PCA Portland Cement Association

Research & Development Information

PCA R&D Serial No. 2465

# 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 of JAN Consultants

## KEYWORDS

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

## ABSTRACT

A partial life cycle inventory (LCI) of a wood frame house and a 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 houses was modeled in five cities, representing a range of U.S. climates: Tucson, Lake Charles, Denver, St. Louis, and Minneapolis.

Each 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 profiles of concrete, concrete masonry units, mortar, grout, and stucco, (ii) the mass of other building materials used, (iii) occupant energy-use, and (iv) transportation energy. 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 the emissions from the production of non-cement-based 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 CMU house and the wood frame house. Less than 1% of the life cycle energy is due to the manufacturing of cement and the production of cement-based materials. The house life cycle energy is primarily a function of climate and occupant behavior. In the three cities representing colder climates (St. Louis, Denver, and Minneapolis), the CMU house has a lower life cycle energy-use than the wood frame house. Furthermore, although the CMU house contains more embodied energy than the wood frame house, after 7 years in Denver, for example, the cumulative energy-use of the wood frame house surpasses that of the CMU house.

Most of the house life cycle emissions of $CO_2$ (95%), $NO_x$ (85%), CO (90%), VOC (85%), 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 (90%) are from the production of concrete, 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. 2465, Portland Cement Association, Skokie, IL, September 2000, 52 pages.

# TABLE OF CONTENTS

## LIST OF FIGURES



## LIST OF TABLES

# 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 concrete masonry units. More information on the target audience 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, concrete masonry units (CMUs), mortar, grout, and stucco.[4] 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 occupants will also be included. Figure 1-1 shows the material and energy inputs that are included in this partial LCI.

---

*Project Assistant, Senior Engineer, Principal Engineer, and Architect (formerly with CTL), Construction Technology Laboratories, Inc. (CTL), 5420 Old Orchard Road, Skokie, Illinois, 60077, (847) 965-7500; and Principal, JAN Consultants 428 Lansdowne Avenue, Montreal, Quebec, Canada, H3Y 2V2.

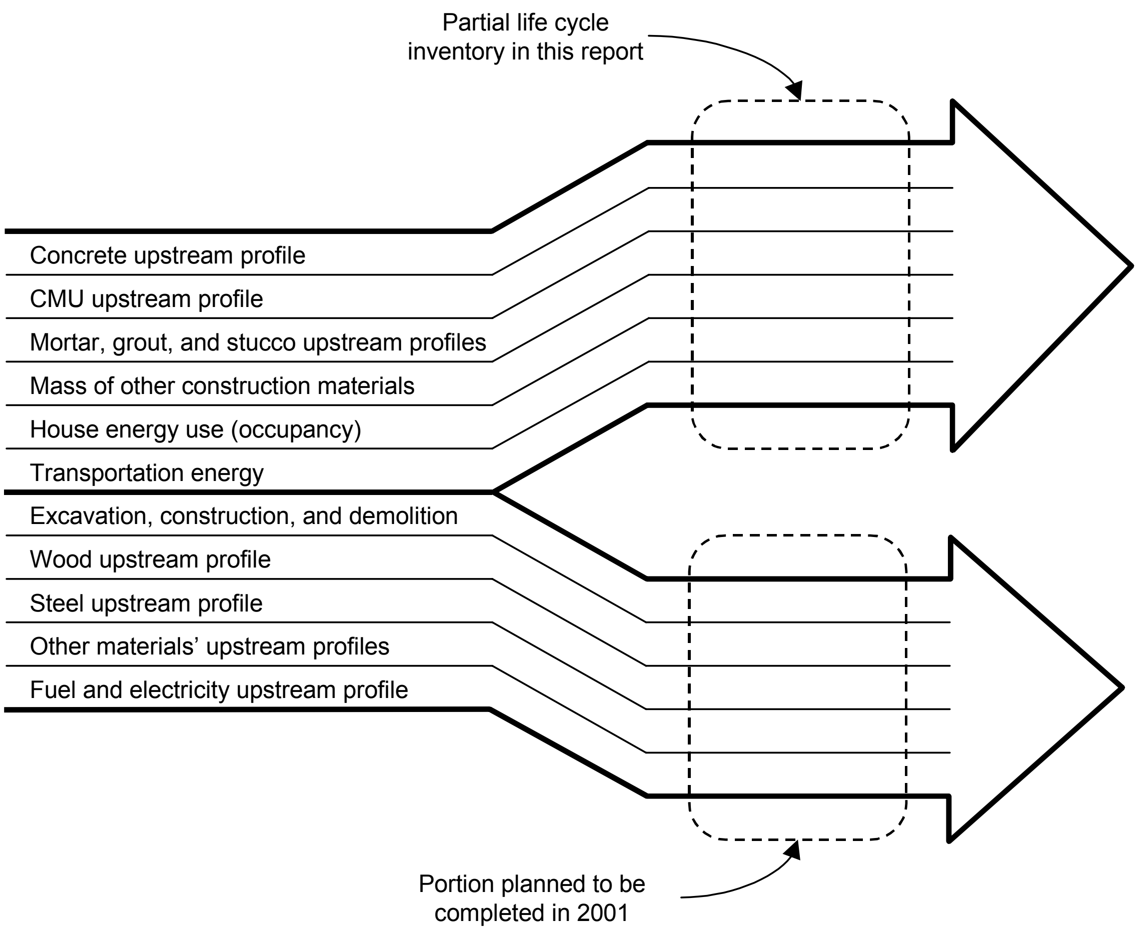


**Figure 1-1. Material and energy inputs included in the partial LCI.**

The partial LCI is presented in terms of energy use, material use, emissions to air, and solid waste generation; and it includes the upstream profiles of concrete, 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 CMU house. The houses are designed to meet the requirements of the 1998 International Energy Conservation Code (IECC)[5] 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 regionss. Five cities were chosen that represent the range of climates in the United States: Tucson, Arizona; Lake Charles, Louisiana; Denver, Colorado; St. Louis, Missouri; and Minneapolis, Minnesota.[6] House energy consumption is modeled on an hourly basis with building energy simulation software that uses the DOE 2.1E calculation engine.[7]

## 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;

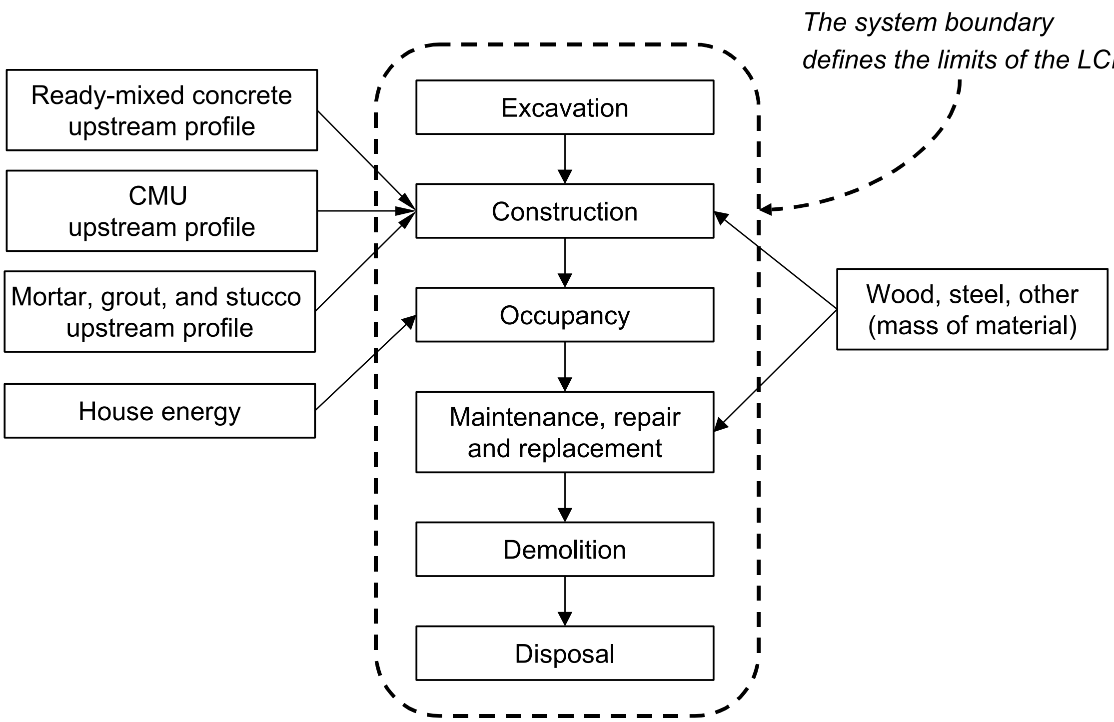


**Figure 2-1. System boundary for house environmental life cycle inventory.**

maintenance, repair, and replacement; demolition; and disposal. The system boundary also includes (i) the upstream profiles of concrete, CMUs, mortar, grout, and stucco; (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 from 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 and emissions from the production of other building materials, such as wood, steel, and plastics. It also does not include the upstream profiles 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).[8] The size of the house is based on the average size of Insulating Concrete Form (ICF) houses constructed in the United States.[9] Figures B1 through B8 in Appendix B present the floor plans and elevations.

The house was modeled in five cities, representing a range of U.S. climates. Tucson 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. Lake Charles was selected because it is a hot humid climate with small temperature swings where thermal mass works almost as well. St. Louis was selected because it is a moderate climate. Denver and Minneapolis were selected because they are cold climates.

The building envelope in each city is designed to meet the minimum requirements of the 1998 International Energy Conservation Code (IECC) using standard building materials.[5] 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 | | | | | |
| | $\frac{W}{m^2 \cdot K}$ | $\frac{Btu}{hr \cdot ft^2 \cdot °F}$ | $\frac{W}{m^2 \cdot K}$ | $\frac{Btu}{hr \cdot ft^2 \cdot °F}$ | $\frac{W}{m^2 \cdot K}$ | $\frac{Btu}{hr \cdot ft^2 \cdot °F}$ | $\frac{W}{m^2 \cdot K}$ | $\frac{Btu}{hr \cdot ft^2 \cdot °F}$ |
| Lake Charles | 0.897 | 0.158 | 1.124 | 0.198 | 0.233 | 0.041 | 2.4 | 0.47 |
| Tucson | 0.886 | 0.156 | 1.102 | 0.194 | 0.233 | 0.041 | 2.4 | 0.47 |
| St. Louis | 0.636 | 0.112 | 0.727 | 0.128 | 0.182 | 0.032 | 1.7 | 0.30 |
| Denver | 0.500 | 0.088 | 0.556 | 0.098 | 0.148 | 0.026 | 1.7 | 0.30 |
| Minneapolis | 0.420 | 0.074 | 0.420 | 0.074 | 0.148 | 0.026 | 1.6 | 0.28 |

* 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 code also requires that windows have a solar heat gain coefficient (SHGC) less than 0.4 in Lake Charles and Tucson.

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 cities except Minneapolis, 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. In Minneapolis, the exterior walls of the wood frame house consist of medium-colored aluminum siding, 12-mm (½-in.) plywood, $R_{SI}$-2.3 (R-13) fiberglass batt insulation, and 12-mm (½-in.) painted gypsum board.

The exterior walls of the CMU house in Lake Charles and Tucson consist of 16-mm (⅝-in.) light-colored portland cement stucco, 200-mm (8-in.) CMU with partly grouted insulated cells*, wood furring, and 12-mm (½-in.) painted gypsum board. The exterior walls of the CMU house in St. Louis and Denver consist of 16-mm (⅝-in.) light-colored portland cement stucco, 200-mm (8-in.) 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 Minneapolis, the exterior walls of the CMU house consist of 16-mm (⅝-in.) light-colored portland cement stucco, 200-mm (8-in.) CMU with partly grouted uninsulated cells, wood furring with $R_{SI}$-2.3 (R-13) fiberglass batt insulation, and 12-mm (½-in.) painted gypsum board. In all cities, the nominal weight of the CMU is assumed to be 1,840 kg/$m^3$ (115 lb/$ft^3$) with U-factors as presented in ASHRAE Standard 90.1-1999.[10] Figures B7 and B8 in Appendix B presents 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 are 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 Lake Charles and Tucson are tinted and contain air in the space between panes. Windows in St. Louis, Denver, and Minneapolis 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.

---

*Partly grouted insulated cells means that some CMU cells are grouted, while others contain insulation. Likewise, partly grouted uninsulated cells means that some 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.[10]

**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">Mass (CMU)</th></tr>
<tr><th>$\frac{W}{m^2 \cdot K}$</th><th>$\frac{Btu}{hr \cdot ft^2 \cdot °F}$</th><th>$\frac{W}{m^2 \cdot K}$</th><th>$\frac{Btu}{hr \cdot ft^2 \cdot °F}$</th><th>$\frac{W}{m^2 \cdot K}$</th><th>$\frac{Btu}{hr \cdot ft^2 \cdot °F}$</th><th>$\frac{W}{m^2 \cdot K}$</th><th>$\frac{Btu}{hr \cdot ft^2 \cdot °F}$</th></tr>
<tr><td>Lake Charles</td><td rowspan="4">0.47</td><td rowspan="4">0.082</td><td rowspan="2">0.85</td><td rowspan="2">0.150</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>Tucson</td></tr>
<tr><td>St. Louis</td><td rowspan="2">0.44</td><td rowspan="2">0.078</td><td rowspan="3">1.5</td><td rowspan="3">0.27</td></tr>
<tr><td>Denver</td><td rowspan="2">0.15</td><td rowspan="2">0.026</td></tr>
<tr><td>Minneapolis</td><td>0.42</td><td>0.074</td><td>0.41</td><td>0.073</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 Lake Charles, Tucson, and St. Louis. $R_{SI}$-6.7 (R-38) attic insulation was used in Denver and Minneapolis.

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.[11] 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.

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,[11] and it assumes the house has an electric clothes dryer and an electric stove.

Air infiltration rates are based on ASHRAE Standard 62.[12] 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 2-1. 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 CMUs. [4] The PCA intends to include the upstream profiles of other materials once a suitable database is found.

**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.

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.

## 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 C.

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

| | Wood frame house | | | | | Normal weight CMU house | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Material, kg** | **Lake Charles** | **Tucson** | **St. Louis** | **Denver** | **Minneapolis** | **Lake Charles** | **Tucson** | **St. Louis** | **Denver** | **Minneapolis** |
| Ready-mixed concrete** | 70,700 | 76,200 | 92,700 | 109,200 | 136,700 | 70,700 | 76,200 | 92,700 | 109,200 | 136,700 |
| CMUs, lightweight | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CMUs, normal weight | 0 | 0 | 0 | 0 | 0 | 63,500 | 63,500 | 63,500 | 63,500 | 63,500 |
| 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 | 3,700 | 3,900 | 4,300 | 4,200 | 4,300 | 4,500 | 4,700 | 5,100 |
| 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 | 120 | 210 | 360 | 120 | 150 | 120 | 210 | 360 |
| Insulation, fiberglass | 540 | 540 | 540 | 630 | 630 | 330 | 330 | 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** | **156,900** | **173,800** | **201,900** | **260,300** | **265,900** | **282,800** | **299,700** | **327,700** |

*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.

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

| | Wood frame house | | | | | Normal weight CMU house | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Material, lb** | **Lake Charles** | **Tucson** | **St. Louis** | **Denver** | **Minneapolis** | **Lake Charles** | **Tucson** | **St. Louis** | **Denver** | **Minneapolis** |
| Ready-mixed concrete** | 155,800 | 167,900 | 204,300 | 240,700 | 301,400 | 155,800 | 167,900 | 204,300 | 240,700 | 301,400 |
| CMUs, lightweight | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CMUs, normal weight | 0 | 0 | 0 | 0 | 0 | 140,000 | 140,000 | 140,000 | 140,000 | 140,000 |
| 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 | 8,200 | 8,700 | 9,500 | 9,400 | 9,500 | 10,000 | 10,500 | 11,200 |
| 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 | 260 | 460 | 790 | 260 | 330 | 260 | 460 | 790 |
| Insulation, fiberglass | 1,200 | 1,200 | 1,200 | 1,380 | 1,380 | 720 | 720 | 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** | **345,900** | **383,200** | **445,000** | **573,800** | **586,200** | **623,500** | **660,800** | **722,600** |

*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.

Both houses contain similar amounts of wood. For example, in both houses the roof, the interior walls, and the second story floor are framed with wood. In addition the CMU house has interior wood furring and wood framing around the doors and windows to allow for placement of insulation. There is less gypsum wallboard in the CMU house because the inside surfaces of the garage are 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 material 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, 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 inputs of cement-based materials to the house in each city. The concrete material upstream profile is based on the upstream profile for 21 MPa (3,000 psi) concrete, 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 CMU house contains more cement-based materials than the wood frame house because, in addition to the foundation, the exterior walls of the CMU house contain mostly cement-based materials. The houses in the cooler climates also have 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 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. 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

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

| | Wood frame house | | | | | CMU house | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Material, kg** | **Lake Charles** | **Tucson** | **St. Louis** | **Denver** | **Minneapolis** | **Lake Charles** | **Tucson** | **St. Louis** | **Denver** | **Minneapolis** |
| **Ready-mixed concrete** | | | | | | | | | | |
| Cement | 6,800 | 7,300 | 8,900 | 10,500 | 13,100 | 6,800 | 7,300 | 8,900 | 10,500 | 13,100 |
| Water | 4,300 | 4,600 | 5,600 | 6,600 | 8,300 | 4,300 | 4,600 | 5,600 | 6,600 | 8,300 |
| Coarse aggregate | 34,300 | 37,000 | 45,000 | 53,000 | 66,400 | 34,300 | 37,000 | 45,000 | 53,000 | 66,400 |
| Fine aggregate | 25,300 | 27,300 | 33,200 | 39,100 | 48,900 | 25,300 | 27,300 | 33,200 | 39,100 | 48,900 |
| **Total** | **70,700** | **76,200** | **92,700** | **109,200** | **136,700** | **70,700** | **76,200** | **92,700** | **109,200** | **136,700** |
| **CMU concrete** | | | | | | | | | | |
| Cement | 0 | 0 | 0 | 0 | 0 | 5,500 | 5,500 | 5,500 | 5,500 | 5,500 |
| Water | 0 | 0 | 0 | 0 | 0 | 3,800 | 3,800 | 3,800 | 3,800 | 3,800 |
| Coarse aggregate | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Fine aggregate | 0 | 0 | 0 | 0 | 0 | 54,200 | 54,200 | 54,200 | 54,200 | 54,200 |
| **Total** | **0** | **0** | **0** | **0** | **0** | **63,500** | **63,500** | **63,500** | **63,500** | **63,500** |
| **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 | 16,100 | 16,100 | 16,100 | 16,100 | 16,100 |
| Lime | 0 | 0 | 0 | 0 | 0 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 |
| **Total** | **0** | **0** | **0** | **0** | **0** | **23,800** | **23,800** | **23,800** | **23,800** | **23,800** |

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

| | Wood frame house | | | | | CMU house | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Material, lb** | **Lake Charles** | **Tucson** | **St. Louis** | **Denver** | **Minneapolis** | **Lake Charles** | **Tucson** | **St. Louis** | **Denver** | **Minneapolis** |
| **Ready-mixed concrete** | | | | | | | | | | |
| Cement | 15,000 | 16,100 | 19,600 | 23,100 | 29,000 | 15,000 | 16,100 | 19,600 | 23,100 | 29,000 |
| Water | 9,400 | 10,200 | 12,400 | 14,600 | 18,300 | 9,400 | 10,200 | 12,400 | 14,600 | 18,300 |
| Coarse aggregate | 75,600 | 81,500 | 99,200 | 116,900 | 146,400 | 75,600 | 81,500 | 99,200 | 116,900 | 146,400 |
| Fine aggregate | 55,700 | 60,100 | 73,100 | 86,100 | 107,800 | 55,700 | 60,100 | 73,100 | 86,100 | 107,800 |
| **Total** | **155,800** | **167,900** | **204,300** | **240,700** | **301,400** | **155,800** | **167,900** | **204,300** | **240,700** | **301,400** |
| **CMU concrete** | | | | | | | | | | |
| Cement | 0 | 0 | 0 | 0 | 0 | 12,200 | 12,200 | 12,200 | 12,200 | 12,200 |
| Water | 0 | 0 | 0 | 0 | 0 | 8,400 | 8,400 | 8,400 | 8,400 | 8,400 |
| Coarse aggregate | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Fine aggregate | 0 | 0 | 0 | 0 | 0 | 119,400 | 119,400 | 119,400 | 119,400 | 119,400 |
| **Total** | **0** | **0** | **0** | **0** | **0** | **140,000** | **140,000** | **140,000** | **140,000** | **140,000** |
| **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** |

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

| | Ready-mixed concrete 21 MPa | 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 | 208 | 352 | 416 | 352 |
| Water | 141 | 142 | 208 | 224 | 208 |
| Coarse aggregate | 1,127 | not applicable | not applicable | not applicable | not applicable |
| Fine aggregate | 831 | 2,033 | 1,362 | 1,314 | 1,362 |
| Lime | not applicable | not applicable | 80 | 48 | 80 |
| **Total** | **2,321** | **2,383** | **2,002** | **2,002** | **2,002** |

*Concrete mix designs vary. These have been chosen because they are representative of residential concrete.

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

| | Ready-mixed concrete 3,000 psi | 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 | 350 | 594 | 702 | 594 |
| Water | 237 | 240 | 351 | 378 | 351 |
| Coarse aggregate | 1,900 | not applicable | not applicable | not applicable | not applicable |
| Fine aggregate | 1,400 | 3,427 | 2,295 | 2,214 | 2,295 |
| Lime | not applicable | not applicable | 135 | 81 | 135 |
| **Total** | **3,913** | **4,017** | **3,375** | **3,375** | **3,375** |

*Concrete mix designs vary. These have been chosen because they are representative of residential concrete.

ton-miles).[13] 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.

### 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 CMU plant. It also includes the energy and emissions from operations at cement, ready-mixed concrete, and 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 ready-mixed concrete, about 70% of the energy embodied in concrete is consumed in the cement manufacturing process.[4]

### 5.2.3. Household occupant energy-use

Energy simulation software is used to model the annual household house energy consumption.[7] 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, each 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, hot water, and occupant use is averaged to produce a building-orientation-independent energy consumption. The annual occupant energy-use is presented in Table 5-5. Results for the 100-year life were presented earlier in Table 5-4.

The data presented in Table 5-5 show that the CMU house has similar occupant energy use as the wood frame house. This is primarily because both the 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 0 to 100% in excess of IECC requirements, while CMU walls have R-values that range from approximately 0 to 50% in excess of IECC requirements.

Results also show that the energy required for heating, ventilating, and air-conditioning is less for the 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 CMU house moderates temperature swings and peak loads, and results in lower HVAC system requirements.

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

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

| | Wood frame house | | | | | CMU house | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Lake Charles** | **Tucson** | **St. Louis** | **Denver** | **Minneapolis** | **Lake Charles** | **Tucson** | **St. Louis** | **Denver** | **Minneapolis** |
| **Diesel fuel, L**** | | | | | | | | | | |
| Transportation to house | 264 | 275 | 308 | 341 | 396 | 487 | 498 | 531 | 564 | 619 |
| Transportation to landfill | 264 | 275 | 308 | 341 | 396 | 487 | 498 | 531 | 564 | 619 |
| **Energy, GJ** | | | | | | | | | | |
| Transportation to house | 10 | 11 | 12 | 13 | 15 | 19 | 19 | 21 | 22 | 24 |
| Embodied in concrete | 52 | 56 | 68 | 80 | 100 | 52 | 56 | 68 | 80 | 100 |
| Embodied in CMUs | 0 | 0 | 0 | 0 | 0 | 45 | 45 | 45 | 45 | 45 |
| 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 | 14,430 | 14,360 | 22,410 | 22,850 | 28,190 | 14,650 | 14,490 | 21,830 | 21,710 | 27,530 |
| Transportation to landfill | 10 | 11 | 12 | 13 | 15 | 19 | 19 | 21 | 22 | 24 |
| **Total (rounded)** | **14,500** | **14,400** | **22,500** | **23,000** | **28,300** | **14,900** | **14,700** | **22,100** | **21,900** | **27,800** |

*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 | | | | | CMU house | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Lake Charles** | **Tucson** | **St. Louis** | **Denver** | **Minneapolis** | **Lake Charles** | **Tucson** | **St. Louis** | **Denver** | **Minneapolis** |
| **Diesel fuel, gallon**** | | | | | | | | | | |
| Transportation to house | 70 | 73 | 81 | 90 | 105 | 129 | 132 | 140 | 149 | 164 |
| Transportation to landfill | 70 | 73 | 81 | 90 | 105 | 129 | 132 | 140 | 149 | 164 |
| **Energy, MBtu** | | | | | | | | | | |
| Transportation to house | 10 | 10 | 11 | 12 | 14 | 18 | 18 | 19 | 21 | 23 |
| Embodied in concrete | 49 | 53 | 65 | 76 | 95 | 49 | 53 | 65 | 76 | 95 |
| Embodied in CMUs | 0 | 0 | 0 | 0 | 0 | 42 | 42 | 42 | 42 | 42 |
| 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 | 13,677 | 13,611 | 21,241 | 21,658 | 26,719 | 13,886 | 13,734 | 20,691 | 20,577 | 26,093 |
| Transportation to landfill | 10 | 10 | 11 | 12 | 14 | 18 | 18 | 19 | 21 | 23 |
| **Total (rounded)** | **13,700** | **13,700** | **21,300** | **21,800** | **26,800** | **14,100** | **13,900** | **20,900** | **20,800** | **26,300** |

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

| Location | Variation | Annual operating data | | | | |
|---|---|---|---|---|---|---|
| | | Electricity | | Natural gas | | Total energy, GJ |
| | | GJ | kWh | GJ | Therms | |
| Lake Charles | Wood frame | 52.8 | 14,660 | 91.5 | 868 | 144.3 |
| | CMU | 52.2 | 14,509 | 94.3 | 894 | 146.5 |
| Tucson | Wood frame | 60.0 | 16,659 | 83.6 | 793 | 143.6 |
| | CMU | 60.4 | 16,772 | 84.5 | 801 | 144.9 |
| St. Louis | Wood frame | 47.8 | 13,273 | 176.3 | 1,672 | 224.1 |
| | CMU | 46.4 | 12,902 | 171.9 | 1,630 | 218.3 |
| Denver | Wood frame | 40.9 | 11,368 | 187.5 | 1,778 | 228.5 |
| | CMU | 39.2 | 10,883 | 177.9 | 1,687 | 217.1 |
| Minneapolis | Wood frame | 40.9 | 11,363 | 241.0 | 2,285 | 281.9 |
| | CMU | 39.9 | 11,093 | 235.4 | 2,232 | 275.3 |

**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 |
| Lake Charles | Wood frame | 25 | 87 | 13 | 45 |
| | CMU | 23 | 78 | 12 | 41 |
| Tucson | Wood frame | 30 | 102 | 16 | 55 |
| | CMU | 29 | 98 | 16 | 54 |
| St. Louis | Wood frame | 29 | 99 | 15 | 53 |
| | CMU | 26 | 89 | 14 | 48 |
| Denver | Wood frame | 27 | 92 | 14 | 47 |
| | CMU | 23 | 78 | 12 | 39 |
| Minneapolis | Wood frame | 25 | 87 | 13 | 45 |
| | CMU | 23 | 79 | 12 | 41 |

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).[13] 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, 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 greater 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, 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 CMU house in Denver. It shows that after 7 years, the cumulative energy use of the wood frame house exceeds that of the 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 occupants will also be included.

### 5.3.1. Emissions to air

The partial LCI includes emissions to air of greenhouse gases and the most common air pollutants as defined by United Sates Environmental Protection Agency.[14] 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 | | | | | CMU house | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Lake Charles | Tucson | St. Louis | Denver | Minneapolis | Lake Charles | Tucson | St. Louis | Denver | Minneapolis |
| **Energy, GJ** | | | | | | | | | | |
| Transportation to house | 10 | 11 | 12 | 13 | 15 | 19 | 19 | 21 | 22 | 24 |
| Embodied in concrete | 52 | 56 | 68 | 80 | 100 | 52 | 56 | 68 | 80 | 100 |
| Embodied in CMUs | 0 | 0 | 0 | 0 | 0 | 45 | 45 | 45 | 45 | 45 |
| 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 | 14,430 | 14,360 | 22,410 | 22,850 | 28,190 | 14,650 | 14,490 | 21,830 | 21,710 | 27,530 |
| Transportation to landfill | 10 | 11 | 12 | 13 | 15 | 19 | 19 | 21 | 22 | 24 |
| **Total (rounded)** | **14,500** | **14,400** | **22,500** | **23,000** | **28,300** | **14,900** | **14,700** | **22,100** | **21,900** | **27,800** |
| | | | | | | | | | | |
| **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 | 0.4 | 0.3 | 0.4 | 0.3 | 0.4 | 0.4 |
| Embodied in CMUs | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.3 | 0.2 | 0.2 | 0.2 |
| Embodied in mortar | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.3 | 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 | 99.5 | 99.7 | 99.6 | 99.3 | 99.6 | 98.3 | 98.6 | 98.8 | 99.1 | 99.0 |
| 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 | | | | | CMU house | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Lake Charles** | **Tucson** | **St. Louis** | **Denver** | **Minneapolis** | **Lake Charles** | **Tucson** | **St. Louis** | **Denver** | **Minneapolis** |
| **Energy, MBtu** | | | | | | | | | | |
| Transportation to house | 10 | 10 | 11 | 12 | 14 | 18 | 18 | 19 | 21 | 23 |
| Embodied in concrete | 49 | 53 | 65 | 76 | 95 | 49 | 53 | 65 | 76 | 95 |
| Embodied in CMUs | 0 | 0 | 0 | 0 | 0 | 42 | 42 | 42 | 42 | 42 |
| 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 | 13,677 | 13,611 | 21,241 | 21,658 | 26,719 | 13,886 | 13,734 | 20,691 | 20,577 | 26,093 |
| Transportation to landfill | 10 | 10 | 11 | 12 | 14 | 18 | 18 | 19 | 21 | 23 |
| **Total (rounded)** | **13,700** | **13,700** | **21,300** | **21,800** | **26,800** | **14,100** | **13,900** | **20,900** | **20,800** | **26,300** |
| | | | | | | | | | | |
| **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 | 0.4 | 0.3 | 0.4 | 0.3 | 0.4 | 0.4 |
| Embodied in CMUs | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.3 | 0.2 | 0.2 | 0.2 |
| Embodied in mortar | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.3 | 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 | 99.8 | 99.3 | 99.7 | 99.3 | 99.7 | 98.5 | 98.8 | 99.0 | 98.9 | 99.2 |
| 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.

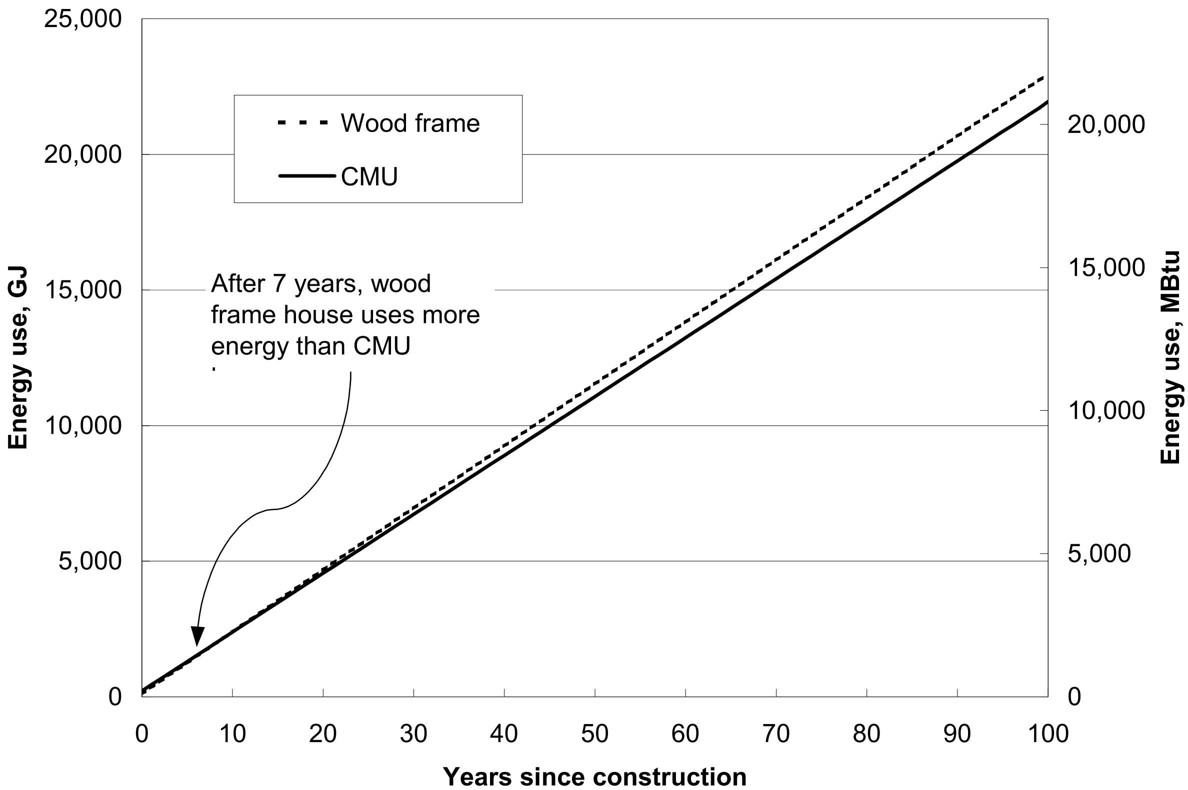


**Figure 5-1. Cumulative life cycle energy use of wood frame house and CMU house in Denver over 100 years. (Does not include upstream profiles of electricity, fuels, or construction materials other than cement-based products.)**

Most of the life cycle emissions to air for the houses 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, CMUs, mortar, grout, and stucco, (iii) the operation of 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 CMU house represent approximately 70% 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 CMU house accounts for 1 to 4% 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 $CO_2$ emissions throughout the life of the house. The production of the cement-based components of the CMU house

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

| | Wood frame house | | | | | CMU house | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Emission, kg** | **Lake Charles** | **Tucson** | **St. Louis** | **Denver** | **Minneapolis** | **Lake Charles** | **Tucson** | **St. Louis** | **Denver** | **Minneapolis** |
| **Ready-mixed concrete** | | | | | | | | | | |
| Particulate matter | 33 | 35 | 43 | 50 | 63 | 33 | 35 | 43 | 50 | 63 |
| $CO_2$ | 6,890 | 7,420 | 9,030 | 10,640 | 13,330 | 6,890 | 7,420 | 9,030 | 10,640 | 13,330 |
| $SO_2$ | 30 | 32 | 39 | 46 | 57 | 30 | 32 | 39 | 46 | 57 |
| $NO_x$ | 28 | 31 | 37 | 44 | 55 | 28 | 31 | 37 | 44 | 55 |
| VOC | 1 | 1 | 1 | 2 | 2 | 1 | 1 | 1 | 2 | 2 |
| CO | 4 | 5 | 6 | 7 | 9 | 4 | 5 | 6 | 7 | 9 |
| $CH_4$ | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| **CMU concrete** | | | | | | | | | | |
| Particulate matter | 0 | 0 | 0 | 0 | 0 | 27 | 27 | 27 | 27 | 27 |
| $CO_2$ | 0 | 0 | 0 | 0 | 0 | 5,760 | 5,760 | 5,760 | 5,760 | 5,760 |
| $SO_2$ | 0 | 0 | 0 | 0 | 0 | 25 | 25 | 25 | 25 | 25 |
| $NO_x$ | 0 | 0 | 0 | 0 | 0 | 23 | 23 | 23 | 23 | 23 |
| 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 | 0 | 0 | 0 | 0 | 0 |
| **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 | | | | | CMU house | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Emission, lb** | **Lake Charles** | **Tucson** | **St. Louis** | **Denver** | **Minneapolis** | **Lake Charles** | **Tucson** | **St. Louis** | **Denver** | **Minneapolis** |
| **Ready-mixed concrete** | | | | | | | | | | |
| Particulate matter | 72 | 77 | 94 | 111 | 139 | 72 | 77 | 94 | 111 | 139 |
| $CO_2$ | 15,190 | 16,370 | 19,920 | 23,470 | 29,380 | 15,190 | 16,370 | 19,920 | 23,470 | 29,380 |
| $SO_2$ | 65 | 71 | 86 | 101 | 127 | 65 | 71 | 86 | 101 | 127 |
| $NO_x$ | 63 | 67 | 82 | 97 | 121 | 63 | 67 | 82 | 97 | 121 |
| VOC | 2 | 3 | 3 | 4 | 5 | 2 | 3 | 3 | 4 | 5 |
| CO | 10 | 11 | 13 | 15 | 19 | 10 | 11 | 13 | 15 | 19 |
| $CH_4$ | 1 | 1 | 1 | 2 | 2 | 1 | 1 | 1 | 2 | 2 |
| **CMU concrete** | | | | | | | | | | |
| Particulate matter | 0 | 0 | 0 | 0 | 0 | 59 | 59 | 59 | 59 | 59 |
| $CO_2$ | 0 | 0 | 0 | 0 | 0 | 12,690 | 12,690 | 12,690 | 12,690 | 12,690 |
| $SO_2$ | 0 | 0 | 0 | 0 | 0 | 55 | 55 | 55 | 55 | 55 |
| $NO_x$ | 0 | 0 | 0 | 0 | 0 | 52 | 52 | 52 | 52 | 52 |
| VOC | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 2 | 2 | 2 |
| 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 | | | | | CMU house | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Lake Charles** | **Tucson** | **St. Louis** | **Denver** | **Minneapolis** | **Lake Charles** | **Tucson** | **St. Louis** | **Denver** | **Minneapolis** |
| Natural gas, GJ: | 9,150 | 8,360 | 17,630 | 18,750 | 24,100 | 9,430 | 8,450 | 17,190 | 17,790 | 23,540 |
| **Emission, kg** | | | | | | | | | | |
| Particulate matter | 29 | 27 | 56 | 60 | 77 | 30 | 27 | 55 | 57 | 75 |
| $CO_2$ | 462,000 | 423,000 | 891,000 | 948,000 | 1,218,000 | 477,000 | 427,000 | 869,000 | 899,000 | 1,190,000 |
| $SO_2$ | 2 | 2 | 4 | 5 | 6 | 2 | 2 | 4 | 4 | 6 |
| $NO_x$ | 362 | 331 | 698 | 742 | 954 | 373 | 335 | 681 | 704 | 932 |
| VOC | 21 | 19 | 41 | 43 | 56 | 22 | 20 | 40 | 41 | 55 |
| CO | 154 | 141 | 297 | 316 | 406 | 159 | 142 | 290 | 300 | 397 |
| $CH_4$ | 9 | 8 | 17 | 18 | 23 | 9 | 8 | 17 | 17 | 23 |

*Natural gas burned in furnace and water heater.
Source: Reference 15.

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

| | Wood frame house | | | | | CMU house | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Lake Charles** | **Tucson** | **St. Louis** | **Denver** | **Minneapolis** | **Lake Charles** | **Tucson** | **St. Louis** | **Denver** | **Minneapolis** |
| Natural gas*, therms: | 86,800 | 79,300 | 167,200 | 177,800 | 228,500 | 89,400 | 80,100 | 163,000 | 168,700 | 223,200 |
| Natural gas*, MBtu: | 8,680 | 7,930 | 16,720 | 17,780 | 22,850 | 8,940 | 8,010 | 16,300 | 16,870 | 22,320 |
| **Emission, lb** | | | | | | | | | | |
| Particulate matter | 65 | 59 | 125 | 132 | 170 | 67 | 60 | 121 | 126 | 166 |
| $CO_2$ | 1,021,000 | 933,000 | 1,967,000 | 2,092,000 | 2,688,000 | 1,052,000 | 942,000 | 1,918,000 | 1,985,000 | 2,626,000 |
| $SO_2$ | 5 | 5 | 10 | 10 | 13 | 5 | 5 | 10 | 10 | 13 |
| $NO_x$ | 800 | 731 | 1,541 | 1,639 | 2,106 | 824 | 738 | 1,502 | 1,555 | 2,057 |
| VOC | 47 | 43 | 90 | 96 | 123 | 48 | 43 | 88 | 91 | 120 |
| CO | 340 | 311 | 656 | 697 | 896 | 351 | 314 | 639 | 662 | 875 |
| $CH_4$ | 20 | 18 | 38 | 40 | 52 | 20 | 18 | 37 | 38 | 50 |

*Natural gas burned in furnace and water heater.
Source: Reference 15.

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

| | Wood frame house | | | | | CMU house | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Lake Charles | Tucson | St. Louis | Denver | Minneapolis | Lake Charles | Tucson | St. Louis | Denver | Minneapolis |
| **Emission, kg** | | | | | | | | | | |
| Particulate matter | 2 | 2 | 2 | 2 | 3 | 3 | 4 | 4 | 4 | 4 |
| $CO_2$ | 1,440 | 1,500 | 1,680 | 1,860 | 2,160 | 2,660 | 2,720 | 2,900 | 3,080 | 3,380 |
| $SO_2$ | 2 | 2 | 3 | 3 | 3 | 4 | 4 | 5 | 5 | 5 |
| $NO_x$ | 13 | 14 | 15 | 17 | 20 | 25 | 25 | 27 | 28 | 31 |
| VOC | 2 | 2 | 3 | 3 | 4 | 4 | 5 | 5 | 5 | 6 |
| CO | 13 | 14 | 15 | 17 | 20 | 24 | 25 | 27 | 28 | 31 |
| $CH_4$ | 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 13.

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

| | Wood frame house | | | | | CMU house | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Lake Charles | Tucson | St. Louis | Denver | Minneapolis | Lake Charles | Tucson | St. Louis | Denver | Minneapolis |
| **Emission, lb** | | | | | | | | | | |
| Particulate matter | 4 | 4 | 5 | 5 | 6 | 8 | 8 | 8 | 9 | 10 |
| $CO_2$ | 3,180 | 3,310 | 3,710 | 4,110 | 4,770 | 5,870 | 6,000 | 6,400 | 6,800 | 7,460 |
| $SO_2$ | 5 | 5 | 6 | 7 | 8 | 9 | 10 | 10 | 11 | 12 |
| $NO_x$ | 29 | 30 | 34 | 38 | 44 | 54 | 55 | 59 | 63 | 69 |
| VOC | 5 | 5 | 6 | 7 | 8 | 10 | 10 | 11 | 11 | 12 |
| CO | 29 | 30 | 34 | 38 | 44 | 54 | 55 | 59 | 62 | 68 |
| $CH_4$ | 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 13.

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

| | Wood frame house | | | | | CMU house | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Lake Charles | Tucson | St. Louis | Denver | Minneapolis | Lake Charles | Tucson | St. Louis | Denver | Minneapolis |
| **Emission, kg** | | | | | | | | | | |
| Particulate matter | 64 | 64 | 101 | 113 | 143 | 130 | 129 | 165 | 175 | 206 |
| $CO_2$ | 471,000 | 431,000 | 902,000 | 960,000 | 1,234,000 | 502,000 | 453,000 | 897,000 | 929,000 | 1,223,000 |
| $SO_2$ | 34 | 36 | 46 | 54 | 67 | 106 | 108 | 117 | 125 | 138 |
| $NO_x$ | 404 | 375 | 751 | 803 | 1,029 | 493 | 457 | 812 | 844 | 1,085 |
| VOC | 25 | 23 | 45 | 48 | 62 | 30 | 27 | 48 | 50 | 64 |
| CO | 172 | 159 | 318 | 340 | 435 | 196 | 180 | 330 | 343 | 444 |
| $CH_4$ | 10 | 9 | 18 | 19 | 25 | 11 | 11 | 19 | 20 | 26 |

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

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

| | Wood frame house | | | | | CMU house | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Lake Charles | Tucson | St. Louis | Denver | Minneapolis | Lake Charles | Tucson | St. Louis | Denver | Minneapolis |
| **Emission, lb** | | | | | | | | | | |
| Particulate matter | 141 | 141 | 224 | 249 | 315 | 286 | 285 | 364 | 386 | 455 |
| $CO_2$ | 1,040,000 | 953,000 | 1,991,000 | 2,119,000 | 2,722,000 | 1,109,000 | 1,000,000 | 1,980,000 | 2,051,000 | 2,698,000 |
| $SO_2$ | 76 | 80 | 102 | 118 | 148 | 233 | 238 | 259 | 275 | 305 |
| $NO_x$ | 892 | 829 | 1,657 | 1,773 | 2,271 | 1,088 | 1,009 | 1,791 | 1,862 | 2,395 |
| VOC | 54 | 51 | 99 | 106 | 136 | 65 | 61 | 107 | 111 | 142 |
| CO | 379 | 352 | 703 | 750 | 959 | 432 | 398 | 729 | 757 | 981 |
| $CH_4$ | 22 | 20 | 40 | 43 | 55 | 25 | 23 | 42 | 44 | 57 |

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

accounts for approximately 90% 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 CMU house. Approximately 98% of the $CO_2$ emissions are from the combustion of natural gas appliances in the wood frame house. Approximately 80% of the $NO_x$ emissions are from the combustion of natural gas appliances in the CMU house. 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 VOC, CO, and $CH_4$.

### 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.[16, 17] 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 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).[18] This is heat lost primarily in exhaust gases from the kiln and cooler and also heat loss by radiation from the kiln shell and other hot surfaces. No data are available on waste heat from other stages of producing concrete, 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.[19] 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 cement-based components is from cement manufacturing.[4] 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 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: Tucson, Arizona; Lake Charles, Louisiana; St. Louis, Missouri, Denver, Colorado; and Minneapolis, Minnesota.

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 profiles of concrete, CMUs, mortar, grout, and 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 always 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 99% of life cycle energy use of the CMU house and the wood frame house. Less than 1% of the life cycle energy is due to manufacturing cement and producing concrete, CMUs, mortar, grout, and stucco. The house life cycle energy is primarily a function of climate and occupant behavior. Furthermore, although the CMU house contains more embodied energy than the wood frame house, after 7 years in Denver, for example, the cumulative energy-use of the wood frame house surpasses that of the 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 emissions from the production 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 particulate matter (60%) and $SO_2$ emissions (90%) are from the production of cement-based materials. Most of the emissions of $CO_2$ (95%), $NO_x$ (85%), CO (90%), VOC (85%), and $CH_4$ (90%) are from the combustion of household natural gas for heating and hot water.

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 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

The research reported in this paper (PCA R&D Serial No. 2465) was conducted by Construction Technology Laboratories, Inc. and JAN Consultants, with the sponsorship of the Portland Cement Association (PCA Project Index No. 94-04, CTL Project Number 180009). The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the data presented. The contents do not necessarily reflect the views of the Portland Cement Association.

## 8. REFERENCES


1. *Life Cycle Assessment: Inventory Guidelines and Principles*, EPA/600/R-92/245, U.S. Environmental Protection Agency, Risk Reduction Engineering Laboratory, Cincinnati, OH, February 1993.

2. "Guidelines for Life-Cycle Assessment: A Code of Practice", Society of Environmental Toxicology and Chemistry, Pensacola, FL, 1993.

3. "Environmental Management - Life Cycle Assessment - Principles and Framework", ANSI/ISO 14040, International Organization for Standardization, Geneva, Switzerland, 1997.

4. Nisbet, M.A., VanGeem, M.G., Gajda, J., Marceau, M.L., "Environmental Life Cycle Inventory of Portland Cement Concrete", PCA R&D Serial No. 2137, Portland Cement Association, Skokie, IL, June 2000.

5. *1998 International Energy Conservation Code*, International Code Council, Falls Church, VA, March 1998.

6. Gajda, J., and VanGeem, M.G., "Energy Use in Residential Housing: A Comparison of Concrete Masonry and Wood Frame Walls", PCA R&D Serial No. 2429, Portland Cement Association, Skokie, IL, May 2000.

7. Visual DOE 2.6, Version 2.61, Eley Associates, San Francisco, CA, 1999.

8. "1998 Characteristics of New Housing - Current Construction Reports", Publication No. C25/98-A, U.S. Department of Housing and Urban Development and U.S. Department of Commerce, Washington, DC, July 1999.

9. PCA Economic Department, Portland Cement Association, Skokie, IL, 1999.

10. "Energy Efficient Design of New Buildings, Except Low-Rise Residential Buildings", ASHRAE Standard 90.1-1999, American Society for Heating Refrigerating, and Air Conditioning Engineers, Atlanta, GA, 1999.

11. "Energy Efficient Design of New Low-Rise Residential Buildings", ASHRAE Standard 90.2-1993, American Society for Heating Refrigerating, and Air Conditioning Engineers, Atlanta, GA, 1993.

12. "Ventilation for Acceptable Indoor Air Quality", ASHRAE Standard 62-1989, American Society for Heating Refrigerating, and Air Conditioning Engineers, Atlanta, GA, 1989.

13. "LCI Data for Petroleum Production and Refining Including those Resulting in the Production of Asphalt", Tables A-5 and A-28b, Franklin Associates, Prairie Village, KS, 1998.

14. *Handbook for Criteria Pollutant Inventory Development: A Beginner's Guide to Point and Area Sources*, U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC, September 1999.

15. *Compilation of Air Pollutant Emission Factors*, Section 1.4, "Natural Gas Combustion," Tables 1.4-1 and 1.4-2, AP-42, Fifth Edition (Updated March 1998), U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC, 1995.

16. Hobbs, G. and Kay, T., "Reclamation and Recycling of Building Materials: Industry Position Report", Building Research Establishment, London, Great Britain, January 2000.

17. Zev Kalin & Associates, and the Centre for Studies in Construction, University of Western Ontario, "The State of Demolition Waste Recycling in Canada", Forintek Canada Corp., 1993.

18. Nisbet, M.A., "Life Cycle Inventory of the Cement Manufacturing Process", PCA R&D Serial No. 2095, Portland Cement Association, Skokie IL, 1996; updated with data from "U.S. and Canadian Labor-Energy Input Survey", Portland Cement Association, Skokie IL, October 1999.

19. Zmeureanu, R. and Marceau, M., "Evaluating the Energy Impact of Peoples' Behaviour in a House: A Case Study". *ASCE Journal of Architectural Engineering*. September 1999.

# 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

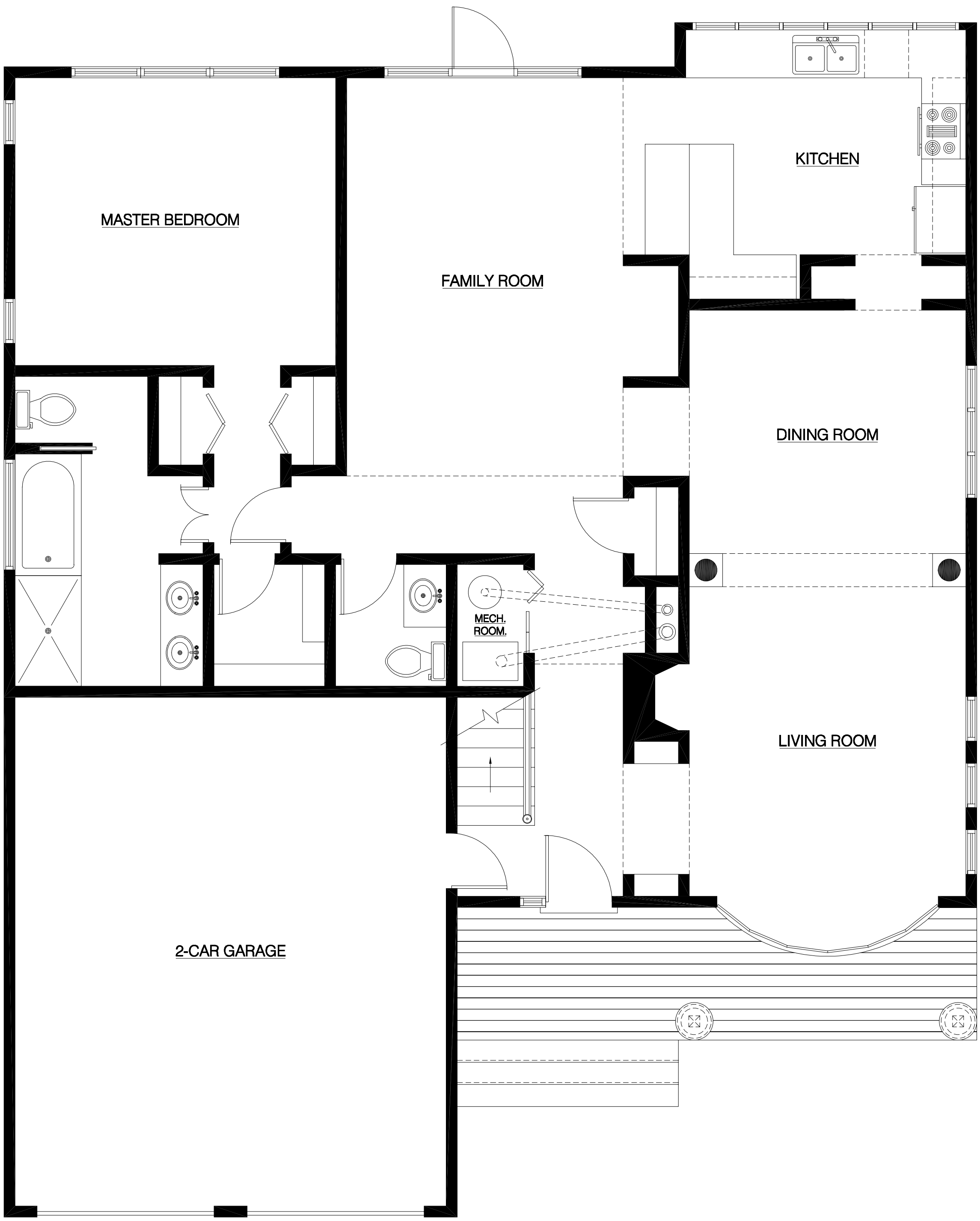


**Figure B-1. Floor plan of the lower level.**

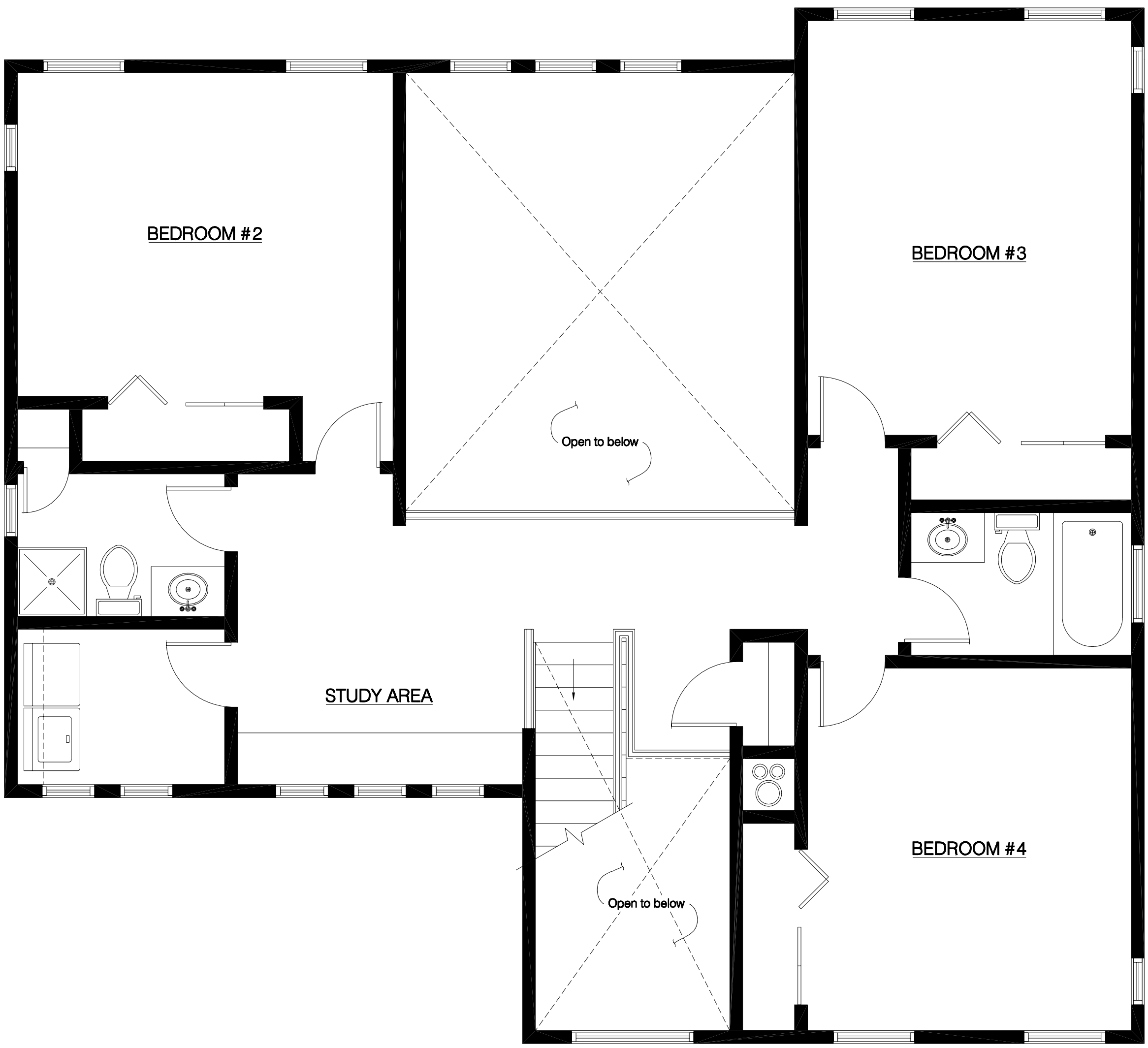


**Figure B-2. Floor plan of the upper level.**

**Figure B-3. Front elevation.**

**Figure B-4. Rear elevation.**

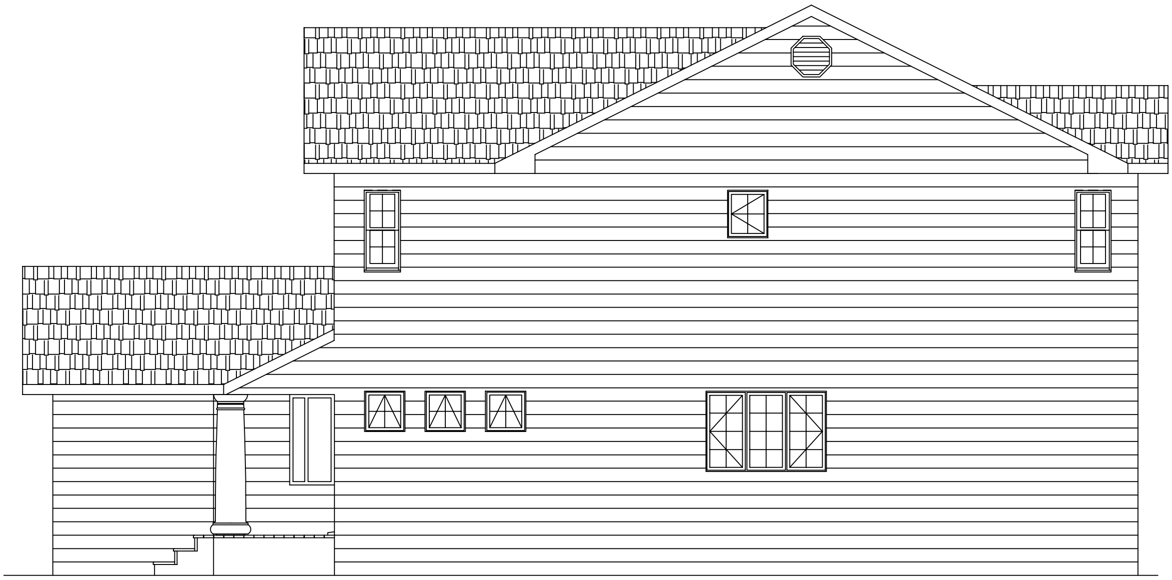

**Figure B-5. Right elevation.**

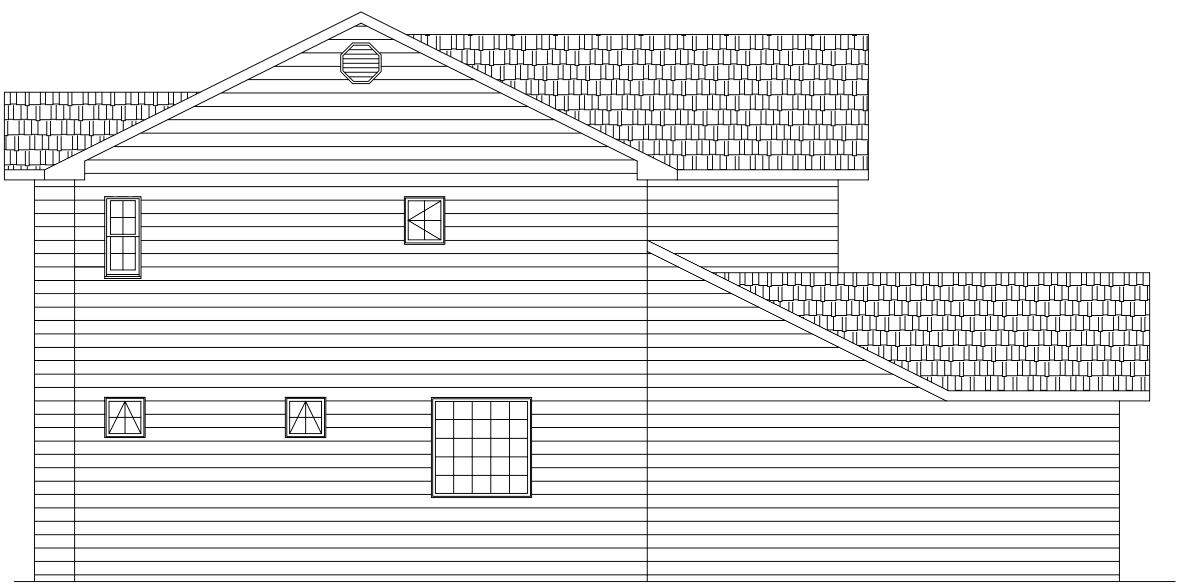

**Figure B-6. Left elevation.**

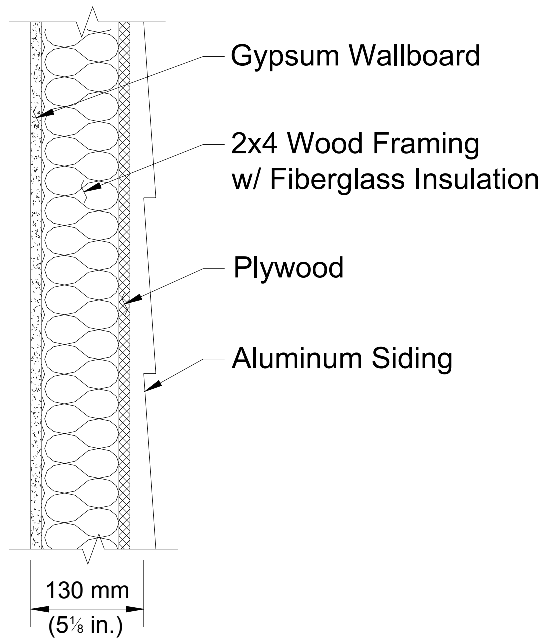


**Figure B-7. Wood frame wall cross-section.**

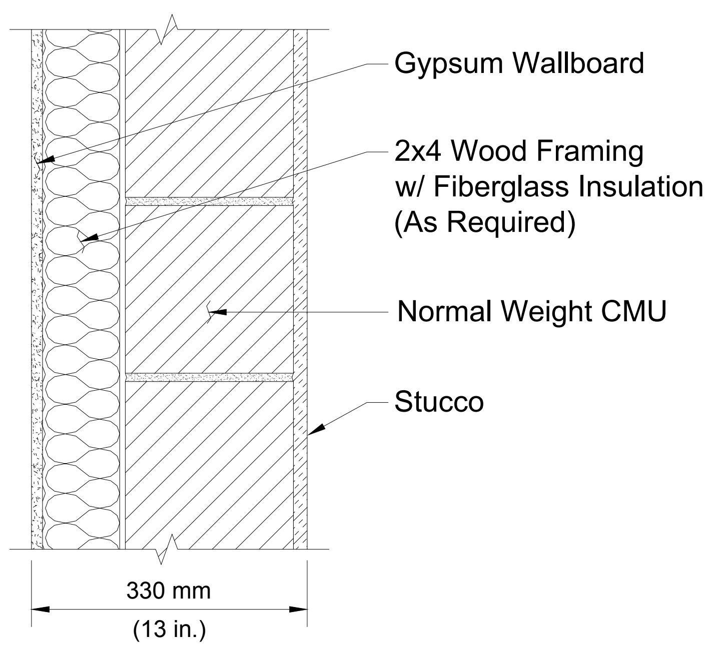


**Figure B-8. CMU wall cross-section.**

# APPENDIX C – MATERIALS LIST

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

| | Wood frame house | | | | | Normal weight CMU house | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Material, kg** | **Lake Charles** | **Tucson** | **St. Louis** | **Denver** | **Minneapolis** | **Lake Charles** | **Tucson** | **St. Louis** | **Denver** | **Minneapolis** |
| Ready-mixed concrete | 70,661 | 76,166 | 92,682 | 109,198 | 136,725 | 70,661 | 76,166 | 92,682 | 109,198 | 136,725 |
| CMUs, normal weight | 0 | 0 | 0 | 0 | 0 | 63,504 | 63,504 | 63,504 | 63,504 | 63,504 |
| 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 | 3,736 | 3,949 | 4,304 | 4,246 | 4,317 | 4,529 | 4,742 | 5,097 |
| 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 | 2,137 | 2,350 | 2,705 | 3,181 | 3,252 | 3,465 | 3,678 | 4,032 |
| 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 | 120 | 209 | 359 | 120 | 150 | 120 | 209 | 359 |
| Insulation, fiberglass | 544 | 544 | 544 | 627 | 627 | 326 | 326 | 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** | **156,900** | **173,800** | **201,900** | **260,300** | **265,900** | **282,800** | **299,700** | **327,700** |

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

| | Wood frame house | | | | | Normal weight CMU house | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Material, lb** | **Lake Charles** | **Tucson** | **St. Louis** | **Denver** | **Minneapolis** | **Lake Charles** | **Tucson** | **St. Louis** | **Denver** | **Minneapolis** |
| Ready-mixed concrete | 155,780 | 167,918 | 204,329 | 240,741 | 301,426 | 155,780 | 167,918 | 204,329 | 240,741 | 301,426 |
| CMUs, normal weight | 0 | 0 | 0 | 0 | 0 | 140,001 | 140,001 | 140,001 | 140,001 | 140,001 |
| 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 | 8,237 | 8,706 | 9,488 | 9,360 | 9,517 | 9,986 | 10,455 | 11,236 |
| 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 | 4,712 | 5,181 | 5,963 | 7,013 | 7,170 | 7,639 | 8,108 | 8,890 |
| 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 | 264 | 461 | 791 | 265 | 331 | 264 | 461 | 791 |
| Insulation, fiberglass | 1,198 | 1,198 | 1,198 | 1,382 | 1,382 | 719 | 719 | 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** | **345,900** | **383,200** | **445,000** | **573,800** | **586,200** | **623,500** | **660,800** | **722,600** |

*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 | | | | | Normal weight CMU house | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Lake Charles** | **Tucson** | **St. Louis** | **Denver** | **Minneapolis** | **Lake Charles** | **Tucson** | **St. Louis** | **Denver** | **Minneapolis** |
| **Fuel input, unit** | | | | | | | | | | |
| Coal, kg | 789 | 850 | 1034 | 1219 | 1526 | 2746 | 2807 | 2992 | 3176 | 3483 |
| Gasoline, L | 0.38 | 0.41 | 0.50 | 0.59 | 0.74 | 1.34 | 1.37 | 1.45 | 1.54 | 1.69 |
| Liquefied petroleum gas, L | 0.12 | 0.13 | 0.15 | 0.18 | 0.23 | 0.41 | 0.42 | 0.45 | 0.47 | 0.52 |
| Diesel fuel, L | 836 | 882 | 1019 | 1158 | 1388 | 1715 | 1761 | 1899 | 2038 | 2268 |
| Natural gas, $m^3$ | 0.25 | 0.22 | 0.47 | 0.50 | 0.65 | 0.25 | 0.23 | 0.46 | 0.48 | 0.63 |
| Petroleum coke, kg | 157 | 169 | 206 | 242 | 303 | 546 | 558 | 594 | 631 | 692 |
| Residual oil, L | 1.20 | 1.29 | 1.57 | 1.85 | 2.32 | 4.17 | 4.27 | 4.55 | 4.83 | 5.29 |
| Wastes, kg | 127 | 137 | 167 | 197 | 247 | 444 | 454 | 483 | 513 | 563 |
| Electricity, 1000 kWh | 1468 | 1668 | 1330 | 1139 | 1140 | 1456 | 1683 | 1296 | 1095 | 1116 |
| | | | | | | | | | | |
| **Energy input, GJ** | | | | | | | | | | |
| Coal | 21 | 23 | 28 | 33 | 42 | 75 | 76 | 81 | 87 | 95 |
| Gasoline | 0.013 | 0.014 | 0.018 | 0.021 | 0.026 | 0.047 | 0.048 | 0.051 | 0.054 | 0.059 |
| Liquefied petroleum gas | 0.003 | 0.003 | 0.004 | 0.004 | 0.005 | 0.010 | 0.010 | 0.011 | 0.011 | 0.012 |
| Diesel fuel | 32 | 34 | 39 | 45 | 54 | 66 | 68 | 73 | 79 | 87 |
| Natural gas | 9,162 | 8,371 | 17,646 | 18,765 | 24,116 | 9,445 | 8,464 | 17,211 | 17,814 | 23,565 |
| Petroleum coke | 5 | 6 | 7 | 8 | 10 | 19 | 19 | 20 | 21 | 24 |
| Residual oil | 0.049 | 0.053 | 0.065 | 0.076 | 0.095 | 0.172 | 0.176 | 0.187 | 0.199 | 0.218 |
| Wastes | 3 | 3 | 4 | 5 | 6 | 10 | 11 | 11 | 12 | 13 |
| Electricity | 5,284 | 6,004 | 4,786 | 4,102 | 4,103 | 5,242 | 6,057 | 4,666 | 3,940 | 4,018 |
| **Total energy input (rounded)** | **14,500** | **14,400** | **22,500** | **23,000** | **28,300** | **14,900** | **14,700** | **22,100** | **22,000** | **27,800** |

*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 | | | | | Normal weight CMU house | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Lake Charles | Tucson | St. Louis | Denver | Minneapolis | Lake Charles | Tucson | St. Louis | Denver | Minneapolis |
| **Fuel input, unit** | | | | | | | | | | |
| Coal, ton | 0.87 | 0.94 | 1.14 | 1.34 | 1.68 | 3.03 | 3.09 | 3.30 | 3.50 | 3.84 |
| Gasoline, gallon | 0.10 | 0.11 | 0.13 | 0.16 | 0.20 | 0.35 | 0.36 | 0.38 | 0.41 | 0.45 |
| Liquefied petroleum gas, gallon | 0.03 | 0.03 | 0.04 | 0.05 | 0.06 | 0.11 | 0.11 | 0.12 | 0.13 | 0.14 |
| Diesel fuel, gallon | 221 | 233 | 269 | 306 | 367 | 453 | 465 | 502 | 538 | 599 |
| Natural gas, million $ft^3$ | 8.68 | 7.93 | 16.72 | 17.79 | 22.86 | 8.95 | 8.02 | 16.31 | 16.88 | 22.33 |
| Petroleum coke, ton | 0.17 | 0.19 | 0.23 | 0.27 | 0.33 | 0.60 | 0.61 | 0.66 | 0.70 | 0.76 |
| Residual oil, gallon | 0.32 | 0.34 | 0.42 | 0.49 | 0.61 | 1.10 | 1.13 | 1.20 | 1.28 | 1.40 |
| Wastes, ton | 0.14 | 0.15 | 0.18 | 0.22 | 0.27 | 0.49 | 0.50 | 0.53 | 0.57 | 0.62 |
| Electricity,1000 kWh | 1468 | 1668 | 1330 | 1139 | 1140 | 1456 | 1683 | 1296 | 1095 | 1116 |
| | | | | | | | | | | |
| **Energy input, MBtu** | | | | | | | | | | |
| Coal | 20 | 22 | 27 | 31 | 39 | 71 | 72 | 77 | 82 | 90 |
| Gasoline | 0.013 | 0.014 | 0.017 | 0.020 | 0.025 | 0.044 | 0.045 | 0.048 | 0.051 | 0.056 |
| Liquefied petroleum gas | 0.003 | 0.003 | 0.004 | 0.004 | 0.005 | 0.009 | 0.010 | 0.010 | 0.011 | 0.012 |
| Diesel fuel | 31 | 32 | 37 | 42 | 51 | 63 | 64 | 69 | 75 | 83 |
| Natural gas | 8,684 | 7,934 | 16,725 | 17,786 | 22,857 | 8,952 | 8,022 | 16,313 | 16,884 | 22,335 |
| Petroleum coke | 5 | 5 | 7 | 8 | 10 | 18 | 18 | 19 | 20 | 22 |
| Residual oil | 0.047 | 0.050 | 0.061 | 0.072 | 0.090 | 0.163 | 0.166 | 0.177 | 0.188 | 0.206 |
| Wastes | 3 | 3 | 4 | 4 | 5 | 10 | 10 | 11 | 11 | 12 |
| Electricity | 5,008 | 5,691 | 4,537 | 3,888 | 3,889 | 4,969 | 5,741 | 4,422 | 3,735 | 3,809 |
| **Total energy input (rounded)** | **13,800** | **13,700** | **21,300** | **21,800** | **26,900** | **14,100** | **13,900** | **20,900** | **20,800** | **26,400** |

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