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Comparison of the Life Cycle Assessments of an Insulating Concrete Form House and a Wood Frame House

ABSTRACT: An environmental life cycle assessment (LCA) was conducted on a single-family house modeled with two types of exterior walls: wood framed and insulating concrete form (ICF). The LCA was carried out in accordance with the guidelines of the ISO 14000 family of standards. The LCA includes the inputs and outputs of energy and materials from (i) extraction and manufacturing of materials, (ii) construction, (iii) occupancy (including heating and cooling energy use), and (iv) maintenance over a 100-year life. The houses were modeled in five cities representing a range of U.S. climates: Miami, Phoenix, Seattle, Washington, and Chicago. The results show that in almost all cases, for a given climate, the environmental impact in each category is greater (worse) for the wood house than for the ICF house. The reduction in environmental impacts provided by the ICF house compared to the wood-frame house varied from 3 % to 6 %, depending on climate. Furthermore, the most significant environmental impacts are not from construction products but from the production and household use of electricity and natural gas. Since the ICF walls are more highly insulating and energy efficient than the wood-frame walls, the ICF house has lower impacts. Among construction products used in the house, wood products and copper tubing have the largest environmental load, followed by cement-based products.

KEYWORDS: concrete, environmental impact, house, insulating concrete form, life cycle assessment

Introduction

This paper presents the results of an assessment of the environmental attributes of concrete construction compared to wood-framed construction. The goal of the work is to compare the environmental impacts of a concrete house to those of a wood-frame house. To achieve this goal we used life cycle inventory data to conduct a life cycle assessment on two kinds of houses: one with insulating concrete form (ICF) walls, the other with wood-frame walls. The work was carried out in accordance with the guidelines in the International Organization of Standardization (ISO) standards Environmental Management - Life Cycle Assessment - Principles and Framework (ISO Standard 14040) [1] and Environmental Management - Life Cycle Assessment - Goal and Scope Definition and Inventory Analysis (ISO Standard 14041) [2].

The work reported in this paper is discussed in much greater detail in a life cycle *assessment* (LCA) report by the Portland Cement Association [3]. However, the LCA report contains much more detail—such as comparing the results from different life cycle impact assessment methods—than can be summarized here. Further, the LCA report draws on life cycle *inventory* (LCI) data we collected and described in various LCI reports [4,5] and energy simulations we performed and described in a separate report on energy use [6]. Summaries of these LCI reports have also been published [7,8].

Life Cycle Assessment

Performing a LCA is one way to assess a product's environmental aspects and the potential impacts it has on the natural environment. The first phase of a LCA is to conduct an inventory analysis of the product's inputs and outputs—from raw material acquisition through production, use, and disposal. The second phase is to assess the potential environmental impacts associated with those inputs and outputs. The third phase is to interpret the result of the inventory analysis and the impact assessment phases in relation to the

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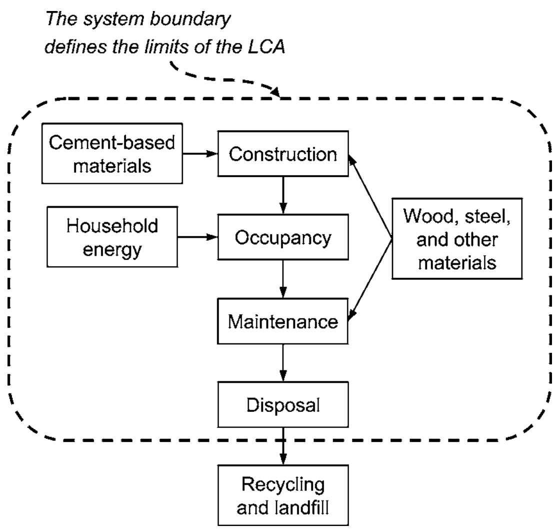

FIG. 1—*System boundary for life cycle assessment of a house.*

objectives of the study. These three phases are commonly referred to as (i) life cycle inventory analysis, (ii) life cycle impact assessment, and (iii) life cycle interpretation, respectively.

Scope

The functional unit in a LCA is defined in ISO Standard 14040 [1] as the quantified performance of a product system. In this work, the functional unit is a single-family house. The system boundary is the interface between the functional unit and the environment (Fig. 1). In this work, the system boundary includes the inputs and outputs of energy and material from construction, occupancy, and maintenance. It excludes human resources, infrastructure, accidental spills, impacts caused by people, and waste treatment after disposal. In general, the life cycle inventory data include second order system boundaries, that is, primary flows plus energy and material flows including operations.

House Description

Layout

The house designs are based on typical houses currently built in the United States. The same layout is assumed for both the wood-frame and the ICF houses. The houses are designed to meet the requirements of the 1998 International Energy Conservation Code (IECC) because, at the time this work was performed, it was the most widely used energy code in the United States.

Each house is a two-story single-family building with four bedrooms and an attached two-car garage. Each house has 228 square metres (2450 square feet) of living space, which is somewhat larger than the 1998 U.S. average of 203 square metres (2190 square feet) [9] but smaller than the current average. The floor area is based on the average size ICF house constructed in the United States [10].

Climate

Since the energy use of a building depends on local climate, the houses are modeled in a variety of regions. Five cities were chosen that represent the range of climates in the United States: Miami, Phoenix, Seattle, Washington, and Chicago. Household energy use is modeled using VisualDOE 2.6 energy simulation software [11].

Building Envelope

The building envelope in each location meets the minimum requirements of the 1998 IECC using standard building materials [12]. The IECC minimum requirements for thermal resistance are presented below for the five cities where the houses are modeled (Table 1).

TABLE 1—*International Energy Conservation Code maximum U factors.*

	Wood-frame wall		Mass wall		Roof		Window[a]	
Location	W/ (m^2 K)	Btu/ (h ft^2 °F)	W/ (m^2 K)	Btu/ (h ft^2 °F)	W/ (m^2 K)	Btu/ (h ft^2 °F)	W/ (m^2 K)	Btu/ (h ft^2 °F)
Miami	0.937	0.165	1.164	0.205	0.278	0.049	4.2	0.74
Phoenix	0.960	0.169	1.187	0.209	0.238	0.042	2.4	0.47
Seattle	0.653	0.115	0.750	0.132	0.187	0.033	1.7	0.30
Washington	0.642	0.113	0.732	0.129	0.182	0.032	1.7	0.30
Chicago	0.466	0.082	0.466	0.082	0.148	0.026	1.6	0.28

[a]The code also requires that windows have a solar heat gain coefficient (SHGC) less than 0.4 in Miami and Phoenix.

In all cities, the houses are slab-on-grade construction. 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 and has a U-factor of 1.53 W/m^2 K (0.27 Btu/h ft^2 °F).

The exterior walls of the wood-frame houses consist of medium-colored aluminum siding, 12 mm (1/2 in.) plywood, RSI-1.9 (R-11) fiberglass batt insulation, and 12 mm (1/2 in.) painted gypsum board. This is typical of wood-framed construction in the United States.

The exterior walls of the ICF houses consist of medium-colored aluminum siding; a flat panel ICF system with 50 mm (2 in.) expanded polystyrene insulation, 150 mm (6 in.) of normal weight concrete, and 50 mm (2 in.) expanded polystyrene insulation with plastic ties; and 12 mm (1/2 in.) painted gypsum board; for a total R-value of 3.2 m^2 K/W (18 h ft^2 °F/Btu). This is typical of ICF construction in the United States, regardless of climate. Interior walls and floors are wood framed and uninsulated.

Roofs are wood-frame construction with RSI-3.3, RSI-5.3, or RSI-6.7 (R-19, R-30, or R-38) fiberglass batt insulation (depending on location). 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 assembly U-factors used in the analyses are presented below (Table 2). In most cases, using typical building materials and typical ICF systems results in assemblies that exceed the IECC U-factor requirements. In all cases but one (the wood-frame house in Chicago), the R-values of ICF and wood-frame walls significantly exceed IECC requirements. Wood-frame walls have R-values that range from 0 % to 105 % in excess of IECC requirements, while ICF walls have R-values that range from 50 % to 210 % in excess of IECC requirements.

Assumptions

In order to create a realistic house model, many assumptions about occupant behavior and house performance have been made. The assumptions ensure that comparisons between houses are valid. The houses have identical controls, schedules, air-infiltration rates, and system performance characteristics (lighting; water heating; and heating, ventilating, and air conditioning). Other than energy for heating and cooling, the houses also have identical occupant energy use. Maintenance, repair, and replacement of various building components are included over the 100-year life [3].

TABLE 2—*Assembly U factors.*

	Wood-frame wall		ICF wall		Roof[a]		Window	
Location	W/ (m^2 K)	Btu/ (h ft^2 °F)	W/ (m^2 K)	Btu/ (h ft^2 °F)	W/ (m^2 K)	Btu/ (h ft^2 °F)	W/ (m^2 K)	Btu/ (h ft^2 °F)
Miami	0.47	0.082	0.31	0.055	0.27	0.048	2.4	0.43
Phoenix	0.47	0.082	0.31	0.055	0.18	0.032	2.4	0.43
Seattle	0.47	0.082	0.31	0.055	0.18	0.032	1.5	0.27
Washington	0.47	0.082	0.31	0.055	0.18	0.032	1.5	0.27
Chicago	0.47	0.082	0.31	0.055	0.15	0.026	1.5	0.27

[a]RSI-3.3 (R-19) attic insulation is used in Miami, RSI-6.7 (R-38) attic insulation is used in Chicago, and RSI-5.3 (R-30) attic insulation is used in the remaining cities.

TABLE 3—*Annual occupant energy use by location.*

		Annual electricity use		Annual natural gas use		
Location	Exterior wall	GJ	kWh	GJ	therms	Total energy GJ
Miami	Wood frame	65.3	18 130	41.1	390	106.4
	ICF	61.1	16 980	39.6	380	100.7
Phoenix	Wood frame	75.6	21 000	69.5	670	145.1
	ICF	70.2	19 500	63.6	600	133.8
Seattle	Wood frame	35.4	9 840	184.6	1 750	220.0
	ICF	34.6	9 600	165.7	1 570	200.3
Washington	Wood frame	43.4	12 060	170.2	1 610	213.7
	ICF	41.5	11 520	155.7	1 480	197.1
Chicago	Wood frame	41.5	11 540	214.4	2 030	256.0
	ICF	39.8	11 060	195.5	1 850	235.3

Phase 1: Life Cycle Inventory Analysis

Data Sources

The life cycle inventory data come from a variety of sources. The data for cement-based materials come from peer-reviewed published reports [4,5]. All other data comes from the databases in the commercially available LCA software tool, SimaPro [13]. North American data were used whenever available.

Unfortunately, not all materials in the houses could be incorporated into the LCA because some materials were not represented in the available databases. However, these materials constitute a minor fraction of the mass of a house, and they represent components that are used in similar amounts in the two houses. The materials excluded are primarily: gypsum wallboard, carpet and underpads, roofing materials, and sealants.

Household Occupant Energy Use

VISUALDOE 2.6 energy simulation software is used to model the annual household energy use [11,6]. This software uses the U.S. Department of Energy DOE-2.1E hourly simulation tool as the calculation engine. It simulates hourly energy use and peak demand over a one-year period. Programs that model hourly energy use are more accurate than other methods and are necessary in order to capture the thermal mass effects in concrete walls, such as ICF systems. Because heating and cooling load vary with solar orientation, the houses are modeled four times: once for each orientation of the façade facing the four principal cardinal directions (north, south, east, and west). The total energy for heating, cooling, hot water, and occupant use is averaged to obtain energy use that is independent of building orientation. Annual occupant energy use (Table 3) shows that, in each of the five climates, the ICF houses have lower occupant energy use than the wood-frame houses.

Another important difference between the two houses is that the heating, ventilating, and air-conditioning (HVAC) size is smaller in the ICF houses than in the wood-frame houses. The HVAC system requirements as determined by the energy simulation software are shown below (Table 4). The thermal mass of the ICF house moderates temperature swings and peak loads, and results in smaller HVAC system requirements.

Phase 2: Life Cycle Impact Assessment

The second phase consists of category definition, classification, and characterization. Category definition consists of identifying which impact categories are relevant for the product being studied. Classification consists of grouping related substances into impact categories. For example, carbon dioxide (CO_2), methane, and nitrous oxide (N_2O) contribute to climate change; so they can be grouped together in the impact category, climate change.

According to ISO Standard 14041 [2], the mandatory step in life cycle impact assessment is characterization. In characterization, weighting factors are assigned according to a substance's relative contribu-

TABLE 4—*Required HVAC system capacity as determined by energy simulation software.*

		Heating capacity		Cooling capacity	
Location	Exterior wall	kW	kBtu/h	kW	kBtu/h
Miami	Wood frame	25	87	13	44
	ICF	21	73	11	37
Phoenix	Wood frame	35	119	21	70
	ICF	30	103	18	61
Seattle	Wood frame	26	90	14	46
	ICF	21	71	11	36
Washington	Wood frame	27	93	14	48
	ICF	23	79	12	41
Chicago	Wood frame	26	90	14	46
	ICF	22	76	12	39

tion to the impact category. For example, CO_2, methane, and N_2O contribute to climate change. In terms of global warming potential, one pound of methane is 20 times more harmful than one pound of CO_2, and one pound of N_2O is 320 times more harmful than one pound of CO_2. Therefore, in assessing the potential for global warming, CO_2 is assigned a weighting factor of 1, methane a factor of 20, and N_2O a factor of 320. It is important to remember that there is no scientific basis for comparing across impact categories [14].

Life Cycle Impact Assessment Methods

According to ISO Standard Environmental Management - Life Cycle Assessment - Life Cycle Impact Assessment [14], life cycle impact assessment is not intended to estimate threshold limits, measure margins of safety, or identify, measure, or predict actual impacts. The methodology is still being developed, and there is no general and widespread practice of life cycle impact assessment at this time or an agreement on specific methodologies. Therefore, several of the available methods were used to measure the life cycle impact assessment. The methods chosen are Eco-Indicator 99, Environmental Design of Industrial Products (EDIP) 96, and Environmental Priority Strategies (EPS) 2000. Furthermore, three different weighting sets in Eco-Indicator 99 were used.

A listing of the impact categories in each method is shown below (Table 5). A complete description of the category definitions, classification methods, and characterization factors for each of the three methods is in Marceau et al. 2002 [3]. However, a brief description follows.

TABLE 5—*Impact categories for three life cycle impact assessment methods.*

Eco-Indicator 99	EDIP 96[a]	EPS 2000[b]
Carcinogens	Global warming potential	Life expectancy
Respiratory organics	Ozone depletion	Severe morbidity and suffering
Respiratory inorganics	Acidification	Morbidity
Climate change	Eutrophication	Severe nuisance
Radiation	Photochemical smog	Nuisance
Ozone layer	Ecotoxicity water, chronic	Crop growth capacity
Ecotoxicity	Ecotoxicity water, acute	Wood growth capacity
Acidification/eutrophication	Ecotoxicity soil, chronic	Fish and meat production
Land use	Human toxicity, air	Soil acidification
Minerals	Human toxicity, water	Production capacity of irrigation water
Fossil fuels	Human toxicity, soil	Production capacity of drinking water
…	Bulk waste	Depletion of reserves
…	Hazardous waste	Species extinction
…	Radioactive waste	…
…	Slags/ashes	…
…	Resources (all)	…

[a]Environmental Design of Industrial Products.
[b]Environmental Priority Strategies.

TABLE 6—*Single score summary (output from SimaPro)*[a].

		Eco-Indicator 99					
House style	Location	Egalitarian	Hierarchic	Individualist	EDIP 96	EPS 2000	Avg. reduction due to ICF (%)
Wood frame house	Miami	106 000	93 200	78 200	486 000	419 000	…
	Phoenix	132 000	120 000	95 500	603 000	551 000	…
	Seattle	144 000	154 000	101 000	599 000	851 000	…
	Washington	146 000	153 000	103 000	618 000	823 000	…
	Chicago	166 000	178 000	116 000	696 000	978 000	…
ICF house	Miami	102 000	90 400	76 300	467 000	412 000	3.0
	Phoenix	124 000	113 000	91 200	568 000	525 000	5.4
	Seattle	135 000	144 000	96 100	565 000	791 000	6.1
	Washington	138 000	144 000	98 400	585 000	775 000	5.4
	Chicago	156 000	167 000	110 000	656 000	915 000	5.9

[a]No units: data have been normalized and weighted.

Eco-Indicator 99—This method is a damage-oriented approach, which is based on how a panel of experts weighted the different types of damage caused by the impact categories. The three versions of Eco-Indicator 99 reflect the subjective uncertainty inherent in LCA. Each one takes a different perspective on how to consider the potential damage from a particular substance. The egalitarian perspective takes an extremely long-term look at substances if there is any indication that they have some effect. The hierarchic perspective takes a long-term look at all substances if there is consensus regarding their effect. The individualist perspective takes a short-term look (100 years or less) at substances if there is complete proof regarding their effect.

Environmental Design of Industrial Products, EDIP 96—This method is based on normalizing values to person-equivalents in 1990 and weighting factors are equivalent to politically set (Danish) target emissions per person in 2000.

Environmental Priority Strategies, EPS—This method was designed as a tool for a company's internal product development process, and the weighting factors are based on a willingness to pay to avoid change.

Characterization

Results of the characterization phase show that in almost all cases, for a given climate the impact indicators in each category are greater (worse) for the wood house than for the ICF house. The exceptions are in the category "minerals" in the Eco-Indicator methods (1 out of 11 categories) and the category "severe nuisance" in the EPS 2000 method (1 out of 13 categories).

Normalization and Weighting

Other methods of impact assessment, such as damage assessment, normalization, and weighting, are optional. In damage assessment, impact categories that have equivalent units are added. In normalization, the impact assessment values are compared to some reference, such as the average yearly environmental load in a country divided by the number of people in the country. In weighting, the impact assessment values in several or all categories are multiplied by weighting factors and added together to get a single score. However, the weighting factors used are always subjective and reflect societal or personal values. Furthermore, according to ISO Standard 14042 [14], weighting cannot be used to make comparative assertions disclosed to the public.

In each of the five methods, the ICF house has a lower score than the wood-frame house in almost all impact categories. A summary of the normalized and weighted single-score results is shown in Table 6. The reduction in impacts provided by the ICF houses compared to the wood frame house varies from 3 % to 6 %, depending on climate, as shown in the right column.

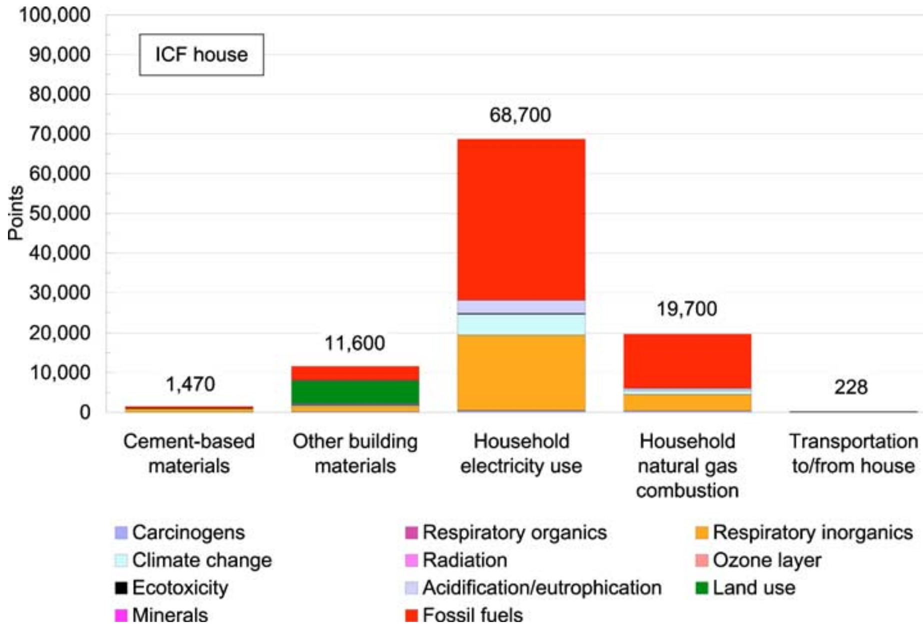

FIG. 2—*Single-score life cycle inventory assessment of ICF house in Miami showing contribution of each major process/product stage (output from SimaPro). The data have been normalized and weighted according to the Eco-Indicator 99 method using the Egalitarian perspective.*

Phase 3: Life Cycle Interpretation

A breakdown of the LCA by major process/product stage shows that most of the environmental load is from the household use of natural gas and electricity during the life of the houses. For example, Figs. 2 and 3 show the breakdown for the ICF houses in Miami and Chicago, respectively, using the egalitarian perspective of Eco-Indicator 99. Figures 4 and 5 show that the wood frame houses exhibit similar patterns. The breakdown for all houses in all locations is shown in Marceau et al. 2002 [3]. The household use of electricity and natural gas represents 84 % to 91 % of the environmental load of the ICF houses. The household use of electricity and natural gas represents 87 % to 92 % of the environmental load of the

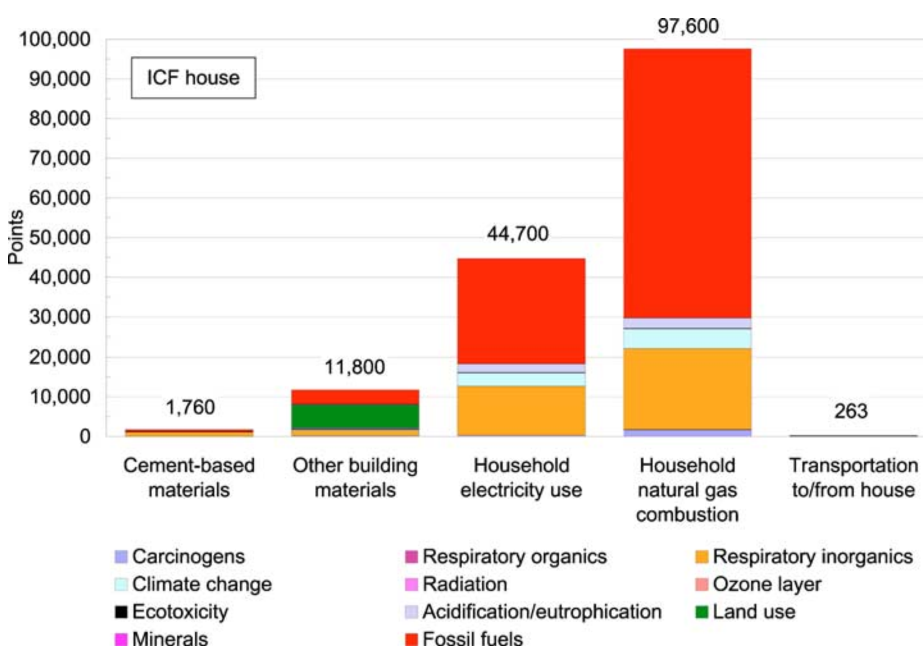

FIG. 3—*Single-score life cycle inventory assessment of ICF house in Chicago showing contribution of each major process/product stage (output from SimaPro). The data have been normalized and weighted according to the Eco-Indicator 99 method using the Egalitarian perspective.*

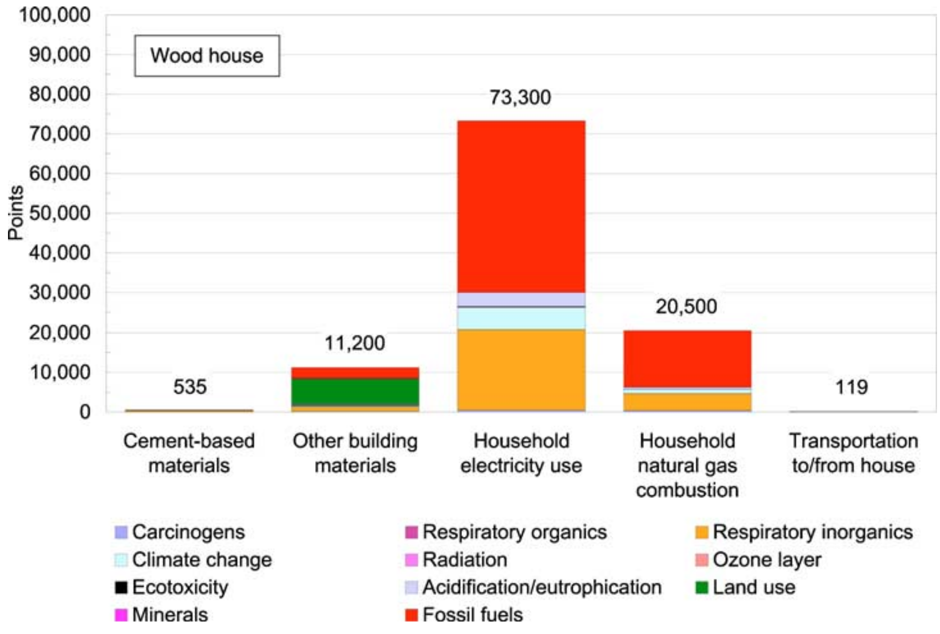

FIG. 4—*Single-score life cycle inventory assessment of wood-frame house in Miami showing contribution of each major process/product stage (output from SimaPro). The data have been normalized and weighted according to the Eco-Indicator 99 method using the Egalitarian perspective.*

wood-frame houses. Household use of energy is less in milder climates (like Miami) than in more severe climates (like Chicago), so the houses in milder climates are at the low end of the range, while houses in more severe climates are at the high end of the range. The household use of electricity (mostly for cooling) contributes the most to the total environmental load in cooling-dominant climates like Miami. Household natural gas use (mostly for heating) contributes the most to the total environmental load in heating-dominant climate like Chicago. In all locations, cement-based materials represent a small fraction of the total environmental load. Furthermore, Figs. 2 through 5 also show that the most significant impact

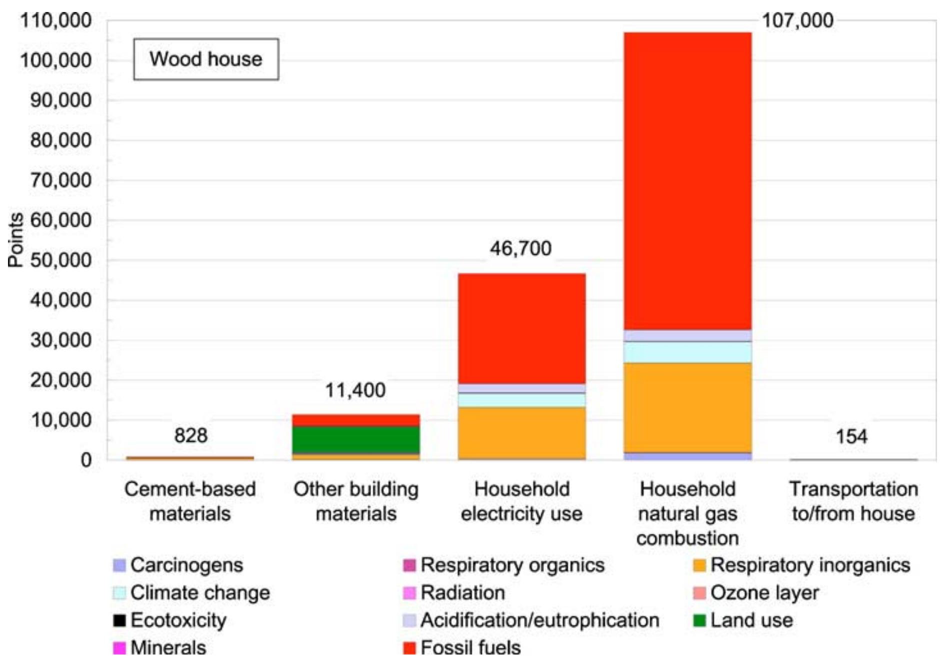

FIG. 5—*Single-score life cycle inventory assessment of wood-frame house in Chicago showing contribution of each major process/product stage (output from SimaPro). The data have been normalized and weighted according to the Eco-Indicator 99 method using the Egalitarian perspective.*

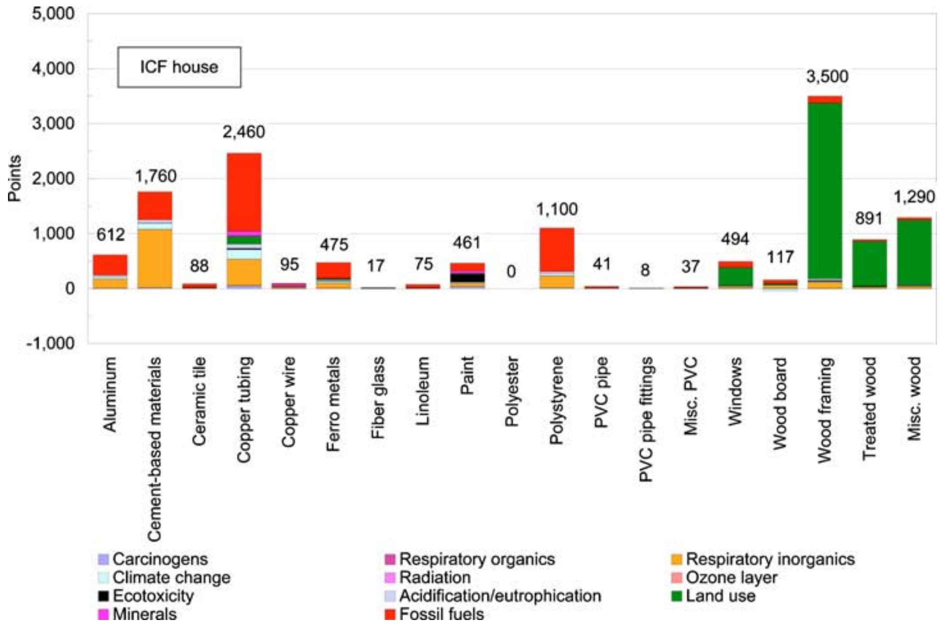

FIG. 6—*Single-score life cycle inventory assessment for construction materials in the ICF house in Chicago (output from SimaPro). The data have been normalized and weighted according to the Eco-Indicator 99 method using the Egalitarian perspective.*

categories are fossil fuel depletion and respiratory inorganics. The other methods of life cycle impact assessment produce similar results.

A breakdown of the environmental load of buildings materials shows that most of the environmental load from construction materials is due to wood and copper tubing, followed by cement-based materials. For example, Figs. 6 and 7 show a breakdown of the environmental load of buildings materials for each of the houses in Chicago using the egalitarian perspective of the Eco-Indicator 99 Method. Further, the impact categories that contribute the most to the environmental load are land use and fossil fuel depletion, primarily from wood and copper tubing. Note that wood-framed houses contain a significant amount of concrete, and ICF houses contain a significant amount of wood.

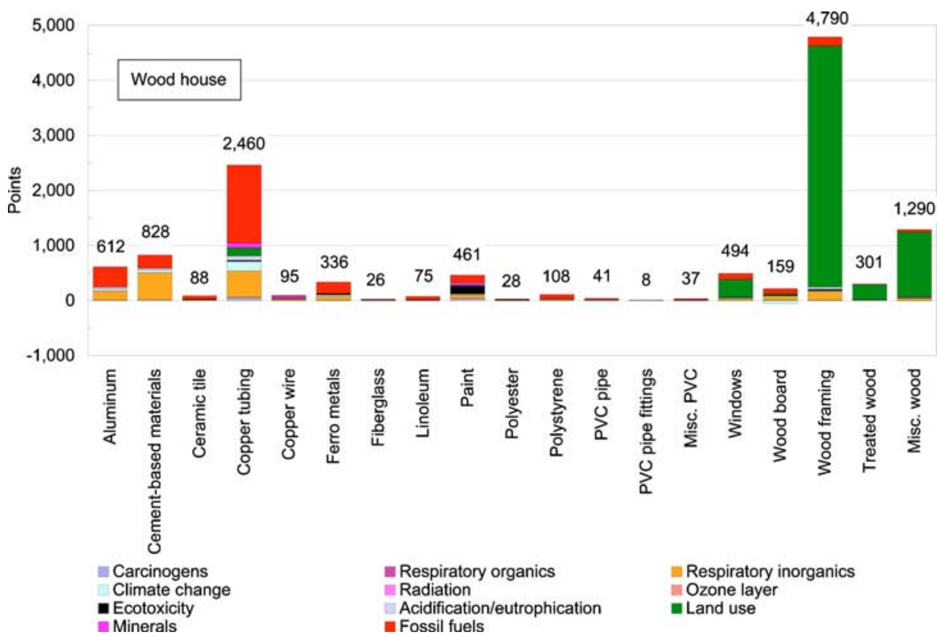

FIG. 7—*Single-score life cycle inventory assessment for construction materials in the wood-frame house in Chicago (output from SimaPro). The data have been normalized and weighted according to the Eco-Indicator 99 method using the Egalitarian perspective.*

Complete disposal scenarios have not been included in this LCA. Including complete disposal scenarios (notably decomposition of wood-based products in landfill) will not significantly alter the results of this LCA. All work was peer reviewed in accordance with ISO Standard 14040 [1].

Conclusions

This paper presents the results of a LCA of a single-family house modeled with two types of exterior walls: wood framed and ICF. The LCA was carried out in accordance with the guidelines in the ISO 14000 family of standards. The house was modeled in five cities, representing a range of U.S. climates: Miami, Phoenix, Seattle, Washington, and Chicago.

The house system boundary includes the inputs and outputs of energy and material from construction, occupancy, and maintenance. The system boundary excludes human resources, infrastructure, accidental spills, impacts caused by people, and decomposition of household components after disposal. The life of the houses is 100 years.

The LCA was conducted by first assembling the relevant LCI data from published reports and commercially available databases. The LCA software tool SimaPro was used to perform a life cycle impact assessment. Impact assessment is not completely scientific; so three different models were used. The methods chosen are Eco-Indicator 99, EDIP 96, and EPS 2000. Furthermore, three different weighting sets in Eco-Indicator 99 were used.

The data show that in almost all cases for all five methods, for a given climate, the impact indicators in each category are greater for the wood house than for the ICF house. The reduction in environmental impacts provided by the ICF house compared to the wood-frame house varied from 3 % to 6 %, depending on climate. Furthermore, in each of the five methods, the ICF house has a lower single score than the wood-frame house in almost all impact categories. The most significant environmental impacts are not from the construction materials but from the production and use of electricity and natural gas in the houses by the occupants. Furthermore, the largest impacts from these uses are in the form of depletion of fossil fuel reserves (categorized as damage to natural resources) and release to the air of respiratory inorganics (categorized as damage to human health).

When considering only the construction materials, most of the environmental load is from wood and copper tubing, with total cement-based materials third.

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