RESIDENTIAL LIFE CYCLE ASSESSMENT MODELING: COMPARATIVE CASE STUDY OF INSULATING CONCRETE FORMS AND TRADITIONAL BUILDING MATERIALS

Neethi Rajagopalan,[1] Melissa M. Bilec,[2] and Amy E. Landis[3]

ABSTRACT

Innovative, sustainable construction products are emerging in response to market demands. One potential product, insulating concrete forms (ICFs), offers possible advantages in energy and environmental performance when compared with traditional construction materials. Even though ICFs are in part derived from a petroleum-based product, the benefits in the use phase outweigh the impacts of the raw material extraction and manufacturing phase. This paper quantitatively measures ICFs' performance through a comparative life cycle assessment of wall sections comprised of ICF and traditional wood-frame. The life cycle stages included raw materials extraction and manufacturing, construction, use and end of life for a 2,450 square foot house in Pittsburgh, Pennsylvania. Results showed that even though building products such as ICFs are energy intensive to produce and thus have higher environmental impacts in the raw materials extraction and manufacturing phase, the use phase dominated in the life cycle. For the use phase, the home constructed of ICFs consumed 20 percent less energy when compared to a traditional wood-frame structure. The results of the impact assessment show that ICFs have higher impacts over wood homes in most impact categories. The high impacts arise from the raw materials extraction and manufacturing phase of ICFs. But there are a number of embedded unit processes such as disposal of solid waste and transport of natural gas that contribute to this high impact and identifying the top unit process and substance contributors to the impact category is not intuitive. Selecting different unit processes or impact assessment methods will yield dissimilar results and the tradeoffs associated with every building product should be considered after studying the entire life cycle in detail.

KEYWORDS

building products, insulating concrete forms, life cycle assessment, environmental impacts

MOTIVATION

Buildings account for 30–40 percent of the world's energy use [1]. In the United States, buildings annually use 70 percent of the nation's electricity [2] and emit around 40 percent of the country's greenhouse gas emissions [3]. The construction industry has a significant impact on resource use. The average American in their lifetime accounts for 540 tons of construction materials [4], while buildings use 40 percent of raw materials globally, equating to 3 billion tons annually [5]. Innovative building products are emerging that have the potential to reduce environmental impacts and contribute to sustainable development. Based on the four principles of green buildings: reducing energy use; minimizing external pollution and environmental damage; reducing embodied energy and resource depletion; and minimizing internal pollution and damage to health- it is clear that the entire life cycle of buildings has a huge impact on the environment [6]. As the construction industry accounts for 4 percent of the $13.2 trillion United States Gross Domestic Product (GDP) in 2007, it makes sense to market construction technologies that have lower environmental impacts, better efficiency, higher energy-savings and produce less waste [7]. Previous research

---

1. PhD Candidate, Department of Civil and Environmental Engineering, University of Pittsburgh, 949 Benedum Hall, Pittsburgh PA 15261. Email: ner8@pitt.edu

2. Assistant Professor, Department of Civil and Environmental Engineering, University of Pittsburgh 949 Benedum Hall Pittsburgh PA 15261. Email: mbilec@pitt.edu

3. Assistant Professor, Department of Civil and Environmental Engineering, University of Pittsburgh 949 Benedum Hall Pittsburgh PA 15261. Email: ael30@pitt.edu

has identified the use phase of residential buildings as the energy intensive phase and emerging innovative building products such as Insulating Concrete Forms (ICFs) can reduce the energy consumption in the use phase [8–11]. But most of the previous studies on ICFs focus on single phase [12] or have only partial life cycle assessment [13] which provide incomplete results.

The aim of this research is two-fold: (i) develop a life cycle assessment model to systematically analyze all life cycle phases of a residential building, and (ii) analyze the sustainability of innovative building products in comparison to conventional building materials. This study provides insight into the energy intensive phases of the life cycle of a building material and environmental impacts.

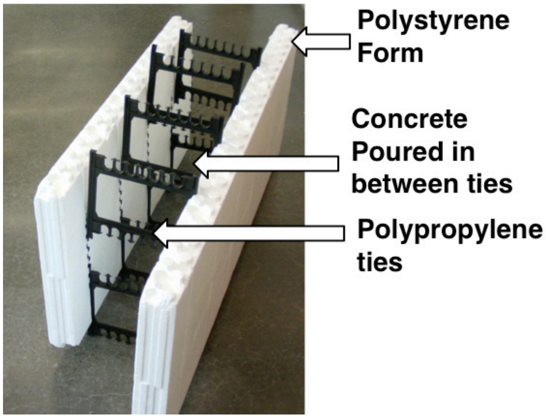
BACKGROUND

Insulating Concrete Form

ICF is a building material that is increasingly being used in construction. An ICF wall section consists of expanded polystyrene (EPS) forms and poured concrete with polymer ties connecting the EPS forms, depicted in Figure 1. One difference between ICF and traditional construction is that after the concrete has cured, the polystyrene forms remain in place. Additional reinforcement, such as rebar, can be added according to the structural design using internal strapping made of polypropylene.

ICFs have several advantages; they are durable and resistant to hazards and natural disasters and reduce energy consumption during a building's use phase compared to traditional building materials. Several organizations, including the National Association of Home Builders (NAHB), have evaluated ICFs' performance through demonstration homes in several locations across the United States [14]. The NAHB study showed that ICFs are increasingly becoming popular and the higher initial price can be overcome by focusing on the desirable qualities of the product such as durability, serviceability and energy conservation properties. An ICF structure has energy savings of more than 25 percent during the use phase, since the forms provide additional insulation and improve energy efficiency in building structures [15]. The heating, ventilation and air conditioning (HVAC) energy consumption can be reduced by 25 to 50 percent [16]. The factors contributing to energy efficiency of ICFs are the R-value (typically at least 20), air infiltration reduction and thermal mass. Generally, if wall sections of the house are made of ICFs and the doors, windows and roof are made of traditional construction materials, air flow rates will be 10 to 30 percent lower than typical frame construction [15].

FIGURE 1. Insulating concrete forms.



Experiments are being conducted at Oak Ridge National Laboratory (ORNL) to determine the relative energy performance and the air tightness of residential homes constructed from ICFs [17]. To demonstrate that ICFs can withstand severe forces, the United States Department of Defense (DoD) conducted its Force Protection Equipment Demonstration (FPED) using ICF boxes blasted with trinitrotoluene (TNT) and found that minimal cracking with no structural damage occurred [18].

There are other advantages to ICFs; from a homeowner's point of view, less air leakage equates to greater thermal comfort and fewer temperature variations. ICF homes provide structural strength as well as less acoustical transmission, reducing undesirable noise in the house and the homes made of ICF are fire-resistant, durable and require less maintenance [14]. Finally, an ICF structure can potentially obtain points in the United States Green Building Council's Leadership in Energy and Environmental Design (LEED) green building rating system for categories of Sustainable Sites, Energy and Atmosphere, and Materials and Resources [19].

Cost

The initial construction cost of ICFs is higher than conventional construction; the cost of ICF exterior wall homes is $1 to $4 per square foot more than the cost of building a house with a conventional wood frame [16]. Savings are achieved during the use of the building with more efficient HVAC systems along with decreased operating costs of ICF homes. Due to the ICF thermal wall efficiency, contractors can downsize the HVAC capacity by as much as 50 percent as compared to wood frame homes. ICF construction prices are beginning to fall due to improved designs with more efficient assembly procedures that reduce installation labor. Most insurance providers provide a premium reduction for high fire or wind resistance homes, which ICFs provide, and the savings for an average home are in the range of $40 to $100 per year [16].

Exterior finishes (e.g., brick and vinyl siding) can be applied to ICFs at a similar cost [15]. ICFs allow the designer to deviate from the traditional shapes of structures. Rather than being constrained to rectangular footprints and openings, curvilinear shapes are easily achieved using ICFs.

Construction Practices

Architects, engineers, and contractors are becoming aware of ICF as a building material. Training programs are available for construction crews by all major ICF suppliers. ICF construction involves assembling the wall sections together onsite and concrete pouring [20]. The concrete mix for ICF construction typically has a compressive strength of 2,500-3,000 psi and a slump of 4″–6″ to facilitate easy pouring through a pump. The free flowing mix allows the concrete to reach all the corners in the form; voids can decrease the strength of an ICF wall. ICF wall construction performs well during temperature extremes [14]. For temperatures below 10°F, the top form is protected using insulation blankets and when the weather is hot, to prevent evaporation, a plastic moisture barrier is used to cover the form, similar to typical concrete pours. In all weather extremes, the insulation helps the curing process. In comparison to traditional structures, ICFs require additional planning before construction of the structures [14]. The location of the openings of doors and windows, attachments of floors, roofs and walls, and utility equipment placements needs to be decided before construction, as changes after concrete has cured will increase the cost of construction. For ICF construction, the bracing is erected on the inside of the wall thus reducing site disturbance to the outside perimeter and helps in preserving natural areas around the site [21].

Based on all the advantages listed above, it is necessary to evaluate ICF for its environmental performance. The energy savings which can be achieved by constructing ICF homes is a major driver for conducting a cradle to grave study of the material.

Introduction to Life Cycle Assessment (LCA)

Life cycle assessment (LCA) is an analysis tool that was used to compare the environmental impacts of ICFs and wood. LCA is a cradle-to-grave method that evaluates all the activities from the manufacturing of a product to its final disposal. Based on the ISO 14040 series, LCA essentially has four steps: (1) goal and scope identification, (2) life cycle inventory assessment (LCI), (3) life cycle impact assessment (LCIA) and, (4) improvement assessment [22]. The first step typically describes the goal or motivation and project boundary. LCI data is obtained from a variety of sources including government, private sources, previously published scientific work and databases (e.g., Franklin and ecoinvent). The LCIA classifies the LCI data into categories in which they have an impact. LCIA results can be presented at four different levels: midpoint, endpoint, damage and weighting factors. Some major LCIA midpoint categories include: global warming, ozone depletion, human health, energy consumption, acidification, eutrophication and smog formation. The final stage of an LCA suggests strategies to improve a product or process.

Review of Residential Building LCA

Previous LCAs showed that the use phase is the most energy intensive life cycle stage for residential buildings. One LCA of a 2,450 square foot traditional wood house built in Ann Arbor, Michigan showed that the heating and cooling of a house with 50 year lifetime, accounted for 96 percent of energy consumption, as compared to 4 percent of embodied energy from maintenance and renovations [8]. Another study on residential LCA using Economic Input Output-Life Cycle Assessment (EIO-LCA), a method which uses aggregate sector-level data for assessing the impact of that sector when purchases are made to and from that sector, to quantify the emissions associated with residential buildings showed that the construction phase is the largest contributor to economic activity as well as to hazardous waste and air emissions while the use phase resulted in significant energy consumption and greenhouse gas emissions [24].

A few LCA-related studies have evaluated houses constructed of ICFs through a partial life cycle inventory assessment [13] and by modeling the energy use of the houses [12]. The houses in both studies [12, 13] were modeled in five different locations: Phoenix, AZ (hot, dry climate); Miami, FL (hot, humid climate); Seattle, WA and Washington, DC (moderate, wet); and Chicago, IL (variable with cold climate). The results of the partial inventory assessment by Marceau et al. [13] showed that the embodied energy of an ICF home was higher than a traditional wood frame house initially but the cumulative energy for wood frame house was much higher than ICFs after a period of five years. The energy use study by Gajda and Vangeem [12] showed that ICF walls had an inherent capacity of higher insulation in comparison to wood frame walls in all locations modeled. Finally, a comparative LCA of a 2,400 square foot ICF, wood and steel frame houses found that the ICF house had the highest embodied energy [25]. The three studies showed that even though ICF has a higher embodied energy, the advantages in the use phase of the building product needed further investigation.

Prior research related to LCA and ICFs has focused mainly on disparate life cycle phases, such as analyzing only the use phase or manufacturing of materials phase to a certain extent, leading to incomplete life cycle results. This paper presents a detailed LCA comparing ICFs to traditional materials such as wood frame. The materials are compared from their raw materials extraction and manufacturing phase to their end of life phase and in addition to energy analysis, the environmental impacts of the materials in all the life cycle phases are also studied.

METHOD

A comparative LCA was performed to study the environmental impacts of ICFs and traditional wood frame homes. The LCA of both the ICF and the wood structures are divided into five phases: raw materials extraction and manufacturing, transportation, construction, use, and end of life of materials.

Extensive research was conducted to select data for each stage. An example of the decision making process is illustrated in Table 1 for ICFs, and a similar procedure was used for the other building materials. Detailed information from an ICF manufacturer was used within this study, therefore it was important to select databases and unit processes from software that could be altered to incorporate the specific ICF data. This research reviewed several potential databases and software tools such as ATHENA, BEES, the US LCI database, ecoinvent and other European databases before selecting primarily a collection of European databases for compiling the LCI. The data from the European databases was more suitable for modeling the ICF and wood manufacturing but where available, data from US databases such as Franklin was utilized. The ATHENA database is a North American LCA tool that can be used for modeling an entire structure [26]. While the ATHENA database does have ICF data, more flexible data sources were required for modeling purposes; thus a custom LCA was created. The impact assessment for the life cycle was performed using the Tool for Reduction and Assessment of Chemical and other Impacts (TRACI), a tool used to assist in impact assessment for sustainability metrics, LCA, industrial ecology, process design and pollution prevention [27]. TRACI is a midpoint level impact assessment tool that was developed by the United States Environmental Protection Agency (EPA) to assess environmental impacts through a decision-making framework. Several scenarios were modeled for the use phase with the energy-modeling program eQuest [28].

Raw Materials Extraction and Manufacturing Phase

When modeling ICFs, it was necessary to account for additional industry input and combine multiple relevant datasets. For concrete, several unit processes were available, and a triangular distribution was developed from the datasets, as there was only limited data in the form of minimum and maximum values. Triangular distribution is used as illustrated in various studies [30, 31].

TABLE 1. Data sources for life cycle stages of insulating concrete forms. Similar databases are used for wood structures.

LCA Phase	Process Involved	Unit Processes and Databases	Remarks
Raw materials extraction and manufacturing	Concrete	Concrete not reinforced (ETH-ESU) Concrete I (IDEMAT 2001) Concrete normal at plant (ecoinvent)	Several concrete unit processes were used and minimum, maximum and median values were obtained. The median value was selected when the data was available; the maximum value was selected when only one data point was available.
	Polystyrene	Polystyrene, general purpose, GPPS, at plant (ecoinvent) Modified with actual ICF plant data	Several databases were explored. Most of the databases except ecoinvent had no inventory items for polystyrene; therefore, the ecoinvent database was used. Manufacturer data was added to the ecoinvent data to create a new polystyrene unit process.
	Polypropylene	Polypropylene, granulate at plant (ecoinvent)	Several databases were explored. Most of the databases except ecoinvent had no inventory items for polypropylene; therefore, the ecoinvent database was used.
Transportation	Transportation of materials	Truck transport, diesel powered (Franklin)	Federal Highway Administration Standards for trucks [29] was used to determine truck dimensions. Number of truck trips was based on material quantity take-offs and truck dimensions. Assumed transportation distance was 31 miles (50 km).
Construction	Construction of house	ATHENA	ICF and wood-framed structures were created in ATHENA. Results for construction phase only were used.
Use	Use of the house based on 50 and 100 year lifetime	eQuest	Department of Energy freeware-eQuest was used to model houses made of wood, ICF.
End of life	Concrete crushing and reuse	Disposal, building concrete, not reinforced, to sorting plant (ecoinvent)	Concrete was assumed to be reused as aggregate in future project. Concrete crushing was modeled with available equipment unit process.

The "concrete not reinforced" unit processes from ETH-ESU 96, IDEMAT 2001, and ecoinvent were used to create the triangular distribution for the concrete process used in this model. The ecoinvent unit process for polystyrene was modified with the manufacturer's data to create a new unit process for polystyrene. The ecoinvent polypropylene unit process was selected for the ties used in ICFs. For the other building materials such as wood the unit processes were selected from the databases mentioned below.

Transportation Phase

The materials used on the construction site were assumed to be transported by trucks at an assumed distance of 31 miles (50 km). A fixed distance was assumed to demonstrate the differences in number of truck trips required for transporting different quantity of materials for the same distance. The number of trips required to transport materials 31 miles (50 km) from the manufacturing site was calculated. A standard heavy duty truck with dimensions of 15 feet × 48 feet × 8 feet with a carrying capacity of 16.5 tons was assumed to transport the materials from the manufacturing site [29]. Based on the material quantities and the dimensions of the materials, ICFs require two trips by truck while ten truck trips were required to transport materials for a traditional wood home. Emissions from truck manufacturing, constructing the associated infrastructure and driving the truck were obtained from the Franklin database. ICFs are lightweight materials when compared to wood frames and stacking of ICFs increases the space available for transportation.

Construction Phase

The modeling of the construction phase was carried out using ATHENA, LCA software for buildings. Two 2,450 square foot residential structures were modeled in ATHENA for both wood and ICF homes to obtain the construction inventory data. The manufacturing, transportation and end of life results are not included from the ATHENA model because the authors wanted to incorporate industry-specific data and evaluate the raw materials and manufacturing processes in detail.

Use Phase

The use phase of two 2,450 square foot single family homes was modeled in eQuest. Different materials were used for the different structural components of the ICF and wood house, see Table 2. The climate was assumed to be the Pittsburgh area for modeling purposes. This was to ensure that ICF was modeled for both hot and cold weather conditions and its environmental performance analyzed. Also, since the data obtained from ICF manufacturer was based in Pittsburgh, the location was selected for the energy modeling. Both houses had the same building footprint, door and window materials, occupancy schedules and HVAC systems were auto sized according to the heating and cooling requirements. Structural components such as roof, walls, ceiling and floors were different in the models to reflect common building practices unique for wood frame and ICF construction. The thickness of wall sections and insulation used are in British units consistent with the style adopted by other authors in the field of LCA [9].

The ceiling was a drywall finish and the floors were vinyl tile finish. The cooling source in both

TABLE 2. Energy modeling scenarios for ICF and wood frame two story residential structures.

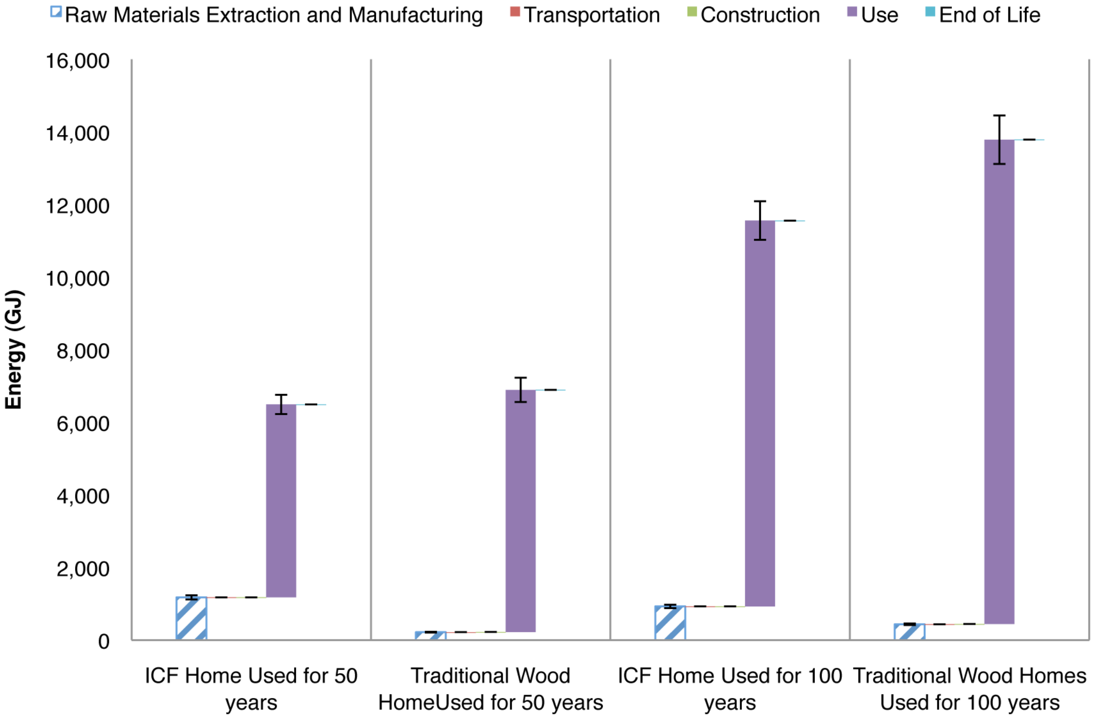
	Traditional Wood Home			ICF Home		
Component	**Construction and/or Interior Finish**	**Insulation**	**R-value**	**Construction and/or Interior Finish**	**Insulation**	**R-value**
Roof surface	Wood frame	2″ polyisocyanurate	14	4″ concrete	6″ polystyrene	30
Above grade wall	Wood frame	2″ polyisocyanurate	14	8″ concrete	3″ polystyrene (exterior)	12
					Additional furred insulation (interior)	21
Basement floor	4″ concrete	No perimeter insulation		4″ concrete	No perimeter insulation	
Basement wall	6″ concrete	Exterior insulation	5	6″ concrete	Exterior insulation	20
Top floor ceiling (2nd floor)	Wood frame	Batt	13	Wood frame	Batt	49
Ceiling (1st floor)	Wood frame	Batt	13	Wood frame	Batt	30
Floor	4″ concrete+ vinyl tile	3″ polyisocyanurate	10.5	4″ concrete+ vinyl tile	3″ polystyrene	12

scenarios was DX Coils and the heating source was a natural gas furnace. The thermostat set points were 65°F when occupied and 82°F when unoccupied for cooling and 75°F when occupied and 64°F when unoccupied for heating. The design temperatures were 75°F indoor and 55°F supply for cooling and 72°F indoor and 80°F supply for heating. Electricity was used for cooling, task lighting and other equipments around the house but heating and hot water source was assumed to be natural gas.

End of Life Phase

The end of life analysis considered the environmental impacts of the building materials due to the dismantling and deconstruction of the house after its useful lifetime. Materials, quantities, and processes were the same as those used to assess the manufacturing stage. For the ICF waste scenario, it was assumed that the polystyrene and polypropylene are separated during deconstruction and demolition, but because recycling markets are lower for construction debris plastics, it was assumed the plastics were disposed of instead of reused or recycled. Therefore, only two waste streams were considered: concrete and all other waste. The processes involved in recycling the concrete were demolition, transportation to sorting facility, and crushing. All of the concrete materials within the ICF followed this waste stream. All remaining materials were sent to the landfill for disposal. For the wood frame waste scenario, research indicated that an average of 30 percent of demolition wood is recovered during deconstruction, chipped, and reused [32, 33]. The wood chipping waste scenario was modeled using the "Chopper, stationary, electric/RER/I U" process from ecoinvent. A new unit process was created with an hourly output of 3.3 cubic meters per hour and a lifetime output of 100,000 cubic meters. Wood chipping was applied to 30 percent of the wood and the remaining materials were sent to the landfill for disposal.

FIGURE 2. Energy consumption of ICF and wood homes for 50 and 100 year lifetimes. The positive and negative error bars are shown with an error of 5 percent. Since traditional wood homes have a lifetime of 50 years, two wood homes built for 50 years each are compared with an ICF home standing for 100 years.



The five broad phases constitute the residential LCA model that is applicable for both ICF and traditional wood homes. Once the data was assembled, the five phases of the life cycle were compared on the basis of their energy consumption and environmental impacts. The life cycle impact assessment is performed using the US based tool, TRACI. The results of energy consumption and the life cycle environmental impacts are displayed in Figures 2, 3, and 4.

RESULTS AND DISCUSSION

Energy

The use phase of homes consumes the maximum energy in the life cycle of a residential structure [8–11]. This study also reiterates that the energy consumption in the use phase is significantly larger than other phases. A comparative LCA of a traditional home and an ICF home showed the energy consumption in each of the phases of the life cycle.

Initially, the two residential structures were compared assuming a 50 year lifetime, which is the value often assumed in LCA research of buildings [8, 9]. However, 50 and 100 year lifetimes was evaluated because ICFs are exceptionally durable. Traditional wood homes have a lifetime of 50 years so two wood homes of lifetime 50 years each are compared with a single ICF home standing for 100 years. Results show that ICFs have lower energy consumption than traditional wood frame homes in all phases except the manufacturing phase (see Figure 2). However, manufacturing makes up only 18 percent of the total ICF life cycle energy use and 3 percent of wood home.

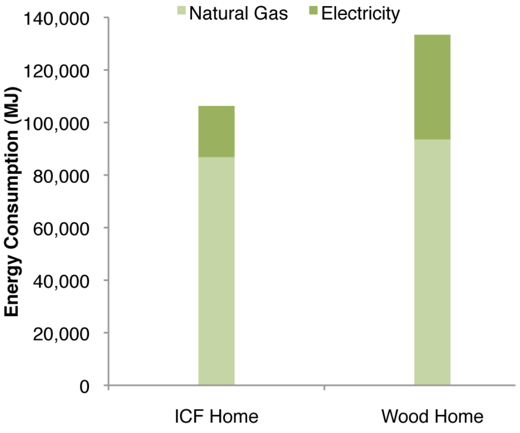
The use phase is a continuous activity for 50 or 100 years and is the most energy intensive phase and accounts for more than 50 percent of energy consumption in both ICF and wood homes. The eQuest simulation provides the annual end use demand of the various components that require electricity and natural gas (see Figure 3). Since factors that influence electricity consumption, such as the orientation of the house, the location, and the heating and cooling equipment are the same for both houses, the difference in electricity consumption can be attributed to the differences between structural elements. For space cooling the traditional wood house has higher electricity consumption. Energy use for heating and cooling are calculated based on various envelope components such as floors, walls, windows, lighting systems, occupancy profiles and miscellaneous equipment. Miscellaneous equipment is defined as other equipment that contributes to heating and cooling loads. Both structures have equal electricity consumption in vent fans, pumps and auxiliary and miscellaneous equipment category as the occupancy profiles and use of equipments was considered the same

To validate the use phase model, statistics provided by the Energy Information Administration (EIA)—Residential Energy Consumption Survey (RECS) was used [2]. The energy consumption of a house of 2,000 to 2,499 square foot consumed 110 GJ of energy annually in 2005. The energy consumption of households has been increasing since 2005 but since new data has not been published, the 2005 data was used to validate the eQuest model's energy consumption. Figure 3 shows that the ICF house has overall lower energy consumption (106 GJ) when compared to a traditional wood house (133 GJ). In a region such as Pittsburgh, where cold weather lasts for almost seven months a year, annual energy consumption can be greatly reduced by using a building product such as ICFs.

Life Cycle Impact Assessment

The life cycle environmental impacts were analyzed for both ICF and wood homes. The energy was sep-

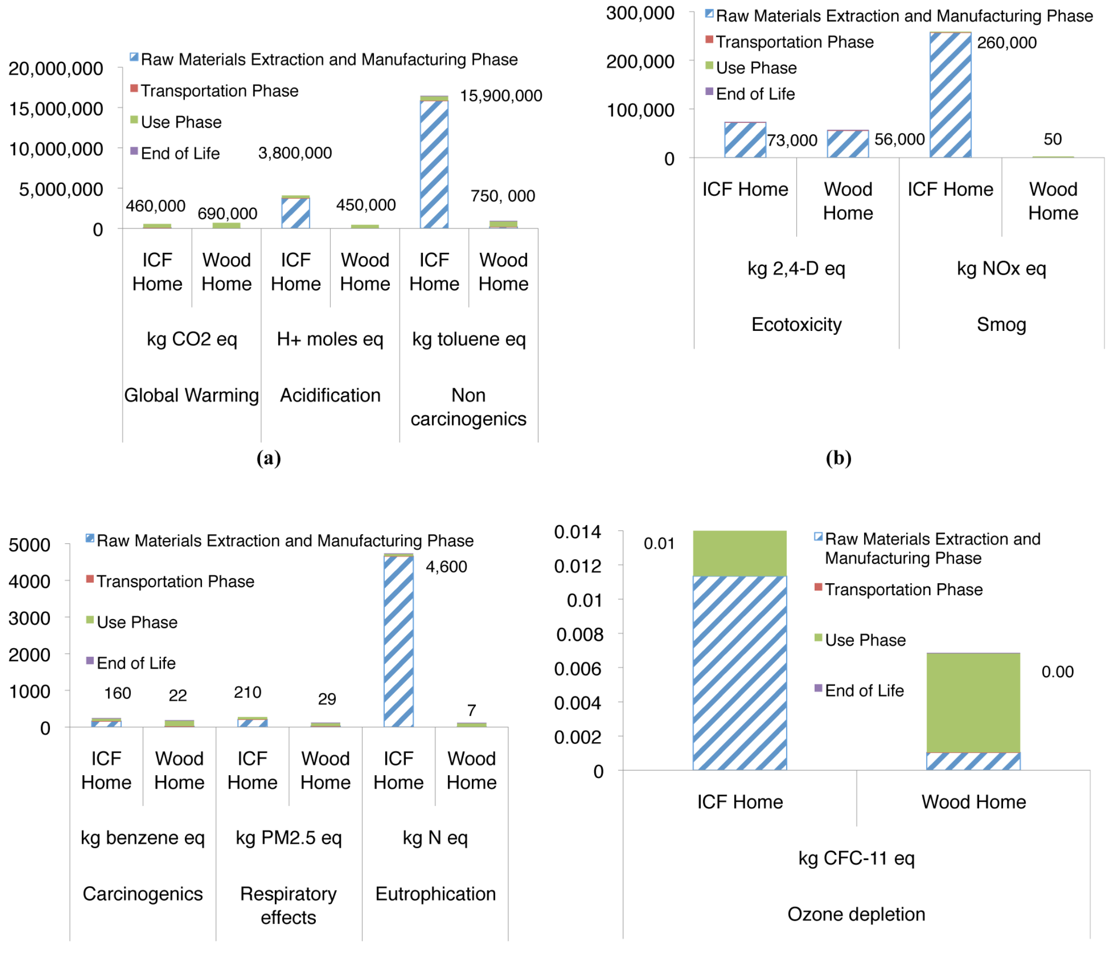
FIGURE 3. Energy consumption for wood and ICF homes for one year.



arated from the environmental impacts to show the benefits of ICF homes in terms of lower energy consumption over the life cycle. With energy savings, it is important to conduct LCIA studies to understand all the environmental impacts of ICFs. Previous studies on ICFs have conducted a partial inventory [13] or used LCA tools like ATHENA for the entire life cycle [34]. This study systematically analyzed all phases of the life cycle of both ICF and wood homes and performed an LCIA on the inventory obtained from the LCI stage. TRACI was the impact assessment method selected and the results for the impact assessment stage show the comparative environmental impacts of all phases in the eight categories which are as follows: global warming, acidification, carcinogenics, non carcinogenics, respiratory effects, eutrophication, ecotoxicity and smog. Figures 4a, b, c, and d show the environmental impact of both houses in all phases except construction as this phase was modeled in ATHENA. The environmental impacts are evaluated for 50 year lifetime of the houses.

The raw materials extraction and manufacturing phase of ICF homes has the highest contribution in

FIGURE 4. Life cycle environmental impacts using TRACI for 50 year lifetime of both wood and ICF homes in global warming, acidification, non carcinogenics, ecotoxicity, smog, carcinogenics, respiratory effects, eutrophication and ozone depletion categories. Construction phase is not included.



(a)

(b)

(c)

(d)

all impact categories except global warming. However, for all impact categories, for wood homes, the use phase dominates. Raw materials extraction and manufacturing is a one-time activity while the use phase is a continuous activity for the lifetime of the home. The remaining life cycle phases (transportation and end of life) have minimal impact on the environment. Construction phase was not included in the impact assessment results due to limited inventory output. The categories cannot be compared amongst themselves numerically as the units are different for each category. Even though ICF homes have lower energy consumption and subsequently lower GWP, this study presented all the environmental impacts of both homes. ICFs may be the products of choice if only energy and GWP are considered but tradeoffs associated need to be carefully considered.

DISCUSSION

A sensitivity analysis of the impact assessment results was performed using the other impact assessment methods of BEES, Eco-indicator 99 and IMPACT 2002+ [35–37]. The wood home had lower impacts in certain categories and ICF home had lower impacts in others when BEES impact assessment method was applied. When Eco-indicator 99 and IMPACT 2002+ methods were applied, the wood home had lower impacts in almost all impact categories. A direct comparison between TRACI, BEES, Eco-indicator 99 and IMPACT 2002+ could not be conducted as TRACI and BEES are midpoint impact assessment methods while the others are endpoint impact assessment methods. Even though, ICF home had lower energy consumption over the life cycle, the environmental impacts from the life cycle are significant.

The main process and substance contributors for each impact category using TRACI impact assessment method were investigated. The raw materials extraction and manufacturing for the ICF assembly and the concrete manufacturing are the unit processes that have the maximum impact in the life cycle of ICFs. Even though intuitively the processes contributing the maximum for each of the impact categories can be inferred, the contributions from the actual unit processes are random. The processes and substances contributing the maximum to each impact category are shown in Table 3.

Most of the processes are either related to the polystyrene used in ICF or to the concrete used in the entire assembly. But some of the top process contributors such as the ones for carcinogenics, ozone depletion and ecotoxicity cannot be instinctively inferred. The substance contributors to most of the categories such as acidification, eutrophication, carcinogenics, non carcinogenics and ozone depletion also appear to be arbitrary selections instead of

TABLE 3. TRACI impact categories and the main process and substance contributors for an ICF home.

TRACI Impact Category	Unit Process that Contributed the Maximum to the Impact Category	Substance that Contributed the Maximum to the Impact Category	% Substance Contribution
Global warming	Heat from natural gas	Carbon dioxide	94
Acidification	Polystyrene used in ICF	Ammonia	95
Carcinogenics	Disposal, municipal solid waste, 22.9% water, to municipal incinerator	Lead	91
Non carcinogenics	Concrete	Antimony	69
Respiratory effects	Polystyrene used in ICF	Nitrogen oxides	93
Eutrophication	Polystyrene used in ICF	Ammonia	95
Ozone depletion	Transport, natural gas, pipeline, long distance	Halon 1211	67
Ecotoxicity	Disposal, municipal solid waste, 22.9% water, to municipal incinerator	Aluminum	56
Smog	Polystyrene used in ICF	VOC	98

substances which are usually associated with these categories.

The results of the impact assessment using TRACI and the subsequent sensitivity analysis using other tools show an uncertainty in the calculation methods and assumptions in the various methods. The unsystematic selection of processes and substances that contribute the maximum to any impact leads to an ambiguity in the results displayed. A method to reduce uncertainty would be to include more data on all the processes involved in a network. Since only very few input values like polystyrene and concrete were modified for the purpose of this research, a more detailed analysis which modifies the entire network chain for a product might yield more accurate results. Moreover, each impact assessment method has different characterization factors that are used for obtaining the impact categories and the results may vary depending on the impact assessment method used or the unit processes selected.

The findings of this study are consistent with other research. Kahhat et al [34] performed an LCA study on a single story residential structure in Phoenix using different exterior wall materials including concrete block, poured concrete, insulated concrete, wood frame, and steel frame using ATHENA. The study divided the life cycle into pre-use, use and end of life phases and showed that in the case of ICFs, the structure had lower energy consumption over the use phase and hence lower global warming potential (GWP). The pre-use phase of ICFs had high environmental impacts and the end of life phase was found to be negligible. Similarly, other LCAs of ICFs have shown that the energy consumption of a house is reduced when ICFs are used as wall sections [12, 13]. ICFs consistently exhibit higher raw materials manufacturing impacts and lower use impacts.

CONCLUSION

The comparative LCA results of a 2,450 square foot home made of both wood and ICF showed that the wood homes had the highest energy consumption and GWP over the entire life cycle. The use phase of wood home—a continuous activity for 50 or more years—consumed 97 percent more energy than all the other phases combined. When compared to the manufacturing phase that consumes 18 percent of the total energy of an ICF home, the use phase environmental impacts of a wood home are significantly larger. When looking beyond energy and GWP, the impact assessment results from other categories (acidification, carcinogenics, non carcinogenics, respiratory effects, eutrophication, ecotoxicity, ozone depletion and smog) are ambiguous as ICF homes underperformed when compared with wood homes. There are tradeoffs associated with every building product and perceptions about greenness of a product (for example, wood) can alter when the complete life cycle is studied. Applying several impact assessment methods and selecting different unit processes could lead to greater uncertainty. ICFs have the potential to reduce the energy consumption if adopted on a large scale but the tradeoffs associated with reduced energy consumption such as increased environmental impacts in other categories should be carefully considered.

ACKNOWLEDGMENTS

The authors are grateful to the support of Project Innovation Grant from the Green Building Alliance. The authors wish to thank Tegrant Corporation for providing valuable data for conducting this research. The authors also wish to thank Deborah Steinberg from Chatham University, Pittsburgh, PA for her contribution to this research.

REFERENCES

1. Heijungs, R.; Frischknecht, R. 1998 “A Special View on the Nature of the Allocation Problem.” *Int. J. LCA* 3(5), 321–332.
2. USDOE. 2005. *Table R1: Energy Consumption by Sector, Ranked by State.* Washington, DC: United States Department of Energy.
3. USDOE Buildings Energy Databook: 1.1 Buildings Sector Energy Consumption. http://buildingsdatabook.eren.doe.gov/docs/1.1.1.pdf (June 25, 2008).
4. Young, J. E.; Sachs, A. 1994. *Worldwatch Paper #121: The Next Efficiency Revolution: Creating a Sustainable Materials Economy*. Washington, DC: Worldwatch Institute.
5. Roodman, D. M.; Lenssen, N. 1995. *Worldwatch Paper #124: A Building Revolution: How Ecology and Health Concerns are Transforming Construction*. Washington, DC: Worldwatch Institute.
6. Woolley, T. 1997. *Green Building Handbook. Vol 1. Guide to Building Products and their Impact on the Environment*. London: Taylor & Francis / Spon Press.
7. U.S. Department of Commerce. 2009. “Value of Construction Put in Place in the United States.” In News, U. S. C. B., Ed.

8. Blanchard, S.; Reppe, P. 1998. "Life Cycle Analysis of a Residential Home in Michigan." University of Michigan, Ann Arbor.
9.Keoleian, G. A.; Blanchard, S.; Reppe, P. 2000. "Life-Cycle Energy, Costs, and Strategies for Improving a Single-Family House." *Journal of Industrial Ecology* 4(2), 135–156.
10. Ochoa, L.; Hendrickson, C.; Matthews, H. S. 2002. "Economic Input-output Life-cycle Assessment of U.S. Residential Buildings." *Journal of Infrastructure Systems* 8(4), 132–138.
11. Ochoa, L.; Ries, R.; Matthews, H. S.; Hendrickson, C. 2005. In *Life cycle assessment of residential buildings*, Construction Research Congress 2005: Broadening Perspectives—Proceedings of the Congress, pp. 173–181.
12. Gajda, J.; VanGeem, G. M. 2000. "Energy Use in Residential Housing: A Comparison of Insulating Concrete Form and Wood Frame Walls." In *Portland Cement Association Research & Development Serial No. 2415*.
13. Marceau, M. L.; Gajda, J.; VanGeem, G. M.; Nisbet, M. 2002. "Partial Environmental Life Cycle Inventory of an Insulating Concrete Form House Compared to a Wood Frame House." In *Portland Cement Association Research & Development Serial No. 2464*.
14. NAHB. 1997. *Insulating Concrete Forms for Residential Construction: Demonstration Homes*; US Department of Housing and Urban Development, Office of Policy Development and Research, The Portland Cement Association.
15. VanderWerf, P. A., Panushev, I.S, Nicholson, M, Kokonowski, D. 2006. *Concrete Systems for Homes and Low-Rise Construction A Portland Cement Association Guide*. New York: McGraw-Hill Publications.
16. VanderWerf, P. A., Feige, S.J, Chammas, P, Lemay, L.A. 1997. *Insulating Concrete Forms for Residential Design and Construction*. New York: McGraw-Hill Publications.
17. USDOE. 2009. *Field Validation of ICF Residential Building Air-Tightness.* Washington, DC: Department of Energy.
18. Panushev, I. S.; VanderWerf, P. A. 2004. *Insulating concrete forms construction: demand, evaluation, and technical practice*. McGraw-Hill Professional.
19. USGBC United States Green Building Council: LEED. http://www.usgbc.org/DisplayPage.aspx?CategoryID=19 (June 20).
20. Polysteel Insulating Concrete Forms. www.polysteel.co.uk/icf/What-are-ICF-s-66.php (June 25, 2008).
21. ICFA. 2008. ICFA Tech-LEED NC. www.forms.org (August 25, 2008).
22. Tibor, T.; Feldman, I. 1996. *ISO 14000: a guide to the new environment management standards*. Chicago: Irwin Publishing.
23. Bare, J.; Gloria, T. 2006. "Critical analysis of the mathematical relationships and comprehensiveness of life cycle impact assessment approaches." *Environ. Sci. Technol* 40(4), 1104–1113.
24. Luis, O.; Chris, H.; Matthews, H. S. 2002. "Economic Input-output Life-cycle Assessment of U.S. Residential Buildings." *Journal of Infrastructure Systems* 8(4), 132–138.
25. Trusty, W. B.; Meil, J. K. 2000. *Building Life Cycle Assessment: Residential Case Study.* Ontario: ATHENA™ Sustainable Materials Institute.
26. The ATHENA Institute. 2003. *The ATHENA Institute's Environmental Impact Estimator (Version 3)/* Ontario: The ATHENA™ Sustainable Materials Institute.
27. EPA Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI). http://www.epa.gov/nrmrl/std/sab/traci/ (December),
28. DOE2.com eQuest. http://www.doe2.com/equest/
29. FHWA Federal Size Regulations for Commercial Vehicles. http://ops.fhwa.dot.gov/freight/publications/size_regs_final_rpt/index.htm#straight (January 28),
30. Thabrew, L.; Lloyd, S.; Cypcar, C.; Hamilton, J.; Ries, R. 2008. "Life cycle assessment of water-based acrylic floor finish maintenance programs." *The International Journal of Life Cycle Assessment* 13(1), 65–74.
31. Bilec, M.; Ries, R.; Matthews, H. S.; Sharrard, A. L. 2006. "Example of a hybrid life-cycle assessment of construction processes." *Journal of Infrastructure Systems* 12(4), 207–215.
32. Falk, R. H.; McKeever, D. B. 2004. In *Recovering wood for reuse and recycling: a United States perspective*, European COST E31 Conference: Management of Recovered Wood Recycling Bioenergy and other Options, Thessaloniki, 2004; University Studio Press: Thessaloniki, 2004; pp 29–40.
33. McKeever, D. B. 1999. "How woody residuals are recycled in the United States." *BioCycle* .
34. Kahhat, R.; Crittenden, J.; Sharif, F.; Fonseca, E.; Li, K.; Sawhney, A.; Zhang, P. 2009. "Environmental Impacts over the Life Cycle of Residential Buildings Using Different Exterior Wall Systems." *Journal of Infrastructure Systems* 15(3), 211–221.
35. Frischknecht, R. 2005. "ecoinvent Data v1.1 (2004): From heterogenous databases to unified and transparent LCI data." *The International Journal of Life Cycle Assessment* 10(1), 1–2.
36. Jolliet, O.; Margni, M.; Charles, R.; Humbert, S.; Payet, J.; Rebitzer, G.; Rosenbaum, R. 2003. "IMPACT 2002+: A new life cycle impact assessment methodology." *The International Journal of Life Cycle Assessment* 8(6), 324–330.
37. Lippiatt, B.; Boyles, A. 2001. "Using BEES to select cost-effective green products." *The International Journal of Life Cycle Assessment* 6(2), 76–80.