ANALYZING BUILDING ENERGY MODELS FROM A LIFE CYCLE PERSPECTIVE

by

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Life cycle assessment (LCA) is a quantitative tool used to evaluate the environmental impacts of products or processes. With respect to buildings, LCA can be used to evaluate the environmental impacts of an entire building life cycle. Currently, LCA in the building area is used in a limited capacity, and primarily for selecting building products. In order to determine the causality for the lack of whole building LCAs, focus groups with members of the architecture, engineering, and construction (AEC) communities were held. This research ascertains first the current level of knowledge of LCA in the AEC community and then discusses the benefits and barriers to the practice of LCA. From the focus group results, the most important benefit to LCA was: *Provides information about environmental impacts.* The results did not identify a prominent barrier; however, building-related metrics were ascertained to be one of the more crucial barriers.

One limitation of LCA is the uncertainty associated with its results, which in this research is exemplified in the correlation between LCA and building energy models. In past research, results from energy models have been utilized to calculate life cycle operating energy of buildings in order to predict environmental impacts through LCA. Due to assumptions and variations between input data, past research has indicated substantial error rates in energy model results. In order to employ a life cycle perspective, the relationship between total life cycle energy use and energy modeling results has been studied. The main question guiding this research was: what is the acceptable error rate between predicted and actual life cycle energy

use? Three different energy modeling programs with varying levels of detail were utilized to generate energy data for a case study, a low energy home. EnergyPlus, Energy-10, and Green Building Studio all indicated error rates of 41%, 70%, and 20% respectively regarding life cycle primary energy consumption.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

PREFACE

This research analyzes the current state of life cycle assessment in the architecture, engineering, and construction community and investigates the impact of building energy model results on life cycle assessment results through a case study.

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ACRONYMS

AEC – Architecture/engineering/construction

AGC – Associated General Contractors of America

AIA – American Institute of Architects

ASCE – American Society of Civil Engineers

ASHRAE – American Society of Heating, Refrigeration, and Air Conditioning Engineers

BEES – Building for Environmental and Economic Sustainability

BOF – Basic oxygen furnace

BOMA – Building Owners and Managers of America

CBECS – Commercial Buildings Energy Consumption Survey

CMU – Carnegie Mellon University

CO_2 – Carbon Dioxide

DHW – Domestic hot water

DOE – Department of Energy

EA – Energy and Atmosphere

EAC – Electric arc furnace

EIO-LCA – Economic input-out life cycle assessment

EPA – Environmental Protection Agency

EPS – Expanded polystyrene

ERV – Energy recovery ventilator

EUI – Energy use intensity

GBA – Green Building Alliance

GBS – Green Building Studio

GHG – Greenhouse Gas Emissions

GWP – Global warming potential

HVAC – Heating, ventilation, and air conditioning

I-O – Input-output

IEQ – Indoor environmental quality

ISO – International Organization for Standardization

LCA – Life cycle assessment

LCI – Life cycle inventory

LCIA – Life cycle impact assessment

LEED – Leadership in Energy and Environmental Design

LEED-NC – LEED for New Construction

LVL – Laminated veneer lumber

M&V – Measurement and verification

MBA – Master Builder’s Association

NBI – New Buildings Institute

OSB – Oriented strand board

PEX – Cross-linked polyethylene

PSL – Parallel strand lumber

PTHP – Packaged terminal heat pump

PV – Photovoltaic

SIP – Structurally insulated panel

USGBC – United States Green Building Council

1.0 INTRODUCTION

Since the early 1900s, the construction of the built environment has been steadily increasing the consumption of global energy and resources and has consequently caused significant environmental impacts. According to the U.S. Department of Energy (DOE) in 2010, buildings annually consumed 73% of electricity usage (about 30 quadrillion BTUs) and 40% of primary energy in the U.S. (2010). Buildings also accounted for 39% of the annual carbon dioxide (CO_2) emissions in the U.S. In terms of resource use, crushed stone, sand, and gravel used for building and road construction compose about 75% of raw materials extracted each year in the U.S. (Wagner 2002). Buildings can generate a substantial impact on the environment in terms of energy use, CO_2 emissions, and material usage.

In order to reduce the environmental impacts of buildings, green buildings have been endorsed by the United States government and a diverse set of organizations. In 2009, President Barack Obama announced a plan to reduce the federal government's greenhouse gas (GHG) emissions by 28% and the nation's GHG emissions by 17% by the year 2020 (Obama 2009). In order to meet this goal, the federal government's plan for sustainable building design involves a multifaceted plan including energy efficiency, water conservation, and healthy indoor environments. National organizations, such as the United States Green Building Council (USGBC), and local organizations, such as the Green Building Alliance (GBA) of Pittsburgh, work to promote sustainable building practices in the U.S. The USGBC's mission is "to transform the way buildings and communities are designed, built and operated, enabling an environmentally and socially responsible, healthy, and prosperous environment that improves the quality of life" (2010). Through these and other organizations, the green building community has transformed dramatically.

In order to substantiate green buildings, life cycle assessment (LCA) can be used to quantify environmental impacts of buildings. LCA, which is formalized by the International Organization for Standardization (ISO) 14040, is a method based on life cycle thinking that quantifies the environmental impacts of products and activities (2006). Life cycle thinking involves studying a product or process from raw materials extraction to manufacturing to transportation and distribution to usage and finally to its ultimate disposal. LCA comprises the following four steps: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation. Overall, life cycle analysis can generate data that illustrates the emissions, resource depletion, and energy usage from a building in order to dictate areas of improvement within the building design.

The goal and scope stage involves the delineation of the objectives of the LCA, as well as, functional unit and system boundary definition. Since quantifying a product or process over its entire life cycle can be a complex process, identifying the goal and context of the study is important. The system boundaries distinguish which processes within the life cycle are included within the study. Some processes could be neglected in the LCA due to uncertain or missing data. Also defined in the goal and scope stage is the functional unit, which "corresponds to a reference flow to which all other modeled flows of the system are related" (Baumann and Tillman 2004). Functional units allow different LCAs to be compared with each other. With buildings for example, the functional unit might be 1 ft^2 or 1 m^2 or one building at a specified size.

The LCI stage entails the compilation of not only quantities of materials and predicted energy use, but also data in the form of raw material usage and emissions to air and water. Process-based and input-output based are two commonly utilized LCI techniques. Process LCI involves the computation of the known inputs and outputs, such as emissions and resource use, through a process flow schema (Bilec, Ries et al. 2006; International Organization for Standardization 2006). The processes are calculated to the point where the flows to and from the process are negligible. Process LCI requires data that can be collected from manufacturers and public sources and then can be stored in databases. Input-output (I-O) was developed by the economist Wassily Leontief in order to determine capital flows and the proportional economic effects of purchases from sector to sector (Leontief 1936; Bilec, Ries et al. 2006; Strømman and Solli 2008; Bilec, Ries et al. 2010). I-O data can be utilized in conjunction with environmental impacts through matrix calculations. Carnegie Mellon University developed an Economic Input-Output life cycle assessment (EIO-LCA) tool using the I-O method (Hendrickson, Horvath et al. 1998; Carnegie Mellon University Green Design Institute 2008). The benefit of the input-output method is that data is widely and publicly available; however, the drawback is that the data is aggregated, creating uncertainty within the results (Bilec, Ries et al. 2006). Hybrid LCA has been developed as a technique to combine the benefits of both LCI methods (Bilec, Ries et al. 2006; Strømman and Solli 2008; Bilec, Ries et al. 2010). For processes that have unreliable data or none at all, EIO-LCA is utilized to fill those gaps. The hybrid method can allow for a broader system boundary and, therefore, to some extent produces less uncertainty associated with the LCA results.

The LCIA stage aggregates LCI data into environmental loads, such as global warming potential (GWP), human health, and eutrophication potential. Several LCIA techniques currently exist, which can be classified as either midpoints or endpoints (Scientific Applications International Corporation 2006). Midpoint categories classify the LCI output into relative environmental impacts and then characterize each category based on a common unit. For example, GWP can be calculated based on emitted equivalents of CO_2. Endpoints further the LCIA stage by grouping and weighting the categories into impacts such as skin cancer and crop damage. For this thesis, midpoint categories will be used in order to reduce uncertainty that can be associated with qualitative weighting in endpoint categories. TRACI, designed by the U.S. Environmental Protection Agency (EPA), is a midpoint LCIA indicator which yields such categories as global warming, acidification, ecotoxicity, and respiratory effects (Bare, Norris et al. 2003). An international LCIA midpoint tool, IMPACT 2002+, computes similar categories to TRACI but also includes primary energy consumed (Jolliet, Margni et al. 2003). In the final LCA stage, interpretation, the results of the LCA are analyzed and recommendations for environmental improvements can be made.

Extensive research has been published that utilizes LCA as a method to quantify life cycle energy and environmental impacts of whole buildings. Junnila et al. (2003) and Junnila and Horvath (2006) have used process LCA to determine environmental impacts of office buildings. Similarly, Scheuer et al. (2003) and Keoleian et al. (2000) calculated life cycle impacts in university buildings through process-based methods. EIO-LCA has also been a well-referenced method and was used by Ochoa, Hendrickson et al. and Ochoa et al. for residential buildings (Ochoa, Hendrickson et al. 2002; Ochoa, Ries et al. 2005). The hybrid LCA method was used by Bilec et al. and Sharrard et al. to determine life cycle impacts of construction processes (Bilec, Ries et al. 2006; Sharrard, Matthews et al. 2008; Bilec, Ries et al. 2010). All three LCI methods have developed as useful tools in calculating environmental impacts over the life cycle of the building.

Nevertheless, several articles have discussed the limitations of LCA as a tool to determine building sustainability (Keoleian, Blanchard et al. 2000; Scheuer, Keoleian et al. 2003; Guggemos and Horvath 2005; Bilec, Ries et al. 2006; Junnila, Horvath et al. 2006; Sharrard, Matthews et al. 2008; Bilec, Ries et al. 2010). Scheuer et al. cited the major limitations to the use of LCA in the design phase of buildings to be the extensive time and data needed to conduct the LCA. Bilec et al. also identified data collection as a limitation in an LCA of construction processes (2006). In addition, Scheuer et al. documented the inadequacy of the static framework of LCA in depicting the dynamic life cycle of buildings (2003). Due to these and several other limitations, LCA is not currently being utilized in practice throughout the building's life cycle in the U.S. and is usually restricted to the analysis of building materials (Hofstetter and Mettier 2003; Cooper and Fava 2006; Rajagopalan, Bilec et al. 2010).

1.1 INTELLECTUAL MERIT

This research analyzes the process of life cycle assessment and its limitations and barriers through both social science research and quantitative analysis. First, social science research was conducted in the form of focus groups composed of members of the architecture, engineering, and construction (AEC) community. The goal of the focus groups was to determine the reason for the lack of use of whole building LCAs within the AEC community. Past research on the barriers to LCA has not specifically focused on the AEC community and its particular issues with whole building life cycle assessments. In contrast, this research investigates this significant hurdle to a widespread application of LCA within the building industry.

Secondly, another limitation to LCA in terms of buildings, energy modeling, was explored utilizing a case study. Past research has shown considerable error rates associated with energy model results; however, the research has not integrated these error rates with life cycle assessment. The goal of the energy model and LCA case study was to determine if there is a substantial uncertainty in life cycle energy calculations due to error in the energy model results. This research examines the relationship between energy modeling and LCA and its impact on LCA results. Conclusions from this investigation could have broader implications for green building rating systems, particularly Leadership in Energy and Environmental Design (LEED).

1.2 RESEARCH QUESTIONS

The goal of this research is to analyze the barriers and limitations to LCA through focus groups and to investigate a specific limitation of LCA, energy modeling, and its impact on LCA results. In order to accomplish this goal several questions guided the research:

- What is the current knowledge level of LCA for a typical AEC professional?
- What are the perceived and/or actual benefits and barriers to LCA for the AEC community?
- What input assumptions are causing significant error rates in energy model results?
- How does the accuracy of energy model results impact life cycle assessment calculations?

In order to investigate these research questions, numerous objectives directed the research:

- Determine the methods and approach for social science research
- Hold focus group sessions with the assistance of the University Center for Social and Urban Research (UCSUR)
- Investigate methods for reporting focus group results and convey results using the appropriate method
- Research and analyze the appropriate methods for energy modeling
- Investigate a case study and collect appropriate data for energy analysis
- Perform a comprehensive life cycle assessment of the case study
- Evaluate the impact of energy model results on life cycle assessment calculations

This thesis will explore these goals and questions and utilize these objectives as a foundation to conduct the following research.

2.0 FOCUS GROUPS AND SURVEY ON LIFE CYCLE ASSESSMENT

2.1 INTRODUCTION

In order to further understand the lack of whole building LCAs, focus groups with members of the architecture, engineering, and construction (AEC) communities were held. This research first determines the focus group participants' current level of knowledge of LCA. Benefits and barriers to LCA for members of the AEC community have been analyzed utilizing data from the focus groups. In summary, the goal of the research was to identify why LCA is not used to its fullest potential in a whole building life cycle assessment.

Focus groups were developed during World War II as a propaganda technique and have become a popular technique in the social sciences to analyze human behavior (Bertrand, Brown et al. 1992; Kidd and Parshall 2000). They have been utilized as a method to determine the effects of television and film on viewers (Kitzinger 1995; Kidd and Parshall 2000; Machado 2007). Focus groups can also be exploited to analyze the validity of a decision-making model or system (Machado 2007; Steinberg, Patchan et al. 2009; Steinberg, Patchan et al. 2009). Focus groups are directed group discussions that generate qualitative data based on the participants' interaction with each other's principles, perceptions, and values (Ward, Bertrand et al. 1991; Bertrand, Brown et al. 1992; Morgan 1996; Calderon, Baker et al. 2000). Overall, the goal of focus groups is to understand the knowledge and experience of people and why they do or do not think in a particular way (Bertrand, Brown et al. 1992; Kitzinger 1995).

Focus groups have several benefits compared to personal interviews and large surveys. First of all, the participants feel more comfortable contributing information in a group setting and often reply in a spontaneous and authentic manner (Bertrand, Brown et al. 1992). Usually, participants of focus groups find that the experience is significantly more invigorating than individual interviews and self-administered surveys (Kidd and Parshall 2000). Focus groups can also be conducted in a relatively short time frame and can generate useful qualitative data for researchers that are not trained in the social sciences (Bertrand, Brown et al. 1992). The results are also more easily understood to a broader audience and could potentially have a greater impact.

Some of the aforementioned benefits can also create drawbacks to the use of focus groups. One major issue is that the findings from focus groups could be skewed due to the opinions of one person affecting the viewpoints of others, arguments and confrontations influencing responses, and indecisiveness between participants altering the conversation (Kidd and Parshall 2000). In order to decrease these biases, multiple focus groups are recommended so that the data will reflect a variety of group dynamics. Another issue with focus groups is the relatively small sample size. The results cannot be generalized to a larger population because the interview number is so small (Ward, Bertrand et al. 1991; Bertrand, Brown et al. 1992). Thus, the combination of focus groups and surveys has been suggested as an appropriate research method (Ward, Bertrand et al. 1991; Morgan 1996; Calderon, Baker et al. 2000). Sample surveys still have the advantage of producing quantitative results; however, the findings from focus groups are usually highly reliable in comparison with survey data (Ward, Bertrand et al. 1991).

Surveys have been utilized by a few researchers in order to determine the reason for the lack of LCA in practice within the architecture, engineering, and construction community. In a survey by Cooper and Fava (2006), LCA practitioners in all fields, not just the AEC community, were to report their current use of LCA and to determine the barriers to further the practice of LCA. The results of the survey indicated 47% of LCA users are in the manufacturing and materials production field, 77% have used process LCA, and 69% have used stream-lined or Economic Input-Output (EIO). The most prominent barriers of LCA were documented as the time and resources for the data collection, the inherent complexity in the LCA model, and the lack of interest and demand from clients. Cooper and Fava cited education of the LCA method, greater transparency in terms of LCA databases, more funding for the expansion of databases, and simplification of the LCA model as possible solutions to the aforementioned barriers. The main constraint to this analysis is that only 65 participants completed the survey and all were already LCA users, which means that education and opinions may have biased the analysis.

A different survey by Hofstetter and Mettier (2003), which was targeted towards the AEC community, focused on the assessment of the Building for Environmental and Economic Sustainability (BEES) tool. Focus groups were not utilized to develop the survey, but several iterations and tests of the survey occurred in order to strengthen its validity. The survey was administered via the email address of the 2666 persons who had downloaded version 2.0 of BEES. The 566 surveys that were returned equated to a 21% response rate. Only 8% of the respondents applied BEES to an actual building case study; 64% utilized the analysis for product selection; and 31% used BEES for product research. Only 30% had a drive to understand BEES and use the assessment for decision-making purposes. Contrasting the Cooper and Fava survey, most of the LCA users (31%) were in the academic field with 8% in manufacturing. The results of the Hofstetter and Mettier survey are consistent with the premise that LCA is not being used as a method to analyze the environmental impacts of a building over its entire life cycle, but rather as a method of building product selection.

The barriers to the use of LCA in greening buildings could be related both to perceptions of LCA and the existing static framework of LCA, which does not incorporate factors that are traditionally of importance to buildings and building users. In general, LCA has been documented as being too complex, time consuming, and unreliable (Hofstetter and Mettier 2003). In order to analyze LCA within the AEC community, two focus groups were conducted with the Green Building Alliance (GBA), the USGBC chapter of Western Pennsylvania.

2.2 FOCUS GROUP METHODS

This research ascertains the current level of knowledge of LCA in the architecture, engineering, and construction community and reveals the associated benefits and barriers to the practice of LCA. The main question guiding this research was: *what are the perceived and/or actual benefits and barriers to LCA for the AEC community?* The method for conducting the focus groups was to:

- Develop a focus group guide to direct the conversations
- Convene diverse focus groups and encourage stimulating discussion
- Generate coded analysis of the sessions
- Document themes discovered within the codes

- Use the analysis to understand the language and information needed to generate an effective subsequent survey

With the help of GBA, architects, engineers, contractors, manufacturers, building owners, and nonprofits with varying experience levels in sustainability and LCA were assembled for a one-hour focus group over lunch; two focus groups were conducted. Since several participants of the focus groups were members of GBA, they were more likely to be familiar with sustainable design. As shown in Table 1, at least one of each AEC professional was invited to participate in the focus group to ensure diversity and generate a fruitful discussion. In the second focus group, however, no building owner was able to attend even though several were invited. In order to ensure adequate discussion while not yielding confusion and disorganization, the target number of participants was 6 to 12. As detailed in Table 1, there were 12 participants in the first group and 8 participants attended the second session. As suggested by Kidd and Parshall (2000), two rounds of focus groups were sufficient to achieve data saturation, the point at which no new themes would be recorded.

Table 1. Number and Labeling of Focus Group Participants.

In order to generate anonymity, generic labels where given to each member of the focus group (e.g. A1).

Focus Group	Architects	Engineers	Contractors	Manufacturers	Owners	Nonprofits	Total
FG1	A1	E1; E2	C1; C2; C3; C4	M1; M2	O1; O2	N1	12
FG2	A1	E1; E2; E3	C1	M1; M2		N1	8

Figure 1 portrays the composition of the focus groups that were held. Each field that was present within the AEC community is documented in the legend, and the number of participants is visually illustrated, denoting either one or two people. This figure also shows the experience level in LCA and sustainability in order to demonstrate the diversity of the focus group. As the trendline indicates, most participants were not experts in either LCA or sustainability but had adequate knowledge to contribute to the conversation. The group composition and the subsequent group dynamics has been documented as both an advantage and drawback to the use of focus groups (Kidd and Parshall 2000).

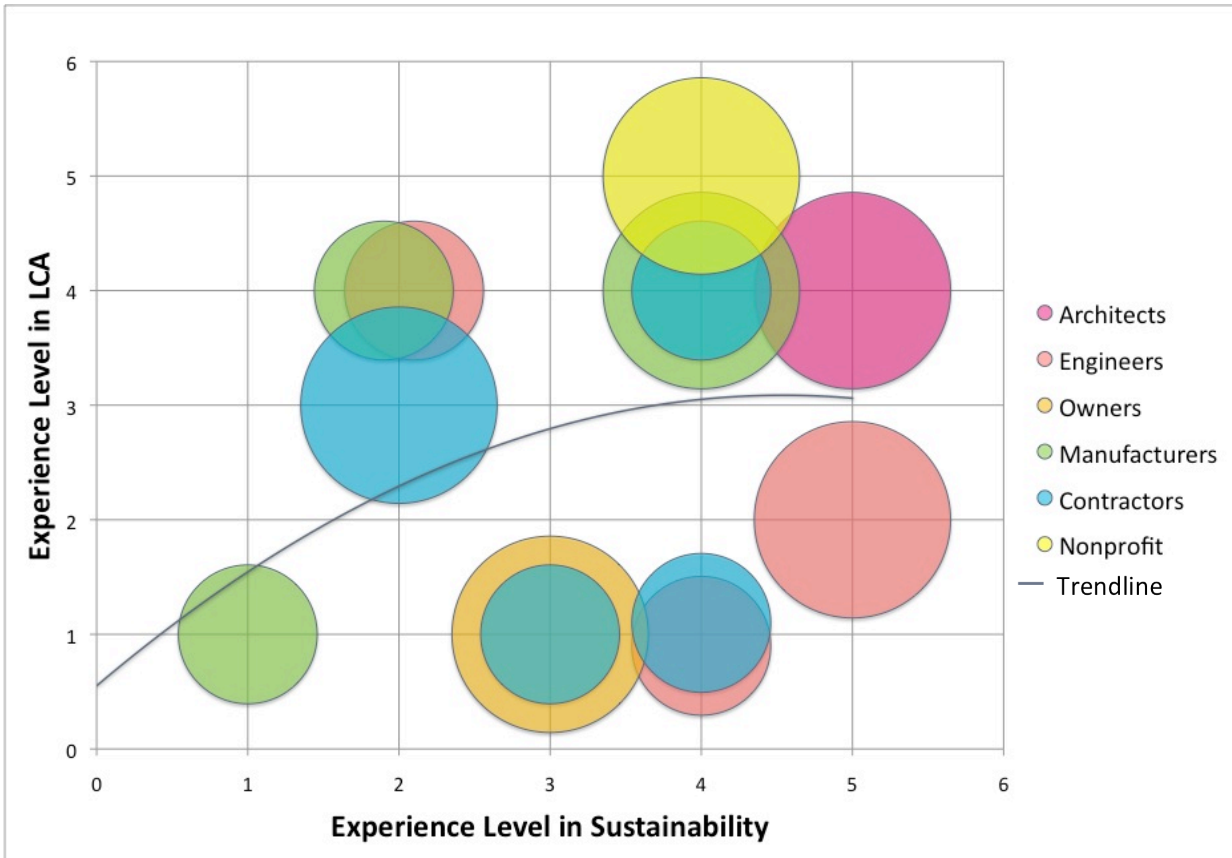


Figure 1. Focus Group Participants' Experience with Sustainability and LCA.

The larger bubbles represent two people, whereas the smaller bubbles represent one person. Scale: 5=Expert; 4=Highly Experienced; 3=Somewhat Experienced; 2=Somewhat Familiar; 1=Not Familiar

A focus group guide was generated in order to help the moderator direct the discussion of the participants. The guide was composed of a series of 9 questions with different formats; an abbreviated version of the guide is presented in Figure 2 (The complete focus group guide is in Appendix A). At the beginning, each person was asked by the social science moderator to individually state his or her field within the AEC community and familiarity with sustainability. A similar, around-the-table question followed asking each individual for his or her own definition of LCA, in order to gauge LCA expertise. After this discussion, a ten-minute educational segment, which described the process of LCA and the results of its analysis, was administered by an LCA practitioner and educator in order to balance out the experience level of the participants.

The educational segment focused on the discussion of life cycle thinking and process LCA. A neutral example of food was utilized as the lesson on life cycle thinking. The process of producing each piece of the food item was emphasized. For example, in the case of a bun, the grain to produce the bun and the feed for the cattle was described in detail; then, the electricity, transportation, and packaging needed for each of these was illustrated. At the end of this description, it was emphasized that this is only one element of the life-cycle supply chain. After the example, the stages of LCA, the ISO standard, and impact assessment categories, were discussed.

Following this educational piece, a series of questions that encouraged an open forum of discussion aimed to pinpoint the benefits and barriers associated with the practice of LCA within the AEC community. Figure 2 indicates the organization and content of the questions. Topics covered included barriers, benefits, software tools, and the Leadership in Energy and Environmental Design (LEED) program. The open forum format of these questions was significantly different than the around-the-table format of the earlier inquiries.

Focus Group Guide – Life Cycle Assessment

1. Let's go around the table and please say your first name and how long have you been a member of GBA or involved with green design. Have you implemented sustainable building practices into your projects?

2. Are you familiar with LCA? If so, how would you describe it in your own words?

-------------------------------------- Break for Educational Segment ---------------------------------------

3. What are the barriers to using LCA in your respective fields?

4. Neglecting the aforementioned barriers, do you think LCA would be beneficial to improving and understanding sustainability in your respective fields? If so, what are the benefits of LCA?

5. Which barriers to using LCA would be negated if LCA were integrated into current software tools?

6. In what ways would LCA be a beneficial tool for the LEED program?

7. Our purpose today was to find out your opinions and ideas about LCA. Are there any other comments that you have about LCA that we have not covered?

Figure 2. Abbreviated LCA Focus Group Guide.

The first three questions listed were an around-the-table format. The questions after the educational segment prompted an open forum of discussion. The complete focus group guide can be found in Appendix A.

The focus group discussions were audio-recorded and the speakers were noted in order (Bertrand, Brown et al. 1992; Kidd and Parshall 2000). The recorded conversations were later transcribed by social researchers into an inventory of quotes by both moderators and participants. All participants remained anonymous and each speaker was identified by his or her specific field, as detailed in Table 1.

After the recording was transcribed, the discussion was analyzed to determine trends within the conversation, which is a method documented by several social science researchers (Bertrand, Brown et al. 1992; LeCompte 2000; Liamputtong 2011). Table 2 shows the identified trends from the transcription of focus group one. The questions that were asked are listed on the left-hand column, and the themes that were discovered are listed along the top row. Ideas discussed in the focus group that followed the themes listed are charted within the table. The anonymous labels indicate which participant conversed about the idea. From the trends discovered in Table 2 codes were developed. These codes included: the questions asked, the participant labels, the AEC field, and the themes that were discovered.

Table 2. Analysis of LCA Focus Group Transcription to Determine Subsequent Coding.

In the column on the left, questions asked in the focus group are listed. The top row lists some trends found within the transcribed quotations. Within the table are ideas that were discussed that follow the trends discovered and who discussed them from focus group one. Highlighted cells indicate quotations that were discussed for a long time in the groups.

	Gaps in LCA	Education/ Social Problems	Economic Problems	Logistical Issues	Confusion with LCC	Environmental Validation of LCA	Social Validation of LCA
What is LCA?		Confusion about use phase inclusion [E-1]			LCC/paying off material over time [O-2; C-1]	Cradle to grave environmental impacts [A-1; E-1; M-2; N-1; C-1]	
Barriers in LCA	LCA cannot compare products [N-1]	Do people understand the analysis? [M-1]	Cost of doing An LCA [M-1]	Tough to gather data [C-1]	Economics: off topic to LCC [C-3; O-2; A-1; E-1]	How so you prove sustainable options are a must to clients? [A-1; E-1; C-1]	
	LCAs between companies are not comparable [N-1]	Complexity of LCA [M-1]	No incentives to perform LCA [M-1]	Location/orientation/building type affects LCA [A-1]			
	LCA does not generate a simple choice [M-1]	Does information have any value? [M-1]					
	After design phase who is responsible for updating LCA? [C-1]	Trust of data/ assumptions [A-1]					
Using LCA to understand sustainability			LCA is misused as a marketing tool [O-1; M-2; N-1]			LCA is the right approach [C-1; M-2]	
						Recycled content/air quality is not holistic [M-1]	
Benefits of LCA						Validation of sustainable development [C-1]	Education [C-1; M-1]
						Environmental/ economic benefit [C-1]	Understanding a product better [M-1]
LCA in current software packages	Need better LCA standards (M-2)						Makes decision-making easier [E-1; C-1]
	Simplified LCA would be more beneficial [N-1; M-1]						Could change behavior of designers [A-1]
	LCA should not be final decision [A-1]						
LEED and LCA	LCA best in materials category [N-1; A-1]						LCA affects the weighting of LEED [M-1]
	Only 4 familiar with LCA and LEED [M-1; N-1; C-1; A-1]						LEED pilot credit [M-1; N-1; C-1]

The transcription was then coded by social scientists using ATLAS.ti 6.0 (ATLAS.ti GmbH 2002). Two coders, who specialize in qualitative data analysis, were utilized to fine-grain, or line-by-line, code each quotation in the transcription, a technique documented by Kidd and Parshall (2000). Each code could also be utilized to develop a family of codes. An example of a coded quotation is depicted in Figure 3. Each code corresponds to a particular part of the quotation. The first two codes in Figure 3 indicate that this was stated by a manufacturer and was marked as a benefit to LCA. Both of the *Validation of LCA* codes (environmental and social) as well as *Using LCA to Understand Sustainability* were themes discovered within the transcription analysis and can be found in Table 2. Coding the quotations allowed the social researchers to group quotations that had the same codes, and therefore, discussed similar ideas. Then, the grouped quotations can be counted in order to determine how many times an idea was mentioned within the session.

Bilec FG_20110331.docx - 1:83

Codes: 1. [Participant M2 - Families (2): P-Manufacturers, Participants]
2. [Benefits of LCA - Family: Non-Participant Codes]
3. [Using LCA to Understand Sustainability - Family: Non-Participant Codes]
4. [Validation of LCA~Environmentally - Family: NP-Validation of LCA]
5. [Validation of LCA~Socially - Family: NP-Validation of LCA]

M2 [1]: "…I go back to my original comment that I really think it is the right approach [2], I think if maybe the last 5 or 10 years have taught us anything it's that there are lots of different ways of looking at sustainability, but LCA is really the only one that looks at the big picture [3]. You can pick off things like recycled content or indoor air quality or whatever, some products perform better than others, but they're going to perform worse in some other categories, so this seems to be the right way to look at the bigger picture, and I'll leave it at that [4,5]."

Figure 3. Representative Quotation from the Output from ATLAS.ti 6.0.

This quotation was stated in the first focus group and started at line 83, which is documented in the top line here. Each code that was applied to this quotation is listed here and its number is used to indicate the corresponding reference for the code within the passage. Each of the themes documented here can be found in Table 2.

2.3 RESULTS OF THE LCA FOCUS GROUPS

After the codes were implemented to the transcription, different means of quantitative analysis of focus groups were researched in order to document and understand the code data. There are a wide variety of ways to report the findings of focus groups. Some studies utilize a flow chart as a means to depict the interaction of the focus group and the hierarchy of the information discussed (LeCompte 2000; Machado 2007). An early iteration of the focus group results in a flow chart type diagram is illustrated in Figure 4 and Figure 5. This highly visual diagram generates an efficient understanding of the conversation of the group, but it lacks any quantitative data to support the logic of the flow chart. Michelle A. Saint-Germain et al present an alternative technique, which documents in a table form the times mentioned of each important factor within the focus group (1993). This chart illustrates that quantitative data can be derived from a qualitative method; however, it also lacks the visual structure of the flow charts. A hybrid method of reporting focus group data, which incorporates both hierarchal and times mentioned data, is presented in Figure 6 and Figure 7.

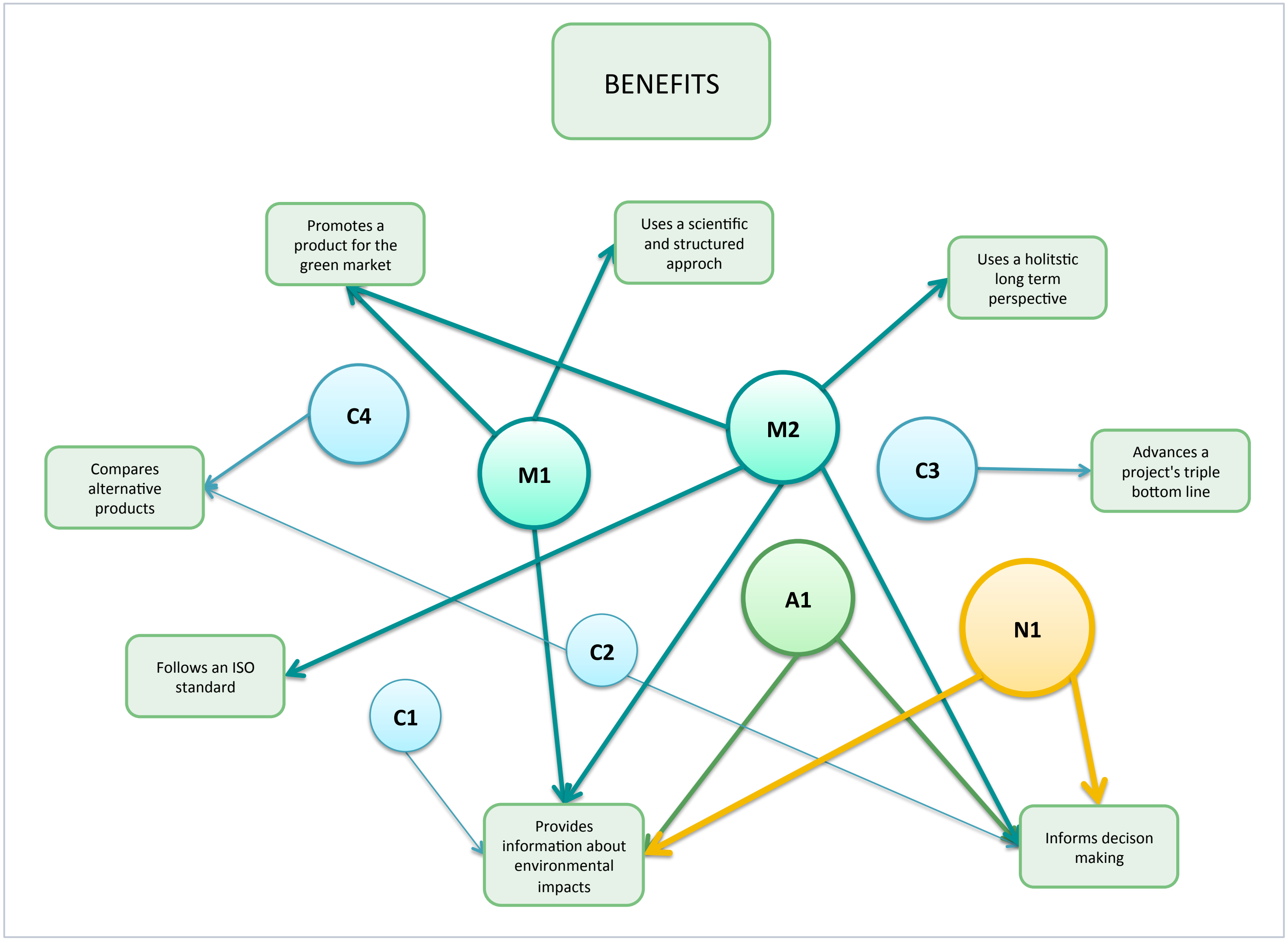


Figure 4. Benefits of LCA Flow Chart from Focus Group 1.

The benefits mentioned are shown here in green squares. Each participant of focus group 1 that mentioned the benefit is connected in a flow chart diagram. The size of the bubble for each participant represents the level of prior knowledge on LCA.

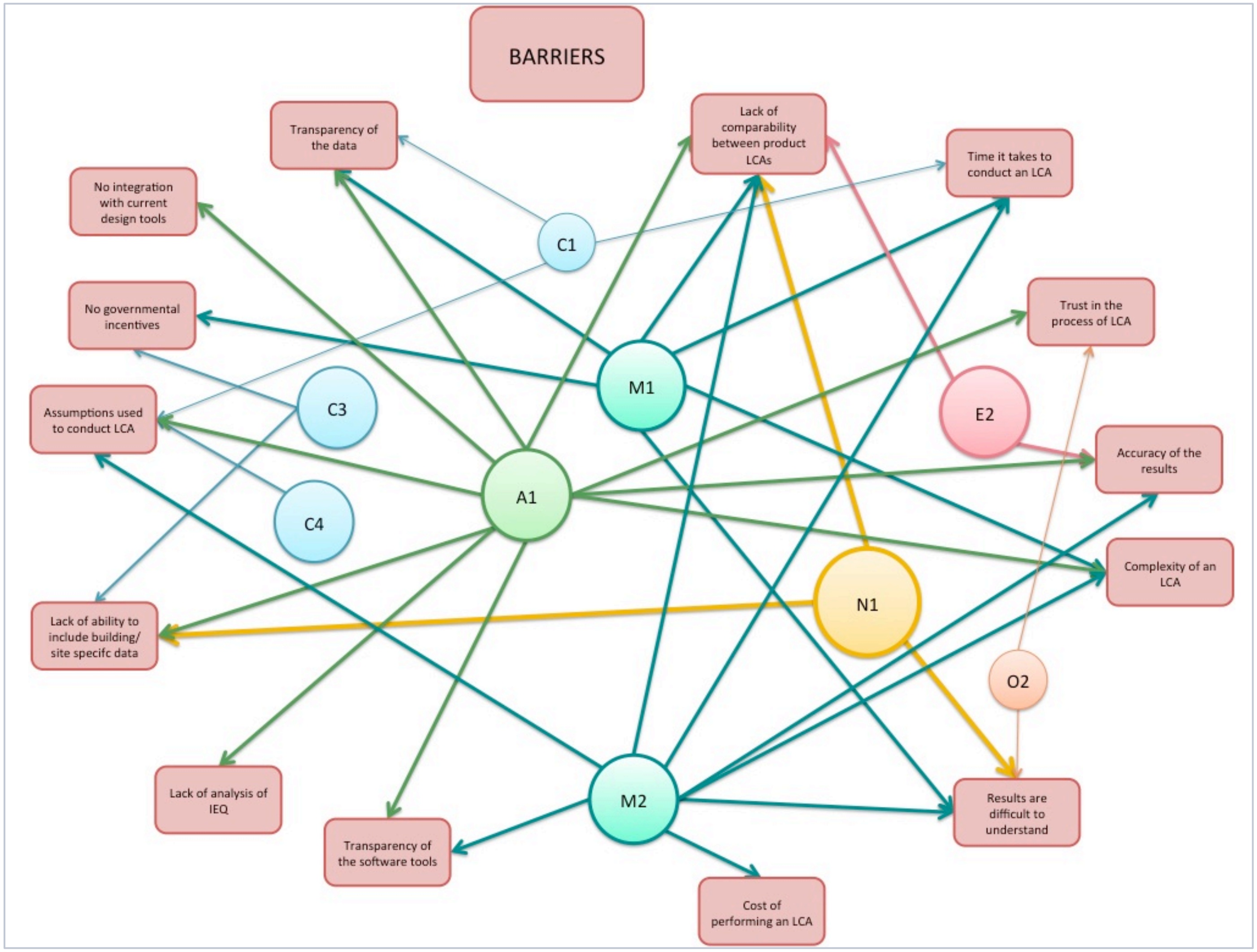


Figure 5. Barriers to LCA Flow Chart from Focus Group 1.

The barriers mentioned are shown here in red squares. Each participant of focus group 1 that mentioned the barrier is connected in a flow chart diagram. The size of the bubble for each participant represents the level of prior knowledge on LCA.

2.3.1 Benefits of LCA

The benefits of LCA that were mentioned throughout the duration of the focus group are shown in Figure 6. As anticipated by the findings of Cooper and Fava, the following benefits were mentioned in the focus group: *Provides information about environmental impacts* and *Compares alternative products* (2006). Debates within the focus groups yielded an in-depth analysis of the benefits. Consequently, the additional benefits of using LCA were: *Uses a long term holistic perspective*, *Promotes a product for the green market*, and *Advances a project's triple bottom line.* The total number of times that benefits were mentioned was 37, which is depicted in row A of Figure 6.

Two major broad categories of LCA benefits were identified: *Benefits of the LCA method* and *Benefits of conducting an LCA,* as illustrated in Figure 6, row B. *Benefits of the LCA method* include the benefits of the life cycle thinking and the four step scientific system in comparison with other building-related sustainability metrics, such as rapidly renewable materials. *Benefits of conducting an LCA* comprise the benefits of LCA analysis that assist in the advancement of sustainability (environmental, social, economic) within the building sector. Figure 6 illustrates that *Benefits of conducting an LCA* were discussed more often than *Benefits of the LCA method*, specifically 30 responses to 7. One example of the advantage of the LCA method was summarized by participant A1 from focus group two, "…[An LCA indicates] how sustainable is [a] product overall, versus whether it meets the recycled content requirements…". Three others from focus group two and three participants from focus group one stated benefits to the LCA method.

In terms of the *Benefits of conducting an LCA,* a prevailing discussion was that the results of an LCA could substantially contribute to aiding in environmental strategies. For example, in focus group one, M1 stated, "I think [LCA] really is the right tool for assessing the environmental impacts of a product or a building… But we also see a lot of limitations about assumptions and boundaries...". One potential interpretation is that the process of LCA is difficult but the benefits may be worth overcoming those issues.

Of subcategories in row C, environmental benefits were cited the most at 12 times out of the total 37. Economic benefits were a close second to environmental with 10 times mentioned. Interestingly, the scientific-based and life cycle thinking subcategories were mentioned 3 and 4 times respectively. These results are perhaps counterintuitive to researchers who consider the holistic view of LCA and its scientific methodology to be its most essential attributes (Hauschild and Wenzel 1998; Baumann and Tillman 2004). Practitioners, however, may have the view that these qualities will cause the LCA process to be even longer and more complex. This observation is supported by one participant of focus group two, M1, who asserted, "..I don't think [LCA] is a short-term approach. You have to look at the long term to see the benefits of it, and that's where it can sometimes be difficult."

Row D of Figure 6 illustrates more specific benefits mentioned by the focus group participants. Some of the results from row D are similar to those from row C. *Provides information about environmental impacts* (under environmental subcategory) was discussed the most (nine times), whereas *Follows an ISO standard* (under scientific based subcategory) was mentioned once. Three benefits represent the application of product LCAs: *Compares alternative products, Informs decision-making,* and *Promotes a product for the green market.* Together, these three benefits have 15 out of the 37 responses, which is more than the environmental subcategory (12) in row C. The high ratio of manufacturers, who were knowledgeable about LCA, compared with the others in the group, as indicated in Figure 1, may be the reasoning for the receptiveness to product LCAs. In summary, Figure 6 highlights the importance of the results of LCAs in relation to environmental impacts.

2.3.2 Barriers to LCA

Using the same methods that pinpointed benefits of LCA, barriers to LCA were indentified and are illustrated in Figure 7. Several barriers to LCA that were ascertained were similar to the conclusions of Cooper and Fava: time and difficulty in collecting data, complexity and transparency of the method, and *Lack of demand from clients* (2006). Additional barriers to LCA were identified in the open discussion format of the focus group, including: *Lack of comparability between product LCAs, Difficulty in understanding results,* and *Lack of governmental incentives.* The total number of times barriers were mentioned in the focus groups was 65, illustrated in Figure 7 (row A). Benefits, on the other hand, were mentioned 37 times, about half as many times as barriers.

Consistent with the benefits analysis, row B of Figure 7 divides the data into two broad categories: *Barriers within the LCA method* and *Barriers to conducting an LCA*. The data is relatively unclear as to which category is the greatest barrier; however, it does trend towards the method category with a rating of 37 responses. Similarly, in Figure 6, the results showed that participants were well aware of the *Benefits of conducting an LCA* but were unsure of the benefits to the method. When directly comparing benefits versus barriers to LCA, the focus group data indicates that the *Barriers within the method* of LCA outweigh the benefits, 37 responses to 7 respectively. However, participants E3 and A1 of focus group two emphasized that further standardization of LCA in terms of boundaries and assumptions may negate some of the *Barriers within the LCA method*, such as *Lack of comparability between product LCAs* and *Time it takes to conduct an LCA*.

One important part of this study was to ascertain the specific barriers of using LCA in the AEC community. Several reasons were discussed; one dominant barrier did not emerge. For example, in row C of Figure 7 types of barriers discussed were: *Logistical Issues* (17), *Gaps within the Method* (20), *Educational issues* (18)*, Social Issues* (18)*, and Economic Issues* (18), where the number in parentheses represents the number of times the barrier was mentioned during the focus group sessions. This data suggests that one clear barrier did not emerge, instead a host of contributing factors exists. For example, in focus group one, participant A1 suggested that *Trust in the process of LCA* was the most important barrier; however, A1 of group two stated that *No demand from client* was the biggest barrier.

At a more detailed level of analysis (see Figure 7, row D), a diverse set of 15 barriers were identified within the focus groups, and 6 of these barriers were mentioned the most, either 6 or 7 times. *Lack of comparability between product LCAs* had the highest number of responses with 7 out of 65. As stated in the benefits analysis, the knowledge level and number of manufacturers could have attributed to the presence of product analysis within the results. After product LCAs, five different barriers were mentioned 6 times. At the other end of the spectrum, *No integration with current design tools* and *Transparency of the software tools* pose the least barriers with 1 and 2 responses respectively. Another finding from this layer involves the barrier, *Cost of performing an LCA*. Cost was only mentioned 4 times, even though cost is so important to projects, as A1 from focus group two said, "…first cost tends to drive a lot of building projects, still."

2.3.3 Synthesis of Focus Group Results

In order to further understand the composition of the focus groups and the benefits and barriers to using LCA, radar charts were developed. Utilizing radar charts as a method to report multiple sets of data within focus groups has been previously documented in a study by Kaczynski et al (2008). In order to employ this method, each geometry in Figure 8 is connected with a particular demographic (e.g. architect) and each point on the pentagon is a subcategory from row C in the flow charts. The radar charts indicate which type of benefit or barrier was mentioned the most by each AEC field.

The benefits are depicted in Figure 8a, with the subcategories from Figure 6 being *Social, Environmental, Economic, Life cycle thinking,* and *Scientific based*. Comparable to the findings from Figure 6, Figure 8a shows that the manufacturers had the most number of benefits to report, 16 responses out of 37, even though there were more contractors and the same number of engineers that participated in the focus groups. Out of 16 total responses, the manufacturers most commonly mentioned economic reasons, which were stated 5 times, as the greatest benefit. The aforementioned results in Figure 6 (row D) illustrates that the economic benefits include *Promotes a product for the green market.* As stated by one manufacturer, M2 of focus group two, "… I think our [sustainability] initiative was driven by a competitor…[and their] news article out there. Why aren't we doing it, you know, this kind of thing, getting that public recognition." Divergent from the manufacturers are the owners, who reported no benefits. Two owners participated in the focus groups, but neither one gave a benefit to the implementation of LCA in the building industry. This result could be due to the owners' relatively low knowledge level of LCA, as illustrated in Figure 1, or a lack of perceived value of LCA. Engineers stated the lowest number of benefit responses at 2. The diversity of responses related to the types of benefits mentioned in the focus groups is apparent in the different geometries presented in Figure 8a.

Data showing the barriers charted by the type of AEC field is depicted in Figure 8b with the subcategories from row C in Figure 7 being *Logistics, Gaps, Education, Social,* and *Economics*. Again, the manufacturers generated a large number of responses, mentioning barriers 14 times. Differing from the benefits, the owners, however, did respond with a few barriers, mentioning them 2 times. The number of responses of the architects was also greater than benefits, specifically from 7 benefits to 17 barriers. The architects perceived that a large portion of the barriers, 7 out of the 17 responses, were attributable to *Gaps within the LCA method* or mores specifically, *Lack of ability to include building/site specific data* and *Lack of analysis of indoor environmental quality (IEQ)*. This information is especially important to sustainable building design, specifically as they relate to occupant health and productivity (Wargocki, Wyon et al. 1999). In summary, the geometries from Figure 8b are not as drastically varied as those from the benefits radar chart, but they do indicate that the types of barrier mentioned the most times differs between AEC field.

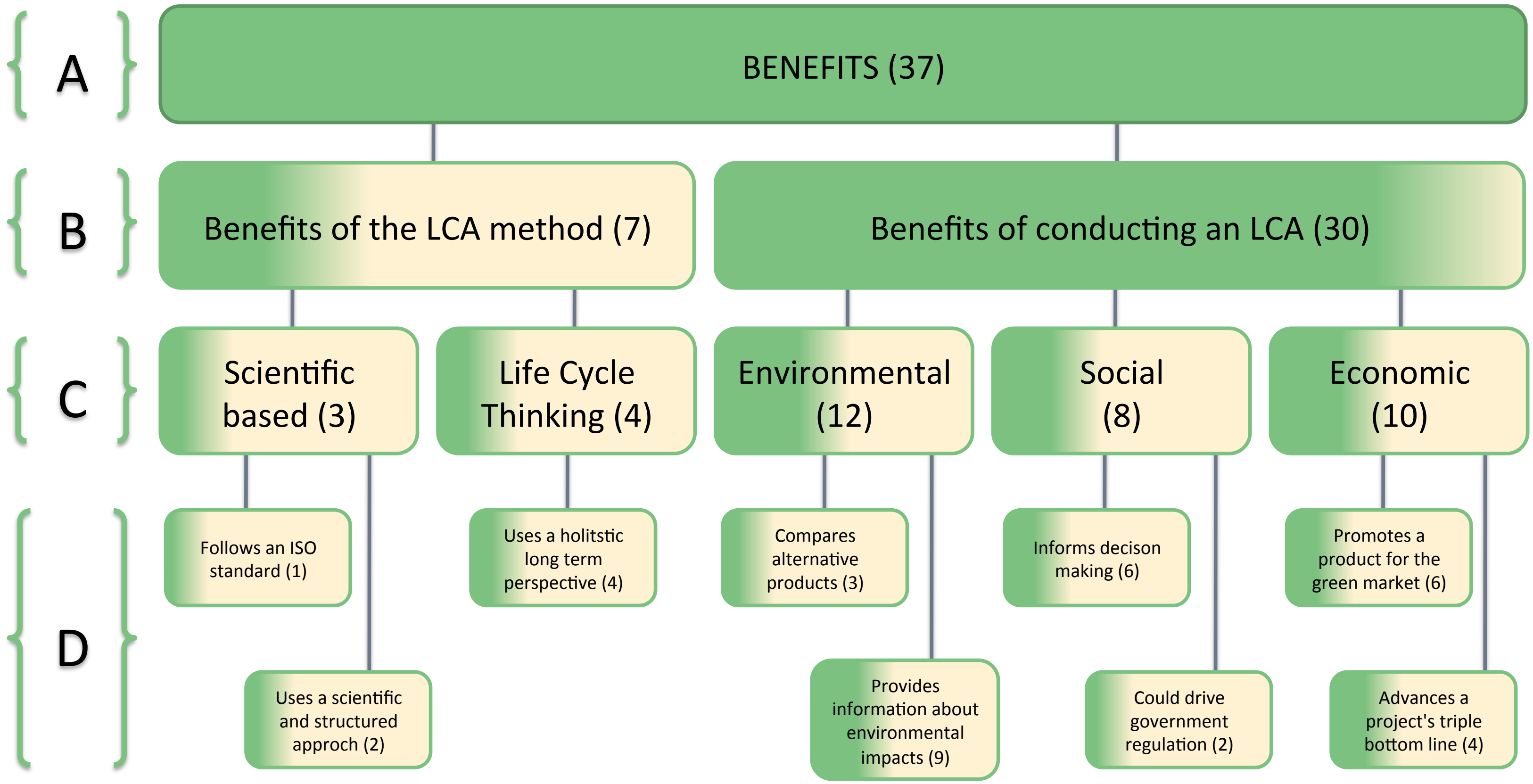


Figure 6. Hybrid Flow Chart Showing Times Mentioned for Each Benefit Cited in the LCA Focus Groups.

Rows: A=Total number of benefits; B=Broad categories; C=Subcategories; D=Benefits identified. Each number in parentheses indicates the number of times the specific benefit was stated during the course of the focus group. For both focus groups, benefits were mentioned 37 times, which is shown in row A. Along with the times mentioned, the gradients represent which "part of the whole" that each benefit or category represents (e.g. 9 out of 37, or 24%).

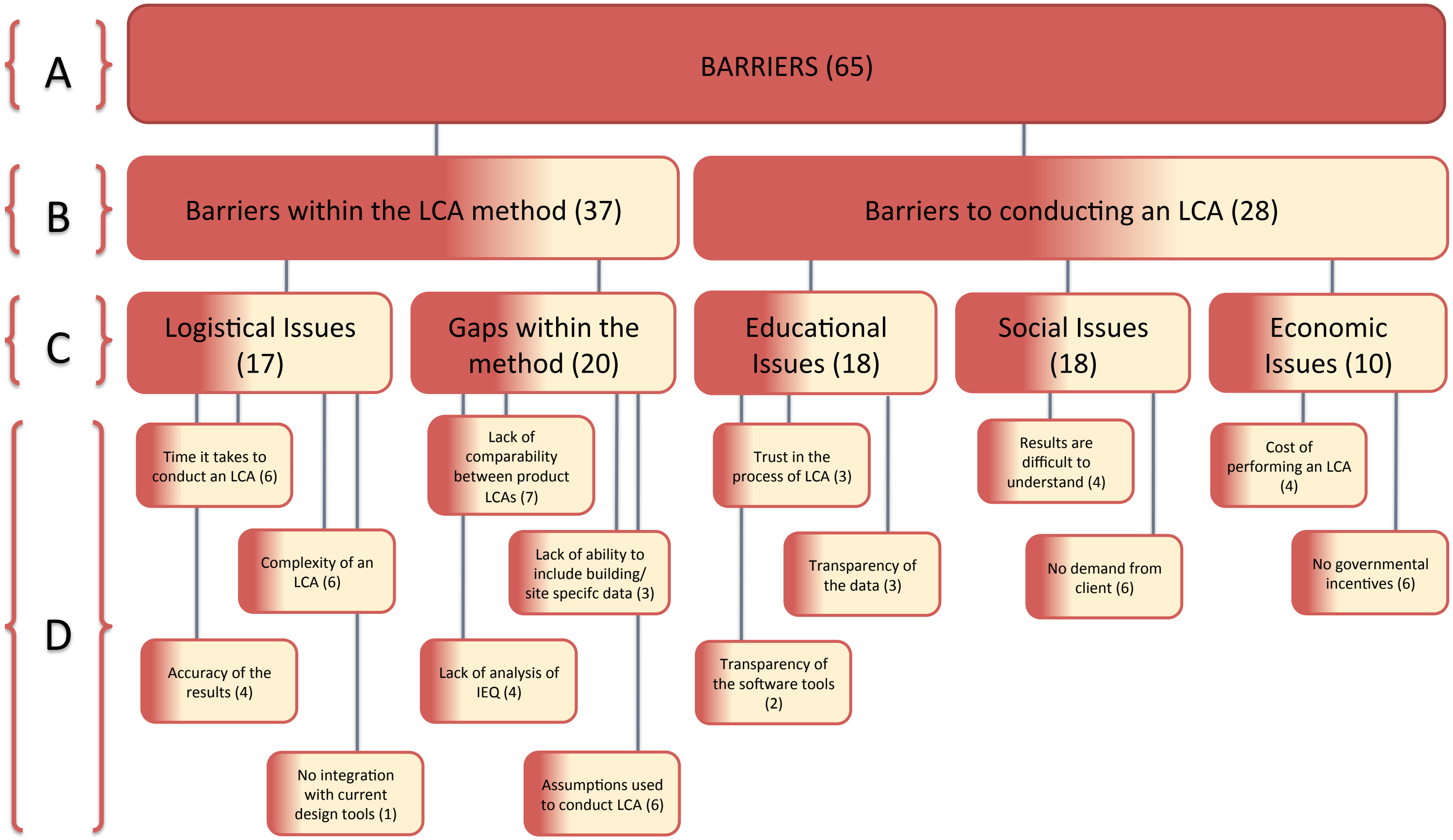
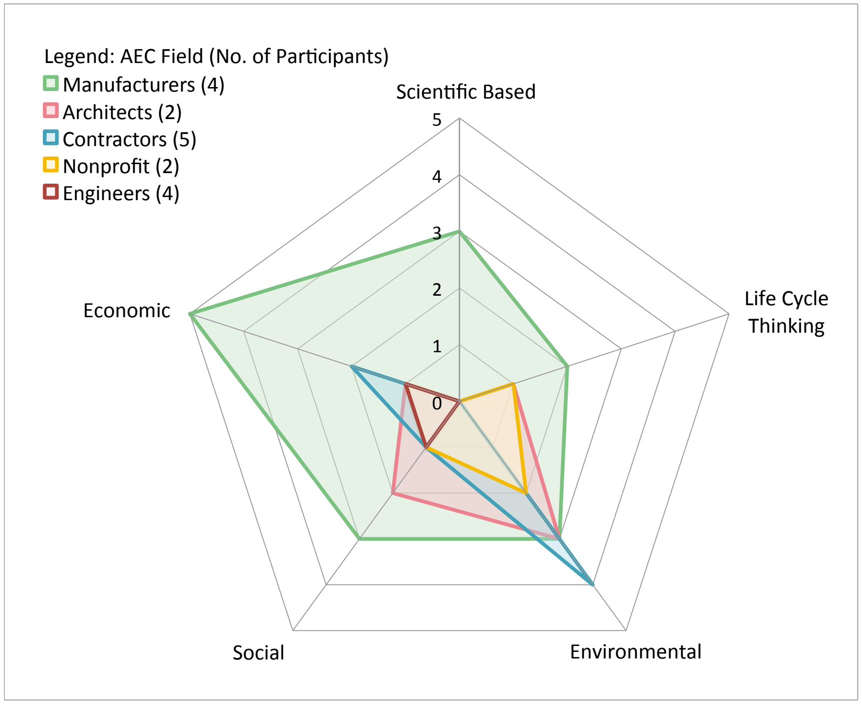
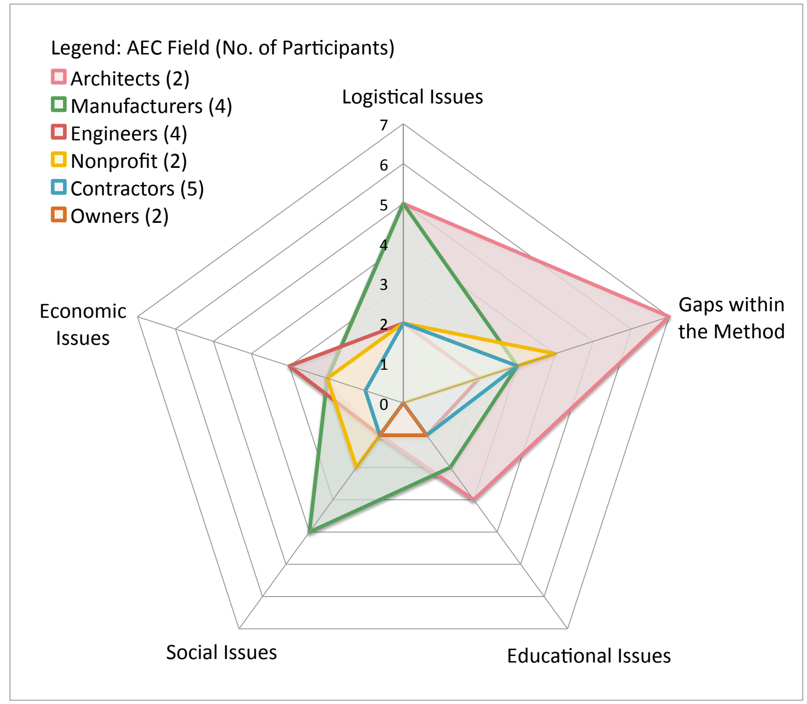


Figure 7. Hybrid Flow Chart Showing Times Mentioned for Each Barrier Cited in the LCA Focus Groups.

Rows: A=Total number of barriers; B=Broad categories; C=Subcategories; D=Barriers identified. Each number in parentheses indicates the number of times the specific barrier was stated during the course of the focus group. For both focus groups, barriers were mentioned 65 times, which is shown in row A. Along with the times mentioned, the gradients represent which "part of the whole" that each barrier or category represents (e.g. 4 out of 65, or 6%)



(a) Benefits



(b) Barriers

Figure 8. Types of Benefits (a) and Barriers (b) to using Life Cycle Assessment from Focus Groups.

The legend indicates the number of participants per sector, which is not plotted on the radar chart. The scale (0 to 5) represents the number of times each benefit or barrier was mentioned during the focus group discussions. The benefits and barriers categories correspond with rows C in Figures 6 and 7, respectively.

2.4 CONCLUSIONS OF FOCUS GROUPS

Findings from the focus group highlighted perceptions in the AEC community concerning the benefits and barriers to LCA. In general, *Benefits of conducting an LCA* are more important than *Benefits of the LCA method*, which yielded 30 responses to 7 respectively. The most important benefit (*Provides information about environmental impacts)* was consistent with the LCA definition in general and was mentioned 9 times out of the 37 total responses. In addition, manufacturers cited economics as the most valued type of benefit. The results of the barriers to LCA, however, were ambiguous. No single barrier emerged as the most important. The architects, however, did seem to agree that building-related metrics, such as IEQ, are missing from current LCA analyses, which could be a crucial barrier to LCA for the AEC community in terms of building design.

The method of LCA could be substantially improved as documented by the focus group. Complexity, time, and accuracy were all acknowledged by the participants as issues of the method. A simpler version of LCA was suggested as a solution to this issue by participants N-1 and M-1 of focus group one. Some current LCA tools, such as Building for Environmental and Economic Sustainability (BEES), provide a simpler version by incorporating building systems as processes instead of just individual products or materials; however, the building system libraries need further research (Lippiatt ; Scheuer, Keoleian et al. 2003). *Gaps within the method* was also recognized by the focus group as a significant barrier to LCA. Participant A-1 of focus group one suggested that LCA expand to include building location and orientation. LCA could also incorporate IEQ metrics, such as air quality, light, and acoustics, in order to evaluate worker productivity (Wargocki, Wyon et al. 1999). Several benefits and barriers documented by the focus group could be utilized to improve the method of LCA.

The differing viewpoints and education of the fields within the AEC community may have affected the results of the focus groups. Due to the recruitment by GBA, participants had a general interest in sustainability and LCA, which could have biased the results. The most prominent group in terms of size and knowledge level was the manufacturers; consequently, their presence and opinions were apparent within the results and could have biased the data. At the opposite end of the spectrum were the owners, who were not well represented in the focus groups and had minimal experience levels. Greater numbers of owners could have produced diverse results. This indicates the limitations of the focus group due to its small sample size, as previously mentioned within the literature review.

To further examine the benefits and barriers, the results of this focus group have been used to develop a national survey. The survey has a similar format to the focus group guide, only extended. The survey is further discussed in Appendix B; however, it is still in the developmental stages of research. In the future, the combination of the survey and the focus groups would produce results that have both a larger sample size and incorporated group interaction.

3.0 ENERGY MODELING AND LIFE CYCLE ASSESSMENT

3.1 INTRODUCTION

In order to further analyze the limitations to LCAs of buildings, this research analyzes the link between energy modeling and life cycle assessment, as well as the uncertainty associated with energy modeling results and their possible impact on LCA results. A case study of a Solar House, a low energy building, has been utilized as a method to understand the issues connected with energy models, including input assumptions and variations between predicted energy use at the design phase and actual consumption.

Some green buildings have been faulted for not performing as energy efficiently as their non-green building counterparts. The New York Times and the New Buildings Institute (NBI) both have published articles highlighting this dilemma within the building industry and emphasizing the disparity between the design phase and the use phase of buildings (Turner and Frankel 2008; Navarro 2009). Green buildings are sometimes labeled as energy efficient in the design phase without monitoring the actual energy usage of the building. This condition places much emphasis on the accuracy of the energy modeling programs that predict building energy usage. Energy modeling has become an integral part of the design phase of buildings, and the accuracy of these programs has been a central focus of some research. The results of these programs can also be utilized to estimate life cycle energy use of buildings (Cole and Kernan

1996; Keoleian, Blanchard et al. 2000; Scheuer, Keoleian et al. 2003). Low energy buildings could have lower operating energy than embodied energy; however, these predicted results in the design phase could or could not depend on the accuracy of the energy model results (Cole and Kernan 1996).

In 2000, the United States Green Building Council (USGBC) developed a third-party rating system called Leadership in Energy and Environmental Design (LEED) (United States Green Building Council 2011). The goal of LEED is to promote the development of high performance in buildings in five categories: site selection, water use, energy, materials, and indoor environmental quality (IEQ). The USGBC states that LEED buildings will "redefin[e] the way we think about the places where we live, work, and learn." Even though LEED for Existing Buildings focuses on maintenance and operations of buildings, more attention has been given to the program's New Construction (LEED-NC) rating system since it has the most certified buildings at 4,785 (United States Green Building Council 2011). LEED-NC concentrates more on the design phase of buildings, rather than the use phase.

Currently, in LEED-NC v2009 the category with the highest number of achievable points is Energy and Atmosphere (EA) at 35 (United States Green Building Council 2009). Within the EA category, several different options exist for potential credit, including commissioning, refrigerant management, and even measurement and verification (M&V), which requires the building's energy performance to be monitored for at least one year. M&V, however, only qualifies for 3 points out of the total 35 for EA. EA credit 1 "Optimal Energy Performance" option 1, on the other hand, is eligible for up to 19 points. This credit is a follow-up of EA Prerequisite 2 "Minimum Energy Performance." The first option of these two credits relies on building energy modeling and a calculated reduction in energy usage from the baseline standard

American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) 90.1-2007. The minimum reduction for the prerequisite is only a 10% reduction from the baseline for new construction and a 5% reduction for major renovations.

In order to determine if these were effective measures to reduce energy usage, the USGBC commissioned NBI to perform a study of the operating energy of occupied LEED buildings (Turner and Frankel 2008). The 2008 study was comprised of 121 LEED-NC v2 buildings that were certified prior to 2006. The participating buildings were required to give at least one year of post-occupancy energy use data. In order to benchmark the LEED buildings, energy-use intensity (EUI) in kBTU/ft^2/yr was compared with data from the Commercial Building Energy Consumption Survey (CBECS), which is a survey distributed every several years by the U.S. Energy Information Administration (U.S. Energy Information Administration 2003). On average, LEED buildings consumed about one quarter less energy than conventional commercial buildings in CBECS (Turner and Frankel 2008). The study did generate interesting results when comparing LEED buildings with other energy efficient building rating systems. NBI determined that 53% of the 121 LEED buildings would not have qualified for Energy Star certification, which is a green building rating system developed by the U.S. Environmental Protection Agency (EPA) that requires measured energy data (U.S. Environmental Protection Agency ; Turner and Frankel 2008; Navarro 2009). In a 2009 New York Times article, writer Mireya Navarro published the findings of the NBI study and also highlighted a LEED-certified General Services Administration building that did not qualify for Energy Star due to its energy intensive cooling system. The article received much press for its report and has prompted further discussions as to the disparity between the design phase EA credits and measured energy usage (Daly, Franconi et al. 2011).

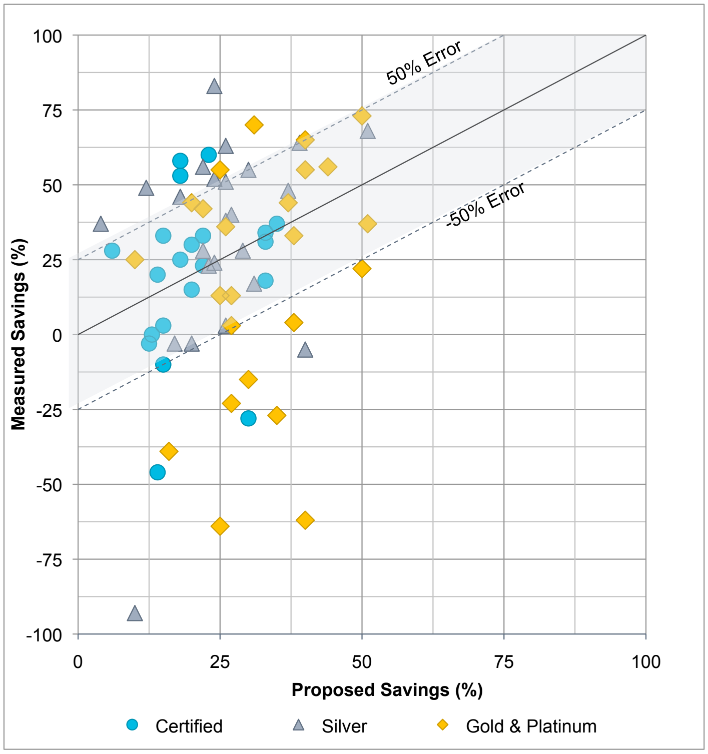


Figure 9. Proposed and Measured Energy Savings of LEED Buildings.

The proposed savings represent the percentage energy savings from the baseline calculated by energy models or by prescriptive methods for the respective LEED buildings. The measured savings represent the percentage of actual metered energy usage that is less than the baseline. Buildings that have a negative measured savings consume more energy than the baseline model. Any buildings below the linear trendline are saving less energy than modeled, whereas any buildings above are saving more. Adapted from Figure ES-5 in Turner and Frankel (2008).

As previously mentioned, LEED-certified buildings can receive the most points from EA credit 1 option 1, which relies on building energy simulation calculations. NBI further analyzed this issue within its study of LEED buildings (Turner and Frankel 2008). While, on average, the buildings generally performed as predicted by the energy models, there was a wide distribution of results. Figure 9 presents the findings of the NBI study. As indicated, the majority of buildings had at most a +/- 50% error rate between the model data and the actual data. Several outliers, however, had even more significant percent errors; one building's proposed savings erred by more than 150%. Another aspect of Figure 9 is that many of the outliers are gold and platinum rated LEED buildings, meaning the predicted savings from the most energy efficient designs are not being accurately modeled.

The results of the NBI study has induced further analysis by the USGBC and other researchers. Currently, the USGBC is collecting more energy data from occupied LEED buildings; however, participation is not mandatory (Navarro 2009). Other benchmarking tools, such as the U.S. EPA Portfolio Manager, allow building owners to track energy usage and compare with buildings of a similar type, size, and location (U.S. Environmental Protection Agency). Some researchers have utilized measured building energy data to adapt energy models in order to better predict a building's energy usage (Daly, Franconi et al. 2011). These "calibrated" energy models have become an asset in predicting energy savings from retrofits of existing buildings and in identifying discrepancies between design-phase energy models and actual energy use. Daly et al. prompted the question-- what is an acceptable variation from modeled usage and actual usage? (2011). Further analysis of metered building data and energy modeling is needed to negotiate this question.

This research analyzes and compares energy modeling results with actual metered building energy data. Energy modeling has been performed utilizing three different modeling programs in order to examine the effect of various levels of detail and accuracy. This research employs a life cycle perspective of green building and, therefore, also studies the relationship between life cycle energy use and energy modeling results. Building from the work of Daly et al. (2011), this research asks, what is an acceptable variation from modeled and actual life cycle energy use?

3.1.1 Energy Modeling

Several modeling programs currently exist that can be utilized to predict building energy performance. Crawley et al. extensively reviewed 20 different energy programs (2008). One energy model program, eQUEST, is popular in the building industry due to its ease of use and model generation wizard (Crawley, Hand et al. 2008; Hirsch 2009). eQUEST is usually more appropriate for large-scale commercial buildings and conventional building designs. DOE-2.2 is the Fortran modeling engine behind eQUEST and was developed by the Lawrence Berkeley National Laboratory and James J. Hirsch & Associates (Hirsch 2004; Crawley, Hand et al. 2008). DOE-2.2 is capable of modeling hourly time-steps, building geometry via drawing files, and general heating, ventilation, and air conditioning (HVAC) descriptions. Autodesk Green Building Studio (GBS) is an energy modeling program similar to eQUEST (Autodesk 2011). Likewise, GBS uses DOE-2.2 as a modeling engine. EnergyPlus is another energy modeling program written in Fortran 90 developed by the U.S. Department of Energy as the next phase of DOE-2.2 (Crawley, Lawrie et al. 2000; Crawley, Lawrie et al. 2001). EnergyPlus is reviewed as being more accurate and more detailed than DOE-2.2 (Crawley, Hand et al. 2008). In addition to the capabilities of DOE-2.2 models, EnergyPlus also details radiant heating and cooling, moisture absorption, and computational fluid dynamics. DesignBuilder is a platform for EnergyPlus similar to eQUEST/DOE-2.2 in that it generates building geometry and properties and HVAC zones visually (DesignBuilder Software 2009). In the newest version (v3), HVAC components can also be modeled visually in a flow chart instead of utilizing descriptive inputs as a basis for the EnergyPlus model. Energy-10 is another simulation program, which is more useful for small-scale commercial and residential buildings (Crawley, Hand et al. 2008; Sustainable Buildings Industry Council 2010). Energy-10 does not model building geometry, but rather utilizes a descriptive approach. Some aspects of Energy-10, such as the photovoltaic panels, are modeled using EnergyPlus. Each of these models can be useful for different building types, sizes, and constructions.

In order to capture varying levels of detail, three different energy models have been developed as a part of this research. GBS, Energy-10, and EnergyPlus were utilized as modeling programs, mainly due to their ability to model PV panels. In terms of DOE-2.2 modeling capabilities, GBS was preferred instead of eQUEST for this analysis. GBS supports gbXML 3D graphical files, which allow complex geometry to be more easily modeled utilizing Autodesk Revit Architecture. A comparison of the advantages and disadvantages of these energy models is presented in Table 3.

Table 3. Advantages and Disadvantages of Green Building Studio, Energy-10, and EnergyPlus.
Each of these energy modeling programs have been researched as part of the literature review. Each one was chosen by analyzing the advantages and disadvantages of various energy modeling programs. The specific input assumptions and modeling issues are further detailed in 3.2.2.

	Advantages	Disadvantages
Green Building Studio	• Supports gbXML import from Revit • Fast and user-friendly interface • Supports modeling of PV systems	• Minimal HVAC system options • Hard to designate HVAC zones and space types • Only one exterior wall type can be used for the entire building • No hourly time-step simulation
Energy-10	• Allows materials to be designated to each wall via geographic coordinates • EnergyPlus engine runs PV simulation • Hourly time-step simulation • Produces quick results	• Does not support 3D file import • Minimal HVAC system options • Outdated user interface (latest version 1.8 was released in 2005)
EnergyPlus	• Supports the import of some 3D file types • Visual modeling of HVAC systems • Detailed input for HVAC systems available • Modeling of materials and activities per zone	• Complex and time-consuming interface • Difficult to produce error-free results

The accuracy of these energy models has been analyzed by some researchers, although few have accurate building data as a basis of comparison. Pan et al. developed EnergyPlus models for two office buildings, and utilized ASHRAE standard 90.1-2004 as a basis for comparison (Pan, Yin et al. 2008). Wang et al. developed an EnergyPlus model of a Solar House; actual energy data for the building was monitored for one week (Wang, Esram et al. 2009). Neto and Fiorelli modeled a university building through EnergyPlus and focused on comparing actual and predicted energy consumption for a typical design day (Neto and Fiorelli 2008). This method could eliminate the issue of potential variations in weather; however, annual energy consumption was not calculated. For 80% of the design days, the error rate was calculated to be +/-13% between measured and predicted energy usage. However, for the other 20% of the days, the calculations were significantly different. Daly et al. developed a calibrated energy model of a university building using eQUEST (Daly, Franconi et al. 2011). Even after a leak in a hot water valve was accounted for in the energy model, the predicted and actual data varied up to 28%. Lomas et al. tested 25 energy modeling programs using a laboratory setting and found that almost all programs varied about 5-10% from actual data and that the models varied up to 22% from each other (Lomas, Eppel et al. 1997). Since this test was performed in a lab, certain variables such as occupant activities were not addressed. On a more comprehensive level, Karlsson et al. performed an analysis of 3 different energy models (the models were anonymous) with actual metered data (Karlsson, Rohdin et al. 2007). Twenty residential houses in Sweden were monitored for three years, and the data was compared with the different energy models. Among energy programs, the predicted usage varied by only about 2%; however, the percent error between modeled and actual energy usage was an average of about 50%. As detailed in this review, the percent errors between research studies vary greatly; however, the reasons for the variations seem to correspond.

In the research studies that utilize measured data, several reasons for the discrepancies between energy models and actual usage have been identified. Occupant activity and their usage of the building may be the hardest variable to model (Lam and Hui 1996; Al-Homoud 2001; Karlsson, Rohdin et al. 2007; Neto and Fiorelli 2008). Occupancy schedules and density can affect HVAC equipment loads (Lam and Hui 1996). The activity of occupants can also greatly affect the energy usage. Occupants can leave lights on or keep them turned off; they can also open windows, alter setpoint temperatures, and add portable HVAC equipment (Karlsson, Rohdin et al. 2007; Neto and Fiorelli 2008). Another issue between modeled and actual results is the efficiency of systems (Lam and Hui 1996; Al-Homoud 2001; Karlsson, Rohdin et al. 2007; Neto and Fiorelli 2008; Daly, Franconi et al. 2011). HVAC equipment could be commissioned in order to determine if all systems are working properly and efficiently as specified by the manufacturer (Turner and Frankel 2008; Daly, Franconi et al. 2011). An additional discrepancy between model information and actual data is the weather (Neto and Fiorelli 2008). In some regions, weather varies greatly from year-to-year, so the average data from the weather file could be significantly different from the actual weather of the particular years of data collection. Plug loads are also a variable input factor for energy models, due to unpredictable computer usage and phantom loads. These and other reasons cause the energy modeling of buildings to be difficult.

Another issue with energy modeling is that it is often presented as a one-year snapshot of a building's energy use. In life cycle assessment, however, energy model results are being extrapolated over the entire life cycle of the building in order to determine life cycle operating energy. When actual metered building data is not available, LCA practitioners usually utilize energy model results to calculate building energy usage. Scheuer et al., Cole and Kernan, and Keoleian et al. utilized eQUEST, DOE2.1, and Energy-10 respectively to calculate operating energy for input into life cycle inventories for subsequent LCA analysis (Cole and Kernan 1996; Keoleian, Blanchard et al. 2000; Scheuer, Keoleian et al. 2003). Research studies indicate that operating energy can be as much as 80-90% of total life cycle building energy usage (Cole and Kernan 1996; Keoleian, Blanchard et al. 2000; Ochoa, Hendrickson et al. 2002; Paulsen and Borg 2003; Scheuer, Keoleian et al. 2003; Ramesh, Prakash et al. 2010). Some low energy buildings, however, have more embodied energy than operating energy (Cole and Kernan 1996; Sartori and Hestnes 2007; Blengini and Carlo 2010). In both conventional and low energy buildings, energy models could play a significant role in determining environmental impacts calculated from life cycle assessments.

3.2 ENERGY MODELING AND LCA METHODS

LCA and energy modeling results can depend on each other to predict life cycle energy and environmental impacts. Error rates in energy modeling results have been well documented (Karlsson, Rohdin et al. 2007; Neto and Fiorelli 2008; Turner and Frankel 2008; Daly, Franconi et al. 2011); however, research is lacking on the effect of this uncertainty within LCA, specifically life cycle energy. Since operating energy has been modeled as about 80-90% of the life cycle energy in conventional buildings and about 50% in low energy buildings, the impact of modeling error rates on life cycle energy could or could not be significant (Cole and Kernan 1996; Keoleian, Blanchard et al. 2000; Ochoa, Hendrickson et al. 2002; Paulsen and Borg 2003; Scheuer, Keoleian et al. 2003; Sartori and Hestnes 2007; Blengini and Carlo 2010; Ramesh, Prakash et al. 2010). The main question guiding this research was: *from a life cycle perspective, what is the acceptable error between modeled and actual life cycle energy use?*

This research analyzes energy modeling results in terms of building life cycle energy use and actual metered energy data by applying a case study of a Solar House. LCA and various energy modeling techniques were utilized as methods to evaluate the difference between predicted data and measured data. The objectives of this research were to:

- Build design-phase energy models of the case study in Green Building Studio, Energy-10, and EnergyPlus
- Model life cycle energy use and environmental impacts of the building
- Record specific building energy data for at least one year
- Determine the accuracy of the energy models compared with real-time data
- Evaluate the variation between modeled and actual life cycle energy use

3.2.1 Case Study Description

The 2005 Solar House is a low energy home that was designed for the Solar Decathlon competition, which is an international competition held by the U.S. DOE to encourage affordable residential solar energy (U.S. Department of Energy 2010). The house was originally designed as net zero by Pittsburgh Synergy, a group of students from Carnegie Mellon University (CMU), University of Pittsburgh, and the Art Institute of Pittsburgh. Today, the Solar House is utilized as office space on the campus of CMU. The house, shown in Figure 10, is about 850 ft^2 and is designed as two different programmatic sections. One part of the building is a great room that is 1.5 stories and faces south. The other part is 2 stories and contains the mechanical, kitchen, bedroom/office and restroom spaces. 30 photovoltaic (PV) panels cover the roof of the great room and solar thermal evacuated tubes occupy the surface of the two-story roof. The roofs are built at an 11° tilt from the horizontal in order to increase sunlight exposure. Supplemental electricity is supplied by the grid, and surplus produced electricity is transmitted to the grid. Many passive features also help to mitigate energy usage. Structurally insulated panels (SIPs) compose the structure of the east and west walls. SIPs create a continuous wall of rigid insulation, reducing the issue of thermal breaks. The north wall is built of polycarbonate material, which allows the penetration of some daylight, while still having a significant U-value. The building is oriented towards the south in order to exploit passive solar heat gain in the winter. The tilt of the south wall also acts as a natural shading device in the summer time. A detailed description of the building systems of the Solar House is outlined in Table 4.

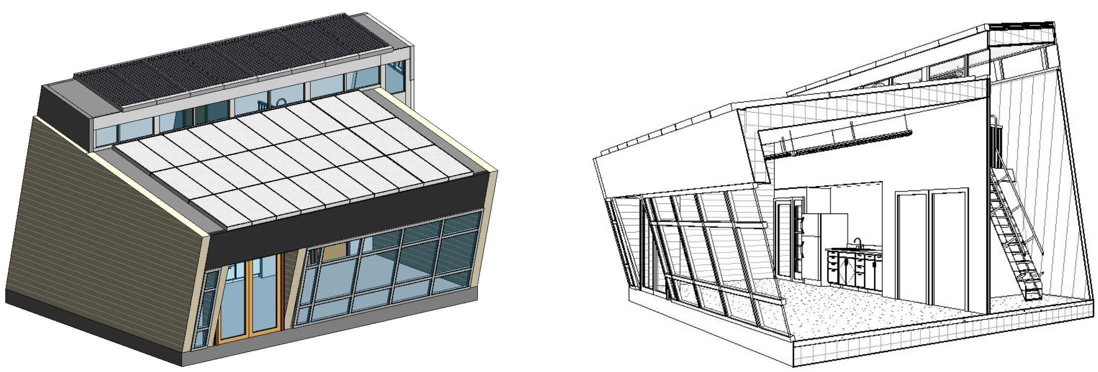


Figure 10. Perspectives of the 2005 Pittsburgh Synergy Solar House.

This building model was built in Autodesk Revit Architecture 2011 for energy modeling purposes and therefore excludes the structural system and foundations.

3.2.2 Case Study Energy Models

As a part of this research, three different design-phase energy models with varying levels of detail were built of the Solar House. The assumptions and inputs for each model are detailed in Table 4. The first model, Autodesk Green Building Studio (GBS), is a web-based modeling tool that can be utilized in the conceptual or schematic design phase in order to make sustainable building decisions early in the design process (Autodesk 2011; Autodesk 2011). In order to utilize the gbXML import feature to GBS, a Revit model was developed of the Solar House and is depicted in Figure 10. This Revit model was exported via gbXML to the online program GBS. A view of the gbXML model is presented in Figure 11. In the web-based tool, basic building features and characteristics were entered into the model. The address, building type, and schedule were delineated under the "project details" tab. Under the "project defaults" tab, space types, occupancies, and setpoint temperatures were set to GBS defaults. The average lighting density for the Solar House was specified in this tab. Here, materials for each surface can be detailed; however, no differentiation exists between different walls. For this case study, all walls were described as SIP panels. Simple HVAC information that was able to be included was the heat pump and tankless water heater. The heat pump was assumed to provide both the cooling and heating, even though that is not the actual case study condition. GBS was capable of modeling a default PV system but not a solar thermal system so that was omitted from the model.

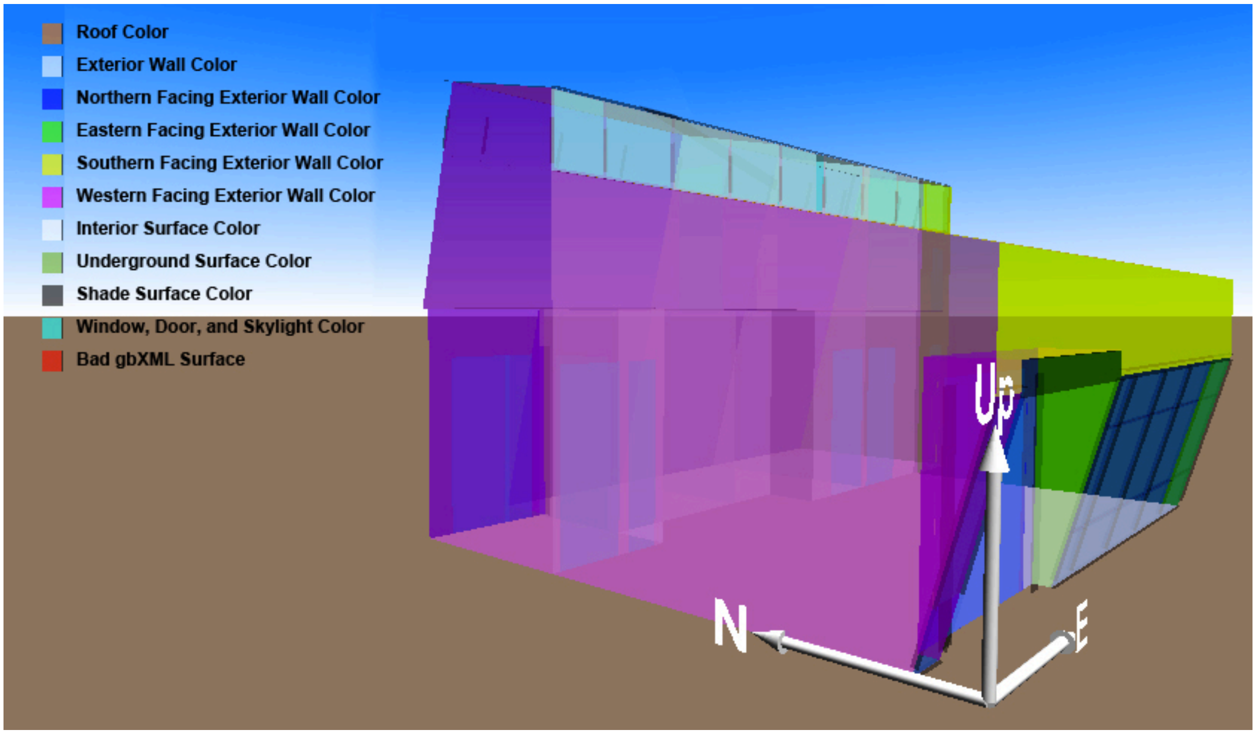


Figure 11. Perspective of Solar House gbXML import to GBS.

This view depicts the gbXML surfaces and allows the user to check the orientation and location of walls, roofs, floors, and windows. If surfaces are incorrect, they will appear bright red.

The second program, Energy-10, is a schematic design energy modeling program that allows the user to compare several design decisions (Sustainable Buildings Industry Council 2010). Energy-10 was the program that was originally used by the Pittsburgh Synergy design team to assess the energy profile of the building and was also chosen due to its ability to model PV and solar thermal systems. The user interface for the program does not support a 3D file input. Due to the complexity of the Solar House, many assumptions were made in this model as to the shape of the building. One was that the model did not include the second floor of the building. Other than the lack of a file input feature, Energy-10 supports all of the same aspects as GBS. Additionally, the program does allow different materials to be designated for each wall, in contrast with GBS. A detailed PV description was entered in the Energy-10 platform and was modeled by the embedded EnergyPlus engine. It does also support solar thermal evacuated tubes, but the solar thermal was assumed to be used for domestic hot water (DHW) not for both DHW and underfloor heating. HVAC assumptions were similar to GBS; however, more detailed specifications were modeled (see Table 4).

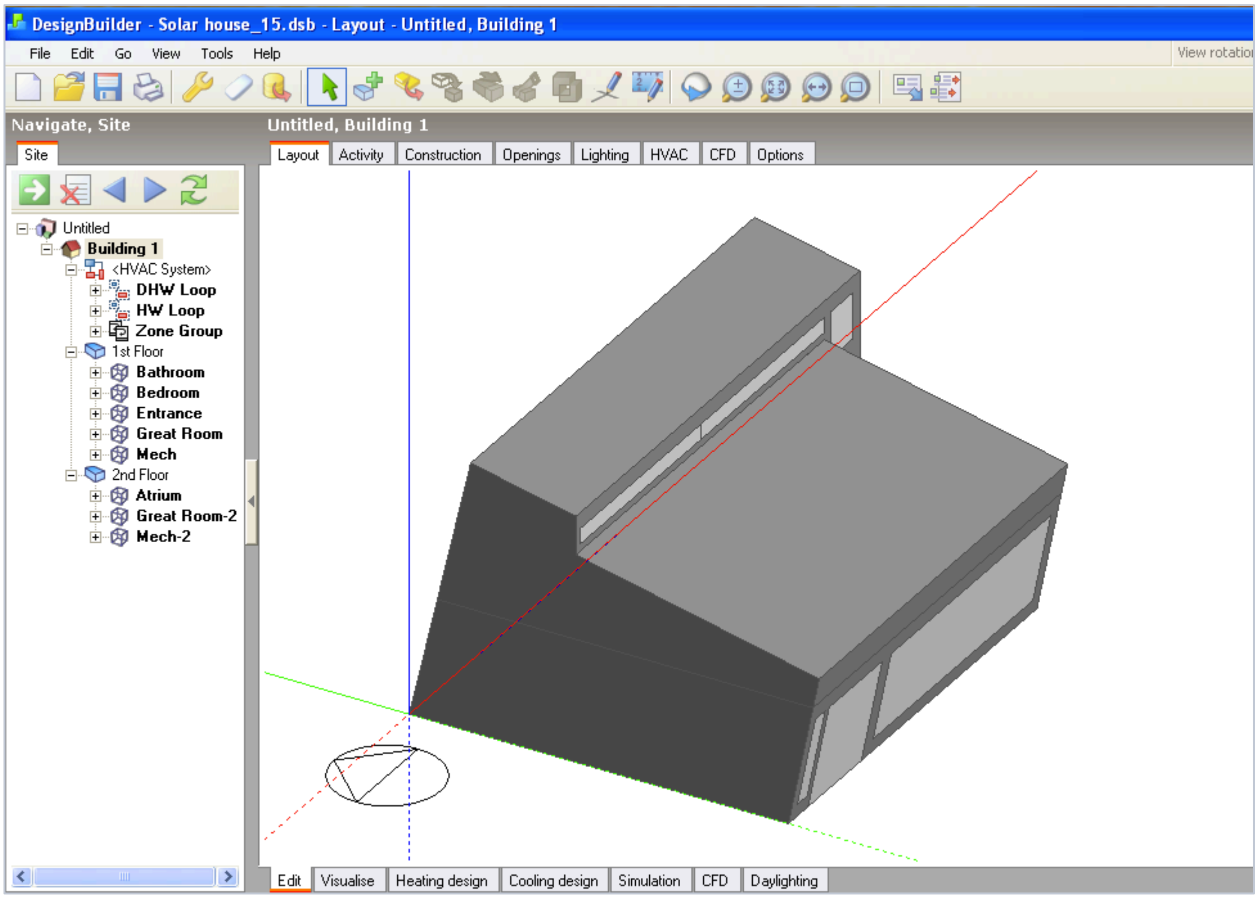


Figure 12. DesignBuilder Model of the Solar House.

A simplified version of the Solar House was developed in DesignBuilder to export to EnergyPlus. The navigation of the user interface is depicted in the left hand column. Each room can be divided into one or more zone and the HVAC system can be built per system loop.

The most detailed energy analysis was conducted using EnergyPlus, which could be considered a design development tool (U.S. Department of Energy 2011). A 3D modeling platform called DesignBuilder supports an export file into EnergyPlus (DesignBuilder Software 2012). An image of the DesignBuilder model is presented in Figure 12. In DesignBuilder, HVAC zones were modeled and edited in 3D. Instead of being allocated to the entire building, HVAC details, such as occupancy, schedules, lighting, and plug loads, could be different for each zone. Specific materials were also detailed in 3D, assuring that each material was designated to the appropriate surface. The HVAC systems were modeled in DesignBuilder using a flow chart system, depicted in Figure 13. This feature was an asset in simplifying the process of connecting the different systems. An electric hot water boiler was attached to the first floor zones in order to model the hydronic radiant heating system. A separate DHW hot water heater had to be modeled in order to acknowledge the energy demand from that system, even though only one tankless water heater actually exists in the building. The cooling load from the heat pump was modeled using a packaged terminal heat pump (PTHP) in each of the zones that have in actuality the fan coil units. The PTHP is shown in Figure 13. Since PV systems cannot be modeled in DesignBuilder, they were detailed as objects directly in EnergyPlus. EnergyPlus does support several types of solar thermal, including flat plate but does not support evacuated tube. The solar thermal would also be difficult to accurately model as supplemental heating and not just DHW. Due to these assumptions, the solar thermal system was omitted from the EnergyPlus model.

Table 4 (a). Description of Building Systems of the Solar House and Inputs for All Three Energy Models.

The Solar House was designed as a net zero energy home. At about 850 ft2, the house contains a great room, one bedroom (now an office space), a kitchen, one bathroom, and mechanical and storage spaces. Due to the goal of net zero energy, the house has unique HVAC systems and building materials.

		Solar House		Green Building Studio		Energy-10		Energy Plus
Space Types		Mechanical, Restroom, Office, Great room with kitchen and office area		Office, open plan		Residential		Open office, office toilet, office reception, and unoccupied (mechanical spaces)
Structure		14 3’-6” reinforced concrete footers		Structure not included in energy models		Structure not included in energy models		Structure not included in energy models
		Steel floor framing MC 10 x 22 and WT 9 x 32.5						
		Laminated veneer lumber (LVL) columns 2-1 ¾” x 9 ¼”						
		LVL beams 2-1 ¾” x 4 ¾”						
		Parallel strand lumber (PSL) columns 3 ½” x 9 ¼”						
		PSL beams 3 ½” x 9 ¼”						
Floors	First	SIP panel composed of 10 ¼” of rigid insulation and 2-¼” oriented strand board (OSB) panels with a 3” concrete floor (R-value: 44)	Interior	R13 Wood Frame	First	*Same as actual	First	*Same as actual
	Second	¼” wood joists 18” O.C. with wood flooring	Raised	SIPS Floor, R-22, 6.5" thick, with crawlspace	Second	No second floor (Building assumed to be one floor due to building geometry)	Second	Wooden floor construction with 3/4" wood floor
Roof		SIP panel composed of 9 ½” of rigid insulation and 2-¼” OSB panels with steel roof decking (R-value: 52.39)		SIP Roof 10.25" thick		*Same as actual		*Same as actual
Exterior Walls	East and West	SIP panel composed of 7 ¾” of rigid insulation and 2-¼” OSB panels with ¾”cypress wood paneling (R-value 33.85)	All Walls	SIP Wall 10.25"	East and West	*Same as actual	East and West	*Same as actual
	North	4” polycarbonate façade with aluminum mullions (U-value: 0.112)			North	Composite wall with 5/8" of softwood, 1/2" of sheathing, 3-1/2" of fiberglass, and 1/2" of drywall	North	Composite wall with 3 1/2" of polycarbonate and 2" of stainless steel
	South	SIP panel composed of 3-1/2” of rigid insulation and 2-¼” OSB panels with a 3/4” cypress wood paneling (R-value: 17.54)			South	*Same as actual	South	*Same as actual
Windows		Low-e triple-paned windows with aluminum mullions (U-value: 0.26)		Triple low-e clear windows (U-value: 0.19)		Triple low-e windows with wood framing (U-value: 0.262)		Triple low-e clear windows (U-value: 0.175) with 3/16" thick aluminum frames and 2" wide window dividers

Table 4 (b). Description of Building Systems of the Solar House and Inputs for All Three Energy Models.

a. The ERV was not modeled in the energy programs due to its highly variable use in the building.

b. The HVAC systems in Energy Plus is diagramed and further detailed in Figure 13.

	Solar House		Green Building Studio		Energy-10		Energy Plus	
Lighting	13 4' T5 lamps and 9 60W compact fluorescent bulbs		0.91 W/ft2 (default office setting) building average lighting density		0.19 W/ft2 (default residential setting) building average lighting density		Lighting modeled per zone using acutal average lighting density	
HVAC	Cooling	Electric heat pump with one outdoor unit and two fan coil units on the first floor	HVAC Equipment	Electric residential split heat pump	Cooling	Electric package termail air conditioner (PTAC)	Cooling[b]	Electric packaged terminal heat pumps (PTHP) in zones that have actual fan coil units
	Heating/ DHW	Hydronic underfloor heat with cross-linked polyethylene (PEX) tubing under the first floor			Heating	Electric heat pump with electric resistence back-up		
		150 ft^2 of solar thermal evacuated tubes to provide DHW and underfloor heating			DHW	150 ft^2 of solar hot water with 30 gallon storage capacity	Heating[b]	Hydronic underloor heat under the first floor
		30 gallon hot water storage tank with an electric tankless water heater	DHW	Domestic on-demand hot water heater				Electric hot water heater for underfloor heat
	Ventilation	Electric energy recovery ventilator (ERV)[a]				Electric hot water heater	DHW[b]	Electric hot water heater with 30 gallon capacity
	Photovoltaics	3 arrays of 10 monocrystalline PV panels on roof with DC to AC inverter (13% efficent)	Photovolatics	Monocrystalline panels on roof (13% efficient)	Photovoltaics	*Same as actual	Photovoltaics	*Same as actual
Interior Temperatures	All Setpoints	Variable	Cooling Setpoint	75°F	Cooling Setpoint	78°F	Cooling Setpoint	77°F (occupied); 86°F (unoccupied)
			Cooling Setup	80°F	Cooling Setup	83°F	Cooling Setup	82.4°F (occupied); 86°F (unoccupied)
			Heating Setpoint	70°F	Heating Setpoint	70°F	Heating Setpoint	70°F (occupied); 50°F (unoccupied)
			Heating Setback	65°F	Heating Setback	65°F	Heating Setback	65°F (occupied); 41°F (unoccupied))
Schedule	Unknown		Year-round school (facility open throughout the year and closed on holidays)		7 am to 11 pm everyday (default residential setting)		Office schedule for occupied spaces (7 am to 7pm workday) with university holiday breaks	
Occupancy	Unknown		3 people (default)		1 person (default)		0.010311 people/ft^2 (default for all occupied spaces); about 9 people	

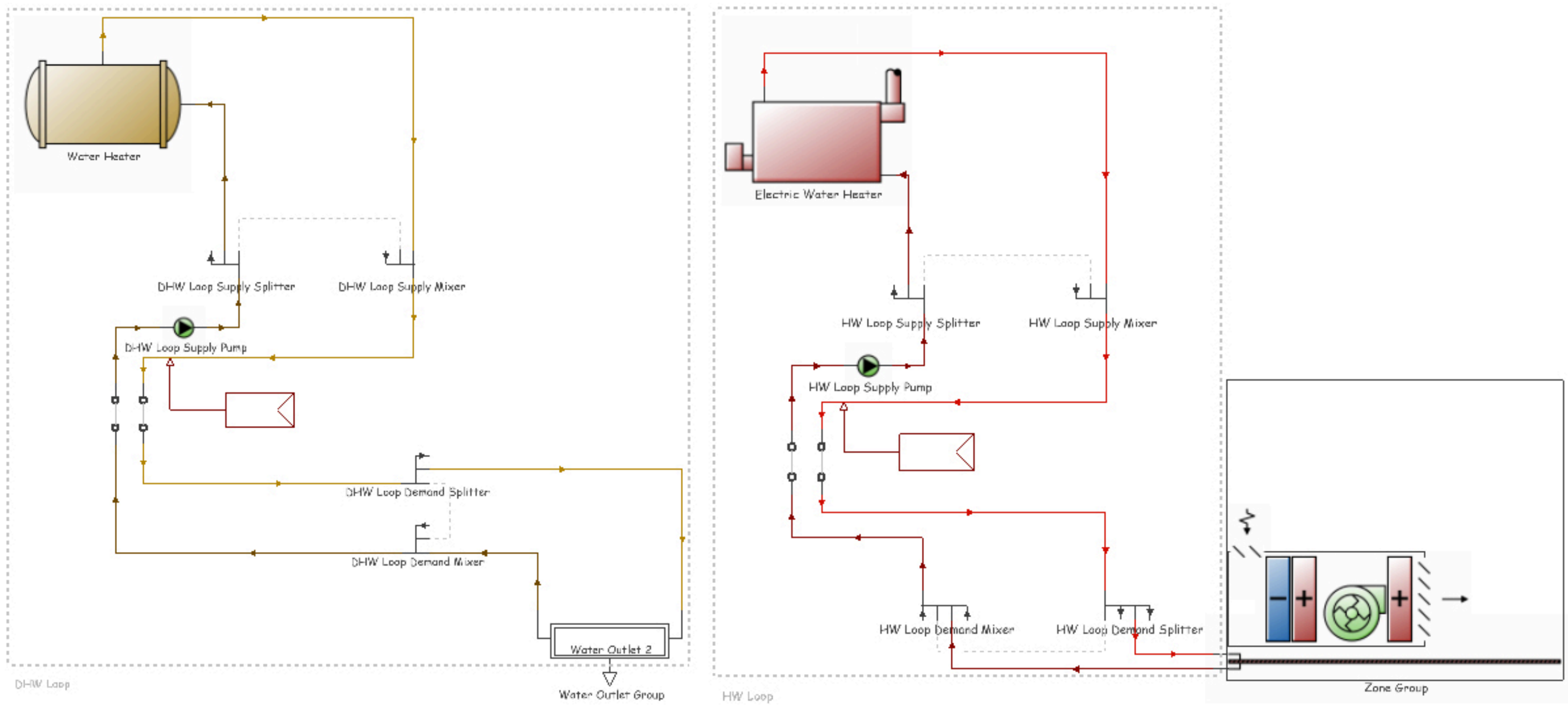


Figure 13. HVAC System Flow Charts of the Solar House from DesignBuilder (DesignBuilder Software 2012). The flow chart on the left depicts the DHW loop with the supply side as an electric tankless water heater and the demand side as a water outlet group that is associated with the restroom. The flow chart on the right described the heating water loop with the supply side as again the electric water heater and the demand side as the hydronic radiant heat in the specified zone group. Within the zone group the PTHP is shown. Even though the PTHP depicts both heating and cooling coils, the PTHPs were used to model only the cooling loads. Within both flow charts, the red boxes with triangles represent the location of the specified setpoint temperatures.

3.2.3 Case Study LCA

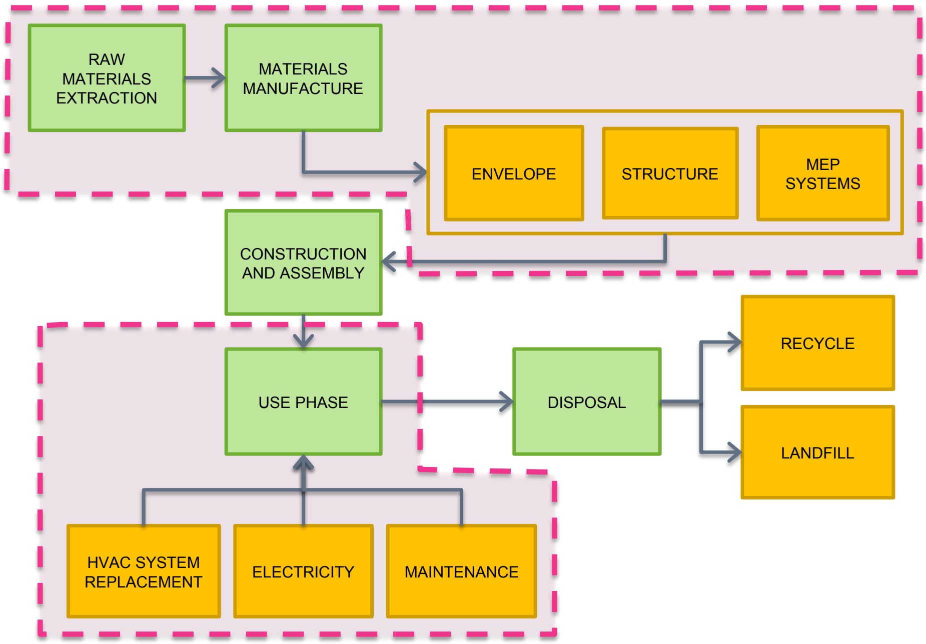


Figure 14. System Boundaries for Solar House LCA.

The pink dotted line represents the definition of the system boundaries of the Solar House LCA. The construction phase was omitted from the analysis due to the unconventional nature in which the building was built. End of life was also neglected due to uncertainty in the disposal of the building.

LCA was utilized to calculate life cycle energy and environmental impacts of the Solar House. The house was studied and analyzed from raw materials extraction through the use phase, excluding the construction and assembly of the building because of the unconventional nature of its construction (The Solar House was constructed by students, torn down, and reconstructed several times). Some research studies indicate that construction impacts are substantially less than materials and energy use (Junnila and Horvath 2003). In other research, however, the construction phase does show a significant impact in hazardous waste production and air emissions (Ochoa, Hendrickson et al. 2002; Junnila, Horvath et al. 2006). Much uncertainty lies in the future of the Solar House; therefore, end of life was omitted from the analysis and no renovations besides essential system upgrades were modeled in the LCA. Research suggests that impacts from the end of life of buildings could be considerably less than the other phases, due to the recycling of materials (Junnila and Horvath 2003; Junnila, Horvath et al. 2006). A detailed system boundary definition of this LCA is illustrated in Figure 14. Similar to previous research, the life cycle of the Solar House was defined as a 25 year time period and the functional unit was one house at 850 square feet (Wang, Esram et al. 2009).

LCA was performed using the hybrid method. When available, process LCI was used via several different databases. USLCI and Franklin 98 (US databases) were selected first; then Ecoinvent, ETU-ESU, and IDEMAT (European databases) were used (Product Ecology Constultants 2011). Table 5 details each material and process used in the LCA and the associated databases. The HVAC systems (the water heater, ERV, and heat pump) were modeled both in the materials phase of the life cycle as well as the use phase. According to the National Association of Home Builders, all of these systems would most likely be replaced at least once over the 25 year life cycle of the house (Seiders, Ahluwalia et al. 2007). The replacement of HVAC systems was within the system boundary and was, therefore, taken into account when calculating the inventory. Since PV panels have a lifespan of about 20-25 years, one life cycle was assumed for the building (Nishimura, Hayashi et al. 2010).

Table 5. Life Cycle Assessment - Modeled Processes and Materials in the Solar House.

All of these materials and processes in Table 2 were utilized to perform the process LCI. Square footage, densities, and weights were determined through construction documents, field measurements, and manufacturer specifications.

MATERIALS AND CONSTRUCTION			
Material	**Database**	**Area (ft2)**	**Weight (lb)**
Manuf. Oriented Strand Board (OSB)	USLCI		5781.51
Waste Oriented Strand Board (OSB)	USLCI		728.78
Manuf. Expanded Polystyrene (EPS)	Ecoinvent		1571.67
Waste Expanded Polystyrene (EPS)	Ecoinvent		177.56
Cross-linked Polyethylene	Ecoinvent		18.57
Red Maple Siding (Softwood)	Ecoinvent	960	2622
Cypress Plywood Ceiling	Ecoinvent	410.64	543.76
Veneer Lumber	USLCI		2834.1
White Oak Floor (Hardwood)	Ecoinvent		331.13
Low-E Glass	Ecoinvent	196.4	314.24
Aluminum Window Frame	Ecoinvent	75.83	132.7
Manufactured Polycarbonate	Ecoinvent	596.3	18455.49
Wasted Poylcarbonate	Ecoinvent	30.4	940.88
20% Fly Ash Concrete	Ecoinvent, ETH-ESU		42918
Total Steel (Hot rolled, Low alloy, EAC)	Ecoinvent		6143
#4 Rebar (Reinforcing Steel)	Ecoinvent		105.95
PV Panel (Monocrystalline Cells)	Ecoinvent	406.24	
Aluminum (Secondary)	USLCI		92.06
Inverter	Ecoinvent		
Solar Tubes	Ecoinvent		476
Interior Door (Wood)	Ecoinvent	65.25	
Exterior Door (Aluminum)	Ecoinvent	130.5	
Tankless Water Heater			
Nylon 66	Ecoinvent	1.56	21.3
Polyester (Thermoplast)	Ecoinvent	3.13	1.43
Copper (Secondary)	Ecoinvent	0.03	0.09
Steel (Cold Rolled, BOF)	Franklin 98	1.56	1.97
Ventilation Equipment Assembly	Ecoinvent		
Energy Recovery Ventilator			
Galvanized Steel Sheet Metal	USLCI		65.23
Expanded Polystyrene (EPS)	Ecoinvent		0.04
Polyester (Fabric)	IDEMAT		1.41
Polyvinylchloride (Suspension)	Ecoinvent		0.95
Copper (Secondary)	Ecoinvent		3.13
Aluminum (Secondary)	USLCI		11.92
Synthetic Rubber	Ecoinvent		0.55
Corrugated Cardboard	Franklin 98		4.78
Packaging Paper	Franklin 98		0.24
Ventilation Equipment Assembly	Ecoinvent		
Heat Pump			
Galvanized Steel Sheet Metal	USLCI		26.04
Steel (Cold Rolled, BOF)	Franklin 98		90.1
Polyvinylchloride (Suspension)	Ecoinvent		2.2
Copper (Secondary)	Ecoinvent		14.68
Aluminum (Secondary)	USLCI		12.5
Nylon 66	Ecoinvent		0.28
Brass	Ecoinvent		1.38
Refrigerant (R134-A)	ETH-ESU		6.61
Ventilation Equipment Assembly	Ecoinvent		
OPERATIONS AND MAINTENANCE			
Process	**Database**	**Power (kWh)**	**Total (25 yrs)**
Electricity (Local Mix)	USLCI	Variable	Variable

Table 6. EIO-LCA Sectors and 2002 Purchaser Prices for Solar House LCA.

Data for the EIO-LCA was collected utilizing construction documents, field measurements, and manufacturer specs. All price data was adjusted for inflation in order to accurately represent 2002 dollars. The 2002 purchaser price model in EIO-LCA was used for the analysis.

Sector	Cost ($) for 1st Yr	Cost ($)/Yr	Cost ($)/25 Yrs
Lighting	24.75	5.88	171.75
Household Cooking Appliance	940.52	37.25	1871.77
Household Refrigerator	1486.03	58.82	2956.53
Other Household Appliance	742.52	88.23	2948.27
Plumbing Fixture Manufacturing	158.4	5.23	289.15

EIO-LCA sectors and prices utilized for the remainder of the LCA are presented in Table 6. The 2002 purchaser price model was used; therefore, product prices from 2011 were adjusted for inflation to the year 2002 (Carnegie Mellon University Green Design Institute 2008; U.S. Bureau of Labor Statistics 2011). Products included in the analysis (e.g. a dishwasher) were researched in order to determine the current purchaser price of the product in 2011. These prices were then adjusted for inflation to 2002 prices using the U.S. Bureau of Labor Statistics' *Inflation Calculator* (U.S. Bureau of Labor Statistics 2011). The determined 2002 purchaser price was then input into the appropriate EIO-LCA sector. The input data consisted mostly of maintenance data, such as the replacement of light bulbs. A few items, such as kitchen appliances and plumbing fixtures, however, were modeled for both the initial materials phase and the use phase. Similar to the HVAC systems, these products would most likely need to be replaced during the 25 year life cycle (Seiders, Ahluwalia et al. 2007).

Data was collected for the life cycle assessment through a variety of means. Construction documents and manufacturer specifications, as well as field measurements, were used to derive the quantities of materials. Previous literature was utilized to calculate the different materials within HVAC systems (Shah, Debella et al. 2008). The weights reported by Shah et al. were scaled to match the total weight specified by the manufacturer. Electricity usage predicted by all three models, as well as the actual metered data, provided the inputs for the *Electricity (Local Mix)* process. For this LCI process, the composition of the electricity generation in Pittsburgh was calculated using the U.S. EPA's *Power Profiler* (U.S. Environmental Protection Agency 2011). In the *Power Profiler*, the local zip code is entered to determine the portion of electricity generated from coal, wind, nuclear, etc. in that particular region. All of this data was used to generate both the process and Economic Input-Output LCIs.

LCIA was completed using IMPACT 2002+ (Jolliet, Margni et al. 2003) with Table 7 indicating the considered impact categories. Non-renewable energy (MJ primary) was used to perform the life cycle energy calculations. Three impact categories in IMPACT 2002+, ionizing radiation, land occupation, and mineral extraction, were omitted from this analysis due to data scarcity among unit processes and sectors.

Table 7. IMPACT 2002+ LCIA Categories Used in the Solar House LCA.

Three impact categories that can be computed from IMPACT 2002+ (ionizing radiation, land occupation, mineral extraction) were excluded from LCA results due to life cycle inventory data scarcity issues.

Impact category	Equivalent Unit
Carcinogens	kg C2H3Cl eq
Non-carcinogens	kg C2H3Cl eq
Respiratory inorganics	kg PM2.5 eq
Ozone layer depletion	kg CFC-11 eq
Respiratory organics	kg C2H4 eq
Aquatic ecotoxicity	kg TEG water
Terrestrial ecotoxicity	kg TEG soil
Terrestrial acidification/ nutrification	kg SO2 eq
Aquatic acidification	kg SO2 eq
Aquatic eutrophication	kg PO4 P-lim
Global warming	kg CO2 eq
Non-renewable energy	MJ primary

3.2.4 Metered Data

Real-time data was measured by various types of sensors within the Solar House. Data and was collected for 16 months from October 2010 through January 2012 in one-minute time steps. The one-minute data was then aggregated into hourly and monthly weather and electrical consumption profiles. Weather data such as relative humidity, indoor and outdoor temperature, wind speed, and solar radiation was measured. Monthly average temperatures, as well as the setpoints used in the energy models, are illustrated in Figure 15. Through some of the winter months, the monthly average indoor temperature was higher than both the setback and setpoint temperature. EnergyPlus and DOE-2.2 weather data for Pittsburgh were used for the energy models. Electricity for the house was also sub-metered for each individual circuit, including lighting, receptacle loads, HVAC equipment, PV panels, heat pump, and water heater. The aggregated real-time metered data was then used as a basis to analyze the energy models and life cycle energy use.

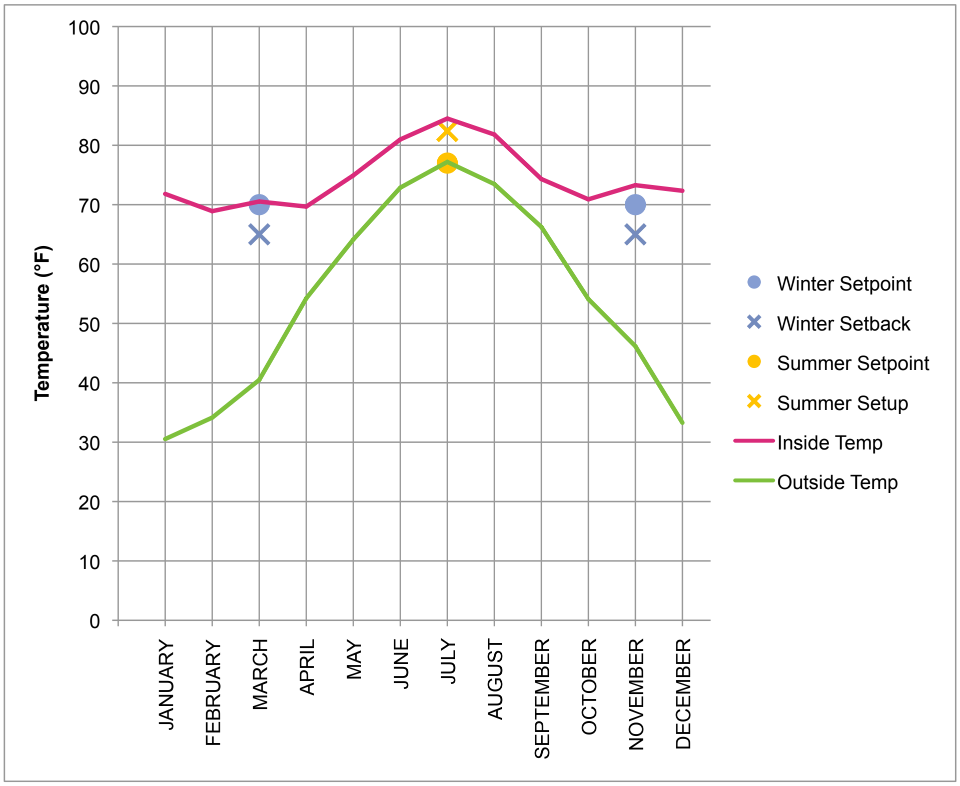


Figure 15. Actual Average Temperatures and Modeled Setpoints for the Solar House.

The average temperatures were measured at one-minute time steps at the Solar House. Since the actual setpoint temperatures are variable within the Solar House, the average modeled setpoint temperatures are shown for comparison.

3.3 ENERGY MODELING AND LCA RESULTS

3.3.1 Energy Modeling Results

Modeled and measured annual electricity usage results of the Solar House are presented in Figure 16. GBS, Energy-10, and EnergyPlus predicted 8511, 687, and 5180 kWh in net annual electricity usage (demand minus PV generation) respectively. *All of the programs* *underestimated the electricity demand of the Solar House.* The actual average net annual electricity usage during the 16 months of measurement was 11,659 kWh. Each month of electricity usage was averaged to calculate both a monthly and annual average. The error rates for GBS, Energy-10 and EnergyPlus were 27%, 94%, and 56% respectively with an average rate of 59%. An average 59% error rate is similar to the 50% in the findings of Karlsson et al. (Karlsson, Rohdin et al. 2007). Also, error rates for low energy buildings seem to be greater than for other buildings (Turner and Frankel 2008).

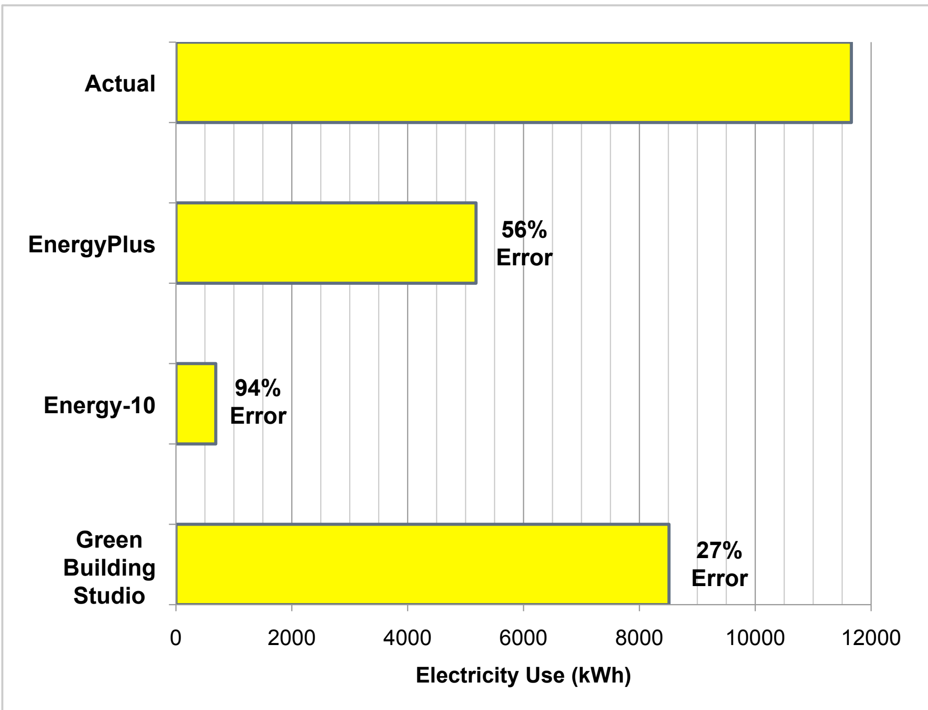


Figure 16. Modeled and Actual Annual Net Electricity Usage of the Solar House.

Annual electricity usage predicted by the three models, as well as actual metered data, has been charted. The net usage is calculated by subtracting the electricity produced by the PV panels from the electricity consumed by the house.

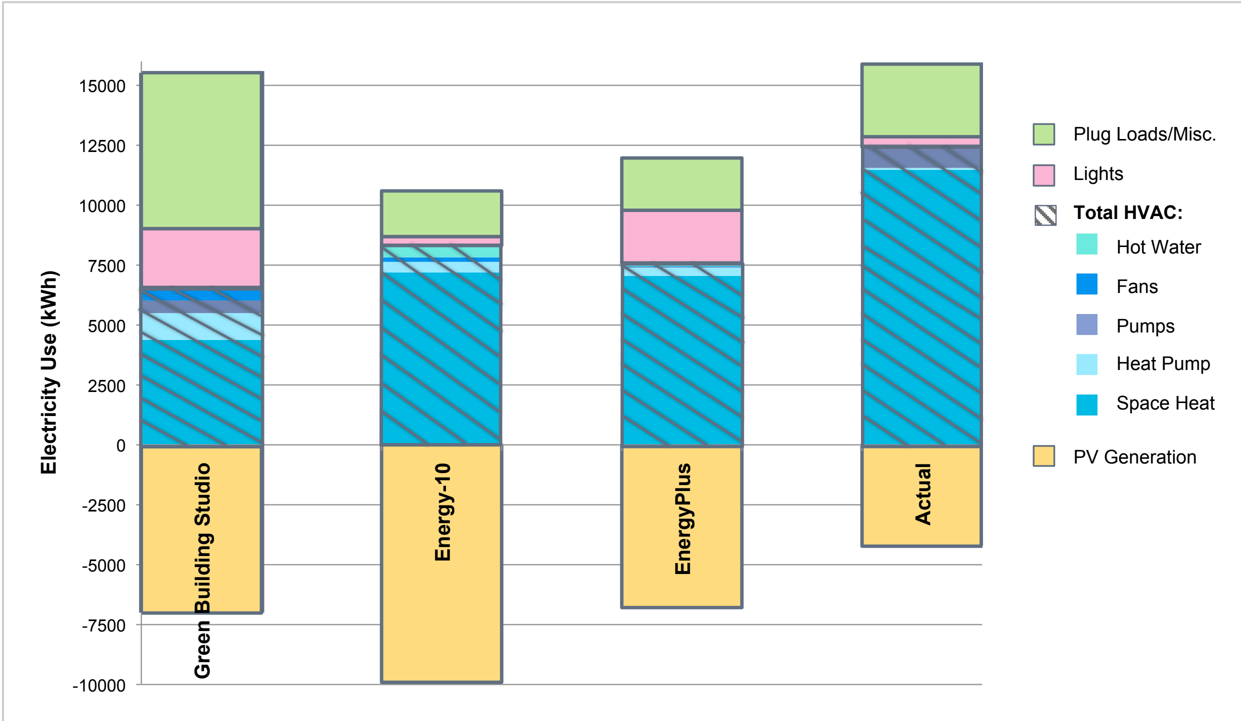


Figure 17. Modeled and Actual Annual Submetered Electricity Usage of the Solar House.

Annual electricity usage predicted by the three models, as well as actual metered data, has been charted. The electricity consumption and production are divided by end use. The HVAC energy use has been submetered even further, as identified by the legend.

Figure 17 presents the annual submetered energy use. Electricity is divided into plug loads, lights, HVAC, and PV generation. Figure 17 indicates several differences between the modeled and annual actual results, including PV electrical generation and HVAC electrical consumption. The PV panels were modeled at an efficiency of 13%, but in actuality, the PV panels are performing at about 9%. The average efficiency of the PV panels is reported in Figure 18. The efficiency was calculated utilizing average weather data for global horizontal solar insolation in the Pittsburgh region. This data was used to determine the solar insolation on an 11° tilt on an hourly basis. The results were compared with submetered data from the Solar

House to determine actual PV efficiency. Annual PV efficiency (E) can also be calculated utilizing the following formula which was described in detail by Wiginton, Nguyen et al. (2010):

$$E = I_{md} * 365 * e * A_{PV}$$

where I_{md} is the global solar insolation on the horizontal (around 3.5-4.0 kWh/m^2/day for Pennsylvania (National Renewable Energy Laboratory 2012)), e is the efficiency of the panels, and A_{PV} is the area of the PV panels. By solving for e in this formula, the actual annual efficiency of the panels in the Solar House is about 8.5%, which is quite similar to the 9% calculated using hourly data. The photovoltaic panels could be underperforming for several reasons. First of all, efficiencies of PV panels vary according to sunlight exposure and temperature (Rustemli and Dincer 2011). The PV panels are about 8 years old, which could cause depreciation in efficiency. Also, the PV panels are not regularly maintained in the house and could be commissioned to determine maintenance issues.

Also depicted in Figure 16, the actual HVAC energy usage is larger than predicted by any of the programs. Energy-10 predicted the most HVAC electrical consumption at 7825 kWh per year; however, the actual metered HVAC usage was 12424 kWh per year. The space heating within the HVAC systems was the largest consumer of the actual electricity, using 11471 kWh per year. One main difference between the modeled and actual HVAC systems was the input assumptions. The Solar House has a very specific and detailed HVAC system, which was difficult to model in the energy programs. The unique building systems of low energy buildings could be one reason why their energy consumption is more difficult to predict. A more detailed investigation of the energy model results was performed in order to understand the disparity between the actual and predicted results.

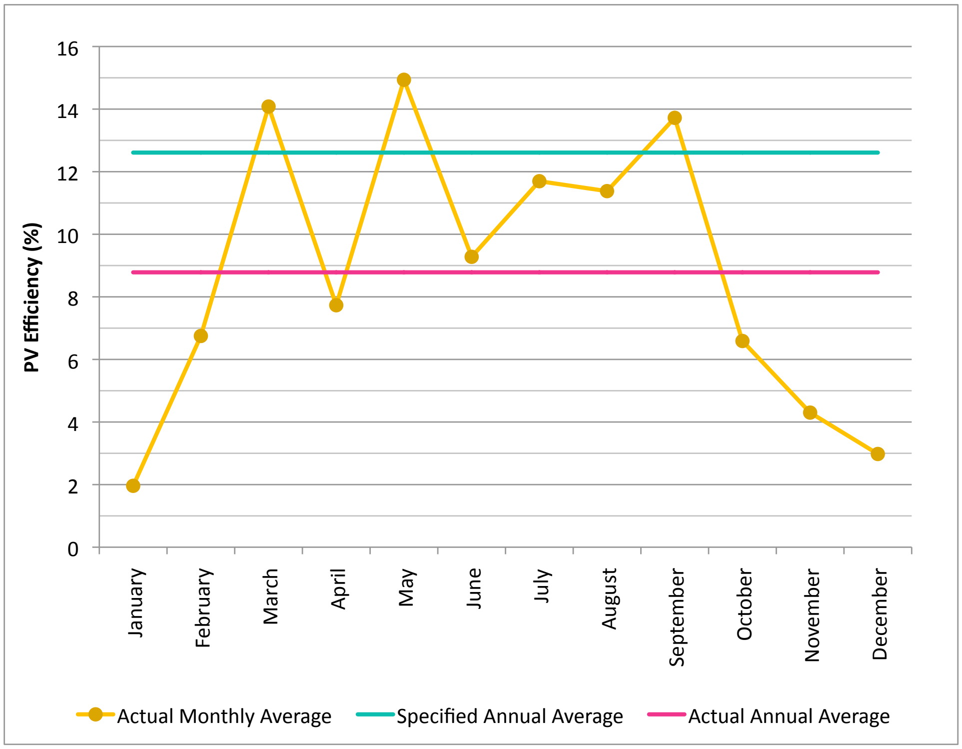


Figure 18. Average Efficiency of Solar House PV Panels.

The efficiency of the PV panels during electricity generation has been averaged for each month and is reported by the yellow line. The efficiency of the PV panels that was specified by the manufacturer and the actual annual average has also been documented here.

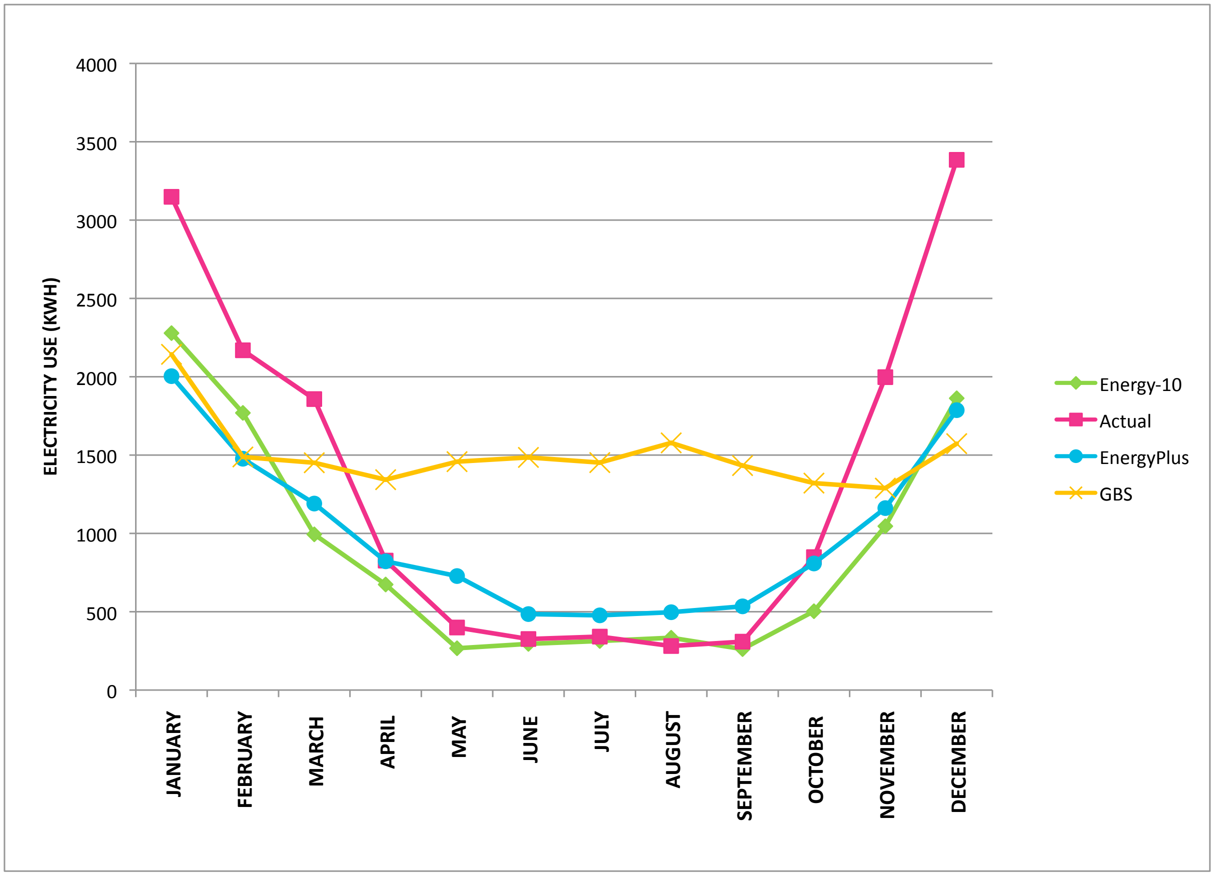


Figure 19. Modeled and Actual Monthly Electricity Consumption of the Solar House.

Monthly electricity usage predicted by EnergyPlus, Energy-10, and GBS and measured by the sub-meters is graphed here. Only electricity consumption has been considered, so production from the PV panels has been neglected.

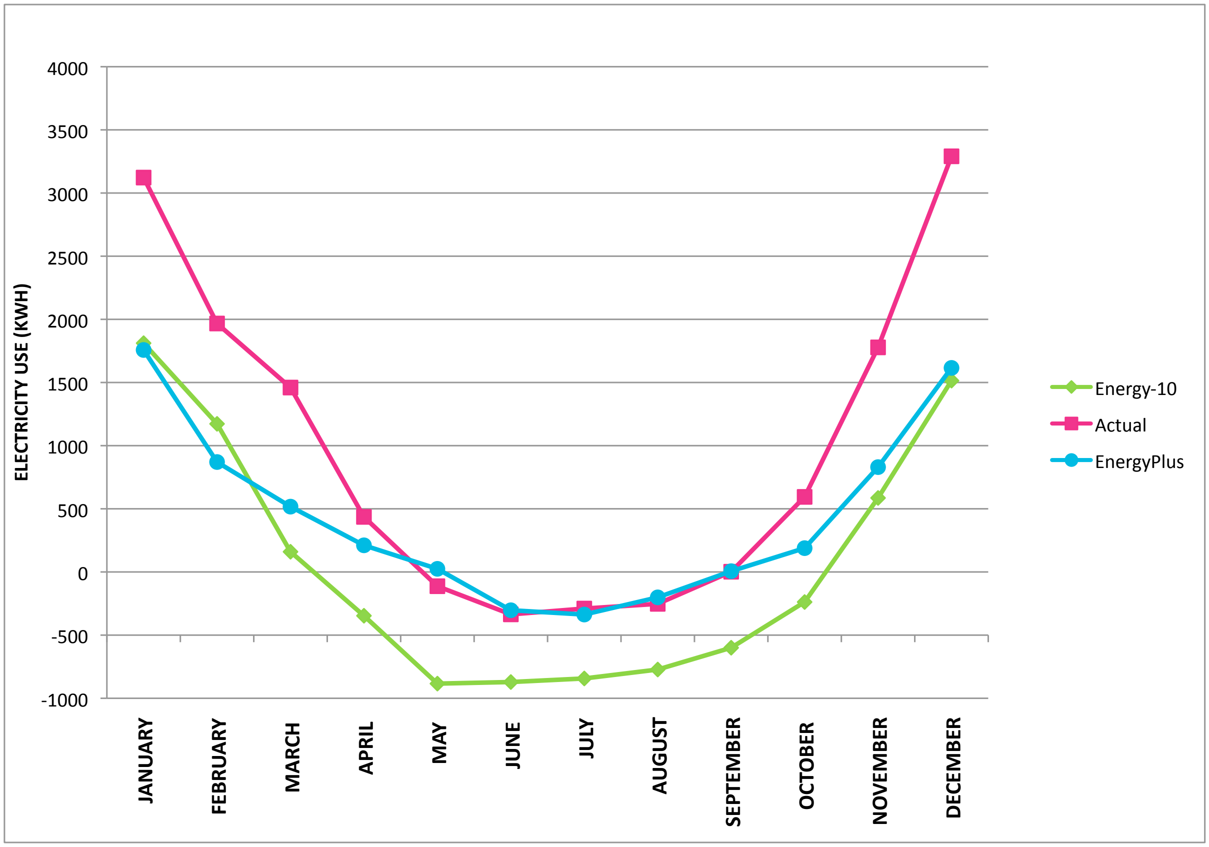


Figure 20. Modeled and Actual Net Monthly Electricity Usage of the Solar House.

Monthly electricity usage is predicted by EnergyPlus and Energy-10 and measured by the sub-meters. The net electricity use is the amount of electricity consumed subtracted by the amount produced from the PV panels. The net usage is negative in the summertime due to a high level of production from the PV panels.

Figure 19 and Figure 20 illustrate monthly electricity consumption and net usage, respectively. The monthly usage indicates the vast difference between GBS and the rest of the energy modeling programs. GBS predicted that a high percentage of the electricity consumption would be composed of lighting and plug loads, which generally remain constant throughout the year. Energy-10 and EnergyPlus more accurately predicted the usage from the plug loads, specifically. High plug and lighting loads would also cause a need for extra cooling in the summer, causing the GBS summer electricity consumption to have an even greater error. Since GBS does not output PV panel production in a monthly format, it was neglected from the net usage analysis in Figure 20. Figure 20 indicates that the metered electricity usage in the summer is similar to the usage modeled in both EnergyPlus and Energy-10, similar to Figure 19. In the winter, however, neither EnergyPlus nor Energy-10 produced results that were similar to the actual data. In January, for example, the electricity usage predicted by EnergyPlus and Energy-10 was 1757 and 1811 kWh respectively; however, the average measured usage was 3122 kWh, almost double the prediction from the models. In order to more thoroughly investigate the winter heating condition, hourly electricity consumption profiles were analyzed for EnergyPlus and Energy-10. GBS, however, is not formatted to output data in hourly time steps.

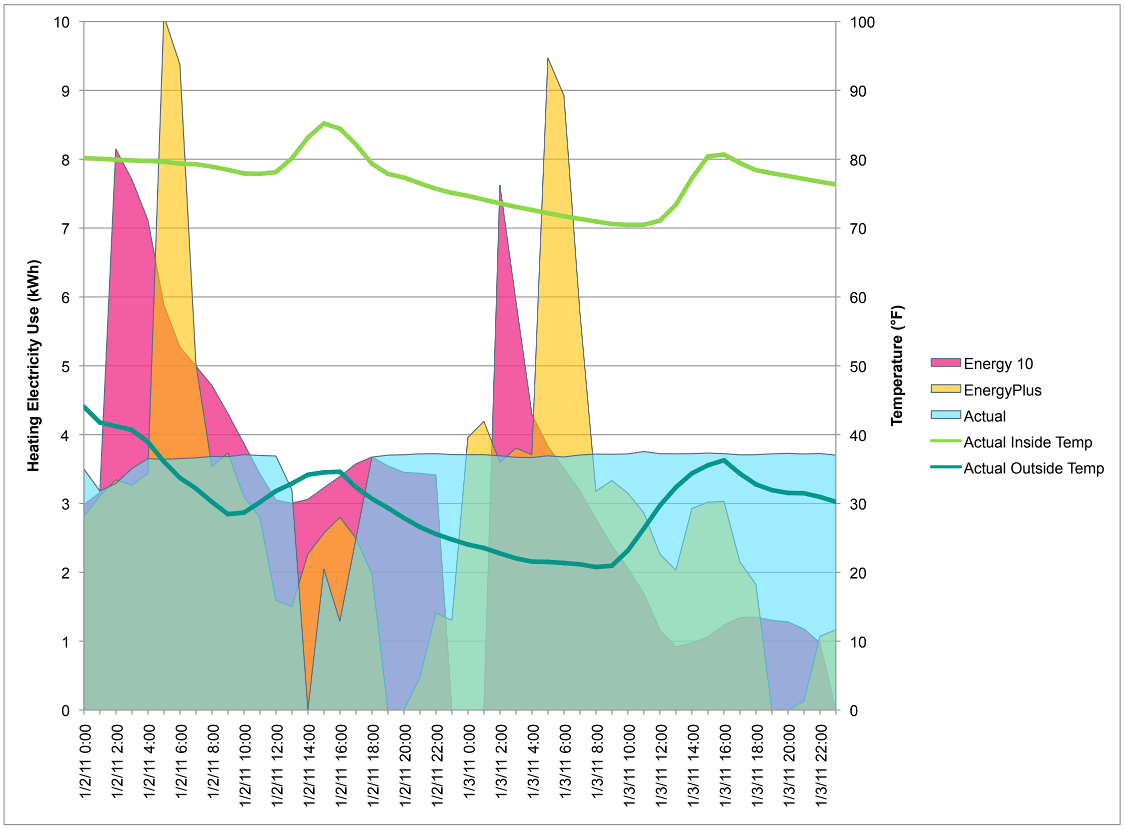


Figure 21. Modeled and Actual Hourly Heating Electricity Usage of the Solar House.

Hourly heating electricity usage is modeled by EnergyPlus and Energy-10 and measured by the sub-meters. Modeled sharp increases in heating usage indicated spikes in heating demand in the early morning so that the scheduled setpoint can be reached. Sharp decreases in the actual usage are due to solar thermal offset of the electricity usage.

Both the measured and predicted hourly energy consumption for two days in January 2011 is illustrated in Figure 21. Energy-10 and EnergyPlus show similar results; however, the default schedules within the programs, which are 7 am to 11 pm and 7 am to 7 pm respectively, could have caused the minor disparity in the results. The modeling programs assume that temperatures are set back at night, causing a drop-off in heating demand. Then, in the early morning, the heating demand spikes, raising the temperature in the space to the setpoint temperature. The actual hourly heating electricity usage, however, is considerably different than the modeled usage. The electric water heater has a maximum load of about 4 kWh and is, therefore, incapable of an early morning spike in demand. The drop-off in actual heating demand during the afternoon period is due to the energy produced from the solar thermal evacuated tubes. Similar to the PV panels, however, the solar thermal is not performing as well as expected. In summary, Figure 21 depicts the variation of the heating demand condition between the design-phase energy models and the actual metered electrical data.

3.3.2 LCA Results

The life cycle assessment was conducted for the materials and construction phase and the operations and maintenance phase of the Solar House. LCA results for the materials phase are illustrated in Figure 22. The polycarbonate wall and glass windows have the largest percentage of environmental impact in several categories, including ozone depletion, global warming, and primary energy. The appliances and lighting have the most impact in several of the other categories such as ecotoxicity and acidification. In some past research, concrete has been the material with the largest impact on the environment (Scheuer, Keoleian et al. 2003). The only concrete in the Solar House, however, is the ground floor slab and the foundations, and the concrete is 20% fly ash, which helps to mitigate its environmental impact.

The LCA was conducted for several aspects of the operations and maintenance phase such as energy usage and replacement of HVAC and lighting systems. The results for this portion of the LCA are detailed in Figure 23. The 16 months of metered energy data was extrapolated over the 25 year life cycle of the house in order to calculate life cycle operating energy use for input in the life cycle assessment. The electricity use of the house is a major contributor in numerous environmental impact categories. Electricity composes over 90% of the impact in respiratory inorganics and organics, aquatic acidification and eutrophication, global warming, and primary energy. In ozone depletion; carcinogens and non-carcinogens; and terrestrial ecotoxicity, acidification, and nutrification, replacement of the appliances has the highest percentage of impact. The other processes, the replacement of plumbing fixtures, HVAC systems, and lights, had little impact on the entire 25-year life cycle of the house. Since the Solar House is all-electric, its operations and maintenance environmental impact is largely due to electricity and not both electricity and fuel usage.

The complete LCA results for the Solar House are detailed in Figure 24. The results from each energy model were utilized to develop comparative LCA results, which were classified into the appropriate materials and use phases and then were normalized to each individual category total. Figure 25 presents just the results from the operations and maintenance phase of the LCA in order to increase the scale of the graph for better visibility. As illustrated in Figure 24 and Figure 25, the disparity between the modeled LCA results and the measured results depends on the impact category. *In the categories of carcinogens, non-carcinogens, ozone layer depletion, and terrestrial ecotoxicity and acidification, electricity usage does not appear to have a substantial impact on the life cycle impact results.* These results could be due to high impacts in those categories from other materials or activities included in the Solar House LCI, such as plastics/glass and appliances/lighting. *In the categories of respiratory organics and inorganics, aquatic acidification, global warming, and primary energy use, the LCA results are largely dependent on the energy results.* In terms of life cycle energy, the measured data indicated that the operations phase accounted for about 74% of the primary energy use, whereas GBS, Energy-10, and EnergyPlus predicted it to be about 68%, 17%, and 57% respectively. *Depending on the impact category, LCA results could or could not be largely affected by modeled versus actual electricity usage.*

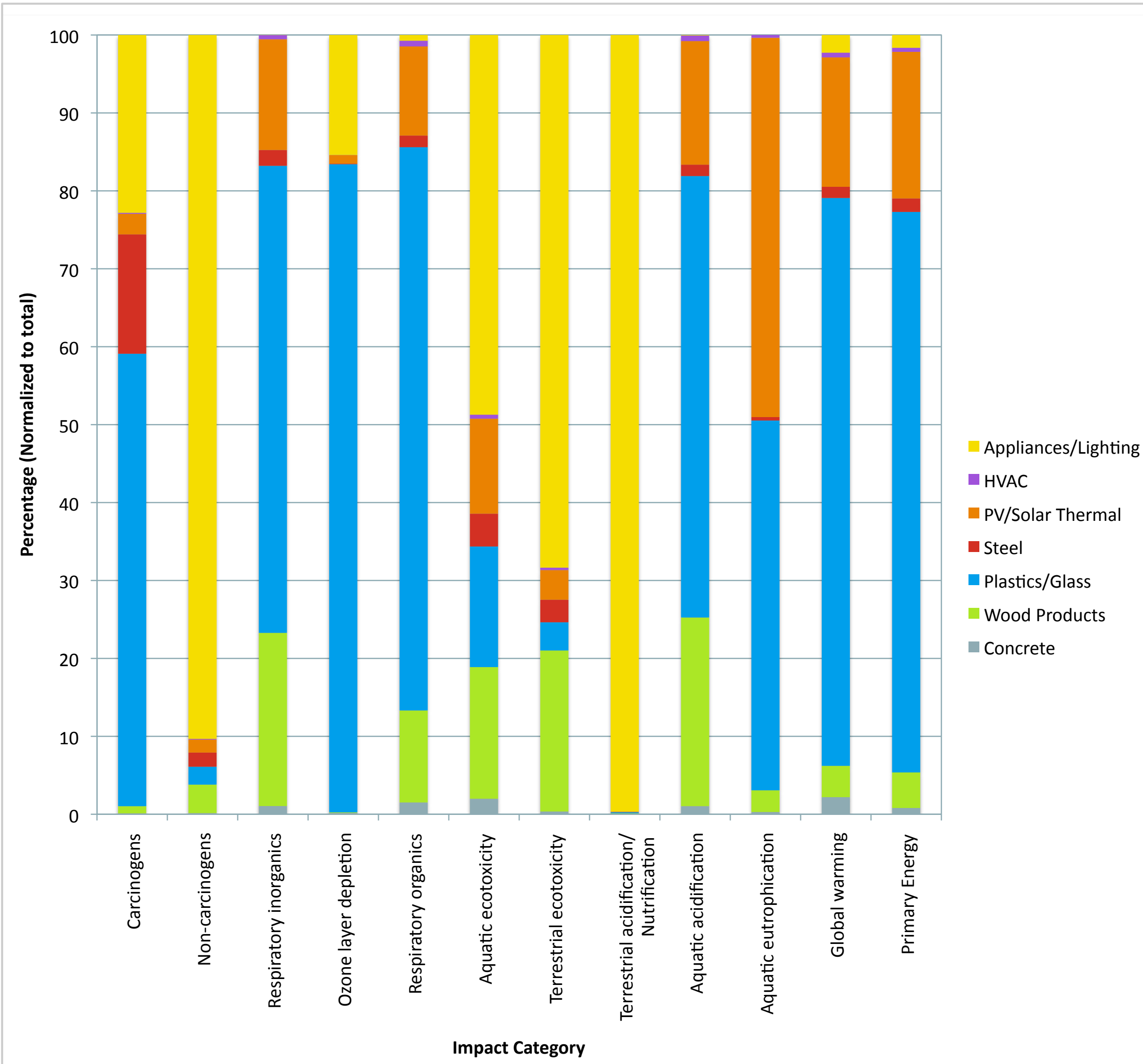


Figure 22. LCA Results in Impact 2002+ for the Material Phase of the Solar House.

All materials that were included within the system boundaries have been analyzed for the material phase of the Solar House. Each impact category has been normalized as a percentage of its own total, due to the different units associated with each category.

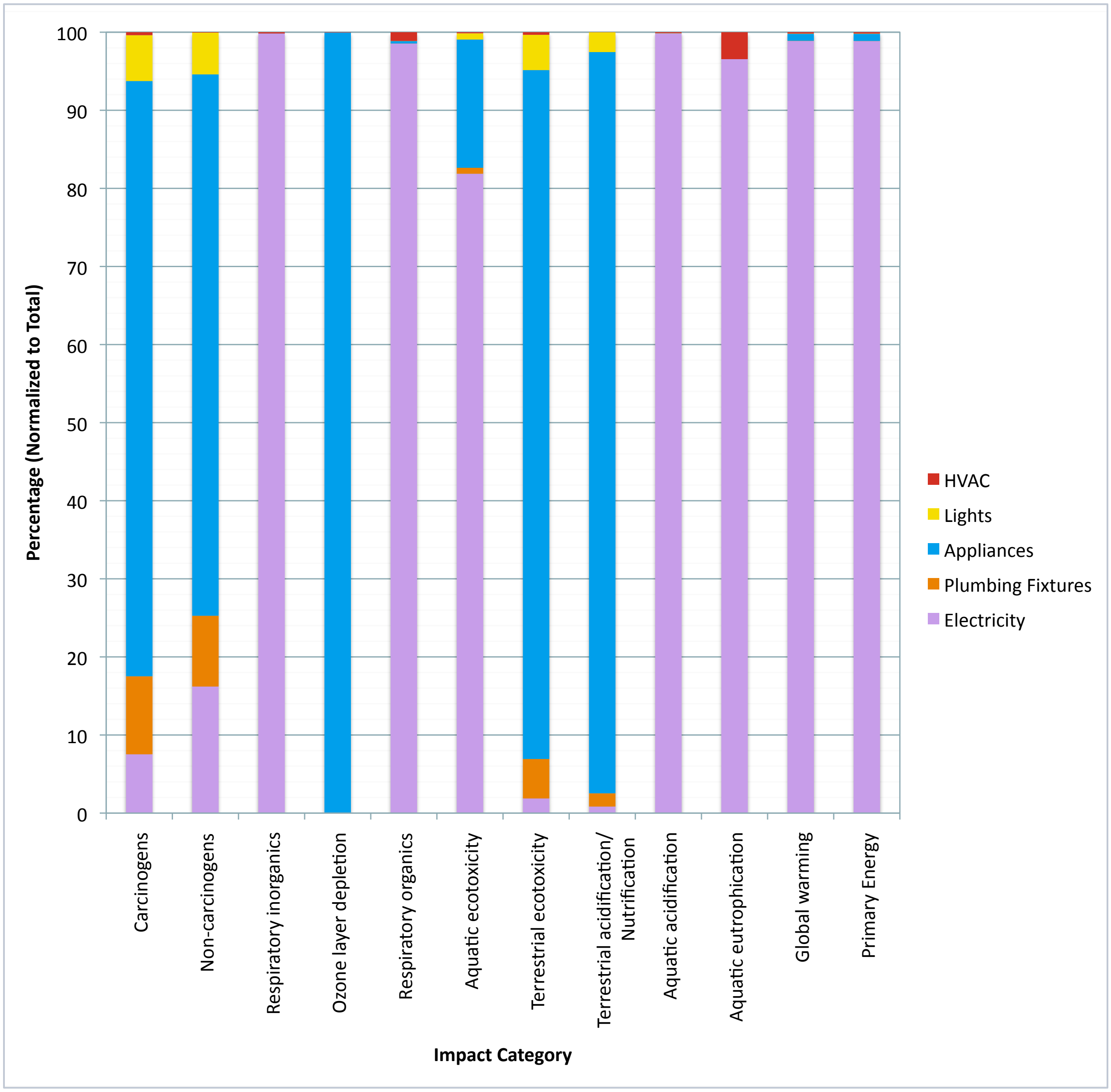


Figure 23. Metered LCA Results in Impact 2002+ for the Operations and Maintenance Phase of the Solar House for 25 Years.

All operations and maintenance activities and materials that were included within the system boundaries have been analyzed for this phase of the life cycle of the Solar House. The electricity usage was calculated using the 16 months of metered data from the Solar House and projected over 25 years. Each impact category has been normalized as a percentage of its own total, due to the different units associated with each category.

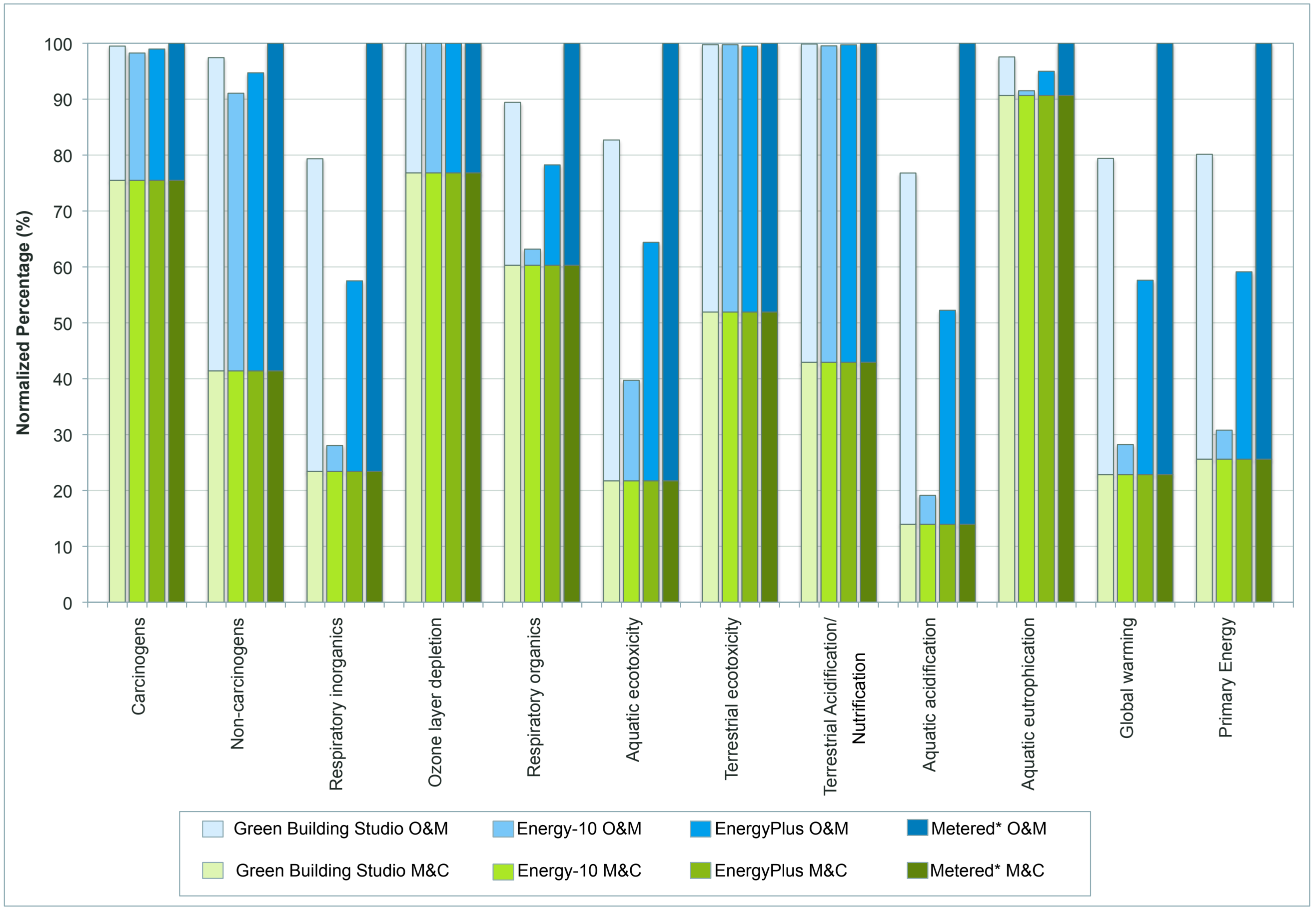


Figure 24. LCA Results in Impact 2002+ for the Solar House for a 25-year Life Cycle.

Results from each energy model and the actual metered data have been used to develop four different LCA results. The results are normalized to the impact derived from the metered energy data in each respective category. O&M = Operations and Maintenance; M&C = Materials and Construction

*Metered data is 16 months of measured energy data averaged for one year and then projected for 24 years.

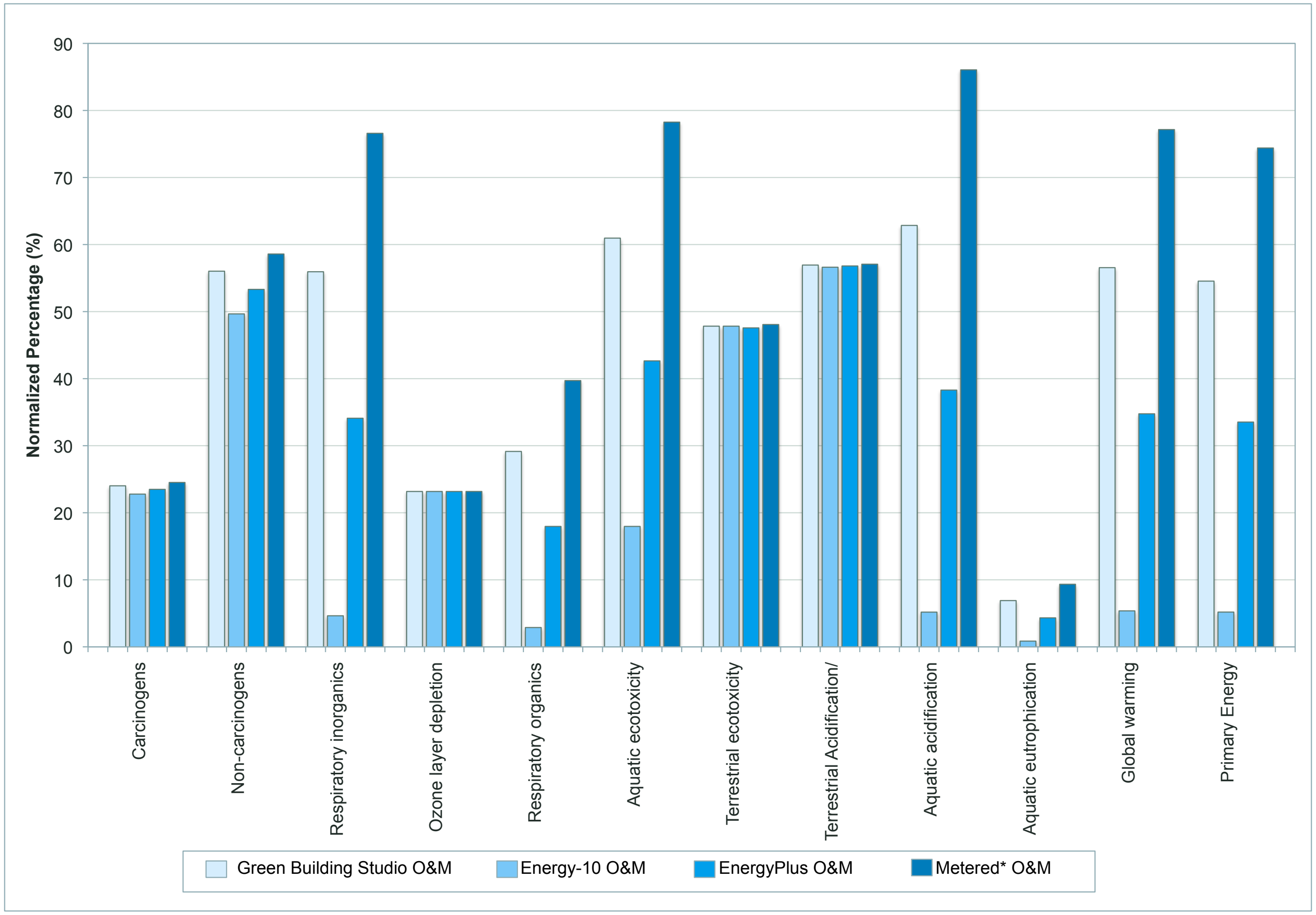


Figure 25. LCA Results in Impact 2002+ for the Operations and Maintenance Phase of the Solar House for a 25-year Life Cycle.

Results from each energy model and the actual metered data have been used to develop four different LCA results. The results are normalized to the total life cycle impact in Figure 24 in each respective category; however, only the Operations and Maintenance (O&M) phase is shown here in order to increase the scale of the graph.

*Metered data is 16 months of measured energy data averaged for one year and then projected for 24 years.

A further analysis of the life cycle energy use of the Solar House is presented in Figure 26. The life cycle energy calculations include both the embodied energy in the materials of the Solar House and the operating energy required for 25 years. The metered and projected data produced a life cycle energy consumption of 5.72 TJ. GBS, Energy-10, and EnergyPlus predicted a life cycle energy use of 4.58, 1.76, and 3.38 TJ, respectively, consequently, producing error rates of 20%, 70%, and 41%, respectively. The average error rate for life cycle energy use, 43%, is less than the average for operating energy, which was 59%; however, the error rate is still substantial. Since low energy buildings seem to have higher energy modeling error rates than other buildings, these results could be different for a conventional building. Overall, the results of energy models have a considerable impact on life cycle energy calculations.

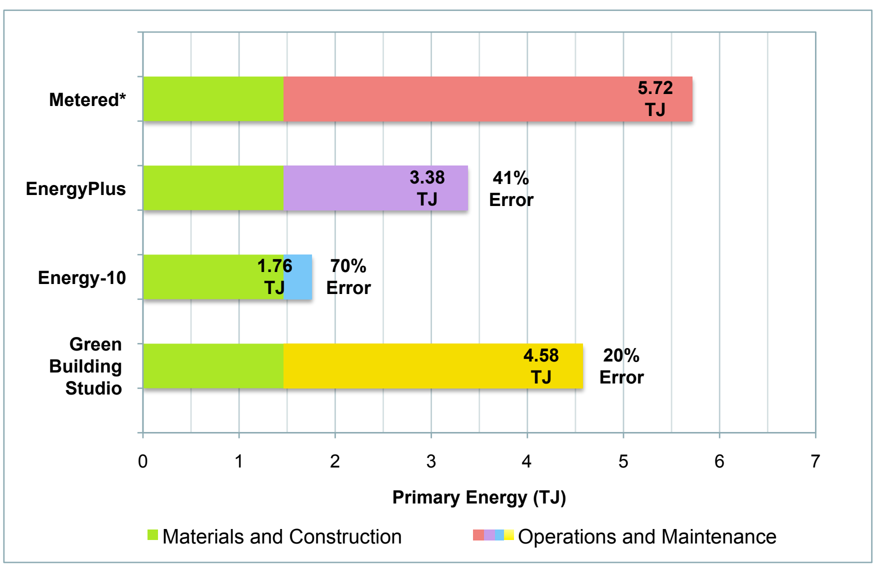


Figure 26. 25-year Life Cycle Energy Use of the Solar House.

Life cycle energy results are illustrated for each of the energy models and the actual metered data. Life cycle energy includes embodied energy (materials and construction phase) and operating energy (operations and maintenance phase). *Metered data is 16 months of measured energy data averaged for one year and then projected for 24 years.

3.4 CONCLUSIONS ON ENERGY MODELING AND LCA

This research utilized life cycle assessment and several different energy modeling programs as methods to analyze the impact of energy modeling results on life cycle energy. The average error rate for the energy programs was about 59%, whereas the average error rate for the life cycle energy calculations was about 43%. Several variables exist between modeled energy usage and actual usage, including occupancy densities, activities within the building, and the efficiency of systems, which could cause these substantial error rates. In the case of the Solar House, the inefficiency of the PV panels and the undersized electric water heater produced the greatest differences between predicted and measured electricity usage. Manufacturers could publish a range of efficiencies for PV panels according to the regional climate. Also, more research in the realm of specialized HVAC systems could help to mitigate large error rates associated with low energy buildings. The accuracy of the energy models highly depends on the inputs and their reflection of the actual systems and activities within the building. With design-phase energy models, however, the future use of the building is difficult to predict.

The variability of energy model results has a substantial impact within the building industry. LEED buildings have lost some credibility in terms of energy efficiency partly due their reliance on model results (Turner and Frankel 2008; Navarro 2009). The prediction of the overall environmental impact of a building can also rely on energy model results to determine operational energy usage. Error rates of predictive energy models can be a considerable variant to a LCA and could be considered as a part of uncertainty within LCA. In order to mitigate these issues with design-phase energy models, buildings can sub-meter energy usage in order to better determine the differences between modeled and actual usage. The tracking and analysis of actual building energy data could help users to identify more accurate input parameters to energy modeling programs. This could, consequently, better predict energy usage and help to generate more reasonable results from life cycle energy calculations.

Calibrated energy models have become useful tools in identifying the differences between modeled data and actuality. Variables such as inefficient systems and occupant activities could be identified for that particular calibrated energy model. Findings from these models could be utilized to better predict energy usage for future building designs. Because of the human and maintenance elements connected with building energy usage, a small error rate between the modeled and measured usage might be almost unavoidable; however, calibrated models could help to lower these error rates.

4.0 CONCLUSIONS

The conclusions of this research could have broader impacts for the LCA and green building community. In order to better incorporate LCA into the AEC community, green building rating systems, such as LEED, could create more opportunities for the advancement of LCA. It is recommended that LCA be more explicitly included and better integrated within LEED, instead of simply an add-on LEED credit. LEED also currently relies on energy modeling results for its energy performance credits. Incorporating error rates associated with energy models into LEED could drastically change the rating system's foundation. Calibrated energy models may be more suited for analysis within the LEED rating system but would require at least one year of building energy data. However, some uncertainty will always exist with both LCA and energy model results, which should be considered if integrated into green building rating systems.

5.0 FUTURE WORK

Future work of this research involves completing the national survey, calibrating the energy models, and conducting additional case studies on life cycle assessment. In order to connect to a broad national audience, future work for the survey could involve:

- Structuring the survey to be user friendly and engaging for the participant
- Obtaining a considerable amount of email addresses from a broad range of organizations
- Promoting the survey through advertisement

Calibration of the energy models is essential to understanding the variations between input assumptions and actuality. The three energy models, GBS, Energy-10, and EnergyPlus, could be re-evaluated based on real-time energy data. The actual data could be further analyzed to determine occupancy loads, schedules, and maintenance issues. This calibration of the energy models could depict the difference between error rates due to assumptions and error rates due to inaccurate modeling tools.

In addition, more case studies are needed to analyze the relationship between energy modeling and life cycle assessment. The Solar House is an interesting case study due to its unique systems and features; however, a more conventional building may yield different results. In order to compare, multiple case studies with buildings differing in type of construction, year built, square footage, and building type could be analyzed. This diverse group of studies could help to establish a comprehensive data set. In the future, this could help to prove if energy modeling results have a statistically significant impact on life cycle energy calculations.

APPENDIX A

FOCUS GROUP GUIDE

Sample Interview Guide – Life Cycle Assessment

Hello, my name is Laurel Person Mecca and I am a researcher at the University of Pittsburgh. Melissa Bilec has contracted me to facilitate focus group discussions with members of Pittsburgh's Green Building Alliance. The purpose of this study is to explore barriers to life cycle assessment. Knowing your opinions and ideas about life cycle assessment will help in the development of a dynamic life cycle based method that quantifies the environmental impacts of buildings and aids in decision-making at multiple scales.

The focus group will take approximately an hour and a half to complete.

The discussions will be recorded, and the audiotapes will later be transcribed by my staff. To ensure your complete confidentiality, reporting of results will only include a re-phrased summary of the discussions so that anything you say cannot be linked back to you.

There are no foreseeable risks associated with this project, nor are there any direct benefits to you. However, what the study team learns from your participation will help develop a dynamic life cycle based methodology. Lunch will be provided during the group discussions. You also will be paid $50 at the end of our discussion for your involvement today.

Your participation is voluntary, and you may withdraw from this project at any time. Do you have any questions before we begin?

---

1. Let's go around the table and please say your first name and how long have you been a member of GBA or involved with green design.

2. Have you implemented sustainable building practices into your design, construction, operation, and/or manufacturing fields?

    a. If so, what have you done in order to incorporate sustainability? [goal – experience]
    b. If not, why is that?

3. Are you familiar with life cycle assessment (LCA)?
    a. If so, how would you describe LCA in your own words?

4. How would you describe life cycle assessment (LCA) in your own words?

5. What are the barriers to using LCA in your respective fields?

6. Neglecting the aforementioned barriers, do you think LCA would be beneficial to improving and understanding sustainability in your respective fields?

    a. If so, what are the benefits of LCA?
    b. If no, why is that?

7. Which barriers to using LCA would be negated if LCA were integrated into current software tools?

8. In what ways would LCA be a beneficial tool for the LEED program?

    a. How could LCA be integrated into LEED?

9. Our purpose today was to find out your opinions and ideas about LCA. Are there any other comments that you have about LCA that we have not covered?

APPENDIX B

B.1 SURVEY METHODS

The web survey was distributed to members of the AEC community through an email that provided a link to the web page. Emails were gathered through professional organizations, such as GBA, American Institute of Architects (AIA), American Society of Civil Engineers (ASCE), Master Builder's Association (MBA) of Western Pennsylvania, the Associated General Contractors of America (AGC), and the Building Owners & Managers Association (BOMA) of Pittsburgh. Emails were recorded only for those members whose names and specific email addresses were listed. 1,666 valid email addresses of members of the AEC community across the U.S. were sent an invitation to complete the survey. In addition, the survey link was distributed through newsletters from the GBA and USGBC, posted on social media by GBA, and handed out on a flyer at the GreenBuild NEXT conference, hosted by the USGBC in 2011 in Toronto.

Web surveys have been documented to have substantially lower response rates than printed surveys (Dillman 2007; Stoop, Billiet et al. 2010). Some of the issues associated with web surveys include color and text formatting changes from computer to computer and complex interfaces that confuse the respondent. In order to mitigate these issues, a simple user interface with minimal buttons was utilized for the survey. To increase response rates each email was personalized to each respondent instead of a part of a mass mailing, as recommended by Dillman (2007). Then, participants were sent a reminder email each week for several weeks after the initial email invitation.

Several iterations of the web survey were developed from the focus group guide. Responses from the focus group were utilized to expand several of the focus group questions. An early text version of the web survey is shown in Appendix B.2. The survey included several different types of questions including multiple choice, Likert scale, agree or disagree, yes or no, and definition questions. The structure of the survey is detailed in Table 8.

The survey followed the same general themes and structure of the focus group. According to Dillman, in web survey development it is essential to begin the survey with simple and easy to answer questions, so demographics such as age, sex, and AEC field were included in the first section (2007). After this section, participants were asked what their general knowledge and experience with sustainability and LCA has been in the past. Respondents were first asked a self-evaluation question and then asked to answer a definition question on LCA. Following the definition question, a web page about LCA gave participants who were unfamiliar with LCA the opportunity to learn about the process. The respondents were then asked about their past experience with LCA. Participants were asked to rate benefits and barriers based on a Likert scale. Following this section, more detailed questions on sustainability, software tools, and LEED were posed. At the end of the survey, respondents were able to write-in any additional comments. The complete web survey can be found in Appendix B.3.

Table 8. Structure of LCA Web Survey.

The left column details the various sections of the web survey in sequential order. The green shaded cells indicate which types of questions were included in each portion.

	Mulitple Choice	Likert Scale	Definition	Table with Likert Scale	Agree/ Disagree	Yes/No	Written Field
A. Demographics							
B. Experience with Sustainability							
C. Knowledge of LCA							
Education on LCA (no questions)							
D. Experience with LCA							
E. Benefits and Barriers							
F. LCA and Sustainability							
G. LCA and Software Tools							
H. LCA and LEED							
Comments							

In order to cater the survey to the respondents' answers, previous knowledge, and AEC field, several threads existed within the survey. An excellent example of these threads exists within the Knowledge of LCA and Education on LCA segments, which are exemplified in Figure 27 and Figure 28. If the participant answered d or e to question 1 in Figure 27, then the participant was directed to a page that stated, "You seem to be unfamiliar with LCA. To learn more about it, click here. It will only take a minute." Instead of answering the definition question, they were directed to the education segment. If a, b, or c was answered from question 1, then the respondent was directed to question 2 in Figure 27. The answers in question 2 were also randomized, so that the correct answer would appear as either a, b, c, or d. If the correct answer was selected (shown in pink in Figure 27), then the participant was directed to a page that read, "You got it right! Would you like to learn more about LCA? It will only take a minute. If so, click there. If not, continue with the survey." If participants chose to continue with survey, they were directed to the *Experience with LCA* segment. If the correct answer was not selected for question 2, participants were taken to a page that stated, "That's incorrect. To learn more about LCA, click here. It will only take a minute." When participants chose to "learn more about LCA" they were directed to the education page, which is depicted in Figure 28. The education page highlights a brief description of process LCA, as defined by ISO. After the education page, participants who answered question 2 incorrectly were asked to redefine LCA in question 3 of Figure 27, so that, when calculating the results, each participant's understanding of LCA could be gauged. The threads within the survey helped to divert respondents from questions that they may not have had enough understanding, knowledge, or experience to adequately answer.

1. Please classify your level of expertise with life cycle assessment (LCA):

    a. I am an expert in LCA

    b. I have completed at least one LCA, but would not consider myself an expert

    c. I have never completed an LCA but can understand and interpret the results

    d. I've heard about LCA but I am not sure what it is

    e. I have no experience with LCA at all

2. Please select the <u>most complete</u> definition of life cycle assessment (LCA).

    a. The calculation of the cost of a product over its entire life cycle.

    b. The assessment of the energy required to produce a product from materials extraction through manufacturing to its use.

    c. The evaluation of the carbon footprint of a product or process from materials extraction through manufacturing to its use.

    d. The quantification of the total environmental impacts of a product or process from cradle to grave.

3. Please select the <u>most complete</u> definition of life cycle assessment (LCA).

    a. Sum of all the one-time and maintenance and replacement costs of a good throughout its life cycle.

    b. The total accounting of the energy required for a product or process throughout its life cycle.

    c. The life cycle inputs and outputs of materials and energy of a product and its associated greenhouse gas emissions.

    d. The inputs and outputs of materials and energy and the associated environmental impacts attributable to a product or system throughout its life cycle.

Figure 27. Questions in Knowledge of LCA Section of Web Survey.

Before the education segment, the web survey participants were asked the first question in order to self–evaluate their experience with LCA. Next, the participants were asked to answer a definition question on LCA in order to test the participants' understanding of LCA before taking the survey. If the answer to question 2 was incorrect, participants were asked to redefine LCA in question 3 after the education segment. The answers highlighted in pink were the correct answers to the definition questions.

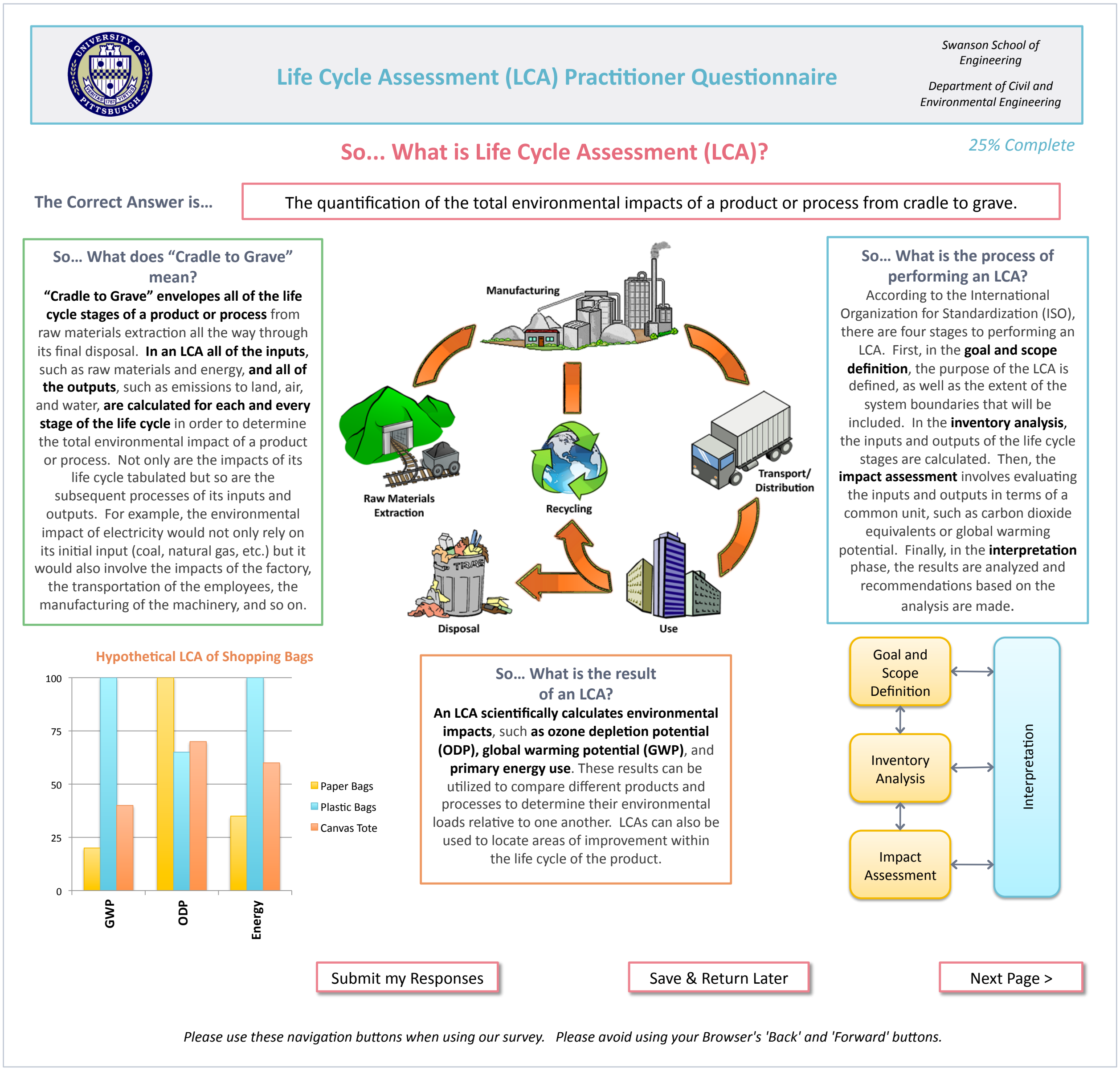


Figure 28. LCA Education Slide from Web Survey.

When question 2 from Figure 27 was answered incorrectly, participants were directed to this education page on LCA. The participants are given the correct answer to the definition question on the top of the page. Supplemental figures, as well as the bolded text, give a simple and short explanation to the process of LCA defined by ISO.

In following with the focus group, the benefits and barriers section was the main focus of the survey. The benefits of LCA table from the survey is outlined in Table 9. Using the benefits of LCA that were discovered in the focus group analysis, the survey question was formatted as a table with an integrated Likert scale. In order to keep from overwhelming the survey respondent, the table was formatted to fit within the bounds of one web page (Dillman 2007). The benefit *Could drive government regulation*, which was mentioned two times in the focus groups, was neglected from the survey in order to fit the table within the constraints. A similar method was utilized for the barriers section, which is depicted in Table 10. *No integration with current design tools, Lack of ability to include building/site specific data, Transparency of software tools,* and *Results are difficult to understand* were all neglected in the survey because of similarity to other barriers or brief mentioning in the focus groups. *Assumptions used to conduct LCA* and *Transparency of data* were combined into one barrier labeled *Lack of data to conduct LCA.* Similar terminology such as "lack of" was utilized between benefits and barriers in order to reduce the confusion of the respondent.

Currently, 148 people have completed almost all of the survey, yielding a response rate of 8.88%. This rate is similar to previous web surveys that indicate response rates between 5 and 20% (Flower 2009). Another version of the survey may be sent to a different set of emails in the future. At this time, analysis of the current survey results has not yet been performed and will be performed in future research.

Table 9. Benefits of LCA Table from Web Survey.

In each of the table boxes, radio buttons were provided to answer the Likert scale. Only one radio button could be filled in for each benefit.

Benefits of LCA	0 Not a benefit	1 Slight benefit	2 Moderate benefit	3 A great benefit	4 An extreme benefit	Do not understand benefit
Uses a long term holistic perspective						
Provides information about environmental impacts						
Uses a scientific and structured approach						
Informs decision making						
Advances a project's triple bottom line						
Promotes a product for the "green" market						
Compares alternative products						
Follows an ISO standard						

Table 10. Barriers to LCA Table from Web Survey.

In each of the table boxes, radio buttons were provided to answer the Likert scale. Only one radio button could be filled in for each benefit.

Barriers to LCA	0 Not a barrier	-1 Slight barrier	-2 Moderate barrier	-3 A great barrier	-4 An extreme barrier	Do not understand barrier
Time it takes to conduct an LCA						
Complexity of an LCA						
Cost of performing an LCA						
Trust in the process of LCA						
Accuracy of LCA results						
Lack of comparability between product LCAs						
Lack of governmental incentives to perform LCAs						
Lack of analysis of indoor environmental quality						
Lack of data to conduct LCAs						
Lack of demand from my clients						

B.2 EARLY TEXT VERSION OF SURVEY

Introduction

x. What is your respective field within the AEC community?
a. architect b. engineer c. contractor d. owner e. manufacturer f. researcher

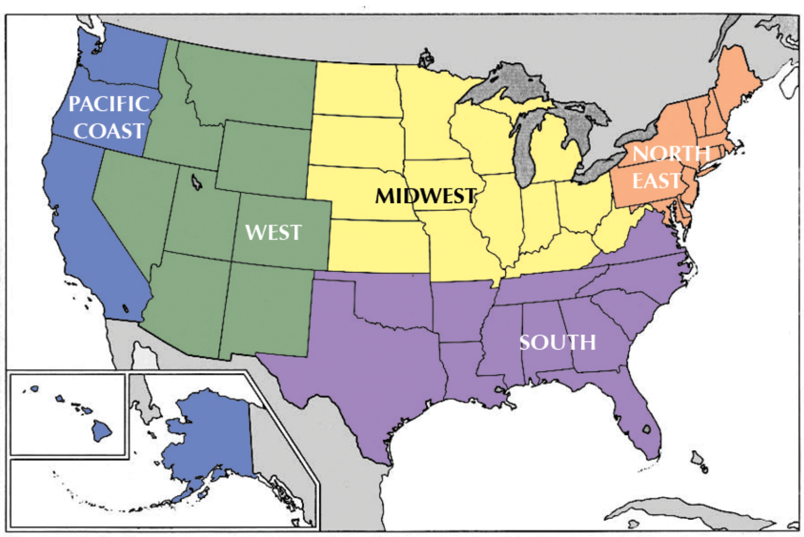
x. Select the highest education you have received:
a. High school diploma b. Associate c. Bachelor d. Masters e. Doctorate

x. Select the following age group appropriate for you:
a. 20-29 b. 30-39 c. 40-49 d. 50-59 e. 60+

x. Select your gender:
a. female b. male

x. Select the appropriate area in which you work:
a. metropolitan area b. suburban area c. small town d. rural

x. Select the region in which you work:
a. northeast b. south c. Midwest d. West e. Pacific coast



Experience/Knowledge about Sustainability

x. How familiar are you about issues within the field of sustainability?
Very
Moderately
Somewhat
Not at all

x. Definition of Sustainability???

x. How many years have you dealt with sustainability within your respective fields?
a. 1 or less than a year b. 2-3 c. 4-6 d. 7-9 e. 10+

x. How much experience have you had in applying sustainability principles to your respective fields?
Sustainability is an important component to approximately:
100% of my commissions
75% of my commissions
50% of my commissions
25% of my commissions
0% of my commissions

<u>Familiarity/Knowledge about LCA</u>
x. How familiar are you with life cycle assessment (LCA)?
Very
Moderately
Somewhat
Not at all

x. Define life cycle assessment in your own words. (Fill in the blank)

x. Select the most complete definition of life cycle assessment (LCA).
a. the calculation of the cost of a product over its entire life cycle
b. the assessment of the energy required to produce a product from materials extraction through manufacturing
c. the quantification of the total environmental impacts of a product or process from cradle to grave
d. the evaluation of the carbon footprint of a product or process from materials extraction through manufacturing to its use

<u>Education Segment about LCA</u>
This q is about LCA – Here are some definitions, etc.
(Definition/Figures/etc – one web page)

<u>Experience/Attitudes toward LCA</u>
Given this definition:
x. In the years that I have dealt with sustainability, I have utilized LCA in approximately:
100% of my commissions
75% of my commissions
50% of my commissions
25% of my commissions
0% of my commissions

If 100%, 75%, 50%, 25%:
x. In your experience, how useful has LCA been for evaluating the environmental impacts of your commissions?
Thoroughly useful
Very Useful
Moderately useful

Somewhat useful
Not at all useful

If 100%, 75%, 50%, 25%:
x. How likely are you to increase your use of LCA in the future?
Extremely likely
Very likely
Moderately likely
Somewhat likely
Not at all likely

If 0%:
x. How useful do you think LCA would be for evaluating the environmental impacts of your commissions?
Thoroughly useful
Very Useful
Moderately useful
Somewhat useful
Not at all useful

If 0%:
x. How likely are you to use LCA in the future?
Extremely likely
Very likely
Moderately likely
Somewhat likely
Not at all likely

<u>Benefits</u>

x. Rate the following perceived and/or actual benefits to the use of LCA:

	Not a benefit at all				An extreme benefit	Not familiar
BENEFITS	1	2	3	4	5	
Validates the need for sustainable development						
Educates others about environmental impacts						
Limits our impact to the environment						
Generates financial gain for your commission						
Uses a life cycle perspective						

Barriers:
x. Rate the following perceived and/or actual barriers to the use of LCA:

	Not a barrier at all				An extreme barrier	Not familiar
BARRIERS	1	2	3	4	5	
Time it takes to conduct an LCA						
Complexity of an LCA						
Transparency of the data and/or software tools						
Trust in the process of LCA and the results						
Cost of performing an LCA						
Lack of comparability between product LCAs						
No governmental incentives to perform LCAs						
Inability to include building/site specific data						
Inability of others to understand LCA results						
Incomplete data/too many assumptions to conduct LCA						

x. Check two actual and/or perceived barriers that are the most problematic to perform an LCA.
a. Time
b. Complexity
c. Transparency
d. Trust
e. Cost
f. Lack of comparability
g. No incentives
h. No site specific data
i. Inability to understand results
j. Incomplete data

LCA and Sustainability
x. LCA can accurately depict the sustainability of your commission.
Strongly agree

Agree
Disagree
Strongly disagree

x. Conducting an LCA during the design process helps to guide the sustainable components of a commission.
Strongly agree
Agree
Disagree
Strongly disagree

x. LCA is a more comprehensive tool for measuring sustainability than other metrics, such as recycled content and indoor air emissions.
Strongly agree
Agree
Disagree
Strongly disagree

Add to those metrics?

x. LCAs are used only as a marketing tool for companies and could cause even more greenwashing.
Strongly agree
Agree
Disagree
Strongly disagree

LCA and software tools
x. Do you use a general design software tool, such as REVIT, Primavera, or Inventor?
yes
no

x. Do you use a software tool, such as Athena, BEES. or SimaPro that allows you to perform an LCA?
yes
no

x. Currently, is LCA too complex to be easily integrated into current design software tools?
yes
no

If yes:
x. A simplified version of LCA would be more useful for integration into current software tools.
Strongly agree
Agree
Disagree
Strongly disagree

x. The integration of LCA into current software tools would change the way you design.
Strongly agree
Agree
Disagree

Strongly disagree

LCA and LEED

x. How familiar are you with the Leadership in Energy and Environmental Design (LEED) program?
Very
Moderately
Somewhat
Not at all

x. Currently, in which LEED category is the LCA pilot credit?
a. Sustainable sites
b. Water efficiency
c. Energy and atmosphere
d. Material and resources
e. Indoor environmental quality

x. Have you registered a commission that utilized the LCA pilot credit?
yes
no

If yes:
x. LCA definitely best fits within the Material and Resources category.
Strongly agree
Agree
Disagree
Strongly disagree

If yes:
x. The LCA pilot credit improved the evaluation of the sustainability of the commission.
Strongly agree
Agree
Disagree
Strongly disagree

B.3 FINAL WEB SURVEY

Life Cycle Assessment (LCA) and Buildings Questionnaire

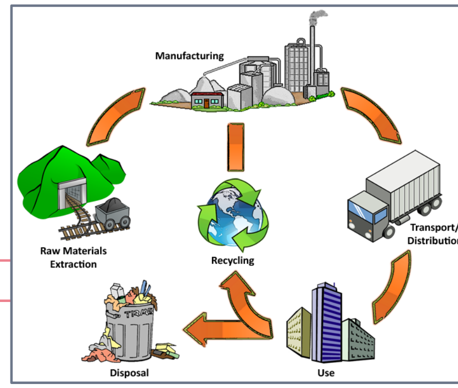
Swanson School of Engineering

Click here for your Questionnaire

Survey Introduction

The survey is an integral part of a current research project at the University of Pittsburgh entitled Barriers, Understanding, Integration – Life cycle Development (BUILD) funded by the National Science Foundation Grant Award EFRI-1038139. The questionnaire has been distributed to members of the architecture, engineering, and construction (AEC) community in conjunction with the United States Green Building Council (USGBC) and the Green Building Alliance (GBA). The goal of the survey is to gauge an understanding of current knowledge of life cycle assessment and to identify benefits and barriers to its use within the AEC community. The following sections indicate what to expect within the survey:

A. Demographics
B. Experience with Sustainability
C. Knowledge of LCA
D. Experience with LCA
E. Benefits and Barriers
F. LCA and Sustainability
G. LCA and Software Tools
H. LCA and LEED



Survey Logistics

This survey should take about **10 minutes to complete**.

If you get interrupted while taking this survey, you can save your responses and continue at a later time by clicking the **«Save & Return Later»** button located at the bottom of most pages.

When you are finished with this survey it is very important that you submit your responses by clicking the «Submit My Responses» button located on the very last page.

This study has been approved by the University of Pittsburgh's Institutional Review Board (IRB PRO10070111). Your participation in the study is completely voluntary and your answers will be confidential. All responses will be analyzed in aggregate and neither your name nor your facility's name will be used in any publication. There are no foreseeable risks associated with completing the survey, nor are there any direct benefits to you. Please feel free to contact the University of Pittsburgh's Principal Investigator, Melissa Bilec, PhD (412-648-8075, mbilec@pitt.edu) or the University of Pittsburgh IRB (412-383-1480), if you have any questions. Please direct all technical questions regarding this website to Rob Keene at websrvy@pitt.edu.

Click here for your Questionnaire

Life Cycle Assessment (LCA) and Buildings Questionnaire

Swanson School of Engineering

0% Complete

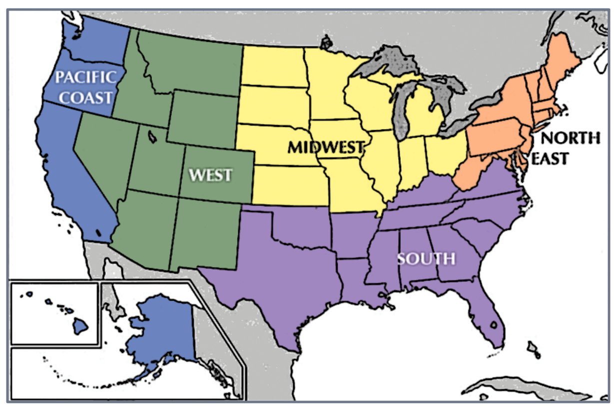
A. Demographics

1. What is your respective field within the architecture, engineering, and construction community?
a. Architect
b. Engineer
c. Contractor
d. Owner
e. Manufacturer
f. Researcher
g. Other, Please Specify:

2. What is the highest level of education you have received?
a. High school diploma
b. Associate
c. Bachelor
d. Masters
e. Doctorate

3. What is your age group?
a. 20-29
b. 30-39
c. 40-49
d. 50-59
e. 60+

4. What is your gender?
a. Female
b. Male



5. What region of the country do you work in?
a. Northeast
b. South
c. Midwest
d. West
e. Pacific coast

6. Is the area you work in:
a. Metropolitan
b. Suburban
c. Small town
d. Rural

< Previous Page | Save & Return Later | Next Page >

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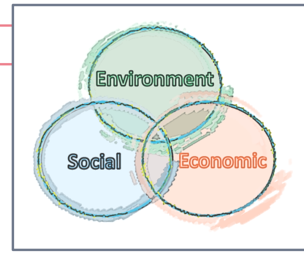
Life Cycle Assessment (LCA) and Buildings Questionnaire

Swanson School of Engineering

15% Complete

B. Experience with Sustainability



1. How familiar are you with sustainability?

a. Very familiar

b. Moderately familiar

c. Only a little familiar

d. Not at all familiar

2. For how many years has sustainability been an important component within your projects?

a. It is not an important component

b. 1 year or less

c. 2 to 3 years

d. 4 to 6 years

e. 7 to 9 years

f. 10+ years

C. Knowledge of LCA

1. Please classify your level of expertise with life cycle assessment (LCA):

a. I am an expert in LCA

b. I have completed at least one LCA, but would not consider myself an expert

c. I have never completed an LCA but can understand and interpret the results

d. I've heard about LCA but I am not sure what it is

e. I have no experience with LCA at all

< Previous Page | Save & Return Later | Next Page >

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Life Cycle Assessment (LCA) and Buildings Questionnaire

Swanson School of Engineering

22% Complete

C. Knowledge of LCA

2. Please select the <u>most complete</u> definition of life cycle assessment (LCA).

a. The calculation of the cost of a product over its entire life cycle.

b. The assessment of the energy required to produce a product from materials extraction through manufacturing to its use.

c. The evaluation of the carbon footprint of a product or process from materials extraction through manufacturing to its use.

d. The quantification of the total environmental impacts of a product or process from cradle to grave.

< Previous Page | Save & Return Later | Next Page >

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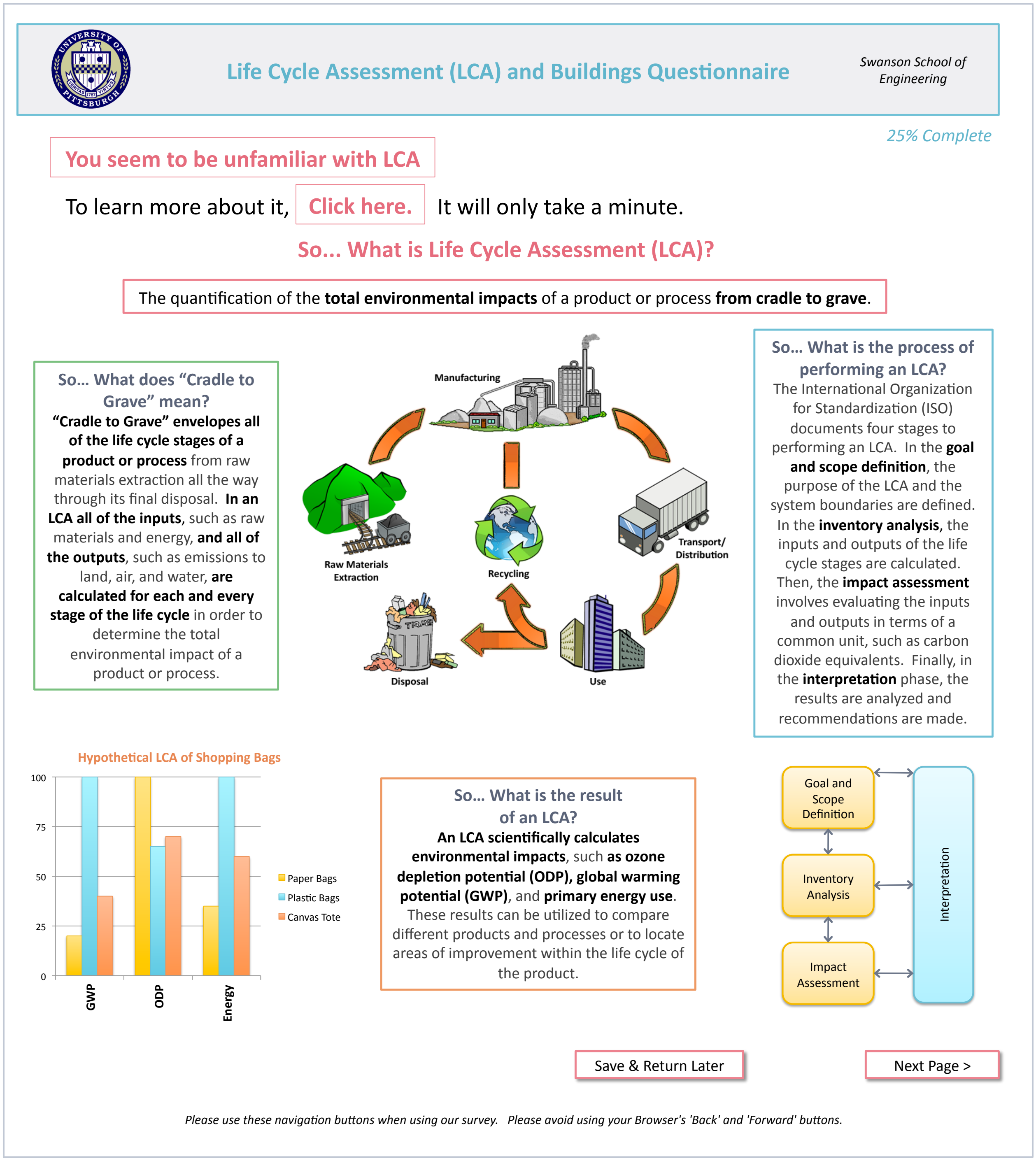
UNIVERSITY OF PITTSBURGH
Life Cycle Assessment (LCA) and Buildings Questionnaire
Swanson School of Engineering
25% Complete
You seem to be unfamiliar with LCA
To learn more about it, Click here. It will only take a minute.
So... What is Life Cycle Assessment (LCA)?
The quantification of the **total environmental impacts** of a product or process **from cradle to grave**.
So... What does “Cradle to Grave” mean?
“Cradle to Grave” envelopes all of the life cycle stages of a product or process from raw materials extraction all the way through its final disposal. **In an LCA all of the inputs**, such as raw materials and energy, **and all of the outputs**, such as emissions to land, air, and water, **are calculated for each and every stage of the life cycle** in order to determine the total environmental impact of a product or process.
Manufacturing
Raw Materials Extraction
Recycling
Transport/ Distribution
Disposal
Use
So... What is the process of performing an LCA?
The International Organization for Standardization (ISO) documents four stages to performing an LCA. In the **goal and scope definition**, the purpose of the LCA and the system boundaries are defined. In the **inventory analysis**, the inputs and outputs of the life cycle stages are calculated. Then, the **impact assessment** involves evaluating the inputs and outputs in terms of a common unit, such as carbon dioxide equivalents. Finally, in the **interpretation** phase, the results are analyzed and recommendations are made.
Hypothetical LCA of Shopping Bags
100
75
50
25
0
GWP
ODP
Energy
Paper Bags
Plastic Bags
Canvas Tote
So... What is the result of an LCA?
An LCA scientifically calculates environmental impacts, such **as ozone depletion potential (ODP), global warming potential (GWP)**, and **primary energy use**. These results can be utilized to compare different products and processes or to locate areas of improvement within the life cycle of the product.
Goal and Scope Definition
Inventory Analysis
Impact Assessment
Interpretation
Save & Return Later
Next Page >
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Life Cycle Assessment (LCA) and Buildings Questionnaire

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30% Complete

C. Knowledge of LCA

So let's try it again..

3. Please select the <u>most complete</u> definition of life cycle assessment (LCA).

a. Sum of all the one-time and maintenance and replacement costs of a good throughout its life cycle.

b. The total accounting of the energy required for a product or process throughout its life cycle.

c. The life cycle inputs and outputs of materials and energy of a product and its associated greenhouse gas emissions.

d. The inputs and outputs of materials and energy and the associated environmental impacts attributable to a product or system throughout its life cycle.

< Previous Page | Save & Return Later | Next Page >

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Life Cycle Assessment (LCA) and Buildings Questionnaire

Swanson School of Engineering

38% Complete

D. Experience with LCA

1. In the years that sustainability has been an important component in my work, I have utilized LCA in approximately:

a. 100% of my projects

b. 75% of my projects

c. 50% of my projects

d. 25% of my projects

e. None of my projects

2. In the years that sustainability has been an important component in my work,
I have utilized the following subsets of LCA: [Check all that apply]

a. Carbon footprinting

b. Energy analysis

c. Ecological footprinting

d. Water footprinting

< Previous Page | Save & Return Later | Next Page >

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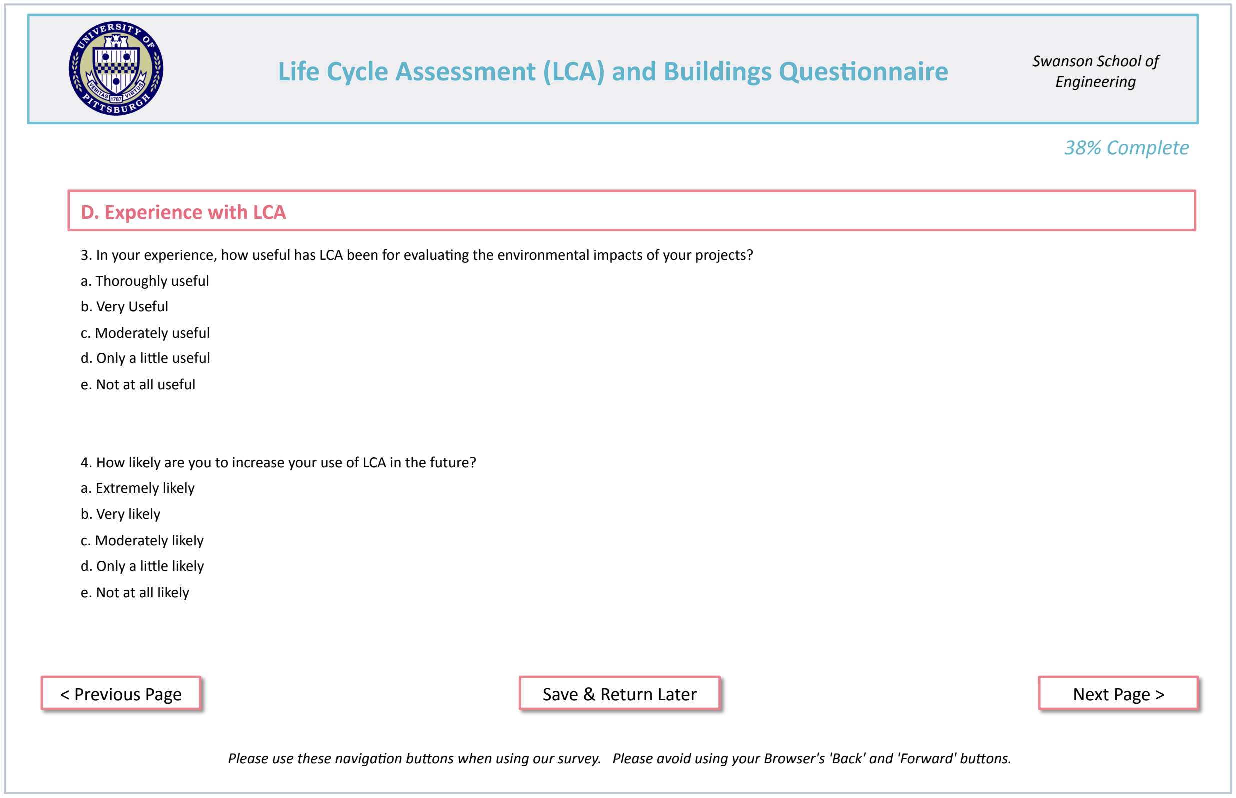
Life Cycle Assessment (LCA) and Buildings Questionnaire
Swanson School of Engineering
38% Complete
D. Experience with LCA
3. In your experience, how useful has LCA been for evaluating the environmental impacts of your projects?
a. Thoroughly useful
b. Very Useful
c. Moderately useful
d. Only a little useful
e. Not at all useful
4. How likely are you to increase your use of LCA in the future?
a. Extremely likely
b. Very likely
c. Moderately likely
d. Only a little likely
e. Not at all likely
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Save & Return Later
Next Page >
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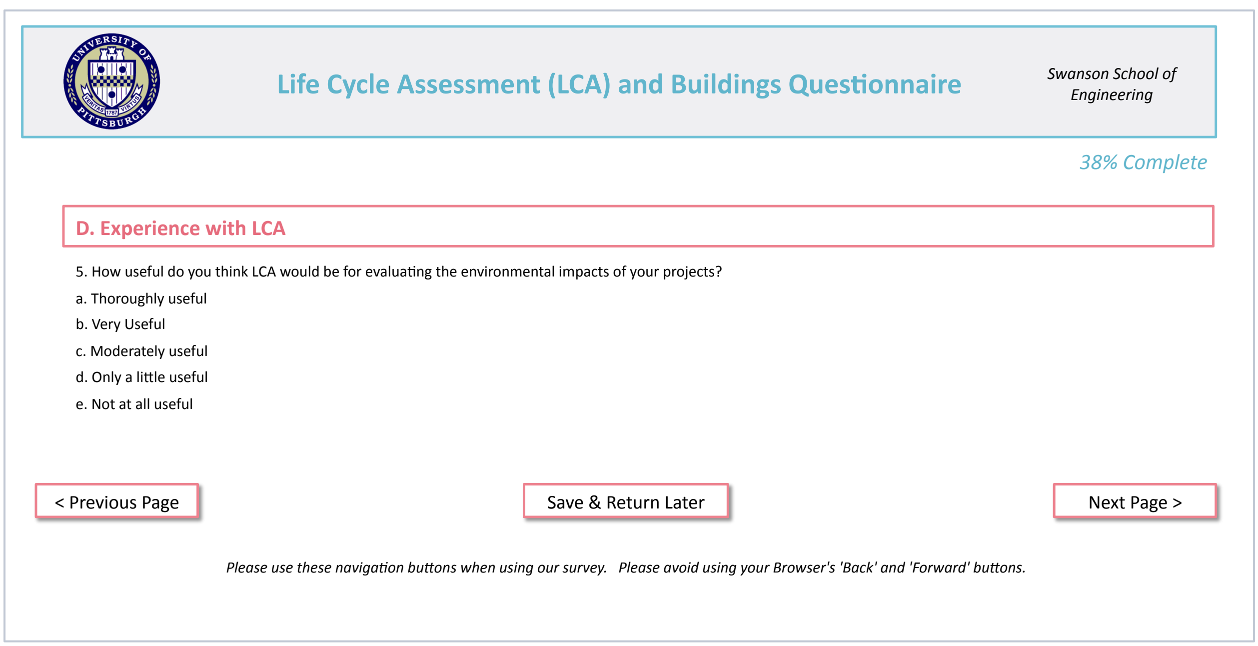
Life Cycle Assessment (LCA) and Buildings Questionnaire
Swanson School of Engineering
38% Complete
D. Experience with LCA
5. How useful do you think LCA would be for evaluating the environmental impacts of your projects?
a. Thoroughly useful
b. Very Useful
c. Moderately useful
d. Only a little useful
e. Not at all useful
< Previous Page
Save & Return Later
Next Page >
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Life Cycle Assessment (LCA) and Buildings Questionnaire

Swanson School of Engineering

42% Complete

E. Benefits and Barriers

1. Rate the following on a scale of 0-4 as an actual and/or perceived benefit to the use of LCA:

Benefits of LCA	**(0) Not a benefit**	**(1) Slight benefit**	**(2) Moderate benefit**	**(3) A great benefit**	**(4) An extreme benefit**	**Do not understand benefit**
Uses a long term holistic perspective						
Provides information about environmental impacts						
Uses a scientific and structured approach						
Informs decision making						
Advances a project's triple bottom line						
Promotes a product for the "green" market						
Compares alternative products						
Follows an ISO standard						

2. What is the most important benefit to LCA?

Long term holistic perspective

Provides information about environmental impacts

Uses a scientific approach

Informs decision making

Advances triple bottom line

Promotes the green market

Compares products

Follows ISO standard

< Previous Page   Save & Return Later   Next Page >

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Life Cycle Assessment (LCA) and Buildings Questionnaire

Swanson School of Engineering

50% Complete

E. Benefits and Barriers

3. Rate the following on a scale of 0-4 as an actual and/or perceived barrier to the use of LCA:

Barriers to LCA	(0) Not a barrier	(1) Slight barrier	(2) Moderate barrier	(3) A great barrier	(4) An extreme barrier	Do not understand barrier
Time it takes to conduct an LCA						
Complexity of an LCA						
Cost of performing an LCA						
Trust in the process of LCA						
Accuracy of LCA results						
Lack of comparability between product LCAs						
Lack of governmental incentives to perform LCAs						
Lack of analysis of indoor environmental quality						
Lack of data to conduct LCAs						
Lack of demand from my clients						

4. What is the most problematic barrier to LCA?

a. Time

b. Complexity

c. Cost

f. Trust

g. Accuracy

h. Lack of comparability

No incentives

k. No indoor environmental quality

l. Lack of data

o. No demand from clients

< Previous Page | Save & Return Later | Next Page >

Life Cycle Assessment (LCA) and Buildings Questionnaire

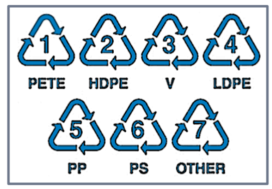
Swanson School of Engineering

65% Complete

F. LCA and Sustainability

1. LCA can be used to successfully calculate the environmental impacts of a whole building from cradle to grave.

Strongly agree
Agree
Disagree
Strongly disagree



2. LCA is a more comprehensive tool for measuring sustainability than other metrics, such as recycled content and indoor air emissions.

Strongly agree
Agree
Disagree
Strongly disagree

G. LCA and Software Tools

1. If you conduct LCAs, which categories do you most often evaluate? [check all that apply]

a. Materials
b. Products (structural only)
c. Products (interior design only)
d. Products (All)
e. Whole Building (Design & Construction Only)
f. Whole Building (Operations & Maintenance Only)
g. Do not use LCA

< Previous Page | Save & Return Later | Next Page >

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Life Cycle Assessment (LCA) and Buildings Questionnaire

Swanson School of Engineering

75% Complete

G. LCA and and Software Tools

2. Which of the following software tools do you use to conduct LCAs? (Check all that apply.)

a. SimaPro

b. BEES

c. Athena

d. GABI

e. EIO-LCA

f. Eco-LCA

g. Autodesk Sustainable Minds

Other, Please Specify:

h. None

3. LCA would be more useful if it were integrated into current software tools.

Strongly agree

Agree

Disagree

Strongly disagree

< Previous Page | Save & Return Later | Next Page >

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Life Cycle Assessment (LCA) and Buildings Questionnaire

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75% Complete

G. LCA and Software Tools

6. Have you utilized building automation systems within your projects?

Yes

No

< Previous Page | Save & Return Later | Next Page >

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Life Cycle Assessment (LCA) and Buildings Questionnaire

Swanson School of Engineering

80% Complete

G. LCA and Software Tools

7. How successful has your building automation systems been for monitoring building metrics?

Very
Moderately
Only a little
Not at all

8. Life cycle assessment would be a beneficial addition to building automation systems in order to monitor the environmental impacts of the building.

Strongly agree
Agree
Disagree
Strongly disagree

< Previous Page | Save & Return Later | Next Page >

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Life Cycle Assessment (LCA) and Buildings Questionnaire

Swanson School of Engineering

82% Complete

H. LCA and LEED

1. How familiar are you with the Leadership in Energy and Environmental Design (LEED) program?

Very
Moderately
Only a little
Not at all

2. The LCA pilot credit is associated with which LEED category?

a. Sustainable sites
b. Water efficiency
c. Energy and atmosphere
d. Material and resources
e. Indoor environmental quality
f. I do not know.

3. LCA should be further incorporated within the LEED program.

Strongly agree
Agree
Disagree
Strongly disagree

4. Have you worked on a LEED registered project that pursued the LCA Pilot Credit?

Yes
No

< Previous Page | Save & Return Later | Next Page >

Please use these navigation buttons when using our survey. Please avoid using your Browser's 'Back' and 'Forward' buttons.

Life Cycle Assessment (LCA) and Buildings Questionnaire

Swanson School of Engineering

92% Complete

H. LCA and LEED

5. The LCA pilot credit improved the evaluation of the sustainability of the project's materials.

Strongly agree

Agree

Disagree

Strongly disagree

6. LCA changed my behavior in regard to sustainable building design.

Strongly agree

Agree

Disagree

Strongly disagree

< Previous Page   Save & Return Later   Next Page >

Please use these navigation buttons when using our survey. Please avoid using your Browser's 'Back' and 'Forward' buttons.

Life Cycle Assessment (LCA) and Buildings Questionnaire

Swanson School of Engineering

100% Complete

Comments

Please provide any additional comments and/or suggestions regarding life cycle assessment (LCA):

< Previous Page   Submit my Responses   Review Survey

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Life Cycle Assessment (LCA) and Buildings Questionnaire

Swanson School of Engineering

Thank you for your assistance.

We would like to extend our sincere appreciation for your time and effort spent completing our questionnaire.

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