii) the mass of other building materials used, (iii) occupant energy-use, and (iv) transportation energy. The transportation energy consists of the energy to transport materials from their place of origin to the house and form the house to a landfill, and the transportation energy in the upstream profiles.

The system boundary excludes human resources, the infrastructure, accidental spills, and impacts caused by personnel.

The LCI is partial because it does not include the embodied energy or emissions from the production of other building materials, such as wood, steel, and plastics. It also does not include the upstream profile of fuel and electricity production and distribution.

3. HOUSE DESCRIPTION

The house described in this report was designed by Construction Technology Laboratories, Inc. (CTL), and it is based on the designs of typical houses currently being built in the United States. The house is a two-story single-family building with four bedrooms, 2.7-m (9-ft) ceilings, a two-story foyer and family room, and an attached two-car garage. The house has 228 square meters

(2,450 square feet) of living space, which is somewhat larger than the 1998 U.S. average of 203 square meters (2,190 square feet).[9] The size of the house is based on the average size concrete house constructed in the United States.[10] Figures B-1 through B-8 in Appendix B present the floor plans and elevations.

The house was modeled in five cities, representing a range of U.S. climates. El Paso was selected because it is a hot dry climate with large temperature swings where thermal mass is effective in increasing thermal comfort and in reducing energy use. Tampa was selected because it is a hot humid climate with small temperature swings where thermal mass works almost as well. Knoxville was selected because it is a moderate climate. Providence and Detroit were selected because they are cold climates.

The building envelope in each location is designed to meet the minimum requirements of the 1998 International Energy Conservation Code (IECC) using standard building materials.[6] The IECC minimum requirements for thermal resistance are presented in Table 3-1 for each of the five cities where the house is modeled. R-value refers to thermal resistance in $m^2 \cdot K/W$ ($hr \cdot ft^2 \cdot °F/Btu$) and U-factor refers to heat flow per unit area in $W/m^2 \cdot K$ ($Btu/hr \cdot ft^2 \cdot °F$). The maximum U-factor is equivalent to the inverse of the minimum R-value. Variations in regional building materials and practices, such as the use of crawl spaces and basements, are not considered in order to simplify the analyses and in order to compare energy use across all cities.

Table 3-1. International Energy Conservation Code Maximum U-factors*

Location	Opaque walls**				Roof		Windows***	
	Wood frame		Mass					
	$\frac{W}{m^2 \cdot K}$	$\frac{Btu}{hr \cdot ft^2 \cdot °F}$	$\frac{W}{m^2 \cdot K}$	$\frac{Btu}{hr \cdot ft^2 \cdot °F}$	$\frac{W}{m^2 \cdot K}$	$\frac{Btu}{hr \cdot ft^2 \cdot °F}$	$\frac{W}{m^2 \cdot K}$	$\frac{Btu}{hr \cdot ft^2 \cdot °F}$
Tampa	1.107	0.195	1.374	0.242	0.261	0.046	2.7	0.47
El Paso	0.704	0.124	0.818	0.144	0.204	0.036	2.5	0.44
Knoxville	0.602	0.106	0.715	0.126	0.204	0.036	2.3	0.41
Providence	0.517	0.091	0.574	0.101	0.153	0.027	1.7	0.30
Detroit	0.488	0.086	0.545	0.096	0.148	0.026	1.7	0.30

* The maximum U-factor is equal to the inverse of the minimum R-value.
** Calculated based on the house design and the window U-factors prescribed by the IECC.
*** The IECC also requires that windows have a solar heat gain coefficient (SHGC) less than 0.4 in Tampa and El Paso.

In all cities, the house is slab-on-grade construction. The slab-on-grade floor consists of carpeted 150-mm (6-in.) thick normal-weight concrete cast on soil. The U-factor of the floor is 1.53 $W/m^2 \cdot K$ (0.27 $Btu/hr \cdot ft^2 \cdot °F$). Although the IECC requires perimeter insulation for slabs-on-grade in most areas of the United States, commonly used and accepted energy modeling software cannot model perimeter insulation. Therefore, the slab-on-grade is uninsulated. Second-story floors are carpeted wood-framed assemblies without insulation.

In all locations the exterior walls of the wood frame house consist of medium-colored aluminum siding, 12-mm (½-in.) plywood, R_{SI}-1.9 (R-11) fiberglass batt insulation, and 12-mm (½-in.) painted gypsum board. The exterior walls of the lightweight CMU house in all locations except Tampa consist of 16-mm (⅝-in.) light-colored portland cement stucco, 200-mm (8-in.) lightweight CMU with partly-grouted uninsulated-cells*, wood furring with R_{SI}-1.9 (R-11) fiberglass batt insulation, and 12-mm (½-in.) painted gypsum board. In Tampa, the exterior walls of the lightweight CMU house are similar, except they do not contain any fiberglass batt insulation. In all locations, the nominal weight of the lightweight CMU is assumed to be 1,440 kg/m^3 (90 lb/ft^3) with U-factors as presented in ASHRAE Standard 90.1-1999.[11] Figures B-7 and B-8 in Appendix B show wall cross-sections.

For both house styles, all exterior garage walls (except the front wall of the garage, which has overhead doors) and the common wall between house and garage are of the same construction as the exterior walls of the house. The front wall of the garage is modeled as a low-mass light-colored wall with a U-factor of 2.8 W/m^2·K (0.50 Btu/hr·ft^2·°F). Interior walls are wood frame construction and uninsulated.

Roofs are wood frame construction with R_{SI}-5.3 or R_{SI}-6.7 (R-30 or R-38) fiberglass batt insulation, and they are covered with medium-colored asphalt shingles.

Windows are primarily located on the front and back façades, and the overall window-to-exterior wall ratio is 16%. The windows were chosen to meet the IECC requirements for solar heat gain coefficient (SHGC) and U-factor. They consist of double pane glass with a low-E coating. To meet the SHGC requirement, windows in Tampa and El Paso are tinted and contain air in the space between panes. Windows in Knoxville, Providence, and Detroit are not tinted and contain argon gas in the space between panes. Interior shades or drapes are assumed to be closed during periods of high solar heat gains. The houses are assumed to be located in new developments without trees or any other form of exterior shading.

Table 3-2 presents the assembly U-factors used in the analyses. In most cases, using typical building materials results in assemblies that exceed the IECC U-factor requirements.

4. ASSUMPTIONS

In order to create a realistic house model, the following assumptions about occupant behavior and house performance have been made. These assumptions also ensure that comparisons between house styles are possible.

Hot water is supplied by a natural gas water heater, which has a peak utilization of 24 liters/minute (2.5 gallons/minute). The hot water load-profile was taken from ASHRAE Standard 90.2.[12] The heating, ventilating, and air-conditioning (HVAC) system consists of a natural gas high-efficiency forced-air system with a high-efficiency central air conditioner. The efficiencies of the HVAC system components are assumed to be identical in all cities.

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*Partly-grouted uninsulated-cells means that some lightweight CMU cells are grouted, while others are empty (do not contain insulation or grout). Grouted cells typically contain reinforcing steel. *Partly grouted* is assumed to mean cells are grouted 80 cm (32 in.) on center vertically and 120 cm (48 in.) on center horizontally.[11]

Table 3-2. Assembly U-Factors*

<table>
<tr><th rowspan="3">Location</th><th colspan="4">Walls</th><th colspan="2" rowspan="2">Roof**</th><th colspan="2" rowspan="2">Windows</th></tr>
<tr><th colspan="2">Wood frame</th><th colspan="2">Lightweight CMU</th></tr>
<tr><th>$\frac{W}{m^2 \cdot K}$</th><th>$\frac{Btu}{hr \cdot ft^2 \cdot {}^\circ F}$</th><th>$\frac{W}{m^2 \cdot K}$</th><th>$\frac{Btu}{hr \cdot ft^2 \cdot {}^\circ F}$</th><th>$\frac{W}{m^2 \cdot K}$</th><th>$\frac{Btu}{hr \cdot ft^2 \cdot {}^\circ F}$</th><th>$\frac{W}{m^2 \cdot K}$</th><th>$\frac{Btu}{hr \cdot ft^2 \cdot {}^\circ F}$</th></tr>
<tr><td>Tampa</td><td rowspan="5">0.47</td><td rowspan="5">0.082</td><td>0.92</td><td>0.162</td><td rowspan="3">0.18</td><td rowspan="3">0.032</td><td rowspan="2">2.4</td><td rowspan="2">0.43</td></tr>
<tr><td>El Paso</td><td rowspan="4">0.43</td><td rowspan="4">0.076</td></tr>
<tr><td>Knoxville</td><td rowspan="3">1.5</td><td rowspan="3">0.27</td></tr>
<tr><td>Providence</td><td rowspan="2">0.15</td><td rowspan="2">0.026</td></tr>
<tr><td>Detroit</td></tr>
</table>

* The maximum U-factor is equal to the inverse of the minimum R-value.
** R_{SI}-5.3 (R-30) attic insulation was used in Tampa, El Paso, and Knoxville. R_{SI}-6.7 (R-38) attic insulation was used in Providence and Detroit.

The HVAC system is controlled by a residential set-back thermostat located in the family room. The cooling set-point temperature is 24°C (75°F) from 6 AM to 10 PM and 26°C (78°F) from 10 PM to 6 AM. The heating set-point temperature is 21°C (70°F) from 6 AM to 10 PM and 18°C (65°F) from 10 PM to 6 AM.

Occupant energy consumption for uses other than heating and cooling is assumed to be 23.36 kWh/day. This value was calculated from ASHRAE Standard 90.2,[12] and it assumes the house has an electric clothes dryer and an electric stove.

Air infiltration rates are based on ASHRAE Standard 62.[13] The air infiltration rate is 0.35 air changes per hour (ACH) in the living areas of the house and 2.5 ACH in the unconditioned attached garage. A family of four is assumed to live in the house.

The life of the house is assumed to be 100 years. The maintenance, repair, and replacement schedules for various building components are shown in Table 4-1.

5. INVENTORY ANALYSIS

The partial life cycle inventory of the house comprises the energy and material inputs and outputs of all the activities included in the system boundary shown in Figure 1-1. These activities are excavation; construction; occupancy; maintenance, repair, and replacement; demolition; and disposal. The partial LCI in this report includes the upstream profile of ready-mixed concrete and the upstream profile of lightweight CMUs. [4,5] The PCA intends to include the upstream profiles of other materials once a suitable database is found.

The SETAC guidelines[2] indicate that inputs to a process do not need to be included in an LCI if (i) they are less than 1% of the total mass of the processed materials or product, (ii) they do not contribute significantly to a toxic emission, and (iii) they do not have a significant associated energy consumption.

Table 4-1. House Component Replacement Schedules

House component	Replacement schedule (years)
Siding, air barrier, and exterior fixtures	33.3
Stucco	50
Latex and silicone caulking	10
Paint, exterior	5
Doors and windows	33.3
Roofing*	20 and 40
Gable and ridge vents	33.3
Bathroom fixtures	25
Bathroom tiles and backer board	25
Paint, interior	10
Carpet and pad	10
Resilient flooring, vinyl sheet	10
Bathroom furniture (toilet, sink, etc.)	25
Garbage disposal	20
Furnace	20
Air conditioner	20
Interior and exterior luminaries	33.3
Water heater	20
Large appliances	15
Manufactured fireplace	50
Kitchen and bathroom casework	25
Kitchen counter tops	25

* A new layer of shingles is added every 20 years, and every 40 years the existing layers of felt and shingles are replaced with a new layer of felt and shingles.

5.1. Material inputs

The material inputs to the partial LCI are made up of the material inputs to construction, maintenance, repair, and replacement.

5.1.1. House material inputs

The material inputs to construction, maintenance, repair, and replacement are calculated from the house plans and elevations and from the house component replacement schedule. Table 5-1 shows a summary of the material inputs over the 100-year life of the house in each city. A detailed material list is shown in Table C-1 in Appendix B.

Both houses contain similar amounts of wood. For example, in both houses, the roof, the interior walls, the second story floor are framed with wood. In addition, the lightweight CMU house has interior wood furring and wood framing around the doors and windows. There is less gypsum wallboard in the lightweight CMU house because the inside surfaces of the garage are

Table 5-1A. House Materials List – SI Units*

	Wood frame house					Lightweight CMU house				
Material, kg	**Tampa**	**El Paso**	**Knoxville**	**Providence**	**Detroit**	**Tampa**	**El Paso**	**Knoxville**	**Providence**	**Detroit**
Ready-mixed concrete**	70,700	76,200	81,700	114,700	114,700	70,700	76,200	81,700	114,700	114,700
CMUs, lightweight	0	0	0	0	0	49,700	49,700	49,700	49,700	49,700
CMUs, normal weight	0	0	0	0	0	0	0	0	0	0
Fiber-cement backer board	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500
Mortar	0	0	0	0	0	35,900	35,900	35,900	35,900	35,900
Grout	0	0	0	0	0	3,900	3,900	3,900	3,900	3,900
Stucco	0	0	0	0	0	23,800	23,800	23,800	23,800	23,800
Metal**	3,500	3,500	3,600	4,000	4,000	4,200	4,300	4,400	4,800	4,800
Wood	20,400	20,400	20,400	20,400	20,400	19,500	19,500	19,500	19,500	19,500
Gypsum wallboard	8,900	8,900	8,900	8,900	8,900	8,000	8,000	8,000	8,000	8,000
Insulation, polystyrene**	0	30	60	240	240	0	30	60	240	240
Insulation, fiberglass	540	540	540	630	630	330	540	540	630	630
Polymers, various	10,200	10,200	10,200	10,200	10,200	10,100	10,100	10,100	10,100	10,100
Roofing materials	5,800	5,800	5,800	5,800	5,800	5,800	5,800	5,800	5,800	5,800
Windows	3,100	3,100	3,100	3,100	3,100	3,100	3,100	3,100	3,100	3,100
Tile	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600
Lighting products	600	600	600	600	600	600	600	600	600	600
Electrical wire	110	110	110	110	110	110	110	110	110	110
Shipping weight, various***	5,500	5,500	5,500	5,500	5,500	5,500	5,500	5,500	5,500	5,500
Total materials, kg	**134,500**	**140,100**	**145,700**	**179,400**	**179,400**	**246,400**	**252,200**	**257,800**	**291,500**	**291,500**

*Includes items replaced during the 100-year life.
**More material is used in colder climates because foundations are deeper.
***See Table C-2 in Appendix C for a listing of items that contribute to shipping weight.

Table 5-1B. House Materials List – U.S. Customary Units*

	Wood frame house					Lightweight CMU house				
Material, lb	**Tampa**	**El Paso**	**Knoxville**	**Providence**	**Detroit**	**Tampa**	**El Paso**	**Knoxville**	**Providence**	**Detroit**
Ready-mixed concrete**	155,800	167,900	180,100	252,900	252,900	155,800	167,900	180,100	252,900	252,900
CMUs, lightweight	0	0	0	0	0	109,600	109,600	109,600	109,600	109,600
CMUs, normal weight	0	0	0	0	0	0	0	0	0	0
Fiber-cement backer board	3,400	3,400	3,400	3,400	3,400	3,400	3,400	3,400	3,400	3,400
Mortar	0	0	0	0	0	79,100	79,100	79,100	79,100	79,100
Grout	0	0	0	0	0	8,700	8,700	8,700	8,700	8,700
Stucco	0	0	0	0	0	52,400	52,400	52,400	52,400	52,400
Metal**	7,600	7,800	7,900	8,900	8,900	9,400	9,500	9,700	10,600	10,600
Wood	45,000	45,000	45,000	45,000	45,000	42,900	42,900	42,900	42,900	42,900
Gypsum wallboard	19,600	19,600	19,600	19,600	19,600	17,700	17,700	17,700	17,700	17,700
Insulation, polystyrene**	0	70	130	530	530	0	70	130	530	530
Insulation, fiberglass	1,200	1,200	1,200	1,380	1,380	720	1,200	1,200	1,380	1,380
Polymers, various	22,600	22,600	22,600	22,600	22,600	22,200	22,200	22,200	22,200	22,200
Roofing materials	12,800	12,800	12,800	12,800	12,800	12,800	12,800	12,800	12,800	12,800
Windows	6,900	6,900	6,900	6,900	6,900	6,900	6,900	6,900	6,900	6,900
Tile	8,000	8,000	8,000	8,000	8,000	8,000	8,000	8,000	8,000	8,000
Lighting products	1,300	1,300	1,300	1,300	1,300	1,300	1,300	1,300	1,300	1,300
Electrical wire	250	250	250	250	250	250	250	250	250	250
Shipping weight, various***	12,100	12,100	12,100	12,100	12,100	12,100	12,100	12,100	12,100	12,100
Total materials, lb	**296,500**	**308,900**	**321,200**	**395,600**	**395,600**	**543,100**	**556,000**	**568,300**	**642,700**	**642,700**

*Includes items replaced during the 100-year life.
**More material is used in colder climates because foundations are deeper.
***See Table C-2 in Appendix C for a listing of items that contribute to shipping weight.

not required to be sheathed. In the wood frame house, the common wall between the garage and the house is required to be sheathed in flame-retardant materials for reasons of fire safety.

The material inputs also include packaging. Almost all material delivered to the site is packaged in some way. The item labeled *shipping weight* in Table 5-1 includes the packaging for large items like appliances, and Table C-2 in Appendix B lists the items that contribute to shipping weight. The amount of packaging for concrete, lightweight CMUs, mortar, grout, stucco, wood, steel, and board stock is minimal so it is ignored. Wood pallets are reused and do not contribute to the waste stream. The amount of packaging for all other materials not listed in Table C-2 can be quite substantial in volume; however, on a mass basis it is less than 1% of the material packaged, so it is ignored. Construction waste is included in the mass of materials listed in Table 5-1.

5.1.2. Concrete upstream profile

Table 5-2 shows the material inputs to the concrete portion of the house in each city. The concrete material upstream profile is based on the upstream profile for 21 MPa (3,000 psi) concrete, lightweight CMU concrete, mortar, grout, and stucco. The mix proportions are presented in Table 5-3. Concrete mix proportions vary depending on available materials and suppliers. More information on the effects of concrete mix proportions on LCI results is given in Reference 4. Data are generally U.S. industry averages where available. The lightweight CMU house contains more cement-based materials than the wood frame house because, in addition to the foundation, the exterior walls of the lightweight CMU house contain mostly cement-based materials. The houses in the cooler climates also contain more cement-based materials because they have deeper concrete foundations.

5.2. Energy inputs

The energy inputs to the partial LCI are made up of the energy inputs to excavation, construction, maintenance, occupancy, demolition, and disposal. The partial LCI also includes energy used to produce ready-mixed concrete and lightweight CMUs. This is the embodied energy of concrete and it is part of the concrete upstream profile.

5.2.1. Excavation and construction

Most of the energy used in excavation and construction is for transporting materials from their place of origin to the house construction site. Energy used on site by excavation and construction equipment is assumed to be less than 1% of the life cycle energy so it is not included in the LCI. All material is assumed to be transported by tractor-trailers using diesel fuel and traveling on paved roads. The average haul distance is assumed to be 80 kilometers (50 miles) for all material. The energy consumption of 1,060 joules per kilogram-kilometer (1,465 Btu per ton-mile) is based on the assumption that transportation energy efficiency is 24 liters of diesel fuel per 1,000 metric ton-kilometers (9.4 gallons of diesel fuel per 1,000 ton-miles)[14]. Table 5-4 shows the transportation energy used to transport materials to the construction site. This partial LCI does not consider the energy used in return trips when the tractor-trailer is empty because this type of vehicle usually makes deliveries to several job sites per trip. Therefore, the assumptions about transportation energy consumption are conservative.

Table 5-2A. Material Input for Concrete and Other Cement-Based Materials – SI Units

	Wood frame house					Lightweight CMU house				
Material, kg	**Tampa**	**El Paso**	**Knoxville**	**Providence**	**Detroit**	**Tampa**	**El Paso**	**Knoxville**	**Providence**	**Detroit**
Ready-mixed concrete										
Cement	6,800	7,300	7,800	11,000	11,000	6,800	7,300	7,800	11,000	11,000
Water	4,300	4,600	4,900	6,900	6,900	4,300	4,600	4,900	6,900	6,900
Coarse aggregate	34,300	37,000	39,700	55,700	55,700	34,300	37,000	39,700	55,700	55,700
Fine aggregate	25,300	27,300	29,200	41,000	41,000	25,300	27,300	29,200	41,000	41,000
Total	**70,700**	**76,200**	**81,600**	**114,600**	**114,600**	**70,700**	**76,200**	**81,600**	**114,600**	**114,600**
CMU concrete										
Cement	0	0	0	0	0	6,500	6,500	6,500	6,500	6,500
Water	0	0	0	0	0	3,100	3,100	3,100	3,100	3,100
ESCS*	0	0	0	0	0	28,400	28,400	28,400	28,400	28,400
Sand	0	0	0	0	0	14,700	14,700	14,700	14,700	14,700
Total	**0**	**0**	**0**	**0**	**0**	**52,700**	**52,700**	**52,700**	**52,700**	**52,700**
Mortar										
Cement	0	0	0	0	0	6,300	6,300	6,300	6,300	6,300
Water	0	0	0	0	0	3,700	3,700	3,700	3,700	3,700
Fine aggregate	0	0	0	0	0	24,400	24,400	24,400	24,400	24,400
Lime	0	0	0	0	0	1,400	1,400	1,400	1,400	1,400
Total	**0**	**0**	**0**	**0**	**0**	**35,800**	**35,800**	**35,800**	**35,800**	**35,800**
Grout										
Cement	0	0	0	0	0	800	800	800	800	800
Water	0	0	0	0	0	400	400	400	400	400
Fine aggregate	0	0	0	0	0	2,600	2,600	2,600	2,600	2,600
Lime	0	0	0	0	0	100	100	100	100	100
Total	**0**	**0**	**0**	**0**	**0**	**3,900**	**3,900**	**3,900**	**3,900**	**3,900**
Stucco										
Cement	0	0	0	0	0	4,200	4,200	4,200	4,200	4,200
Water	0	0	0	0	0	2,500	2,500	2,500	2,500	2,500
Fine aggregate	0	0	0	0	0	16,200	16,200	16,200	16,200	16,200
Lime	0	0	0	0	0	1,000	1,000	1,000	1,000	1,000
Total	**0**	**0**	**0**	**0**	**0**	**23,900**	**23,900**	**23,900**	**23,900**	**23,900**

*ESCS is lightweight aggregate and consists of expanded shale, clay, or slate.

Table 5-2B. Material Input for Concrete and Other Cement-Based Materials – U.S. Customary Units

	Wood frame house					Lightweight CMU house				
Material, lb	**Tampa**	**El Paso**	**Knoxville**	**Providence**	**Detroit**	**Tampa**	**El Paso**	**Knoxville**	**Providence**	**Detroit**
Ready-mixed concrete										
Cement	15,000	16,100	17,300	24,300	24,300	15,000	16,100	17,300	24,300	24,300
Water	9,400	10,200	10,900	15,300	15,300	9,400	10,200	10,900	15,300	15,300
Coarse aggregate	75,600	81,500	87,400	122,800	122,800	75,600	81,500	87,400	122,800	122,800
Fine aggregate	55,700	60,100	64,400	90,500	90,500	55,700	60,100	64,400	90,500	90,500
Total	**155,700**	**167,900**	**180,000**	**252,900**	**252,900**	**155,700**	**167,900**	**180,000**	**252,900**	**252,900**
Lightweight CMU concrete										
Cement	0	0	0	0	0	14,400	14,400	14,400	14,400	14,400
Water	0	0	0	0	0	6,800	6,800	6,800	6,800	6,800
ESCS	0	0	0	0	0	62,700	62,700	62,700	62,700	62,700
Sand	0	0	0	0	0	32,500	32,500	32,500	32,500	32,500
Total	**0**	**0**	**0**	**0**	**0**	**116,400**	**116,400**	**116,400**	**116,400**	**116,400**
Mortar										
Cement	0	0	0	0	0	13,900	13,900	13,900	13,900	13,900
Water	0	0	0	0	0	8,200	8,200	8,200	8,200	8,200
Fine aggregate	0	0	0	0	0	53,800	53,800	53,800	53,800	53,800
Lime	0	0	0	0	0	3,200	3,200	3,200	3,200	3,200
Total	**0**	**0**	**0**	**0**	**0**	**79,100**	**79,100**	**79,100**	**79,100**	**79,100**
Grout										
Cement	0	0	0	0	0	1,800	1,800	1,800	1,800	1,800
Water	0	0	0	0	0	1,000	1,000	1,000	1,000	1,000
Fine aggregate	0	0	0	0	0	5,700	5,700	5,700	5,700	5,700
Lime	0	0	0	0	0	200	200	200	200	200
Total	**0**	**0**	**0**	**0**	**0**	**8,700**	**8,700**	**8,700**	**8,700**	**8,700**
Stucco										
Cement	0	0	0	0	0	9,200	9,200	9,200	9,200	9,200
Water	0	0	0	0	0	5,400	5,400	5,400	5,400	5,400
Fine aggregate	0	0	0	0	0	35,600	35,600	35,600	35,600	35,600
Lime	0	0	0	0	0	2,100	2,100	2,100	2,100	2,100
Total	**0**	**0**	**0**	**0**	**0**	**52,300**	**52,300**	**52,300**	**52,300**	**52,300**

*ESCS is lightweight aggregate and consists of expanded shale, clay, or slate.

Table 5-3A. Mix Design for 21 MPa Ready-Mixed Concrete and Lightweight CMU Concrete, Mortar, Grout, and Stucco – SI Units*

	Ready-mixed concrete 21 MPa	Lightweight CMU concrete	Mortar	Grout	Stucco
Raw material	**kg/m^3 concrete**	**kg/m^3 concrete**	**kg/m^3 mortar**	**kg/m^3 grout**	**kg/m^3 stucco**
Cement	223	190	352	416	352
Water	141	89	208	224	208
Coarse aggregate	1,127	825**	not applicable	not applicable	not applicable
Fine aggregate	831	427	1,362	1,314	1,362
Lime	not applicable	not applicable	80	48	80
Total	**2,321**	**1,531**	**2,002**	**2,002**	**2,002**

*Concrete mix designs vary. These ones have been chosen because they are representative of residential concrete.
**Coarse aggregate in this case is lightweight aggregate and consists of expanded shale, clay, and slate.

Table 5-3B. Mix Design for 3,000 psi Ready-Mixed Concrete and Lightweight CMU Concrete, Mortar, Grout, and Stucco – U.S. Customary Units*

	Ready-mixed concrete 3,000 psi	Lightweight CMU concrete	Mortar	Grout	Stucco
Raw material	**lb/yd^3 concrete**	**lb/yd^3 concrete**	**lb/yd^3 mortar**	**lb/yd^3 grout**	**lb/yd^3 stucco**
Cement	376	320	594	702	594
Water	237	150	351	378	351
Coarse aggregate	1,900	1390**	not applicable	not applicable	not applicable
Fine aggregate	1,400	720	2,295	2,214	2,295
Lime	not applicable	not applicable	135	81	135
Total	**3,913**	**2,580**	**3,375**	**3,375**	**3,375**

*Concrete mix designs vary. These ones have been chosen because they are representative of residential concrete.
**Coarse aggregate in this case is lightweight aggregate and consists of expanded shale, clay, and slate.

Table 5-4A. 100-Year Life Cycle Energy Use – SI Units*

	Wood frame house					Lightweight CMU house				
	Tampa	El Paso	Knoxville	Providence	Detroit	Tampa	El Paso	Knoxville	Providence	Detroit
Diesel fuel, L**										
Transportation to house	264	275	286	352	352	460	471	482	548	548
Transportation to landfill	264	275	286	352	352	460	471	482	548	548
Energy, GJ										
Transportation to house	10	11	11	14	14	18	18	19	21	21
Embodied in concrete	52	56	60	84	84	52	56	60	84	84
Embodied in ltwt. CMUs	0	0	0	0	0	128	128	128	128	128
Embodied in mortar	0	0	0	0	0	38	38	38	38	38
Embodied in grout	0	0	0	0	0	5	5	5	5	5
Embodied in stucco	0	0	0	0	0	25	25	25	25	25
Occupant use	11,620	15,780	17,790	23,940	26,180	11,730	15,060	17,000	23,040	25,220
Transportation to landfill	10	11	11	14	14	18	18	19	21	21
Total (rounded)	**11,700**	**15,900**	**17,900**	**24,100**	**26,300**	**12,000**	**15,300**	**17,300**	**23,400**	**25,500**

*Does not include upstream profiles of electricity, fuel, or materials other than cement-based products. Fiber-cement backer board is also not included.

**Heating value of diesel fuel: 0.038 GJ/L.

Table 5-4B. 100-Year Life Cycle Energy Use – U.S. Customary Units*

	Wood frame house					Lightweight CMU house				
	Tampa	**El Paso**	**Knoxville**	**Providence**	**Detroit**	**Tampa**	**El Paso**	**Knoxville**	**Providence**	**Detroit**
Diesel fuel, gallon**										
Transportation to house	70	73	75	93	93	121	125	127	145	145
Transportation to landfill	70	73	75	93	93	121	125	127	145	145
Energy, MBtu										
Transportation to house	10	10	10	13	13	17	17	18	20	20
Embodied in concrete	49	53	57	80	80	49	53	57	80	80
Embodied in ltwt. CMUs	0	0	0	0	0	121	121	121	121	121
Embodied in mortar	0	0	0	0	0	36	36	36	36	36
Embodied in grout	0	0	0	0	0	5	5	5	5	5
Embodied in stucco	0	0	0	0	0	24	24	24	24	24
Occupant use	11,014	14,957	16,862	22,691	24,814	11,118	14,274	16,113	21,838	23,904
Transportation to landfill	10	10	10	13	13	17	17	18	20	20
Total (rounded)	**11,100**	**15,000**	**16,900**	**22,800**	**24,900**	**11,400**	**14,500**	**16,400**	**22,100**	**24,200**

*Does not include upstream profiles of electricity, fuel, or materials other than cement-based products. Fiber-cement backer board is also not included.

**Heating value of diesel fuel: 0.138 MBtu/gallon.

5.2.2. Concrete embodied energy

Table 5-4 also shows the embodied energy of concrete and other cement-based products in each house in each city. The embodied energy includes energy and emissions form the transportation of primary materials from their source to the cement plant, the ready-mixed concrete plant, and the lightweight CMU plant. It also includes the energy and emissions from operations at cement, ready-mixed concrete, and lightweight CMU plants. It does not include upstream profiles of fuels or electricity. The embodied energy of the cement-based materials in the house is directly related to the amount of cement-based materials used in the house. Although cement makes up less than 10% by weight of concrete, about 70% of the energy embodied in concrete is consumed in the cement manufacturing process.[4] Similarly, although the cement content of lightweight CMUs is about 10% by weight, 30% of the energy content is from the manufacture of cement and 60% is from the production of lightweight aggregate.

5.2.3. Household occupant energy-use

Energy simulation software is used to model the annual household energy consumption.[8] This software uses the United States Department of Energy DOE 2.1-E hourly simulation tool as the calculation engine. It is used to simulate hourly energy use and peak demand over a one-year period. Because heating and cooling load vary with solar orientation, the house is modeled four times: once for each orientation of the façade facing the four cardinal points (north, south, east, and west). Then the total energy consumption for heating, cooling, water heating, and occupant use is averaged to obtain energy consumption that is independent of building orientation. The annual occupant energy-use is presented in Table 5-5. Results for the 100-year life were presented earlier in Table 5-4.

Table 5-5. Annual Occupant Energy-Use by Location

Location	Variation	Annual operating data				
		Electricity		Natural gas		Total energy, GJ
		GJ	kWh	GJ	Therms	
Tampa	Wood frame	56.4	15,664	59.8	567	116.2
	Lightweight CMU	56.6	15,712	60.7	576	117.3
El Paso	Wood frame	54.0	14,987	103.9	985	157.8
	Lightweight CMU	51.7	14,367	98.9	938	150.6
Knoxville	Wood frame	44.1	12,249	133.9	1,269	177.9
	Lightweight CMU	42.3	11,758	127.6	1,210	170.0
Providence	Wood frame	39.4	10,946	200.0	1,896	239.4
	Lightweight CMU	38.3	10,650	192.0	1,821	230.4
Detroit	Wood frame	39.5	10,985	222.2	2,107	261.8
	Lightweight CMU	38.6	10,712	213.6	2,025	252.2

The data presented in Table 5-5 show that the lightweight CMU house has similar occupant energy use as the wood frame house. This is primarily because both the lightweight CMU house and the wood frame house were modeled with standard materials needed to meet IECC requirements. Wood frame walls have R-values that range from approximately 5 to 140% in excess of IECC requirements, while lightweight CMU walls have R-values that range from approximately 0 to 90% in excess of IECC requirements.

Results also show that the energy required for heating, ventilating, and air-conditioning is less for the lightweight CMU house than for the wood frame house. Table 5-6 shows the HVAC system requirements as determined by the energy simulation software. The thermal mass of the lightweight CMU house moderates temperature swings and peak loads, and results in lower HVAC system requirements.

Table 5-6. Required HVAC System Capacity as Determined by Energy Simulation Software

Location	Variation	System capacity			
		Heating		Cooling	
		kW	kBtu/hr	kW	kBtu/hr
Tampa	Wood frame	25	84	13	43
	Lightweight CMU	23	79	12	40
El Paso	Wood frame	29	99	15	52
	Lightweight CMU	25	86	13	46
Knoxville	Wood frame	26	89	13	45
	Lightweight CMU	23	77	11	39
Providence	Wood frame	26	89	13	46
	Lightweight CMU	23	78	12	40
Detroit	Wood frame	26	88	13	45
	Lightweight CMU	23	78	12	41

Natural gas fired high-efficiency forced-air furnaces are typically available in 20 kBtu/hr capacity increments (equivalent to 5.9 kW) and high-efficiency central air conditioners are typically available in 6 to 12 kBtu/hr (½ to 1 ton) capacity increments (½ to 1 ton is equivalent to 1.8 to 3.5 kW). Because HVAC systems are typically oversized (the installed capacity is the required capacity rounded to the next larger available capacity), actual installed system capacity savings will be different.

5.2.4. Maintenance, repair, and replacement

The materials used for maintenance, repair, and replacement are included in the house materials list in Table C-1, Appendix C. Most of the energy used in maintenance, repair, and replacement is used to transport materials from their place of origin to the house. This transportation energy is included in the transportation values in Table 5-4.

5.2.5. Demolition and disposal

The energy used in demolition and disposal is similar to that used in excavation and construction. The energy used to demolish the house is assumed to be less than 1% of the life-cycle energy and is therefore not included in the LCI. Most of the energy is used to transport materials from the house to the landfill. All material is assumed to be transported by tractor-trailers using diesel fuel and traveling on paved roads. The average haul distance is assumed to be 80 kilometers (50 miles) for all material. The energy consumption of 1,060 joules per kilogram-kilometer (1,465 Btu per ton-mile) assumes that transportation energy efficiency is 24 liters of diesel fuel per 1,000 metric ton-kilometers (9.4 gallons of diesel fuel per 1,000 ton-miles).[14] Disposal energy is listed as transportation to landfill in Table 5-4. This partial LCI does not consider energy used in return trips when the tractor-trailer is empty.

5.2.6. Total energy inputs

Table 5-7 shows a summary of the life cycle energy of each house. This partial LCI includes the embodied energy of ready-mixed concrete, lightweight CMU concrete, and other cement-based materials. It does not include the embodied energy of other building materials, such as wood, steel, and plastic. These upstream profiles will be added to the LCI once a suitable database is found. Table D-1 in Appendix D shows the life cycle fuel and electricity use in more detail.

Table 5-7 shows that occupant energy-use is 99% of the total embodied energy. This means that the house life cycle energy is not sensitive to variations in cement manufacturing, ready-mixed concrete production, lightweight CMU production, nor transportation. The house life cycle energy is primarily a function of climate and occupant behavior. Figure 5-1 shows the life cycle energy-use profile of the wood frame house and the lightweight CMU house in Detroit. It shows that after 11 years, the cumulative energy use of the wood frame house exceeds that of the lightweight CMU house.

5.3. Material outputs

The life cycle material outputs from the house are made up of the material outputs from excavation; construction; occupancy; maintenance, repair, and replacement; demolition; and disposal. The material outputs are emissions to air and solid waste. The PCA intends to include the upstream profiles of other materials, such as wood and steel, and fuels, such as coal and electricity, once a suitable database is found. Furthermore, water usage from upstream profiles and from household occupant use will also be included.

5.3.1. Emissions to air

The partial house LCI includes emissions to air of greenhouse gases and the most common air pollutants as defined by United Sates Environmental Protection Agency.[15] These emissions consist of particulate matter from point and fugitive sources and the following combustion gases: carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), volatile organic compounds (VOC), and methane (CH_4). Hazardous air pollutants, such as hydrogen chloride, mercury, dioxins, and furans, are excluded from the house LCI because there is insufficient information to accurately quantify their emissions from the manufacture of cement.

Table 5-7A. Energy Summary for 100-Year Life Cycle – SI Units*

	Wood frame house					Lightweight CMU house				
	Tampa	El Paso	Knoxville	Providence	Detroit	Tampa	El Paso	Knoxville	Providence	Detroit
Energy, GJ										
Transportation to house	10	11	11	14	14	18	18	19	21	21
Embodied in concrete	52	56	60	84	84	52	56	60	84	84
Embodied in ltwt. CMUs	0	0	0	0	0	128	128	128	128	128
Embodied in mortar	0	0	0	0	0	38	38	38	38	38
Embodied in grout	0	0	0	0	0	5	5	5	5	5
Embodied in stucco	0	0	0	0	0	25	25	25	25	25
Occupant use	11,620	15,780	17,790	23,940	26,180	11,730	15,060	17,000	23,040	25,220
Transportation to landfill	10	11	11	14	14	18	18	19	21	21
Total (rounded)	**11,700**	**15,900**	**17,900**	**24,100**	**26,300**	**12,000**	**15,300**	**17,300**	**23,400**	**25,500**
Percent of total energy use, %										
Transportation to house	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Embodied in concrete	0.4	0.4	0.3	0.3	0.3	0.4	0.4	0.3	0.4	0.3
Embodied in ltwt. CMUs	0	0	0	0	0	1.1	0.8	0.7	0.5	0.5
Embodied in mortar	0.0	0.0	0.0	0.0	0.0	0.3	0.2	0.2	0.2	0.1
Embodied in grout	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Embodied in stucco	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.1	0.1	0.1
Occupant use	99.3	99.2	99.4	99.3	99.5	97.8	98.4	98.3	98.5	98.9
Transportation to landfill	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

*Does not include upstream profiles of electricity, fuels, or materials other than cement-based products.

Table 5-7B. Energy Summary for 100-Year Life Cycle – U.S. Customary Units*

	Wood frame house					Lightweight CMU house				
	Tampa	El Paso	Knoxville	Providence	Detroit	Tampa	El Paso	Knoxville	Providence	Detroit
Energy, MBtu										
Transportation to house	10	10	10	13	13	17	17	18	20	20
Embodied in concrete	49	53	57	80	80	49	53	57	80	80
Embodied in ltwt. CMUs	0	0	0	0	0	121	121	121	121	121
Embodied in mortar	0	0	0	0	0	36	36	36	36	36
Embodied in grout	0	0	0	0	0	5	5	5	5	5
Embodied in stucco	0	0	0	0	0	24	24	24	24	24
Occupant use	11,014	14,957	16,862	22,691	24,814	11,118	14,274	16,113	21,838	23,904
Transportation to landfill	10	10	10	13	13	17	17	18	20	20
Total (rounded)	**11,100**	**15,000**	**16,900**	**22,800**	**24,900**	**11,400**	**14,500**	**16,400**	**22,100**	**24,200**
Percent of total energy use, %										
Transportation to house	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Embodied in concrete	0.4	0.4	0.3	0.4	0.3	0.4	0.4	0.3	0.4	0.3
Embodied in ltwt. CMUs	0	0	0	0	0	1.1	0.8	0.7	0.5	0.5
Embodied in mortar	0.0	0.0	0.0	0.0	0.0	0.3	0.2	0.2	0.2	0.1
Embodied in grout	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Embodied in stucco	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.1	0.1	0.1
Occupant use	99.2	99.7	99.8	99.5	99.7	97.5	98.4	98.2	98.8	98.8
Transportation to landfill	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

*Does not include upstream profiles of electricity, fuels, or materials other than cement-based products.

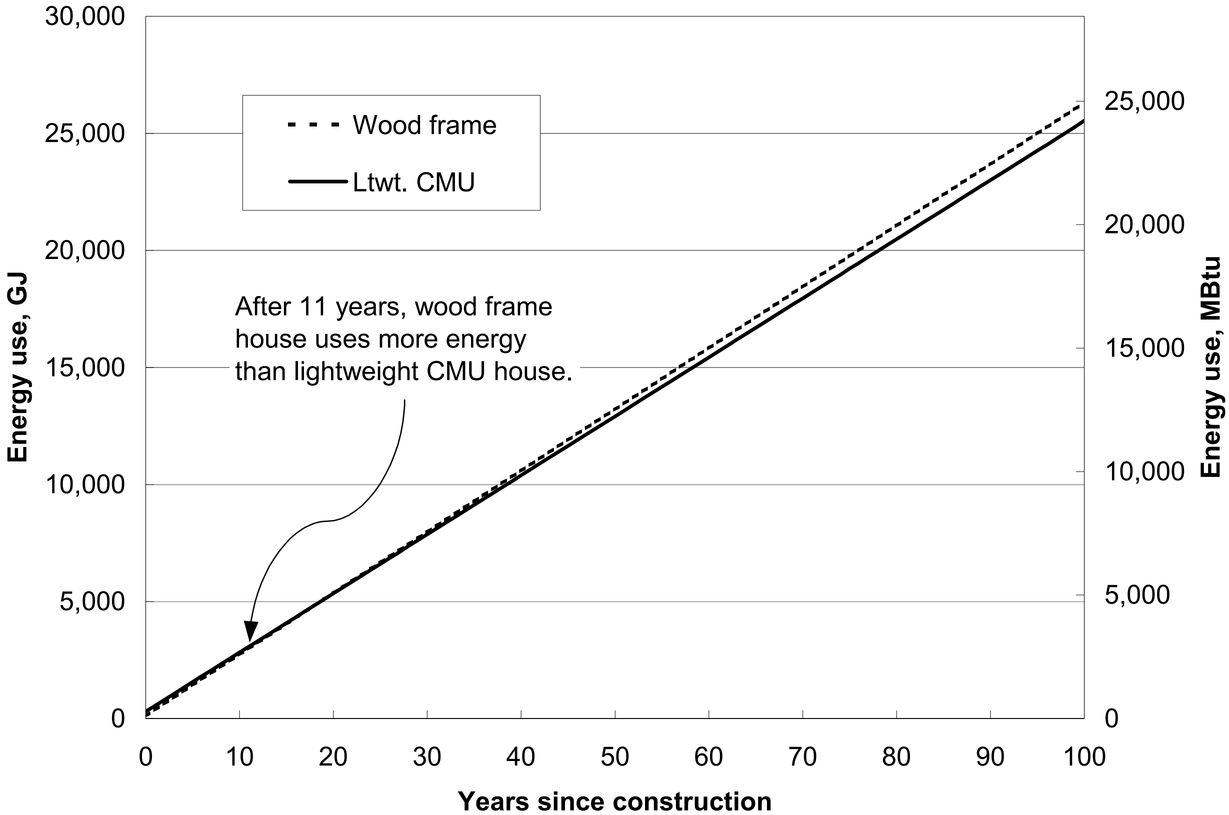

Figure 5-1. Cumulative life cycle energy use of wood frame house and lightweight CMU house in Detroit over 100 years. (Does not include upstream profiles of electricity, fuels, or other construction materials other than cement-based products.)

Most of the house life cycle emissions are from the two natural gas burning appliances (furnace and water heater). Table 5-8 shows the emissions associated with the production of the cement-based components of the house, and Table 5-9 shows the emissions from the operation of the natural gas appliances. Table 5-10 shows the emissions from transportation of materials from their place of origin to the house site and from the house site to the landfill for disposal. Table 5-11 shows the total life cycle emissions of each house. These emissions include the emissions from (i) the manufacture of cement, (ii) the production of concrete, lightweight CMUs, mortar, grout, and stucco, (iii) the operation of the two natural gas burning appliances (furnace and water heater), and (iv) the transportation of materials to and from the house. This LCI does not include the emissions from the manufacture of other building materials, such as wood, steel, and plastic. Nor does it include the upstream profiles for fuels and electricity. These upstream profiles will be added to the LCI once a suitable database is found.

The cement-based components of a lightweight CMU house represents approximately 75% of the total particulate matter released to the air. The cement-based components of a wood frame house represent approximately 50% of the total particulate matter released to the air.

The production of the cement-based components of the lightweight CMU house accounts for 3 to 9% of the total CO_2 emissions throughout the life of the house. The production of the cement-based components of the wood frame house accounts for 1 to 2% of the total CO_2

Table 5-8A. Emissions from Upstream Profiles of Concrete and Other Cement-Based Materials – SI Units

	Wood frame house					Lightweight CMU house				
Emission, kg	**Tampa**	**El Paso**	**Knoxville**	**Providence**	**Detroit**	**Tampa**	**El Paso**	**Knoxville**	**Providence**	**Detroit**
Ready-mixed concrete										
Particulate matter	33	35	38	53	53	33	35	38	53	53
CO_2	6,890	7,420	7,960	11,180	11,180	6,890	7,420	7,960	11,180	11,180
SO_2	30	32	34	48	48	30	32	34	48	48
NO_x	28	31	33	46	46	28	31	33	46	46
VOC	1	1	1	2	2	1	1	1	2	2
CO	4	5	5	7	7	4	5	5	7	7
CH_4	0	1	1	1	1	0	1	1	1	1
CMU concrete										
Particulate matter	0	0	0	0	0	49	49	49	49	49
CO_2	0	0	0	0	0	12,480	12,480	12,480	12,480	12,480
SO_2	0	0	0	0	0	82	82	82	82	82
NO_x	0	0	0	0	0	58	58	58	58	58
VOC	0	0	0	0	0	12	12	12	12	12
CO	0	0	0	0	0	4	4	4	4	4
CH_4	0	0	0	0	0	1	1	1	1	1
Mortar										
Particulate matter	0	0	0	0	0	21	21	21	21	21
CO_2	0	0	0	0	0	5,830	5,830	5,830	5,830	5,830
SO_2	0	0	0	0	0	25	25	25	25	25
NO_x	0	0	0	0	0	24	24	24	24	24
VOC	0	0	0	0	0	1	1	1	1	1
CO	0	0	0	0	0	2	2	2	2	2
CH_4	0	0	0	0	0	0	0	0	0	0
Grout										
Particulate matter	0	0	0	0	0	3	3	3	3	3
CO_2	0	0	0	0	0	750	750	750	750	750
SO_2	0	0	0	0	0	3	3	3	3	3
NO_x	0	0	0	0	0	3	3	3	3	3
VOC	0	0	0	0	0	0	0	0	0	0
CO	0	0	0	0	0	0	0	0	0	0
CH_4	0	0	0	0	0	0	0	0	0	0
Stucco										
Particulate matter	0	0	0	0	0	14	14	14	14	14
CO_2	0	0	0	0	0	3,860	3,860	3,860	3,860	3,860
SO_2	0	0	0	0	0	17	17	17	17	17
NO_x	0	0	0	0	0	16	16	16	16	16
VOC	0	0	0	0	0	0	0	0	0	0
CO	0	0	0	0	0	2	2	2	2	2
CH_4	0	0	0	0	0	0	0	0	0	0

Table 5-8B. Emissions from Upstream Profiles of Concrete and Other Cement-Based Materials – U.S. Customary Units

	Wood frame house					Lightweight CMU house				
Emission, lb	Tampa	El Paso	Knoxville	Providence	Detroit	Tampa	El Paso	Knoxville	Providence	Detroit
Ready-mixed concrete										
Particulate matter	72	77	83	117	117	72	77	83	117	117
CO_2	15,190	16,370	17,550	24,650	24,650	15,190	16,370	17,550	24,650	24,650
SO_2	65	71	76	106	106	65	71	76	106	106
NO_x	63	67	72	102	102	63	67	72	102	102
VOC	2	3	3	4	4	2	3	3	4	4
CO	10	11	11	16	16	10	11	11	16	16
CH_4	1	1	1	2	2	1	1	1	2	2
CMU concrete										
Particulate matter	0	0	0	0	0	108	108	108	108	108
CO_2	0	0	0	0	0	27,520	27,520	27,520	27,520	27,520
SO_2	0	0	0	0	0	182	182	182	182	182
NO_x	0	0	0	0	0	128	128	128	128	128
VOC	0	0	0	0	0	28	28	28	28	28
CO	0	0	0	0	0	8	8	8	8	8
CH_4	0	0	0	0	0	1	1	1	1	1
Mortar										
Particulate matter	0	0	0	0	0	46	46	46	46	46
CO_2	0	0	0	0	0	12,852	12,852	12,852	12,852	12,852
SO_2	0	0	0	0	0	55	55	55	55	55
NO_x	0	0	0	0	0	54	54	54	54	54
VOC	0	0	0	0	0	2	2	2	2	2
CO	0	0	0	0	0	5	5	5	5	5
CH_4	0	0	0	0	0	1	1	1	1	1
Grout										
Particulate matter	0	0	0	0	0	6	6	6	6	6
CO_2	0	0	0	0	0	1,654	1,654	1,654	1,654	1,654
SO_2	0	0	0	0	0	7	7	7	7	7
NO_x	0	0	0	0	0	7	7	7	7	7
VOC	0	0	0	0	0	0	0	0	0	0
CO	0	0	0	0	0	1	1	1	1	1
CH_4	0	0	0	0	0	0	0	0	0	0
Stucco										
Particulate matter	0	0	0	0	0	30	30	30	30	30
CO_2	0	0	0	0	0	8,510	8,510	8,510	8,510	8,510
SO_2	0	0	0	0	0	36	36	36	36	36
NO_x	0	0	0	0	0	36	36	36	36	36
VOC	0	0	0	0	0	1	1	1	1	1
CO	0	0	0	0	0	4	4	4	4	4
CH_4	0	0	0	0	0	1	1	1	1	1

Table 5-9A. Combustion Emissions from Occupant Use of Natural Gas – SI Units

	Wood frame house					Lightweight CMU house				
	Tampa	El Paso	Knoxville	Providence	Detroit	Tampa	El Paso	Knoxville	Providence	Detroit
Natural gas, GJ:	5,980	10,390	13,390	20,000	22,220	6,070	9,890	12,760	19,200	21,360
Emission, kg										
Particulate matter	19	33	43	64	71	19	32	41	61	68
CO_2	302,000	525,000	677,000	1,011,000	1,123,000	307,000	500,000	645,000	970,000	1,080,000
SO_2	2	3	3	5	6	2	2	3	5	5
NO_x	237	411	530	792	880	240	392	505	760	846
VOC	14	24	31	46	51	14	23	30	44	49
CO	101	175	226	337	374	102	167	215	323	360
CH_4	6	10	13	19	22	6	10	12	19	21

*Natural gas burned in furnace and water heater.
Source: Reference 16.

Table 5-9B. Combustion Emissions from Occupant Use of Natural Gas – U.S. Customary Units

	Wood frame house					Lightweight CMU house				
	Tampa	El Paso	Knoxville	Providence	Detroit	Tampa	El Paso	Knoxville	Providence	Detroit
Natural gas*, therms:	56,700	98,500	126,900	189,600	210,700	57,600	93,800	121,000	182,100	202,500
Natural gas*, MBtu:	5,670	9,850	12,690	18,960	21,070	5,760	9,380	12,100	18,210	20,250
Emission, lb										
Particulate matter	42	73	95	141	157	43	70	90	136	151
CO_2	667,000	1,159,000	1,493,000	2,231,000	2,479,000	678,000	1,104,000	1,424,000	2,142,000	2,382,000
SO_2	3	6	7	11	12	3	6	7	11	12
NO_x	523	908	1,169	1,747	1,942	531	864	1,115	1,678	1,866
VOC	31	53	68	102	114	31	51	65	98	109
CO	222	386	498	744	826	226	368	475	714	794
CH_4	13	22	29	43	48	13	21	27	41	46

*Natural gas burned in furnace and water heater.
Source: Reference 16.

Table 5-10A. Transportation Emissions from Transporting Materials to and from House Site – SI Units

	Wood frame house					Lightweight CMU house				
	Tampa	El Paso	Knoxville	Providence	Detroit	Tampa	El Paso	Knoxville	Providence	Detroit
Emission, kg										
Particulate matter	2	2	2	3	3	3	3	3	4	4
CO_2	1,440	1,500	1,560	1,920	1,920	2,510	2,580	2,640	3,000	3,000
SO_2	2	2	2	3	3	4	4	4	5	5
NO_x	13	14	14	18	18	23	24	24	28	28
VOC	2	2	3	3	3	4	4	4	5	5
CO	13	14	14	18	18	23	24	24	27	27
CH_4	0	0	0	1	1	1	1	1	1	1

*Fuel efficiency is 24 liters of diesel fuel per 1000 metric ton-kilometers.
Source: Reference 14.

Table 5-10B. Transportation Emissions from Transporting Materials to and from House Site – U.S. Customary Units

	Wood frame house					Lightweight CMU house				
	Tampa	El Paso	Knoxville	Providence	Detroit	Tampa	El Paso	Knoxville	Providence	Detroit
Emission, lb										
Particulate matter	4	4	4	6	6	7	7	8	9	9
CO_2	3,180	3,310	3,440	4,240	4,240	5,540	5,680	5,810	6,610	6,610
SO_2	5	5	5	7	7	9	9	9	10	10
NO_x	29	30	32	39	39	51	52	54	61	61
VOC	5	5	6	7	7	9	9	10	11	11
CO	29	30	32	39	39	51	52	53	61	61
CH_4	1	1	1	1	1	2	2	2	2	2

*Fuel efficiency is 9.4 of gallon diesel fuel per 1000 ton miles.
Source: Reference 14.

Table 5-11A. Summary of 100-Year Life Cycle Emissions – SI Units*

	Wood frame house					Lightweight CMU house				
	Tampa	El Paso	Knoxville	Providence	Detroit	Tampa	El Paso	Knoxville	Providence	Detroit
Emission, kg										
Particulate matter	54	70	83	119	127	141	156	168	204	211
CO_2	311,000	534,000	686,000	1,024,000	1,136,000	339,000	533,000	678,000	1,007,000	1,117,000
SO_2	33	37	40	56	57	162	166	169	185	185
NO_x	278	456	577	856	943	393	547	664	935	1,021
VOC	17	28	35	51	56	33	42	49	65	70
CO	118	194	245	362	399	138	203	252	366	403
CH_4	7	11	14	21	23	8	12	15	21	24

*Does not include upstream profile of electricity, fuel, or materials other than concrete.

Table 5-11B. Summary of 100-Year Life Cycle Emissions – U.S. Customary Units*

	Wood frame house					Lightweight CMU house				
	Tampa	El Paso	Knoxville	Providence	Detroit	Tampa	El Paso	Knoxville	Providence	Detroit
Emission, lb										
Particulate matter	118	155	182	263	279	311	344	370	450	466
CO_2	685,000	1,179,000	1,514,000	2,259,000	2,508,000	749,000	1,176,000	1,497,000	2,224,000	2,464,000
SO_2	74	82	89	124	125	358	365	372	408	409
NO_x	614	1,006	1,274	1,888	2,082	868	1,208	1,465	2,065	2,253
VOC	38	61	77	113	125	73	93	108	143	154
CO	261	427	541	798	881	304	448	557	809	889
CH_4	15	24	31	46	50	18	27	33	47	52

*Does not include upstream profile of electricity, fuel, or materials other than concrete.

emissions throughout the life of the house. The production of the cement-based components of the lightweight CMU house accounts for approximately 95% of the total SO_2 emissions. The production of the cement-based components of the wood frame house accounts for approximately 85% of the total SO_2 emissions.

Approximately 95% of the CO_2 emissions are from the combustion of natural gas appliances in the lightweight CMU house. Approximately 98% of the CO_2 emissions are from the combustion of natural gas appliances in the wood frame house. Approximately 75% of the NO_x emissions are from the combustion of natural gas appliances in the lightweight CMU house, and approximately 90% of the NO_x emissions are from the combustion of natural gas appliances in the wood frame house. In both houses, natural gas appliances contribute an average of 85 to 90% of the emissions of CO and CH_4. Approximately 60% of the VOC emissions are from the combustion of natural gas appliances in the lightweight CMU house, and 90% of the VOC emissions are from the combustion of natural gas appliances in the wood frame house.

5.3.2. Solid waste

At the end of the 100-year life, the house materials and components can be reused and recycled. However, there is little information on how much building material is reused and recycled from the demolition of a building.[17, 18] So, until reliable data are available, all house materials are assumed to be disposed of in a landfill.

5.4. Energy output

The life cycle energy output from the house is made up of the energy outputs from construction; occupancy; maintenance, repair and replacement; and demolition. The energy output is primarily in the form of waste heat from all of these stages of the life cycle.

Waste heat associated with cement manufacturing is 1.39 megajoules per kilogram of cement (1.19 million Btu per ton of cement).[19] This is heat lost primarily in exhaust gases from the kiln and cooler and also heat lost by radiation from the kiln shell and other hot surfaces. No data are available on waste heat from other stages of producing concrete, lightweight CMUs, mortar, grout, or stucco

Waste heat associated with occupancy is heat lost primarily in exhaust gases from combustion of natural gas and heat loss through the building envelope. There is also energy output in the form of energy loss from the air conditioner. However, no data are available on the waste heat associated with house heating and cooling and other occupant uses. Therefore, energy output is not included in this LCI.

5.5. Sensitivity

The house life cycle energy is not sensitive to variations in the manufacturing process of cement or the production of cement-based materials. Approximately 99% of the house life cycle energy is occupant energy-use, that is, energy for heating, cooling, lighting, washing, and other uses. After climate, occupant behavior is the single most important factor contributing to energy consumption in a home.[20] Approximately 1% of the house life cycle energy is the energy embodied in the cement-based components of the house. Furthermore, about 70% of the energy embodied in ready-mix concrete is from cement manufacturing.[4] Similarly, 30% of the energy embodied in lightweight CMUs is from cement manufacturing and 60% is from the production of lightweight aggregate. Therefore, the house life cycle energy use is a function of climate and occupant behavior, not concrete content.

6. SUMMARY AND CONCLUSIONS

A partial LCI of a wood frame house and a lightweight CMU house has been carried out according to SETAC guidelines and ISO standards 14040 and 14041. The house was modeled in five cities, representing a range of U.S. climates: El Paso, Texas; Tampa, Florida; Knoxville, Tennessee, Providence, Rhode Island; and Detroit, Michigan.

The house is a two-story single-family building with a contemporary design. The house system boundary includes the energy and material inputs and outputs of excavation; construction; occupancy; maintenance, repair, and replacement; demolition; and disposal. The partial LCI is presented in terms of energy use, material use, emissions to air, and solid waste generation over a 100-year life. It also includes the upstream profile of concrete, lightweight CMUs, mortar, grout, stucco, and the masses of other building materials used in the house.

This partial LCI does not include the emissions from the manufacture of other building materials like wood, steel, and plastics. It also does not include the upstream profile of fuel and electricity production and distribution. Furthermore, the LCI does not include inputs that (i) are less than 1% of the total mass of the processed materials or product, (ii) do not contribute significantly to a toxic emission, and (iii) do not have a significant associated energy consumption.

The results show that occupant energy-use accounts for is 99% of life cycle energy use of the lightweight CMU house and the wood frame house. Less than 1% of the life cycle energy is due to manufacturing cement and producing concrete, lightweight CMUs, mortar, grout, and stucco. The house life cycle energy is primarily a function of climate and occupant behavior. Furthermore, although the lightweight CMU house contains more embodied energy than the wood frame house, after 11 years in Detroit, for example, the cumulative energy-use of the wood frame house surpasses that of the lightweight CMU house.

The partial LCI includes emissions to air of greenhouse gases and the most common air pollutants as defined by United Sates Environmental Protection Agency. These emissions consist of particulate matter from point and fugitive sources and the following combustion gases: carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), volatile organic compounds (VOC), and methane (CH_4). Hazardous air pollutants, such as hydrogen chloride, mercury, dioxins, and furans, are excluded from the house LCI because there is insufficient information to accurately quantify their emission from the manufacture of cement.

Most of the life cycle emissions to air are from the two natural gas burning appliances (furnace and water heater). Most of the emissions of CO_2 (95%), NO_x (85%), CO (90%), VOC (75%), and CH_4 (90%) are from the combustion of household natural gas for heating and hot water. Most of the particulate matter (60%) and SO_2 emissions (95%) are from the production of concrete, lightweight CMUs, mortar, grout, and stucco.

In the next phase of the project, PCA will include the upstream profiles of other materials, such as wood and steel, and fuels, such as coal and electricity, in the house LCI. The ultimate goal is to use the LCI data to conduct a life cycle assessment (LCA) of the wood frame house and lightweight CMU house. The LCA will quantify the impacts of concrete products on the environment, such as climate change, acidification, nutrification, natural resource depletion, risks to human health, and other ecological consequences.

7. ACKNOWLEDGEMENT

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APPENDIX A – TARGET AUDIENCES AND INFORMATION TO BE COMMUNICATED

This report is one of many for the Environmental Life Cycle Assessment (LCA) of Portland Cement Concrete project sponsored by the Portland Cement Association.

The objectives of publishing reports and disseminating information are to:

- Determine the environmental life cycle benefits associated with the use of these products.
- Produce comparisons of concrete and other building materials.
- Provide information about these benefits to manufacturers and users of these products.
- Provide life cycle inventory (LCI) and LCA information to practitioners and others, such as data base providers in need of accurate data on cement and concrete.

The contents of the reports will provide information for the following audiences:

- Members of the Portland Cement Association (PCA) and other organizations that promote the use of cement and concrete, generally called "allied industries."
- Members of the Environmental Council of Concrete Organizations (ECCO).
- LCA practitioners and database developers.
- Engineers, architects, and designers.
- Public agencies (Departments of Transportation [DOTs], Energy Star, Environmentally Preferable Purchasing Program).
- General public.

The report formats are not particularly suited for all audiences. The reports are intended to document the particular partial LCI, LCI, or LCA. They provide data in a transparent, traceable format for documentation purposes. The intent is that abbreviated papers, brochures, data packages, presentations, or press releases can be developed from the project reports. The materials presenting the results of this project will be matched, in form and format, to the needs of the target audience. The materials have been categorized as follows:

- General Information:
  - Purpose of life cycle assessments (LCAs) and how they are done.
  - Limited life cycle results of portland cement concrete products from production through use to demolition and recycling.
- Summary Results:
  - Presentation of selected life cycle inventory (LCI) data in the form of summary information, bar charts or other diagrams; for example PowerPoint™ presentations.
  - Published papers or articles.
- Detailed Results:
  - LCI results for databases or LCA models, such as BEES or Athena.
  - Description of the LCI methodology used in the project and specific assumptions, information sources/references, and detailed results.

APPENDIX B – HOUSE PLANS AND WALL CROSS SECTIONS

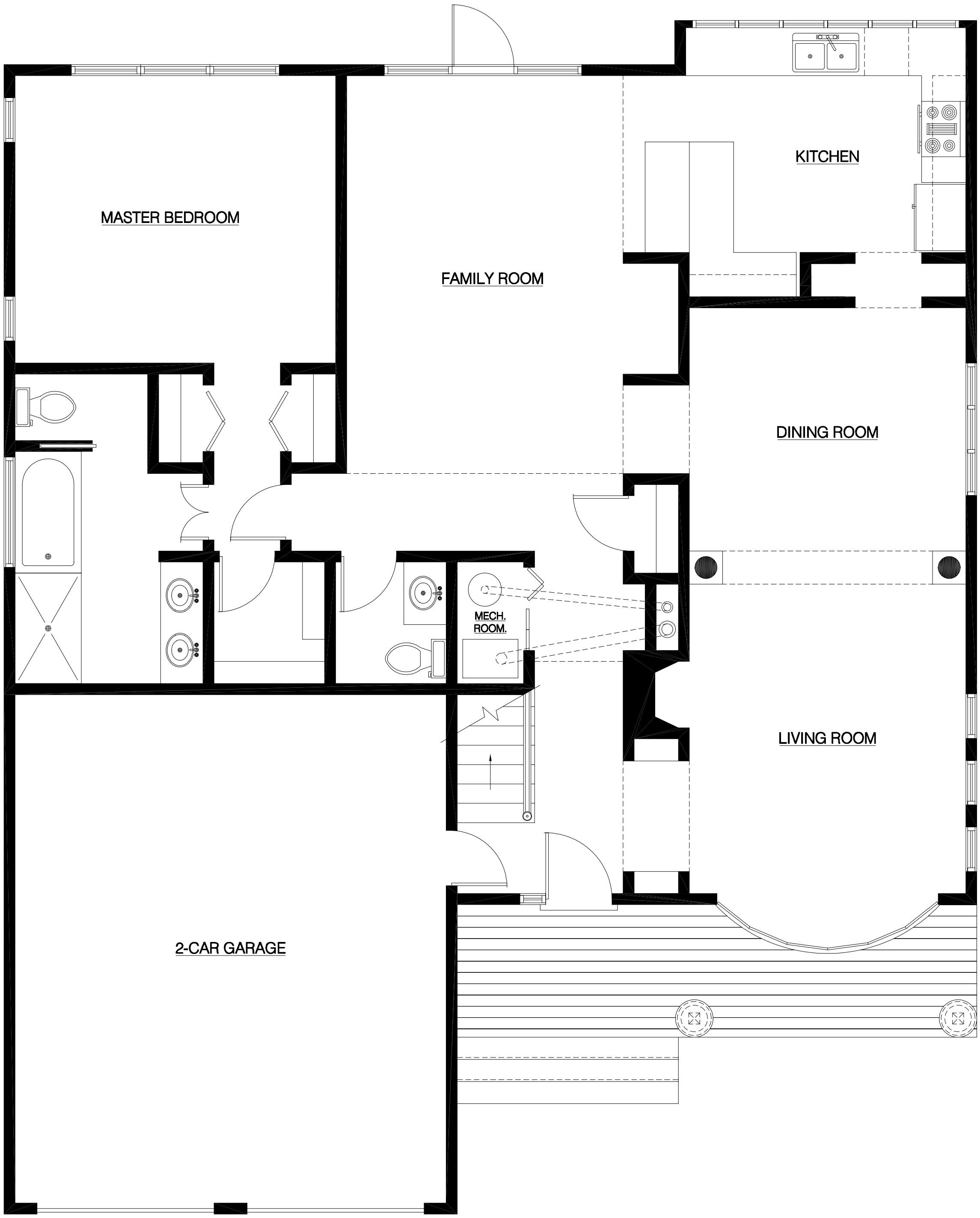

Figure B-1. Floor plan of the lower level.

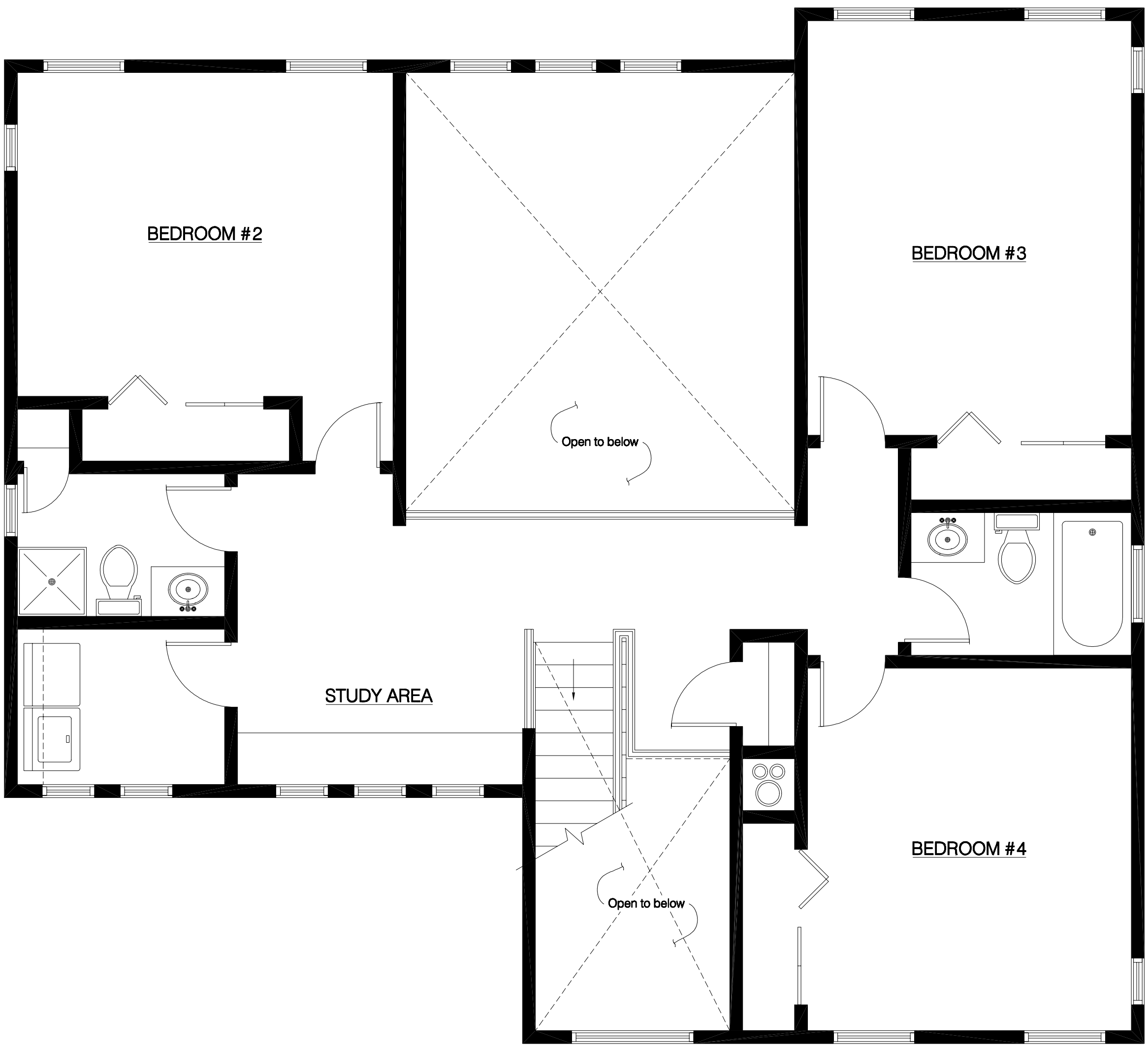

Figure B-2. Floor plan of the upper level.

Figure B-3. Front elevation.

Figure B-4. Rear elevation.

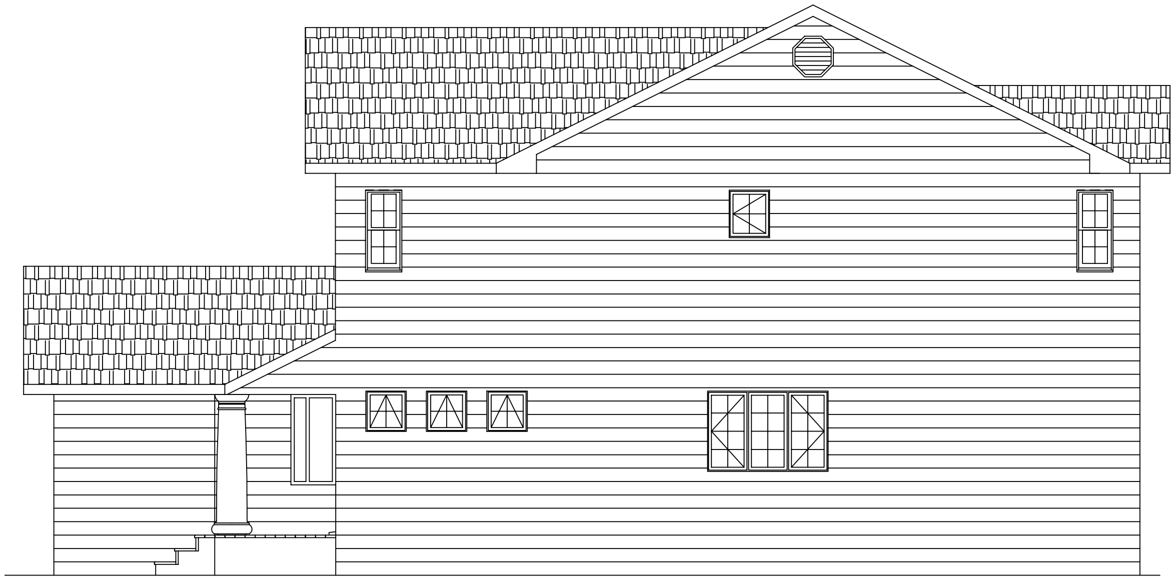

Figure B-5. Right elevation.

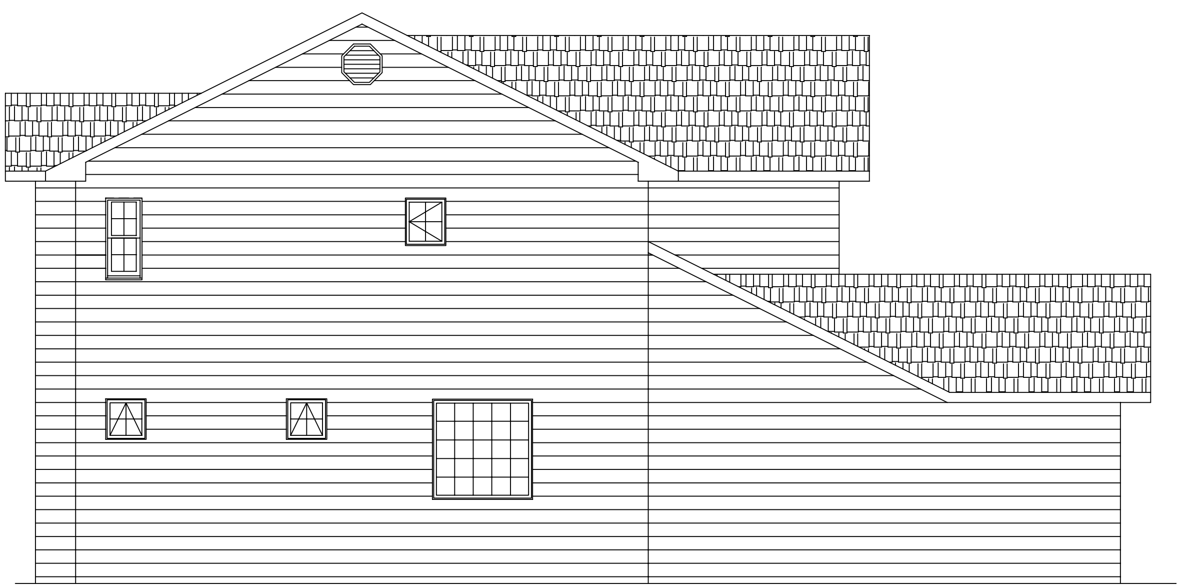

Figure B-6. Left elevation.

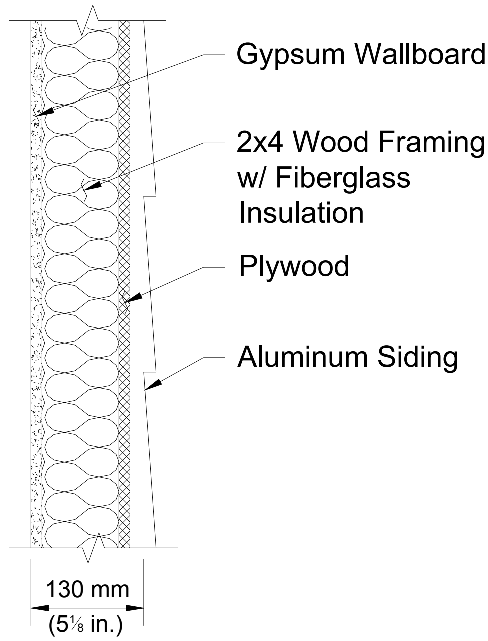

Figure B-7. Wood frame wall cross-section

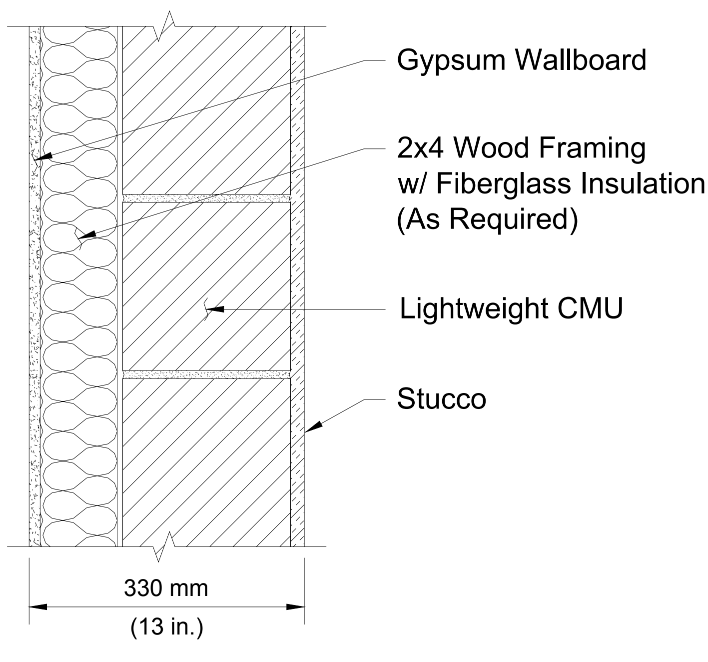

Figure B-8. CMU wall cross-section

APPENDIX C – MATERIALS LIST

Table C-1A. House Materials List – SI Units*

	Wood frame house					Lightweight CMU house				
Material, kg	**Tampa**	**El Paso**	**Knoxville**	**Providence**	**Detroit**	**Tampa**	**El Paso**	**Knoxville**	**Providence**	**Detroit**
Ready-mixed concrete	70,661	76,166	81,671	114,703	114,703	70,661	76,166	81,671	114,703	114,703
CMUs, lightweight	0	0	0	0	0	49,698	49,698	49,698	49,698	49,698
Fiber-cement backer board	1,545	1,545	1,545	1,545	1,545	1,545	1,545	1,545	1,545	1,545
Mortar	0	0	0	0	0	35,889	35,889	35,889	35,889	35,889
Grout	0	0	0	0	0	3,929	3,929	3,929	3,929	3,929
Stucco	0	0	0	0	0	23,763	23,763	23,763	23,763	23,763
Metal	3,453	3,523	3,594	4,020	4,020	4,246	4,317	4,388	4,813	4,813
Aluminum	849	849	849	849	849	315	315	315	315	315
Copper	67	67	67	67	67	67	67	67	67	67
Galvanized steel	310	310	310	310	310	310	310	310	310	310
Sheet metal	372	372	372	372	372	372	372	372	372	372
Steel	1,854	1,925	1,995	2,421	2,421	3,181	3,252	3,323	3,749	3,749
Wood	20,400	20,400	20,400	20,400	20,400	19,450	19,450	19,450	19,450	19,450
Framing	10,753	10,753	10,753	10,753	10,753	10,099	10,099	10,099	10,099	10,099
Treated	676	676	676	676	676	2,001	2,001	2,001	2,001	2,001
Plywood	5,040	5,040	5,040	5,040	5,040	4,446	4,446	4,446	4,446	4,446
Sheathing	1,027	1,027	1,027	1,027	1,027	0	0	0	0	0
Miscellaneous	2,904	2,904	2,904	2,904	2,904	2,904	2,904	2,904	2,904	2,904
Gypsum wallboard	8,896	8,896	8,896	8,896	8,896	8,035	8,035	8,035	8,035	8,035
Insulation, expanded polystyrene	0	30	60	239	239	0	30	60	239	239
Insulation, fiberglass	544	544	544	627	627	326	544	544	627	627
Polymers	10,243	10,243	10,243	10,243	10,243	10,072	10,072	10,072	10,072	10,072
Carpet and pad	6,421	6,421	6,421	6,421	6,421	6,421	6,421	6,421	6,421	6,421
Linoleum	364	364	364	364	364	364	364	364	364	364
Paint	2,690	2,690	2,690	2,690	2,690	2,690	2,690	2,690	2,690	2,690
Polyester fabric	22	22	22	22	22	0	0	0	0	0
PVC	430	430	430	430	430	430	430	430	430	430
Sealant	299	299	299	299	299	150	150	150	150	150
General	16	16	16	16	16	16	16	16	16	16
Roofing materials	5,827	5,827	5,827	5,827	5,827	5,827	5,827	5,827	5,827	5,827
Windows	3,128	3,128	3,128	3,128	3,128	3,128	3,128	3,128	3,128	3,128
Tile	3,641	3,641	3,641	3,641	3,641	3,641	3,641	3,641	3,641	3,641
Lighting products	577	577	577	577	577	577	577	577	577	577
Electrical wire	111	111	111	111	111	111	111	111	111	111
Shipping weight, various**	5,470	5,470	5,470	5,470	5,470	5,470	5,470	5,470	5,470	5,470
Total (rounded)	**134,500**	**140,100**	**145,700**	**179,400**	**179,400**	**246,400**	**252,200**	**257,800**	**291,500**	**291,500**

*Includes items replaced during 100-year life.

**See Table C-2 in Appendix C for a listing of other items that contribute to shipping weight.

Table C-1B. House Materials List – U.S. Customary Units*

	Wood frame house					Lightweight CMU house				
Material, lb	**Tampa**	**El Paso**	**Knoxville**	**Providence**	**Detroit**	**Tampa**	**El Paso**	**Knoxville**	**Providence**	**Detroit**
Ready-mixed concrete	155,780	167,918	180,055	252,878	252,878	155,780	167,918	180,055	252,878	252,878
CMUs, lightweight	0	0	0	0	0	109,566	109,566	109,566	109,566	109,566
Fiber-cement backer board	3,406	3,406	3,406	3,406	3,406	3,406	3,406	3,406	3,406	3,406
Mortar	0	0	0	0	0	79,121	79,121	79,121	79,121	79,121
Grout	0	0	0	0	0	8,663	8,663	8,663	8,663	8,663
Stucco	0	0	0	0	0	52,388	52,388	52,388	52,388	52,388
Metal	7,611	7,768	7,924	8,862	8,862	9,360	9,517	9,673	10,611	10,611
Aluminum	1,873	1,873	1,873	1,873	1,873	694	694	694	694	694
Copper	147	147	147	147	147	147	147	147	147	147
Galvanized steel	684	684	684	684	684	684	684	684	684	684
Sheet metal	821	821	821	821	821	821	821	821	821	821
Steel	4,086	4,243	4,399	5,337	5,337	7,013	7,170	7,326	8,264	8,264
Wood	44,975	44,975	44,975	44,975	44,975	42,881	42,881	42,881	42,881	42,881
Framing	23,707	23,707	23,707	23,707	23,707	22,265	22,265	22,265	22,265	22,265
Treated	1,489	1,489	1,489	1,489	1,489	4,412	4,412	4,412	4,412	4,412
Plywood	11,111	11,111	11,111	11,111	11,111	9,802	9,802	9,802	9,802	9,802
Sheathing	2,265	2,265	2,265	2,265	2,265	0	0	0	0	0
Miscellaneous	6,402	6,402	6,402	6,402	6,402	6,402	6,402	6,402	6,402	6,402
Gypsum wallboard	19,612	19,612	19,612	19,612	19,612	17,715	17,715	17,715	17,715	17,715
Insulation, expanded polystyrene	0	66	132	527	527	0	66	132	527	527
Insulation, fiberglass	1,198	1,198	1,198	1,382	1,382	719	1,198	1,198	1,382	1,382
Polymers	22,583	22,583	22,583	22,583	22,583	22,204	22,204	22,204	22,204	22,204
Carpet and pad	14,156	14,156	14,156	14,156	14,156	14,156	14,156	14,156	14,156	14,156
Linoleum	803	803	803	803	803	803	803	803	803	803
Paint	5,931	5,931	5,931	5,931	5,931	5,931	5,931	5,931	5,931	5,931
Polyester fabric	49	49	49	49	49	0	0	0	0	0
PVC	949	949	949	949	949	949	949	949	949	949
Sealant	659	659	659	659	659	330	330	330	330	330
General	35	35	35	35	35	35	35	35	35	35
Roofing materials	12,847	12,847	12,847	12,847	12,847	12,847	12,847	12,847	12,847	12,847
Windows	6,896	6,896	6,896	6,896	6,896	6,896	6,896	6,896	6,896	6,896
Tile	8,026	8,026	8,026	8,026	8,026	8,026	8,026	8,026	8,026	8,026
Lighting products	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272
Electrical wire	245	245	245	245	245	245	245	245	245	245
Shipping weight, various**	12,058	12,058	12,058	12,058	12,058	12,058	12,058	12,058	12,058	12,058
Total (rounded)	**296,500**	**308,900**	**321,200**	**395,600**	**395,600**	**543,100**	**556,000**	**568,300**	**642,700**	**642,700**

*Includes items replaced during 100-year life.

**See Table C-2 in Appendix C for a listing of other items that contribute to shipping weight.

Table C-2A. House Component Replacement Schedule – SI Units*

Item	Quantity	Weight*, kg	Replacement schedule	100-year weight, kg
Fiberglass column, exterior non-structural	2	54	none	54
Medicine cabinet w/ mirror	3	36	25	144
Range, 75 cm wide, natural gas	1	100	15	699
Dishwasher, 60 cm wide	1	45	15	318
Refrigerator, 90 cm wide	1	159	15	1,111
Washer & dryer (set)	1	113	15	794
Toilet, two piece tank type	4	65	25	261
Lavatory, synthetic marble w/ drain and faucet	5	87	25	348
Shower base, fiberglass w/ drain and faucet	2	27	25	109
Bathtub w/ shower, steel w/ drain and faucet	2	93	25	370
Double bowl kitchen sink, steel w/ drains and faucets	1	19	25	77
Garbage disposal	1	6	20	28
Domestic water heater, natural gas, 28 liters	1	45	20	227
Furnace, natural gas	1	73	20	363
Air conditioner, electric	1	113	20	567
Total		**1,036**		**5,470**

*Includes packaging materials.

Table C-2B. House Component Replacement Schedule – U.S. Customary Units*

Item	Quantity	Weight*, lb	Replacement schedule	100-year weight, lb
Fiberglass column, exterior non-structural	2	120	none	120
Medicine cabinet w/ mirror	3	79	25	317
Range, 30" wide, natural gas	1	220	15	1,540
Dishwasher, 24" wide	1	100	15	700
Refrigerator, 36" wide	1	350	15	2,450
Washer & dryer (set)	1	250	15	1,750
Toilet, two piece tank type	4	144	25	576
Lavatory, synthetic marble w/ drain and faucet	5	192	25	767
Shower base, fiberglass w/ drain and faucet	2	60	25	240
Bathtub w/ shower, steel w/ drain and faucet	2	204	25	816
Double bowl kitchen sink, steel w/ drains and faucets	1	43	25	170
Garbage disposal	1	13	20	63
Domestic water heater, natural gas, 75 gallons	1	100	20	500
Furnace, natural gas	1	160	20	800
Air conditioner, electric	1	250	20	1,250
Total		**2,284**		**12,058**

*Includes packaging materials.

APPENDIX D – FUEL AND ELECTRICITY USE

Table D-1A. Life Cycle Fuel and Electricity Use – SI Units

	Wood frame house					Lightweight CMU house				
	Tampa	**El Paso**	**Knoxville**	**Providence**	**Detroit**	**Tampa**	**El Paso**	**Knoxville**	**Providence**	**Detroit**
Fuel input, unit										
Coal, kg	789	850	912	1280	1280	4228	4289	4351	4719	4719
Gasoline, L	0.38	0.41	0.44	0.62	0.62	2.70	2.73	2.76	2.94	2.94
Liquefied petroleum gas, L	0.12	0.13	0.14	0.19	0.19	0.90	0.91	0.92	0.98	0.98
Diesel fuel, L	836	882	928	1204	1204	1717	1764	1810	2086	2086
Natural gas, m^3	0.16	0.28	0.36	0.54	0.60	1.14	1.24	1.32	1.49	1.55
Petroleum coke, kg	157	169	181	254	254	569	581	593	667	667
Residual oil, L	1.20	1.29	1.39	1.95	1.95	4.59	4.68	4.78	5.34	5.34
Wastes, kg	127	137	147	207	207	463	473	483	542	542
Electricity, 1000 kWh	1568	1501	1227	1097	1101	1577	1443	1182	1072	1078
Energy input, GJ										
Coal	21	23	25	35	35	114	116	117	128	128
Gasoline	0.013	0.014	0.015	0.022	0.022	0.082	0.083	0.084	0.090	0.090
Liquefied petroleum gas	0.003	0.003	0.003	0.005	0.005	0.043	0.044	0.044	0.045	0.045
Diesel fuel	32	34	36	46	46	66	68	70	80	80
Natural gas	5,986	10,397	13,393	20,010	22,236	6,128	9,947	12,817	19,266	21,418
Petroleum coke	5	6	6	9	9	19	20	20	23	23
Residual oil	0.049	0.053	0.057	0.080	0.080	0.179	0.183	0.187	0.210	0.210
Wastes	3	3	3	5	5	11	11	11	13	13
Electricity	5,645	5,402	4,417	3,951	3,965	5,677	5,194	4,255	3,859	3,881
Total energy input (rounded)	**11,700**	**15,900**	**17,900**	**24,100**	**26,300**	**12,000**	**15,400**	**17,300**	**23,400**	**25,500**

*Does not include upstream profiles of electricity, fuels, or materials other than cement-based products.

Table D-1B. Life Cycle Fuel and Electricity Use – U.S. Customary Units

	Wood frame house					Lightweight CMU house				
	Tampa	El Paso	Knoxville	Providence	Detroit	Tampa	El Paso	Knoxville	Providence	Detroit
Fuel input, unit										
Coal, ton	0.87	0.94	1.00	1.41	1.41	4.66	4.73	4.80	5.20	5.20
Gasoline, gallon	0.10	0.11	0.12	0.16	0.16	0.71	0.72	0.73	0.78	0.78
Liquefied petroleum gas, gallon	0.03	0.03	0.04	0.05	0.05	0.24	0.24	0.24	0.26	0.26
Diesel fuel, gallon	221	233	245	318	318	454	466	478	551	551
Natural gas, million ft^3	5.67	9.85	12.69	18.97	21.08	40.15	43.77	46.49	52.60	54.64
Petroleum coke, ton	0.17	0.19	0.20	0.28	0.28	0.63	0.64	0.65	0.73	0.73
Residual oil, gallon	0.32	0.34	0.37	0.51	0.51	1.21	1.24	1.26	1.41	1.41
Wastes, ton	0.14	0.15	0.16	0.23	0.23	0.51	0.52	0.53	0.60	0.60
Electricity,1000 kWh	1568	1501	1227	1097	1101	1577	1443	1182	1072	1078
Energy input, MBtu										
Coal	20	22	24	33	33	108	110	111	121	121
Gasoline	0.013	0.014	0.015	0.021	0.021	0.077	0.078	0.079	0.085	0.085
Liquefied petroleum gas	0.003	0.003	0.003	0.004	0.004	0.041	0.041	0.041	0.043	0.043
Diesel fuel	31	32	34	44	44	63	64	66	76	76
Natural gas	5,674	9,854	12,694	18,966	21,076	5,808	9,428	12,148	18,260	20,300
Petroleum coke	5	5	6	8	8	18	19	19	21	21
Residual oil	0.047	0.050	0.054	0.076	0.076	0.170	0.173	0.177	0.199	0.199
Wastes	3	3	3	5	5	10	10	11	12	12
Electricity	5,351	5,120	4,186	3,745	3,758	5,381	4,923	4,033	3,658	3,679
Total energy input (rounded)	**11,100**	**15,000**	**16,900**	**22,800**	**24,900**	**11,400**	**14,600**	**16,400**	**22,100**	**24,200**

*Does not include upstream profiles of electricity, fuels, or materials other than cement-based products.