Exploring the Environmental Impact of A Residential Life Cycle, Including Retrofits:

Ecological Footprint Application to A Life Cycle Analysis Framework In Ontario

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

The residential sector is recognized as a major energy consumer and thus a significant contributor to climate change. Rather than focus only on current energy consumption and the associated emissions, there is a need to broaden sustainability research to include full life cycle contributions and impacts. This thesis looks at houses from the perspective of the Ecological Footprint (EF), a well-known sustainability indicator. The research objective is to integrate EF and Life Cycle Analysis (LCA) measures to provide an enhanced tool to measure the sustainability implications of residential energy retrofit decisions. Exemplifying single-detached houses of the early 20th century, the century-old REEP House (downtown Kitchener, Canada), together with its high performance energy retrofits, is examined in detail.

This research combines material, energy and carbon emission studies. Its scope covers the life cycle of the house, including the direct and indirect consumption of material and energy, and concomitant carbon emissions during its stages of material extraction, transportation, construction, operation, and demolition.

The results show that the REEP House had a significant embodied impact on the environment when it was built and high operating energy and EF requirements because of the low levels of insulation. Even though the renovations to improve energy efficiency by 80% introduce additional embodied environmental impacts, they are environmentally sound activities because the environmental payback period is less than two years.

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List of Acronyms

BC = biocapacity

BEES = Building for Environmental and Economic Sustainability

BTU = British Thermal Unit

CA = Canada

EE = embedded energy

EF = Ecological Footprint

EPA = Environmental Protection Agency

EQF = Equivalence Factor

EROI = Energy Return on Investment

ERV = Energy Recovery Ventilator

EU = European Union

FAO = Food and Agriculture Organization (of the United Nations)

gha = global hectare

GHG = Greenhouse Gas

GJ = Gigajoule

GPI = Genuine Progress Indicator

GS = Genuine Savings

GSR = Genuine Savings Rate

ha = hectare

HVAC = Heating, Ventilation, and Air Conditioning

ICE = Inventory of Carbon and Energy

IIASA = International Institute for Applied Systems Analysis

ISEW = Index of Sustainable Economic Welfare

ISO = International Organization for Standardization

Kg = kilogram

kW = kilowatt

kWh = kilowatt-hour

L = litre

LCA = Life Cycle Analysis

LCI = Life Cycle Inventory

LCIA = Life Cycle Impact Assessment

LNM = linear meter

MJ = Megajoule

NAHB = National Association of Home Builders

NETS = Numerical Eco-load Total Standardization

NREL = National Renewable Energy Laboratory

NZ = New Zealand

OE = operating energy

REEP = Residential Energy Efficiency Project

RGS = REEP Green Solutions

SRC = steel reinforced concrete

UK = United Kingdom

US = United States

WCED = World Commission on Environment and Development

XPS = Extruded Polystyrene

YF = Yield Factor

Chapter 1 INTRODUCTION

1.1 Sustainability Debate

Although the debate on its definition and scope continues, sustainability is generally seen as a comprehensive concept and our common goal. Humans have been enjoying the bounty of our planet in an unconstrained manner without seriously recognizing the far-reaching implications until a wave of wakeup calls rang in the 1960s and 1970s. These calls resonated with the statements of Malthus, who back in the late 18th century foresaw the limits to growth due to resource scarcity. Exemplifying early awareness of ongoing or potential consequences of the contemporary lifestyle, *Silent Spring* (Carson, 1962) and *Limits to Growth* (Meadows & Meadows, 1972) offered a chilling view of the outcome of human achievements. The 1972 UN Conference on Human Environment in Stockholm opened the door to a new era for humans to pursue sustainability. The key question arose: What is sustainability or sustainable development?

Although *Our Common Future* offered the world-famous definition of sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED 1987), it is still difficult to precisely define sustainability. The above definition is open to interpretation in any given context and discipline. Some define it simply as “not cheating on your kids” (Simon Bell & Morse, 2008). Others describe it as a tripod with environmental, economic and social legs (Elkington, 1998) or the maintenance of three forms of capital (Hart, 1999). Recognizing that sustainability is a broad concept with multiple facets, this thesis focuses on ecological sustainability. Debate over the concept of sustainability and approaches to achieving it has been ongoing. A famous argument pits the Limits to Growth school against technocrat or economist optimists (Mebratu, 1998). The former predicts “a drastic showdown and even collapse” (Bhaskar, 1995) as cited in (Mebratu, 1998) due to resource constraints, while the latter maintains that such constraints can be overcome by market stimulated behaviour at relatively minor cost.

However heated the debate is, constraints are acknowledged; evidence, although contested, has shown that humans are now facing the constraints and thus have reached the turning point where it is urgent to take corrective action to move towards a sustainable future. Finite non-renewable energy is one of the constraints. Peak oil has been predicted (Hubbert, 1956), and so has the peak extraction of other fossil fuel sources such as coal (Milici, 1997) and natural gas (Lam, 1998). Although there is still debate on when such peaks occur, it is commonly agreed that it will happen in the 21st century ((Kerr, 2005; Wood, Long, & Morehouse, 2003), as cited in (Kharecha & Hansen, 2008)). Not only are we depleting traditional energy sources rapidly, but we are running out of easily accessible energy sources. This is measured as a rapidly declining Energy Return on Investment (EROI) with increasing amounts of energy invested to extract each incremental unit of energy.

1.2 Sustainability Measurement

To support improved decision making and action, there is a great need to measure sustainability, not only at the macro-level, but at the micro-level. Knowing where we stand is one of the prerequisites for successful collective efforts toward sustainability. Sustainability measurement reveals how far away we are from sustainability and how much our decisions and resultant behaviours affect our goal of achieving sustainability. Sustainability has been extensively measured at global, national and regional levels in the past decades. Examples of large-scale measurement alternatives include the Index of Sustainable Economic Welfare (ISEW) or Genuine Progress Indicator (GPI), the Ecological Footprint (EF) (which will be defined and discussed in detail in Chapter 2), and Genuine Savings (GS) or Genuine Savings Rates (GSR); each focuses on one of the aforementioned three key aspects of sustainability. Large-scale measurement has been favoured not only because data are easily accessible at higher levels such as global and national, but because it, at a critical turning point, helped us understand the huge cost of our economic prosperity, a cost we once ignored. Now that such a cost has been acknowledged, sustainability measurement at micro levels also becomes important because it helps us understand our impact and make continuous progress, as we can adjust our behaviour with correct information.

Although ecological sustainability measurement at micro levels is not as extensively discussed, some alternative measures have been identified or proposed. The Commission on Sustainability Development (1995) introduced a full list of sustainability indicators such as Emission of Greenhouse Gases and Forest Area as a Percent of Land Area, which also work at micro levels. Food Miles is another example of an indicator that may be able to measure ecological sustainability at micro levels. However, such alternatives usually focus on one specific component (greenhouse gas, ozone depletion, use of fertilizers, etc.) of ecological sustainability and, thus, are unable to reveal an aggregated impact on sustainability. They are also usually unable to reveal the individual component's implications on carrying capacity, which is one of the key issues affecting sustainability.

The debate over EF as a convincing sustainability measuring indicator continues, but for several reasons, it has the potential to work better than other indicators, especially at micro levels. Major critiques of EF suggest that it oversimplifies complicated natural processes (McManus & Haughton, 2006; Roth, Rosenthal, & Burbridge, 2000; van den Bergh & Verbruggen, 1999), lacks data and comparability (Wiedmann, Minx, Barrett, & Wackernagel, 2006) and is unable to incorporate the depletion of some important resources (Yencken & Wilkinson, 2000). However, at micro-levels, the materials in question are either in much smaller quantity or involve a simpler process compared to those of large scale studies, a situation that lessens the inherent weaknesses that may affect results. At the same time, EF maintains its advantage as an effective heuristic and pedagogical tool because it displays the results in spatial units that can easily be understood by policy makers and the public (Holmberg, Lundqvist, Robert, & Wackernagel, 1999), and, in comparison to energy, CO_2, or biodiversity, land is more familiar, acceptable, and motivating to most people (Herendeen, 2000). EF also simplifies calculation because it treats all materials and their parent materials as global average products; thus, it bases the calculation on established global productivity and saves researchers the trouble of going through regional data on production. Other indices potentially suitable for micro-level measurement usually focus on one specific environmental issue (GHG emission, energy consumption, etc.) and thus lack the ability to interpret an overall impact on sustainability. EF, by contrast, is able to aggregate the impact from three major sources (material, energy, CO_2) and interpret an aggregated impact on sustainability within its well-established framework.

1.3 Sustainability Measurement of Houses

Houses are an important and challenging micro-level arena for efforts towards sustainability and have been examined from various perspectives. As a significant consumer of products, the residential sector sits in a crucial node of the energy and material flow circle in our society, and thus impacts the environment heavily. In Canada, the residential sector has been identified as one of the seven most significant GHG emitters. Because a house is a distinct arena where daily decisions are made, it can be seen as a combination of the human mind, resultant behaviour, and resultant impact. A good way to change behaviour is to first change minds; and a good way to do so is to make people aware of their impact. Representing a significant source of impact, house envelopes have been intensively examined from the LCA perspective, as will be reviewed in Chapter 2. Household activities such as transportation and food consumption are also of interest, to some EF studies (Gerbens-Leenes & Nonhebel, 2002; Sanchez-Choliz, Duarte, & Mainar, 2007). If well-informed decisions are made in each household, the aggregate effect on sustainability will be enormous.

However, as they relate to sustainability, do we know much about our houses? People who care for sustainability prefer to live in green houses. There is even an ongoing competition with an expanding list of people who all claim that they live in “the greenest house on the planet” (Deneen, 2011). But what qualifies a house as “the greenest”? Is it great insulation, renewable energy, passive design, or some other green features? Meanwhile, homeowners make tradeoffs on a daily basis, often with unpredictable consequences. For example, at a certain stage, homeowners need to decide whether to upgrade the energy efficiency of their homes. If they do not, they save money initially, but pay high energy bills over many years. If they do, they spend money on renovations, but later pay less for energy. Which is the better choice in terms of sustainability?

Home energy efficiency is part of the answer. Home energy efficiency programs aim at increasing the efficiency with which a house consumes energy and achieving a better rating under a certain rating system. In essence, what is favoured is the reduction in consumption. Although energy efficiency has been promoted as a precursor to energy conservation, which is the rationale of home energy efficiency retrofits, its scope is limited. First, it ignores the role human behaviour plays and the potential rebound effect that can compromise energy conservation efforts. Second, it looks only at the operational phase of a house and leaves out the energy performance in the other stages of the house’s life. Third, its implications on sustainability are not clear.

A life cycle approach offers a more holistic view of houses, although there are still issues. A life cycle analysis (LCA), also known as life cycle assessment, ecobalance, and cradle-to-grave analysis, refers to a technique for analyzing and evaluating the environmental performance of a given product, activity, or service over its whole life cycle, by identifying its absorption of material and energy, and the discharge of gases and wastes (Berlin, 2002). LCA offers a broad scope of the entire life cycle of a given product: extracting and processing raw materials; manufacturing, transportation and distribution; use, reuse, maintenance; recycling, and final disposal (Consoli, 1993).In the building industry, LCA traces raw material appropriation, global warming potential, emissions to air and water, energy consumption, solid waste and other indices of impact throughout all stages of each building component to achieve broader pictures at different levels, e.g., “cradle to site”, “cradle to grave”, and “cradle to cradle”. Using LCA, one can generate a full list of indices as stated above, and this list can be interpreted as either comprehensive and meaningful, or overwhelming.

In doing life cycle research, or more specifically, life cycle impact assessment (LCIA), there are alternatives and various foci. Examples include the weighting scheme from Bell Labs, which relies on the judgment of experts, and Japanese Numerical Eco-load Total Standardization (NETS), which focuses on global warming potential. Both have acknowledged strengths and weaknesses, but share a technically-oriented interpretation of their life cycle inventories, an approach not easily understood by people outside the academic world.

In contrast, EF is a more user-friendly way of interpreting life cycle inventory, although not widely recognized. EF is originally defined as an area-based indicator, “which quantifies the intensity of human resource use and waste discharge activity in a specified area” (Wackernagel & Yount, 1998). By incorporating resource use and waste discharge, EF already embraces the principle of LCA, even though it does not include all possible types of resource (e.g., water) use and waste (e.g., toxins) discharge. At macro levels, for example national levels, a year’s EF of a country can be seen as a variant of a year’s cradle-to-cradle LCA for that country because EF accounts for the hypothesized land areas needed to produce the energy and material flows that enter the country and to absorb the waste that country discharges. Although a house is relatively large and complex because of its comparatively long life and other factors, it is no more than a man-made product. Therefore, the framework of EF-LCA also applies.

1.4 Thesis Outline and Evaluation

The overall research objective of this thesis is to integrate the EF and LCA measures to provide a better tool to measure the sustainability implications of residential energy retrofit decisions. The proposed measures will be used in a case study of a century old house to determine its ability to provide useful information for decision making regarding residential energy retrofit choices.

This thesis examines houses from the EF perspective based on LCA, and compiles databases for use in Kitchener-Waterloo, southern Ontario. It consists of five chapters, starting with an introduction (Chapter 1). Chapter 2 reviews current studies and debates on EF and house LCA in order to provide the bigger picture of the current situation. Major gaps in current studies are identified, and the rationale for choosing EF as a measure of sustainability and complement to LCA is explored. Based on current LCA and EF frameworks and standards, Chapter 3 presents the design of methodology. Chapter 4 examines a century home in downtown Kitchener as a case study to demonstrate how the designed methodology is applied. Chapter 5 presents major conclusions.

This research has a natural connection to geography, which is typically defined as “an integrative discipline that brings together the physical and human dimensions of the world in the study of people, places, and environments”, its subject matter being “Earth’s surface and the processes that shape it, the relationships between people and environments, and the connections between people and places” (Bednarz et al., 1994). LCA is essentially a topic of human-nature relationships since it examines the environmental performance of man-made products. Geographical location is an important factor that determines the environmental performance of a product and differentiates among various LCA databases. It has been pointed out that geographical location is the combination of factors, including energy sources, supply assumptions, product specifications, manufacturing differences and complications in economic activities (Khasreen M.M., 2009). EF as a sustainability indicator is considered to be a geographic concept and is included in *The Oxford Dictionary of Geography* because it measures the impact humans exert on earth and presents its results in a spatial unit.

This research fills a niche in the juncture of LCA and EF, promotes public understanding of complex LCA procedures and results, and hence, facilitates informed decisions and behavioural change. On the side of LCA, as is revealed in Chapter 2, the first issue is that current LCA studies of houses rely heavily on LCA databases and tools without necessarily examining the broad context, which is an important determinant of LCA results. Secondly, LCA studies focus intensively on new buildings or building renovations while ignoring the initial energy embodied in old homes. It is understandable that analyses of renovation alternatives and scenarios are of paramount importance, because they facilitate better informed decision making. However, in the field of energy planning, as in any other field, comprehension of the past is the key to a promising future. In general, the understanding of old buildings, whose LCA-related information is poorly documented, is limited. On the side of EF, although it is well known for large-scale applications (e.g., global, national, etc.) and sometimes extremely small scale ones (e.g., cellphones, computers, etc.), houses have remained untested. The importance of such LCA and EF research has not been realized by many, for multiple reasons. Devised over 50 years ago, LCA has grown into a mature discipline or even an industry. Researchers and developers are concentrating on establishing and enhancing LCA databases and tools with the intention of providing the most informative results, which is laudable because they build the foundation that followers can use. However, so much attention has gone into enhancing technical details that much less is given to philosophical thinking that might find the balance between complexity and acceptability. Unlike basic sciences such as math and geology, LCA aims at facilitating behavioural change, which requires correct information in an easily understandable format. As with other well established disciplines, it is not easy to challenge current LCA systems. As for EF, its success in macro-level application dwarfs its potential in micro-level application. The increased difficulty in sourcing relevant data (especially when it comes to a complex unit such as a house) also impedes such efforts.

The results of this research may benefit many potential stakeholders. Home owners will be able to better understand the output of LCA and the consequences of their decisions concerning sustainability. Designers will know the implications of their designs by having the impact on sustainability demonstrated in a vivid manner. Researchers will have an alternative means to explore the LCA of housing stock and have the ground work for their efforts to measure sustainability and promote behaviour change. Most importantly, EF provides a simple language in which people can communicate, and thus, facilitates collective efforts.

This study inevitably has its limitations: EF is unable to aggregate all of the LCA indices, meaning that some LCA information is missing in this framework. Weaknesses inherited from LCA and EF are also acknowledged. Therefore, future research is still required.

Chapter 2 LITERATURE REVIEW

2.1 Life Cycle Analysis of Houses

2.1.1 Introduction

Home energy rating systems have been widely relied on when it comes to home energy analyses. However, most of those systems only look at the operational phase of houses and therefore are incomplete. In order to achieve better operational energy performance, much carbon- and energy-intensive material or technology will be adopted. Embedded energy and carbon result in upfront costs and associated environmental impacts. The desire for a fairly short payback period and decent savings is frequently framed only in financial terms. In this broader perspective, it is unclear whether or how much an energy efficient home is better than a less efficient one. In order to answer this question, houses need to be examined in a broader scope where LCA is used to recognize the initial energy embedded in the products.

LCA, also known as life cycle assessment, ecobalance, and cradle-to-grave analysis, refers to a technique for analyzing and evaluating the environmental performance of a given product, activity, or service over its whole life cycle, by identifying its absorption of material and energy, and the discharge of gases and wastes (Berlin, 2002). LCA offers a broad scope of the entire life cycle of a given product: extracting and processing raw materials; manufacturing, transportation and distribution; use, reuse, maintenance; recycling and final disposal (Consoli, 1993).

A complete LCA study is composed of four steps (Consoli, 1993; Guinee, Heijungs, Udo de Hacs, & Huppes, 1993b; Guinee, Udo de Haes, & Huppes, 1993a): i) goal definition and scoping (planning phase); ii) inventory analysis, where the material and energy balance of the system is examined (calculating phase); iii) impact assessment, consisting of classification, characterization and valuation, where the potential environmental influences of the system are assessed (evaluating phase); and iv) improvement assessment, where best solutions to reducing the environmental impacts are sought (reacting phase).

2.1.2 Review of Studies

Building construction industry accounts for 40% of the global consumption of materials and a large proportion of the global greenhouse gas emissions. Therefore, buildings, especially residential houses as part of people’s everyday lives are becoming a hot spot for LCA examination.

2.1.2.1 LCA of house assembly and material alternatives

Among the first explorers are Pierquet et al. (1998), who worked on the embodied energy and consequent increase in thermal performance of wall systems and enhanced the previous study by the Stein Partnership in 1981. This study compared 12 wall systems to determine their environmental friendliness by examining embodied energy and thermal performance. It warned that simply judging an alternative by its payback period could be misleading. Thus, long-term performance should be examined. However, this study only calculated total numbers (in Megajoules) of energy consumption; thus, the appropriation of different energy sources (fuels) could not be differentiated.

Windows were first examined by Weir and Muneer (1998) in Norway. They presented details gained during their onsite investigation; however, this study focused exclusively on one type of window (double-glazed) of a given size (1.2m by 1.2m). Ten years later, another study by Salazar and Sowlati (2008) examined windows for the North American residential market. This comprehensive study included major window types popular for home renovation and construction in North America. No single window was found superior in all impact categories, such as respiratory inorganics, terrestrial acidification/nutrification, global warming and nonrenewable energy categories.

As part of an LCA study, Reddy and Jagadish (2003) ascertained the embodied energy of common building materials in the Indian context. Embodied energy was considered as a result of production, transportation and installation of building materials. However, current databases usually have a “cradle-to-gate” scope, meaning that they do not usually include transportation and installation because of the high uncertainty. This study mainly focused on masonry building materials as well as floor and roofing systems, probably because of the construction preference in India. Huberman and Pearlmutter (2008) analyzed the life cycle energy of building materials (mainly masonry materials) in the Negev desert of Israel. Bergman and Bowe (2008) investigated 20 hardwood mills in the Northeast of the US. Although it claims to be an LCA study, its cradle-to-gate scope suggests that it is an embodied impact one. Hammond and Jones’s work (2008) is an introduction and summary of their comprehensive Inventory of Carbon and Energy (ICE) database, which incorporates most building materials in the UK context.

2.1.2.2 LCA of house envelopes

Before LCA became popular, researchers had conducted its precursor, an embodied energy and carbon study. Buchanan and Honey (1994) investigated the amount of energy required for building construction and its consequent carbon emission in New Zealand. They examined the fuel composition of the consumed energy, which is very thorough work, but rarely followed by other researchers. Their research leads to the proposed environmental friendly change from concrete and steel to more wood construction in order to reduce embodied impact. The wood vs. concrete topic raised in their study became interesting to other researchers. For example, Suzuki et al. (1995) and Cole (1999) investigated the same topic in Japan and Canada, respectively; their conclusions remained the same as Buchanan and Honey's.

Around year 2000, researchers started broadening their scope of study and incorporating use and post-use phases of houses. Studies have been conducted in many countries such as the US (Blanchard & Reppe, 1998), Spain and Columbia (Ortiz-Rodriguez, Castells, & Sonnemann, 2010). Contemporary low-energy or net-zero housing has become a popular study object to examine the net effect of energy-saving technologies and materials. Examples include a Swedish case study (Thormark, 2002) and two Italian ones (Aste, Adhikari, & Buzzetti, 2010; Blengini & Di Carlo, 2010).

2.1.2.3 General critiques and research gaps

As a supplement to home energy efficiency rating systems, LCA studies of houses have been extensively conducted to test the net environmental effects or consequences of adopting advanced technologies or materials. However, although LCA has been developed for over 50 years, LCA of houses is still a developing area and has not been fully explored. Based on the above review, some weaknesses and research gaps are identified.

The first issue involves the unit in use. All the studies reviewed use Gigajoule (GJ) or Megajoule (MJ) as a unit to measure energy consumption. It may be conventional, but practically inconvenient, especially for some “end users” because academic expressions may intimidate people outside academy. Given that lay people are in fact the major working force of promoted behaviour change, user-friendly expression works better in motivating them. In this light, KiloWatt-hour is a better choice of unit considering that the power of common domestic electrical appliances (light bulbs, microwave ovens, fridges, etc.) is rated in watts.

The second inconsistency is the conversion into primary energy. In order to compare and aggregate energy consumption at different levels, each portion of energy use needs to be converted into its primary energy to take into account the energy loss during transmission and delivery. However, most studies do not clarify whether such a conversion is done. Early studies such as Pierquet et al.’s (1998) do not even indicate the fuel composition of energy consumption. Many researchers have realized this and started converting their results into primary energy use around year 2010 like Utama and Gheewala (2009) and Gustavsson and Joelsson (2010); however, inconsistency still exists.

As LCA studies usually incorporate different future scenarios based on choices of materials and technologies, they do not, however, take into account maintenance and component replacement, which will happen in the service life of a house. During the usually assumed 50-year life span, a house potentially needs replacement of its components. According to the study by National Association of Home Builders (NAHB) (David Seiders et al., 2007), in 50 years, wooden decks need replacement twice, doors once, engineered lumber once, HVAC system twice or more, some roofing once. If appliances are taken into account, replacement takes place more often and scenario analyses will be more complicated.

The most noticeable weakness concerning LCA studies is that, as pointed out by Bribian et al. (2009), LCA is complex and its results are hard to understand. As indicated in the introduction section, the full list of indices demonstrated in an LCA report can be seen as either comprehensive, or overwhelming, especially for lay people, who need easily understandable information to facilitate their behaviour change. Thus, better interpretation and communication of LCA results is required.

2.2 Ecological Footprint

2.2.1 Introduction

There has been overwhelming consensus that, instead of depleting the globe's natural capital, humans should restrict consumption to be within the Earth's regenerative capacity, a practice generally called ecological sustainability. As people endeavour to move toward this goal, there is a great need to indicate where we are and how far we are from sustainability. This need has encouraged various sustainability indicators to arise, including EF (Wackernagel and Rees, 1996).

EF is known as a vivid and straightforward sustainability indicator, and deals with the issue of the carrying capacity and human impact on nature. It is a measure of human demand on the earth's ecosystems following ecological principles. Based on the key concept of global average productivity, EF tracks all traceable consumptions of goods and services and translates them into the area of land needed to produce these items and assimilate the associated waste. A comparison between carrying capacity and the ecological footprint indicates whether a community or a population is living sustainably within the jurisdiction's capacity.

Since its successful introduction by Rees and Wackernagel in the early 1990s, EF has been well accepted, extensively applied and deeply explored. This section summarizes and evaluates EF studies, identifies critical issues, gaps and limitations concerning the concept, methodology and application.

2.2.2 Review of EF application

2.2.2.1 Tempo-spatial studies

The initially proposed and most popular application of EF involves a given community or population. After the originators had successfully taken snapshots of the globe as well as of 52 major countries using the EF camera (Wackernagel et al., 1999), a large number of scholars followed their lead. To date, detailed profiles have been produced showing lifestyles and their concomitant appropriation of natural capital at various levels.

Regional studies, such as the EF of the Baltic Sea region (Folke, Jansson, Larsson, & Costanza, 1997; Jansson, Folke, Rockstrom, & Gordon, 1999) and of North America (Senbel, McDaniels, & Dowlatabadi, 2003) have been conducted to fill the niche between global and national application. In contrast to the investigation of different nations in a given year, incremental interest has been witnessed in time series of nations, among which are Japan 1961-1995 (P. Parker, 1998), Austria 1926-1995 (Haberl, Erb, & Krausmann, 2001), and Ireland 1983-2001 (Lammers, Moles, Walsh, & Huijbregts, 2008). Extending national studies are cross-national comparisons revealing major determinants of EF, such as world-system position, the level of urbanization, and literacy rates (Jorgenson, 2003). Numerous sub-national studies, such as the one on the province of Siena in Italy (Bagliani, Galli, Niccolucci, & Marchettini, 2008), have been carried out to facilitate provincial and municipal planning. Even smaller-scale studies can be seen at the campus (Li et al., 2008), port (Carrera-Gomez et al., 2006) or household (Sanchez-Choliz, et al., 2007) levels.

2.2.2.2 Man-made products or natural resources

It is intriguing to find out what is embedded in an item, whether it is a man-made product or a natural one. This idea embraces the LCA framework, and is being acted on by many researchers using tools such as life cycle assessment.

Among typical manufactured goods are electronic products, which have been widely evaluated using LCA examining toxicity, end-of-life management and energy use (Frey, Harrison, & Billett, 2006). However, the great opportunity of combining electronic products with sustainability is often neglected. A rare study in this area by Frey and his colleagues (2006) assessed one of the most popular electronic products, mobile phones, using the EF approach based on LCA frameworks. All materials and energy consumed during the life cycle of a mobile phone were tracked and translated into corresponding land areas. An even greater breakthrough occurred when Huijbregts et al. (2008) claimed to have calculated product-specific EFs from consistent and quality-controlled life cycle information of 2630 products and services consumed in the western economy, including energy, materials, transport, waste treatment, and infrastructural processes. However, in their study, Europe average and Switzerland accounted for over 70% of the locations where the data were sourced. As stated above, LCA is time and space sensitive (locality is more important in this case), the results from that study can be adopted only when a similar production process is assumed, or when local data are taken into account.

Exemplifying the EF of natural resources, water footprints have long been excluded from EF calculations, although freshwater is an essential natural resource, especially in arid areas. It has been admitted that it would methodologically complement the assessment if the ecological spaces for freshwater use were included (Wackernagel, et al., 1999). Although pioneers did not determine the footprint areas for water supplies, they did contribute by offering methods and results of human dependence on freshwater for ecosystem services in terms of amount (Geber & Bjorklund, 2001; Jansson, et al., 1999). A substantial effort was made when Jenerette and Larsen (2006) computed urban water footprint areas with data analyzed within a geographic information system to calculate every large city across the world with a population over 750,000. This undertaking achieved comprehensive results by incorporating GIS methods and comparing the water footprints of 524 large cities. However, water remains inconsistently included in EF studies.

2.2.2.3 Human activities

Human activities are the subject of EF studies through the measurement of various types of consumption of goods and services. Tourism has been chosen for many case studies (V. Cole & Sinclair, 2002; Gossling, Hansson, Horstmeier, & Saggel, 2002; Nepal, 2008; Patterson, Niccolucci, & Marchettini, 2008). EF is used as an assessment tool for tourism sustainability and planning. The EF due to energy consumption during tourist trips is revealed as the largest component in the total tourism EF (Patterson, Niccolucci, & Bastianoni, 2007).

Transport (especially by vehicles) is another typical human activity. The calculation of transport EF consists of three major parts: land use of roads, energy consumption of vehicles, and greenhouse gas (mainly CO_2) sequestration. EF is proposed as a tool for transport planning (Carrera-Gomez, et al., 2006; Chi & Stone, 2005) and revealing the relationship between urban form and transport (Muniz & Galindo, 2005).

Food consumption is also investigated, especially the comparison of meat-intensive and other diet patterns (e.g., wheat-intensive) in terms of environmental impact (Gerbens-Leenes & Nonhebel, 2002; White, 2000). It is revealed that changes in consumer behaviour at the domestic level are a powerful way to curtail the appropriation of natural resources such as agricultural land.

Other studies on the EF of human activities include a soccer game exemplifying major sporting events (Collins, Flynn, Munday, & Roberts, 2007) and aquaculture (Chopin et al., 2001; Ferng, 2007; Folke, Kautsky, Berg, Jansson, & Troell, 1998; Kautsky, Berg, Folke, Larsson, & Troell, 1997; Roggenbauer, 2005; Ronnback, Troell, Zetterstrom, & Babu, 2003).

2.2.2.4 Energy-oriented application

In this review, the buzzword “carbon footprint,” commonly regarded as a subset of EF, is excluded as it only describes the amount or equivalent of CO_2 emitted or embodied in weight-based units like tons or kilograms rather than area-based units. Since calculation of the carbon footprint is based on LCA and rarely related to the EF framework, it would be more appropriate and less confusing for it to be referred to as “carbon weight” or a similar term (G. Hammond, 2007).

In practical terms, most applications of EF have incorporated energy-related studies because the EF derived from energy use dominates in many cases. Energy-oriented applications designed to address such issues as energy planning, energy efficiency, and global climate change, still need further attention.

In terms of energy planning, Ferng (2002) and Stoglehner (2003) proposed EF as a tool for assessing sustainable energy supplies using modified calculation methods, and offered preliminary frameworks. Browne et al. (2009) demonstrated EF’s ability to facilitate energy policy making by comparing the EFs of six scenarios for domestic energy and electricity consumption in Ireland.

A rare study directly touching climate change is from Santamouris et al. (2007), who calculated the EF of the urban heat island effect in Athens. The study provides an innovative application of EF to a human-induced climatic phenomenon.

Another significant effort involves assessment of energy materials or products. De Oliveira et al. (2005) started with an examination of ethanol produced from sugarcane (Brazil) and corn (U.S.), although their approach, which was to determine the ecological footprint by measuring the forest area for CO_2 sequestration, was challenged (Azar, Berndes, Hansson, & Grahn, 2006). Holden and Hoyer (2005) went even further by ascertaining the EFs of several alternative fuels based on LCA studies, revealing that none of the contemporary alternative fuels was perfect in terms of the EF, renewability, and global abundance. Therefore, new means of transportation and reduction of transport were suggested, which showed the ability of EF to measure the benefits of behaviour change and to support policy making in this area. In a similar study, Stoeglehner et al. (2009) concluded that, although biofuels were considerably more sustainable than fossil options from an EF perspective, the sustainability of biofuel use was in doubt, and this question could only be answered in a regional context considering other land use demands, visions, and values.

2.2.3 **Evaluation of index and identification of research gaps**

Since the EF index was created, researchers have continuously evaluated it. Some like it while others do not, and the dispute has become heated since a commentary forum on EF was held in 2000 by the journal of *Ecological Economics*.

During its early years, even supporters of EF admitted that it was “strange” that EF had incurred so little academic criticism (Ferguson, 1999). As EF application thrives, more weaknesses have been revealed. Table 2-1 briefly reviews and evaluates the major criticisms. As can be seen, most critiques involve the core idea of EF, *simplification*. Some criticize the assumptions made to simplify our complicated world, some are unhappy with the aggregation and weighting methodologies, some question the conclusions drawn from the simplification, and some doubt the value of the simplification. These criticisms have been a great impetus for EF researchers to enhance this tool. For instance, the awareness of EF’s lack of data on indirect impacts has led to the incorporation of input-output analysis.

Table 2-1 Major criticisms of EF

Criticism	Category	Comment
EF does not indicate if land use practices are sustainable and ignores possible multiple services or functions of land use (McManus & Haughton, 2006; van den Bergh & Verbruggen, 1999).	Assumption	This weakness of EF indicates a new area for exploration – the third dimension, i.e., the 'depth' of the ecological footprint. This new dimension could be the level of the sustainability of land use.
The land appropriated by fossil energy use is only considered as that used for assimilation of CO_2 emissions from burning fossil fuels, i.e., 'carbon sink' land (van den Bergh & Verbruggen, 1999).	Assumption	A reasonable critique. Technically, energy footprints should comprise the land for both energy production and carbon sink. However, since the intention is to underestimate the impact, this criticized assumption errs on the cautious side.
Water footprints are only partially incorporated in calculations (Yencken & Wilkinson, 2000).	Methodology	This reveals a big problem. As an important natural resource, water consumption should be incorporated.
This linear, two-dimensional, area-related model is too simplified to incorporate earlier scientific findings on multi-dimensional interactions and ecosystem functions (Roth, et al., 2000).	Methodology	EF is a science-based indicator, and it is open to the incorporation of more scientific findings, such as emergy studies. Also, simplicity is a part of the vitality of an indicator.
It lacks data and comparability (Wiedmann, et al., 2006).	Methodology	This is why EF standards are released and standard data sourcing and processing schedules are introduced.
EF has an anti-trade inference (McManus & Haughton, 2006; van den Bergh & Verbruggen, 1999).	Conclusion	EF does not oppose trade, but favours ecologically balanced trade.
EF exaggerates human impacts on nature (van den Bergh & Verbruggen, 1999).	Conclusion	This assertion is counter to the method's design to underestimate human impacts so as to appear less painful and more acceptable to the public.
Although EF has some value to indicate global unsustainability, it is too aggregated to qualify for policy	Value	The aggregation used in EF makes it useful for policy purposes because it is simple so that both politicians and the

purposes at the national level (Ayres, 2000; van den Bergh & Verbruggen, 1999).		general public can understand it and communicate it.
Its incorrect use and the inherent problems in its application to such activities as aquaculture can ‘mislead rather than inform policy makers, planners, managers and the general public’ (Roth, et al., 2000).	Value	It is a tool, thus, it is important to use it correctly.

However, these concerns and critiques do not prevent most people from also recognizing the advantages of EF. EF is regarded as one of the best heuristic and pedagogical tools as it displays the results in spatial units that can easily be understood and accepted by policy makers and the public (Holmberg, et al., 1999), and, in comparison to measures of energy, CO_2, or biodiversity, land is more familiar, acceptable, and motivating to most people (Herendeen, 2000). Despite certain weaknesses and flaws in the details, EF’s ability to aggregate the consumption of natural resources is highly appreciated (Holden & Hoyer, 2005).

In the above review of EF applications, it is seen that the index has been applied to test many aspects of human lives at various levels. Any material appropriation, fuel consumption or carbon emission will result in an impact measurable under the EF framework. Any product or human activity can be broken down into the above three categories and then measured. Man-made products are of increasing interest, and EF (as an effective way of interpreting LCA results) has gained increased recognition. However, only small products such as computers and cell phones have been examined. Houses, which are much bigger and more complicated, remain untested. The studies on products based on the LCA framework are geographically limited to the continent of Europe, where LCA features of a product may differ significantly from Canada. Thus, Canadian factors must be taken into account when one reproduces such a study.

2.3 Conclusion

LCA and EF have been developing separately for decades and received worldwide acceptance. However, efforts to combine their strengths by interpreting LCA results using EF have been rarely attempted. Such studies on small products have been conducted, but houses as larger, more complicated products, remain untested. This thesis attempts to address this research gap and extend the EF-LCA methodology. The methods chosen are presented in the next chapter.

Chapter 3 METHODOLOGY

3.1 Introduction

In order to achieve the research objective of developing a better tool to measure the sustainability implications of residential energy retrofit decisions, this thesis has reviewed the literature on LCA and EF. In the published research, efforts to combine their strengths by interpreting LCA results using EF have been rarely attempted, and this project meant to work on this research and knowledge gap. This project will extend the EF and LCA literatures by using EF methods to translate LCA insights into a standard measure that can be used to communicate results regarding the ecological impacts of energy choices. The methods used to calculate the EF results are explained in this chapter.

3.2 Ecological Footprint

Humans interact with the earth. One example is having a square meal; another is taking a warm shower. Which imposes a larger impact on our environment? Our planet witnesses such human behaviours every second; some of them can be much more complicated. EF is a way of simplifying the complicated interaction by aggregating and comparing various goods and services provided by nature in order to find out the status of the “supply-demand” chain between nature and humans.

The Ecological Footprint tracks all traceable consumptions of goods and services and translates them into the area of land needed to produce these items and assimilate the associated waste. According to Ewing, et al. (2008, p. 4), Ecological Footprint accounting is based on six fundamental assumptions:

1) The majority of the resources people consume and the wastes they generate can be tracked.
2) Most of these resource and waste flows can be measured in terms of the biologically productive area necessary to maintain flows. Resource and waste flows that cannot be measured are excluded from the assessment, leading to a systematic underestimate of humanity's true Ecological Footprint.
3) By weighting each area in proportion to its bioproductivity, different types of areas can be converted into the common unit of global hectares, hectares with world average bioproductivity.
4) Because a single global hectare represents a single use, and all global hectares in any single year represent the same amount of bioproductivity, they can be added up to obtain an aggregate indicator of Ecological Footprint or biocapacity.
5) Human demand, expressed as the Ecological Footprint, can be directly compared to nature's supply, biocapacity, when both are expressed in global hectares.
6) Area demanded can exceed area supplied if demand on an ecosystem exceeds that ecosystem's regenerative capacity (e.g., humans can temporarily demand more biocapacity from forests, or fisheries, than those ecosystems have available). This situation, where Ecological Footprint exceeds available biocapacity, is known as overshoot.

Based on these assumptions, the Ecological Footprint (EF) of a country, in global hectares, is given by

$$\mathrm{EF} = \frac{\mathrm{P}}{\mathrm{Y_N}} \cdot \mathrm{YF} \cdot \mathrm{EQF}$$

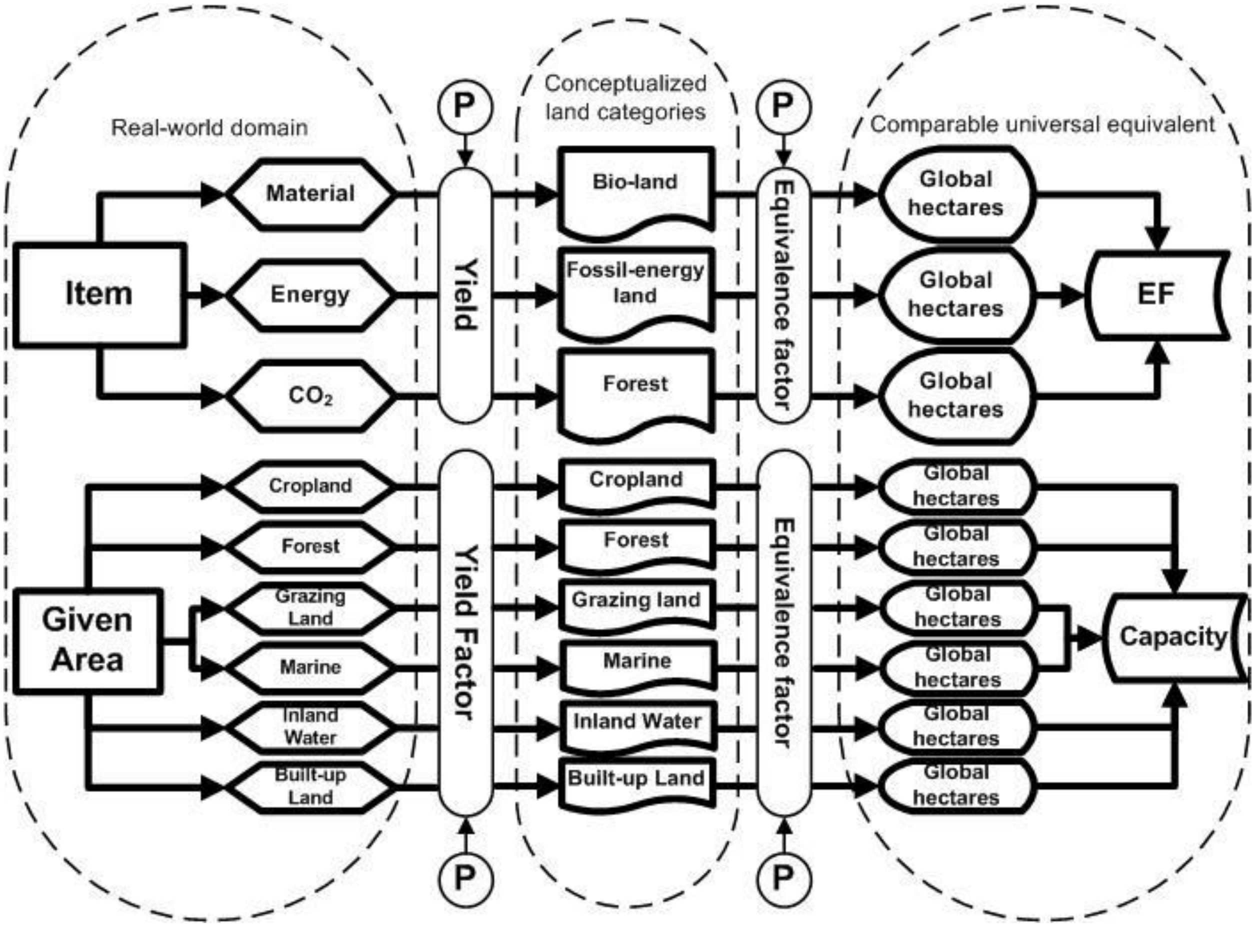
where P is the amount of a product harvested or waste emitted, Y_N is the national average yield for P, and YF and EQF are the yield factor and equivalence factor, respectively, for the land use type in question.

A country's biocapacity (BC) for any land use type, also in global hectares, is calculated by

$$\mathrm{BC} = \mathrm{A} \cdot \mathrm{YF} \cdot \mathrm{EQF}$$

where A is the area available for a given land use type (Ewing, et al., 2008, p. 5).

The strategy stated above is a "top-down" one, since it is easier to access data at higher levels when it comes to large scale (e.g., national) footprint calculation. On the other hand, the "bottom-up" strategy works better for cases on smaller scales, making it an appropriate strategy for the study of this thesis. Figure 3-1 illustrates the conceptual framework of such a "bottom-up" strategy. As can be seen, two parallel flows go through two major converters controlled by productivity; then EF and biocapacity are calculated separately and ready for comparison.



P=productivity

Figure 3-1“Bottom-up” EF calculation procedure

Global average productivity and global hectares

EF is designed to examine the ecological world. The way it works can easily be understood by comparing it to the well-known framework Karl Marx designed to examine the economic world. In the economic world, goods and services are measured and compared by the embedded homogeneous human labour, which eventually appears in the form of currency. Thus, any goods or services are seemingly measured by money, which is addressed as a universal equivalent, but practically by homogeneous human labour.

Such coupled concepts exist in the ecological world and form the essence of EF. In this world, global hectares work as a universal equivalent representing homogeneous global average productivity. As can be seen in Figure 3-1, the flow shows the key idea of EF, which is turning the real world items into comparable global hectares. It cannot be done without productivity as a connector between major domains.

In the early years of practice, people regarded real area units, e.g., hectare (ha) and m2, as units of the EF. This is obviously caused by misunderstanding the EF area as a real-world area rather than a virtual one. Worse even, this misunderstanding has led to direct comparisons between areas of regions and those of their EFs, as seen often in papers prior to 2003 (Folke, et al., 1997; Kautsky, et al., 1997). Actually, the originators of EF are partially at fault because they started the aforementioned direct comparisons in their earlier publications (Rees, 1996). In the table of the EFs of nations (Wackernagel, et al., 1999), ha/cap was used as a unit of the ecological footprint, though the authors did claim “expressed in area with world average yield” (p. 386) right following it highlighting the difference, global average biological productivity. Although, in this very paper, “biological productive areas with world average productivity” (p. 380) were claimed as a common measurement unit for footprints and ecological capacity, some calculations did not work in this way. Such contradictions could easily confuse followers.

In the following years, standardized hectares, called global hectares (gha), were developed as an appropriate unit for footprints to underscore the underlying productivity assumption. In recent studies, gha, instead of ha, has been officially confirmed as an appropriate unit of both EF and biocapacity; thus gha/ha has been assigned as a unit for the equivalence factor rather than ignoring the conversion issue as in early studies (Wackernagel et al., 2002).

Land categories

Also shown in Figure 3-1, the Ecological Footprint and biocapacity accounts are comprised of six land use types: cropland, grazing land, forest land, fishing grounds, carbon uptake land (fossil energy land), and built-up land (Ewing, et al., 2008; Ewing et al., 2009).

1) *Cropland*

Cropland is the most bioproductive type of land use and consists of areas used to produce food and fiber for human consumption, feed for livestock, oil crops, and rubber. As of the year 2006, 1.6 billion hectares were designated as cropland worldwide (FAO ResourceSTAT Statistical Database 2007).

2) Grazing land

Humans use grazing land to raise livestock for meat, dairy, hide, and wool products. In 2006, 3.4 billion hectares of land were classified as grazing land globally.

3) Forest land

Forest land provides lumber, pulp, timber products and fuelwood. The total area of world forests is estimated at 3.9 billion hectares (FAO ResourceSTAT Statistical Database 2007).

4) Fishing grounds

Fishing grounds produce fish and other aquatic species as alternative food sources. Globally, there were 2.4 billion hectares of continental shelf and 433 million hectares of inland water areas in 2006 (World Resources Institute and FAO ResourceSTAT Statistical Database 2007).

5) Carbon uptake land

Carbon uptake land does not exist in the real world. Carbon footprint is calculated as the amount of forest land required to absorb given carbon emissions.

6) Built-up land

The built-up land is the area of land covered by human infrastructure — transportation, housing, industrial structures, and reservoirs for hydropower. Built-up land covered 167 million hectares globally in 2006, as per satellite imaging and research data sets (FAO 2005 and IIASA Global Agro- Ecological Zones 2000). Built-up land presumably occupies what would previously have been cropland.

Each of these land use types is assigned a corresponding biocapacity except carbon uptake land, which is made up and does not exist in the real world. In 2005, the area of biologically productive land and water on Earth was approximately 13.4 billion hectares. All land use categories are summarized in Table 3-1.

Table 3-1 Land use types and equivalence factors

(source: Ewing et at. (2008))

Category	Area per capita (ha)	Weight (%)	Equivalence factor (gha/ha)
Fossil energy	0	0	1.1
Built-up area	0.03	1.8	2.21
Arable land	0.24	13.2	2.21
Forest	0.62	34.2	1.34
Pasture	0.56	30.7	0.49
Sea	0.37	20.2	0.36

Conversion factors

The essence of EF is “conversion”: the conversion of consumptions (Kg, L, etc.) into real land areas (hectares) and then into standardized virtual ones (global hectares). Therefore, designated conversion factors are of paramount importance to the calculation. The EF framework involves three types of conversion factors, shown in Table 3-2. These factors help to compare different consumptions on the basis of “world average productivity”. This approach makes much sense, but is also seen as arbitrary.

Table 3-2 Brief comparison of conversion factors

Conversion factor	Unit	Description
Yield	Kg/ha, GJ/ha, etc.	The world average output of a land type pertinent to each product. For example, the yield of beef out of pasture is 33 kg/ha, meaning that globally one hectare of pasture produces 33kg of beef on average.
Equivalence	gha/ha	The ratio of the global average productivity of a certain land type to the

factor		global average productivity of all land types as a whole. For example, the equivalence factor of arable land is 2.8, meaning that the productivity of arable land is 2.8 times that of the global average.
Yield factor	--	The ratio of the productivity of a certain land type in the surveyed region to the global average productivity of the same land type. For example, if the yield factor of the arable land in Region A is 2, then the arable land in Region A is twice as productive as the global arable land average.

Interpretation of results: eco-balance

With the classification of land types, it is feasible to calculate the land areas of certain categories needed to produce anything people consume, given its global average productivity. An examination of all our consumptions will culminate in a table showing our appropriated land areas for all six land types respectively. After standardizing the areas of each category by its specific productivity against global average productivity, we can add them together to arrive at the value of our ecological footprint.

The same procedure of standardization and aggregation is also applied to the real land and water areas the earth offers. The result of this aggregation is so-called biocapacity. A comparison of demand (EF) and supply (biocapacity) will inform us of the current situation: an ecological deficit – EF larger than biocapacity – indicates a current unsustainable developing mode, whereas either an ecological surplus – EF smaller than biocapacity – or an ecological equilibrium depicts ecological sustainability. The world biocapacity per capita is also labeled the ‘global ecological benchmark’, which represents the critical boundary within which humanity should live. Consequently, the EF has conveyed the notion of ‘living off the interest’, which is a key to sustainability and an approach to inter- and intra-generational equity.

Coefficients to measure the ecological footprint are primarily taken from the latest versions (2006 data) of the National Footprint Accounts Methodology (Ewing, et al., 2008) and Ecological Footprint Atlas (Ewing, et al., 2009), as these public sources have been widely reviewed. The global average annual CO_2 sequestration rate of forests, 3.66 tons per hectare, is an example of an important coefficient that influences the final EF calculation (Coto-Millán, Quesada, & Mantecón, 2008). The coefficients used in this study and their sources can be found in the appendices.

3.3 LCA

Life cycle analysis (LCA, also known as life cycle assessment, ecobalance, and cradle-to-grave analysis) refers to a technique for analyzing and evaluating the environmental performance of a given product, activity, or service over its whole life cycle, by identifying its absorption of material and energy, and the discharge of gases and wastes (Berlin, 2002). LCA offers a broad scope of the entire life cycle of the given product: extracting and processing raw materials; manufacturing, transportation and distribution; use, reuse, maintenance; recycling and final disposal (Consoli, 1993).

As per International Organization for Standardization’s (ISO) 14040 series, a complete LCA study is composed of four steps (Consoli, 1993; Guinee, et al., 1993b; Guinee, et al., 1993a; International Organization for Standardization (ISO), 2006): i) goal definition and scoping (planning phase); ii) inventory analysis, where the material and energy balance of the system is examined (calculating phase); iii) impact assessment, consisting of classification, characterization and valuation, where the potential environmental influences of the system are assessed (evaluating phase); and iv) improvement assessment, where best solutions to reducing the environmental impacts are sought (reacting phase).

3.3.1 Life Cycle Inventory (LCI) and databases

Life Cycle Inventory (LCI) is the precursor to LCA. An inventory of flows from and to nature for a product system is created to account for elements that pose impacts on the environment. Inventory flows usually count in water, energy, and raw materials, and releases to air, land, and water. However, in this study, only those relevant to EF are taken into account, including raw materials, energy and carbon emission.

A flow chart of the examined system and its boundary is created in order to develop the inventory (shown in Figure 3-2). All activities within the system boundary need to be considered in the final calculation. The first step is to calculate the energy consumption and carbon emission embedded in the pre-use phase. In order to select appropriate embodied energy and carbon coefficients, life cycle information is sourced from several databases (shown in Table 3-3) based on two criteria. Authority is the first criterion, meaning that databases that are well established and updated regularly are preferred. Locality is the second criterion, meaning that Canadian databases are favoured, followed by US sources, and then those from EU and other countries (e.g., New Zealand). Among the databases, ATHENA is based on the Canadian context, has reliable survey procedures and, thus, is the preferred source used in this study.

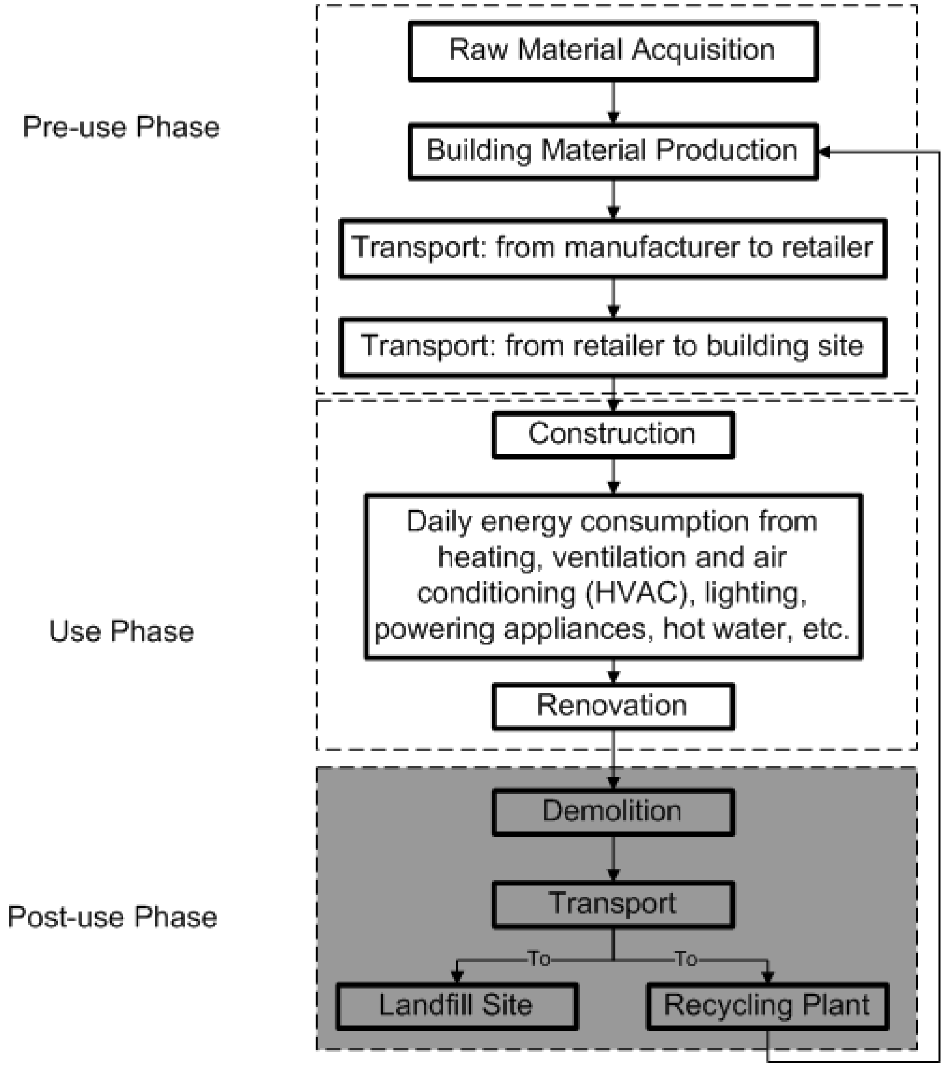


Figure 3-2 System boundaries for life cycle analysis of houses

Table 3-3 Data sources concerning embodied energy and carbon

Source	Category	Location	Availability
ATHENA Impact Estimator for Buildings	Software	CA	Licence fee
Canadian Architect	Website	CA	Free
Canadian Raw Materials Database	Database	CA	Free
Building for Environmental and Economic Sustainability (BEES)	Software	US	Free
National Renewable Energy Laboratory (NREL)	Database	US	Free
Ecoinvent	Database	International	Licence fee
Inventory of Carbon & Energy (ICE)	Database	UK	Free
Centre for Building Performance Research	Website	NZ	Free

As stated, key LCA information of materials is primarily extracted and compiled from ATHENA reports. The energy and carbon coefficients need adjustment to account for the estimated difference in manufacturing, transportation and energy profile between the present and a century ago, and also between Ontario, Canada, and other countries.

3.3.2 Data adjustment according to case study

In order to properly use coefficients drawn from databases, one needs to be aware of the tempo-spatial implications of the databases. The first implication is the scope of research. Various databases may differ in life stages included. For instance, the scope can be “cradle-to-grave”, “cradle-to-gate” or “cradle-to-cradle”. Each is associated with a different level of embodied impact and, ideally, detailed documentation of energy flows and emissions. The second implication is a gradual improvement in manufacturing technology and energy efficiency. As a result, any major difference in manufacturing procedures or fuel types and efficiency needs to be watched. The third implication is also such a difference, but in various regions of the world.

The project case study, the REEP House for Sustainable Living is located in downtown Kitchener, Ontario. It is owned by the Regional Municipality of Waterloo and since 2007 has been leased to REEP Green Solutions (RGS), the local green community not-for-profit that operates the Residential Energy Efficiency Project (REEP) to deliver standardised home energy audits in the region. The REEP House is a two-storey single-detached brick house of 140 m^2 built in 1910, and is among the 43,000 pre-1960 homes in Waterloo Region.

Given that low-grade energy such as human or other animal labour was still very common a century ago in Canada, the energy and carbon intensity in material extraction, manufacturing and transportation processes was considerably lower than today when machine work and high-grade energy (e.g., electricity) dominate. However, the difference does not affect the results very much. For example, in this case study, the most significant source of embodied energy and carbon comes from bricks, and the basic procedure of brick making has remained unchanged for centuries (The ATHENA Sustainable Materials Institute, 1994-2005). Compared to manufacturing, the energy for clay extraction and transportation is minor (less than 1% of total) nowadays, which makes no noticeable difference when the coefficient is adjusted to suit 1910 patterns. Considering the present energy profile in Ontario, some local coefficients may be significantly different from those of other regions. For example, coal accounts for only a relatively minor part (18%) of the electricity supply mix in Ontario (Ontario Ministry of Energy, 2007), which leads to a smaller transformation loss and carbon intensity per unit energy output compared to where coal-fired power plants are more prevalent.

Given that domestic electrical appliances are rated in kilowatts (kW) or kilowatt hours (kWh), energy is measured in kWh instead of Gigajoules (GJ) or Megajoules (MJ) to promote a better understanding among different user groups.

3.3.3 Gate-to-site transportation

LCA results are based on a cradle-to-gate scope, meaning that they cover only the phase from when raw materials are extracted to when the final products are ready to leave the manufacturer. Thus, it is necessary to examine gate-to-site transportation in order to determine the concomitant energy consumption (and other environmental impacts), which is calculated by multiplying the distance travelled, the energy intensity of the transportation mode, and the quantity of the product.

In the case study, the original building material was most likely transported in modes with low energy consumption and low GHG emission (sailing barges, horses, etc.) and thus excluded from the calculation. It might be argued that the energy embedded in the food that humans, horses or other animals consumed during the transportation should be taken into account. However, given that food is essential for living bodies, it is not seen as an extra contribution to embodied energy. In other words, one has to eat every day, no matter whether he (or it) works or not. As a result, the exclusion does not noticeably affect the results. On the other hand, building material for recent renovations was transported in energy-intense modes and thus has to be considered.

3.3.4 Sources of information on building materials

The detailed information on the building materials of the REEP House and its renovations was sourced via REEP, including Ben Barclay, Paul Parker and Shane O’Neill who were key members of the REEP House project. Such information includes types, quantity, and sources of building material. Two interviews were arranged at Hanson Brick in Burlington in 2011 and at Inline Fiberglass in Toronto in 2010 with engineers to determine the embodied energy intensity of their products as a complement to the above mentioned LCA databases.

3.3.5 Simulation with HOT 2000

The use phase impact is determined using the program HOT 2000, home energy evaluation software developed by Natural Resources Canada. The following elements are major inputs: 1) the home's dimensions; 2) the energy performance characteristics of key components, such as windows, wall assemblies, roof type and attic insulation; 3) specifications on the heating, cooling and ventilation system types and efficiencies; and 4) the home's location and site orientation. Based on these pieces of information, it generates the annual energy consumption and carbon emission of a given family size residing in that home.

This program also helps identify energy savings and emission reduction achieved by home renovation. In this way, retrofit scenarios can be compared in terms of energy savings, emission reduction and embodied energy investment.

3.3.6 Post-use estimation

The post-use phase includes material recycling and the energy consumed during demolition. However, because it will happen in the distant future (a 50-year span is assumed), significant uncertainties concerning demolition and recycling technology emerge, which is why it is the “grey area” in Figure 3-2. Since there is no appropriate estimate of the demolition in the future, energy input is the only element taken into account using the calculator developed by the May T. Watts Appreciation Society , which is based on the 2007 Building Energy Data Book produced by the US Department of Energy.

3.4 Conclusion

This chapter has proposed LCA as the method of accounting for impacts of house envelopes, and EF as the method of interpreting these impacts. The bottom-up strategy is chosen for EF calculations, as it suits studies on smaller scales better. Databases such as ATHENA are relied on for LCA information of building materials. Coefficients sourced from LCA databases usually need adjustment based on the comprehension of the level of difference between a database reference scenario and a specific case. HOT 2000 and a demolition calculator are used to estimate the energy consumption along with carbon emission in the operational phase and post-use phase, respectively. In the next chapter, the proposed methods will be applied to the aforementioned case study, the REEP House in downtown Kitchener, Ontario.

Chapter 4 CASE STUDY[1]

4.1 Introduction

4.1.1 Background: some questions

Under the Kyoto Protocol, Canada aimed to reduce its greenhouse gas (GHG) emissions to 6% below 1990 levels by 2012. However, 2007 emissions were 20% above 1990 levels (Environment Canada, 2008), and the federal government declared the target to be unachievable. Thus, greater improvement is urgently needed. In Canada, the residential sector has been identified as one of the seven most significant GHG emitters and thus a substantial contributor to climate change. Following the introduction of the national home energy rating system (EnerGuide for Houses) developed by the federal government of Canada, many partners and delivery agents have worked to improve the efficiency with which households consume energy to meet their space and water heating needs (operational energy efficiency). However, energy consumption, as well as carbon emissions, needs to be considered over the lifespan of a house, which is the scope of LCA. In addition to operational energy, which is usually measured by home energy efficiency programs, embodied energy, which is embedded in building materials and construction procedures (often ignored), and the energy needed for demolition and recycling should be taken into account. Associated questions arise: How much energy is embodied in the building materials of a house? In order to

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[1] This chapter comprises a journal article that has been accepted for publication in the journal Applied Energy. G. Bin and P. Parker (in press), Measuring buildings for sustainability: Comparing the initial and retrofit ecological footprint of a century home - the REEP House, *Applied Energy.* Guoshu Bin is the primary author of the paper.

increase the energy efficiency of a house, how much embodied energy has to be invested upfront? Are home renovations worth the effort in terms of energy savings and broader environmental impacts?

4.1.2 Relevant studies and research gaps

Researchers have intensively investigated the energy and carbon implications of building materials and design in "cradle to grave" life cycle studies of a house or its key components. Table 4-1 highlights several of these life cycle studies.

Table 4-1 Residential life cycle energy and carbon emission studies

Category	Case study	Vintage	Location	Scope/method (software, data source)	Source
Building construction and designs	commercial, industrial and residential buildings	1990s	New Zealand	pre-use phase	(Buchanan & Honey, 1994)
	SRC (steel reinforced concrete), wooden single-family, and lightweight steel structure single-family houses	1990s	Japan	pre-use phase / IOA (input-output analysis)	(Suzuki, et al., 1995)
	multi-storey building		Sweden	pre-use phase / IOA (input-output analysis)	(Lenzen & Treloar, 2002)
	the most energy efficient apartment housing in Sweden	2000s	Sweden	50-year life span	(Thormark, 2002)
	a generic single-storey office building	not indicated	UK	25-year life span / EDM	(Yohanis & Norton, 2002)
	four-bedroom detached house	1930s solid masonry; 1960s wood	Canada	life cycle / ATHENA	(Dong, Kennedy, & Pressnail,

		frame; and 1980s wood frame			2005)
	wood vs. non-wood framed houses	not indicated	US	100-year house half-life / CORRIM data	(Upton, 2008)
Building assemblies and materials	alternative wall systems for a single-story ranch-style house	not indicated	US	life cycle / HOT-2000	(Pierquet, et al., 1998)
	double-glazed windows	1990s	UK	pre-use stage	(Weir & Muneer, 1998)
	alternative building materials and technologies	2000	India	pre-use phase	(Reddy & Jagadish, 2003)
	hardwood lumber	2000s	US	pre-use phase	(Bergman & Bowe, 2008)
	construction materials	not indicated	UK	pre-use phase / data extracted from peer-reviewed literature on the basis of a defined methodology and five criteria	(G. P. Hammond & Jones, 2008)

Most carbon emission studies use carbon dioxide equivalent (CO_2e) to measure GHG emissions and this study follows the same practice. The embodied environmental impact (carbon related) of residential construction can be slashed by half when alternative building materials and technologies are employed (Reddy & Jagadish, 2003). Wooden structures are generally found to be preferable since they are less energy- and carbon-intensive compared to non-wood structures (Buchanan & Honey, 1994; Upton, 2008). Attention is also paid to building assembly and materials such as windows, walls, and hardwood lumber. Although it is admitted that LCA studies on building assembly and materials are incomplete because they have to be in a specific house for the examination of use-phase performance to work (Salazar & Sowlati, 2008), these studies are still valuable to establish the foundation for further research on residential life cycle impacts.

Much work has been done but much more is still required. LCA studies are case sensitive because they incorporate specific technologies and processes for material extraction, manufacturing, transportation and installation, which often differ with time and place. Unfortunately, compared to India, Europe, and the US, there are relatively few Canadian LCA studies in this area.

Another gap identified in the review of literature is that most LCA studies focus intensively on new buildings or building renovations while ignoring the initial energy embodied in the old homes. It is understandable that analyses of renovation alternatives and scenarios are of paramount importance, because they facilitate decision making. However, understanding the impacts of past decisions is equally important, not only because old homes (pre-1960s) constitute a significant proportion of the residential stock in Canada, as well as many other countries, but because it provides critical information for construction technology comparisons, “refurbishment or replacement” debates and other discussions.

Even with all the studies on life cycle energy consumption and the carbon emissions of buildings, a gap still exists between academic results and what people really care about – sustainability. The critical question is: What do these results mean to the environment or sustainability? For example, people who care about sustainability prefer to live in green houses. There is even an ongoing competition with an expanding list of people who all claim that they live in “the greenest house on the planet” (Deneen, 2011). But what qualifies a house as “the greenest”? Is it efficient insulation, renewable energy, passive design or some other green features? This paper answers this question from the perspective of the Ecological Footprint (EF), a well-known indicator for measuring ecological sustainability.

The EF tracks all traceable consumption of goods and services and translates them into the amount of land areas needed to support this consumption and assimilate the associated waste. It is seen as a vivid and straightforward communication tool that resonates with the public. Since its introduction by Rees and Wackernagel in the early 1990s, the EF has been successfully promulgated, well accepted, extensively applied, and deeply explored. Using the EF, efforts have been made to probe various aspects of human society, including communities or populations, natural resources or man-made products, and human activities. However, in-depth EF studies at the household level are still missing. Thus, this paper complements both LCA and EF studies.

4.2 Studied Object

The REEP House for Sustainable Living is located in downtown Kitchener, Ontario. It is owned by the Regional Municipality of Waterloo and since 2007 has been leased to REEP Green Solutions (RGS), the local green community not-for-profit that operates the Residential Energy Efficiency Project (REEP) to deliver standardised home energy audits in the region. The REEP House is a two-storey single-detached brick house of 140 m^2 built in 1910 (Figure 4-1), and is among the 43,000 pre-1960 homes in

Waterloo Region. The goal of the project is to demonstrate advanced energy and water efficiency upgrades available for older homes, document the energy, water, and carbon savings that result, and assess the financial, home-comfort, and environmental benefits.

Figure 4-1 REEP House

A series of energy-saving upgrades have been made to increase the energy efficiency of the house while maintaining its early 20th century heritage features. A high level of insulation is one of the features of this project. This house was originally poorly insulated compared to the standard level of insulation in this climate zone (Zone B, (Office of the Energy Efficiency, 2000)). During the renovation, the roof, walls, foundation and basement floor were insulated. Because of the educational nature of this project, the retrofit went much further than required by provincial building standards (shown in Table 4-2). It also includes air sealing and replacement of windows and doors, as well as the adoption of renewables and energy efficient appliances. As a result, the Energuide rating of the house was raised from 51 (consuming 2.5 times more energy than a standard R2000 house) to 89 (consuming 45% less energy than the

R2000 house standard). The annual energy consumption was dramatically slashed (Figure 4-2). However, the life cycle energy consumption, carbon emission, and ecological footprint of the initial house or its upgrades are not known yet.

Table 4-2 Change in insulation levels of key components, R values (source: Parker and O'Neill (2010))

Component	Before	Standard	After
Attic	13	32	50
Walls	13	20	44
Basement walls	2	17	44

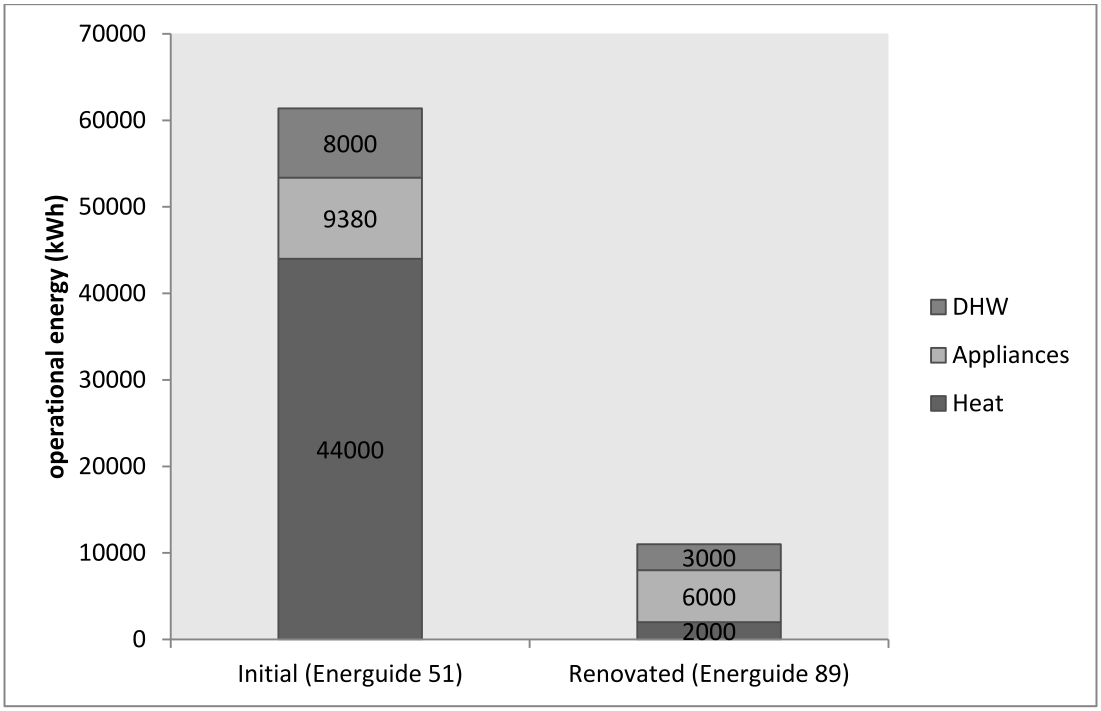

Figure 4-2 Change in modeled operational energy

4.3 Assumptions and Methods

4.3.1 Unit of energy flows and calculation in primary energy

To achieve a complete picture, this paper examines the environmental performance of the REEP House during the three phases of its full service life. The energy unit adopted is the kilowatt hour (kWh) instead of the megajoule (MJ), gigajoule (GJ) or British Thermal Unit (BTU). The rationale is that the kWh is more easily understood and pictured by the general public, since the power of common domestic electrical appliances (light bulbs, microwave ovens, fridges, etc.) is rated in watts.

End use energy is the energy available on site, and thus is often referred to as "delivered energy". Primary energy refers to the amount of energy in its original form, or, put another way, all the energy input used to provide the end use energy; thus, it includes extraction, conversion and distribution losses. For example, 1kWh of electrical energy delivered to and used in the home is typically based on 3kWh of thermal energy provided as primary energy input to a coal fired power station. Embodied energy in a building material is usually defined as "the total primary energy consumed over its life cycle" (G. P. Hammond & Jones, 2011, p. 3); however, operational energy is often calculated in a mixed form of end use energy or primary energy (Ramesh, Prakash, & Shukla, 2010), which causes confusion.

Given that life cycle energy analysis of buildings attempts to work out solutions to achieve a reduction in primary energy use and to curtail emissions, all of the energy consumption values in this study are converted into the corresponding primary energy.

4.3.2 Incomplete life cycle approach

Figure 4-3 illustrates the energy and material flows and system boundaries of the life cycle study. The pre-use ("cradle to site") phase involves embodied energy consumption and concomitant carbon emission during material extraction, transportation, and installation. The calculation starts with quantification of the building materials first used to build this house a century ago. Because such information is poorly documented, architectural drawings of the house are adopted as an alternative method to determine the volume of building materials (Table 4-3). Although this house has undergone a series of renovations in the past century (such as inserting a bathroom in a former bedroom, and replacing the roof shingles), it is very difficult to track each one of them. Overall, it is assumed that the major parts of the REEP House have remained intact.

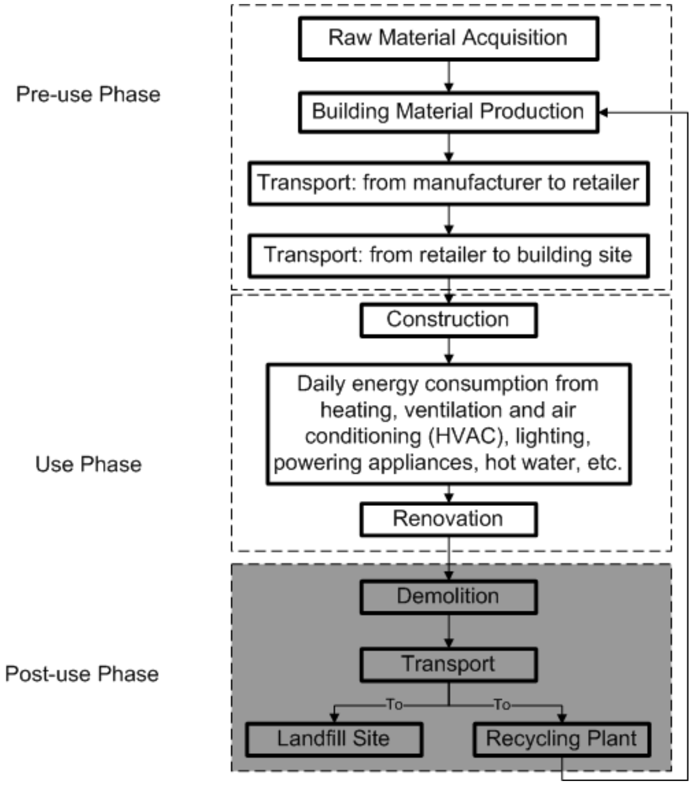

Figure 4-3 System boundaries for life cycle analysis of REEP House

Table 4-3 Original building materials

Material	Volume (m^3)
Slate (roof, south/east/west gables)	0.62
Pine (roof deck, rafter, joist, floor, lathe, boards, etc.)	15.88
Stone (basement wall)	26.52
Concrete (basement floor)	4.43
Clay (brick wall)	36.99
Lime plaster (external and internal walls)	5.45
Glass (window)	0.04
Fibreglass (insulation)	34.15
Metal (screw, piping, etc.)	<0.01

The use phase includes operational energy use and carbon emissions, as well as embodied energy and carbon for renovations to the house. The renovated REEP House has not been occupied by residents yet, so no real-life energy bills exist. Instead, its operational energy consumption and carbon emission are simulated using the software HOT 2000 (results shown above in Figure 4-2). Quantities and sources of retrofit materials are well documented (Table 4-4). In this case, current Canadian or US embodied energy coefficients from ATHENA reports, or other sources, can be used with more confidence than the values for historic materials.

The post-use phase includes material recycling and the energy consumed during demolition. However, because it will happen in the distant future (a 50-year span is assumed), significant uncertainties concerning demolition and recycling technology emerge. Since there is no appropriate estimate of the demolition in the future, energy input is the only element taken into account using the calculator developed by the May T. Watts Appreciation Society (May T. Watts Appreciation Society), which is based on the 2007 Building Energy Data Book produced by the US Department of Energy.

Table 4-4 Summary of renovation materials

Assembly	Material	Quantity	Source	Distance

				(km)
Building envelope panels (basement floor)	XPS	0.075m thick	Detroit, US	300
Insulation	Polyurethane	0.15m thick	Montreal, Quebec	700
Window (kitchen, double glazed)	Glass	1.3m×1.3m×0.005m	Etobicoke, Ontario	100
Window (kitchen ×2, double glazed)	Glass	0.6m×1.8m×0.005m	Etobicoke, Ontario	100
Window (basement ×4, double glazed)	Glass	0.7m×0.4m×0.005m	Etobicoke, Ontario	100
Window (kitchen side ×2, triple glazed)	Glass	0.8m×1.6m×0.005m	Etobicoke, Ontario	100
Wall studs (external&internal)	Wood	562LNM×0.038m×0.089m	Hearst, Ontario	1000
Flooring	Wood	0.025m thick	Local recycled	25
Roofing (high density foam)	Polyurethane	0.1m thick	New York, US	800
ROXUL	Mineral wool	0.1m thick	Milton, Ontario	100
Communication wiring	Copper	230m	Toronto, Ontario	120
Electrical wiring	Copper	200m	Toronto, Ontario	120
Duct work (hot air + cold air)	Galvanized steel	21LNM×0.15mΦ×0.002m	Hamilton, Ontario	70
	Galvanized steel	11 LNM×0.4m×0.4m×0.002m	Hamilton, Ontario	70
ERV duct work	Galvanized steel	15 LNM×0.15mΦ×0.002m	US	1600
Heat pump (3 wells)	Mild steel	46 LNM×0.15mΦ×0.004m	Florida, US	2500
Solar thermal	Copper (panel ×2)	1.2m×2.4m×0.002m	Unknown, Ontario	100
	Copper (pipe ×2)	10LNM×0.0125mΦ×0.0015m	Unknown, Ontario	100
	Polyurethane	1.3m×2.5m×0.05m	Unknown, Ontario	100
PEX pipe (×20)	Low-density polyethylene	6.3 LNM×0.012mΦ×0.002m	Unknown, Ontario	100

4.3.3 EF outcome

This study is based on LCA, but extends it to become an EF study. Each material is translated into its embodied EF through calculation of the EFs derived from material production (EF_m), energy production (EF_e) and carbon sequestration (EF_c); the resultant EFs are then totalled.

$$EF = \sum EFm + \sum EFe + \sum EFc$$

Similarly, the operating heating EF is determined by summing up the EF_e and EF_c of the domestic fuels.

4.3.4 Data sources and adjustments

As for embodied energy and carbon, it is not feasible to test all the materials and delineate their detailed production processes. Thus, several databases (Table 4-5) were used to select appropriate coefficients based on two criteria. Authority is the first criterion, meaning that databases that are well established and updated regularly are preferred. Locality is the second criterion, meaning that Canadian databases are favoured, followed by US sources, and then those from EU and other countries (e.g., New Zealand). Among the databases, ATHENA is based on the Canadian context, has reliable survey procedures and, thus, is the preferred source used in this study.

Table 4-5 Data sources concerning embodied energy and carbon

Source	Category	Location	Availability
ATHENA Impact Estimator for Buildings	Software	CA	Licence fee
Canadian Architect	Website	CA	Free
Canadian Raw Materials Database	Database	CA	Free
Building for Environmental and Economic Sustainability (BEES)	Software	US	Free
National Renewable Energy Laboratory (NREL)	Database	US	Free
Ecoinvent	Database	International	Licence fee
Inventory of Carbon & Energy (ICE)	Database	UK	Free
Centre for Building Performance Research	Website	NZ	Free

The energy and carbon coefficients need adjustment to account for the estimated difference in manufacturing, transportation and energy profile between the present and a century ago, and also between Ontario, Canada, and other countries. Given that low-grade energy such as human or other animal labour was still very common a century ago in Canada, the energy and carbon intensity in material extraction, manufacturing and transportation processes was considerably lower than today when machine work and high-grade energy (e.g., electricity) dominate. However, the difference does not affect the results very much. For example, in this case study, the most significant source of embodied energy and carbon comes from bricks, and the basic procedure of brick making has remained unchanged for centuries. Compared to manufacturing, the energy for clay extraction and transportation is minor (less than 1% of total) nowadays, which makes no noticeable difference when the coefficient is adjusted to suit 1910 patterns. Considering the present energy profile in Ontario, some local coefficients may be significantly different from those of other regions. For example, coal accounts for only a relatively minor part (18%) of the electricity supply mix in Ontario (Ontario Ministry of Energy, 2007), which leads to a smaller transformation loss and carbon intensity per unit energy output compared to where coal-fired power plants are more prevalent.

The fuel used to heat the REEP House is natural gas, so a series of calculations were required to convert the energy consumed to primary energy and associated EF. The old furnace was 80% efficient at converting delivered natural gas into heat. A source-site ratio is necessary to convert the delivered energy into the primary energy at the supply end. The US Environmental Protection Agency uses a value of 1.047 (US EPA, 2009) which is used in this study. Natural Resources Canada provides the energy content (10.342kWh/m^3) and GHG emission (1.902kgCO_2e/m^3) factors (Natural Resources Canada).

Coefficients to measure the ecological footprint are primarily taken from the latest versions (2006 data) of the National Footprint Accounts Methodology (Ewing, et al., 2008) and Ecological Footprint Atlas (Ewing et al., 2009), as these public sources have been widely reviewed. The global average annual CO_2 sequestration rate of forests, 3.66 tons per hectare, is an example of an important coefficient that influences the final EF calculation (Coto-Millán, et al., 2008). The coefficients used in this study and their sources can be found in the appendices.

4.3.5 Gate-to-site transportation

LCA results are based on a cradle-to-gate scope, meaning that they cover only the phase from when raw materials are extracted to when the final products are ready to leave the manufacturer. Thus, it is necessary to examine gate-to-site transportation in order to determine the concomitant energy consumption (and other environmental impacts), which is calculated by multiplying the distance travelled, the energy intensity of the transportation mode, and the quantity of the product.

The original materials were heavy (145 tons), and primarily produced nearby, resulting in relatively short transportation distances. Plus, a century ago, few roads were paved, posing a great barrier to automobile transportation (Hall & Dodds, 1978). Horse and wagon was the most common transportation mode for local timber and bricks at the time. As a result, the primary energy consumed for gate-to-site transportation was small and is not included.

As for the retrofit materials, the distance can be short (locally produced), medium (produced in other cities in Ontario or Quebec) or long (produced in the US). It is assumed that local products travelled an average distance of 25km. If the source of a

Canadian made product is unknown, it is assumed to have travelled 100km to include major southern Ontario sources such as Hamilton and Toronto. When a source city is known, the distance from Kitchener to the city is measured. The transportation mode is assumed to be diesel-fuelled truck.

4.4 Results and Analyses

Detailed calculations are shown in the appendices; major results and findings are presented in this section. As summarized in Table 4-6, this house has an initial embodied energy of 133,000kWh, which is increased by 68,000kWh with the 2010 renovation. Therefore, the embodied energy per unit of floor area is 950kWh/m^2 from construction, and an additional 480kWh/m^2 from the 2010 renovation; these numbers correspond with the normal magnitude of embodied energy found in the literature (usually over 800kWh/m^2).The embodied carbon per unit area is 240kg/m^2 initially, with a further 110kg/m^2 added by the renovation. These numbers are small compared to findings in other studies (usually over 400kg/m^2). Bricks, which are made of clay, and walls, which are mainly composed of bricks, account for most of the initial embodied energy and carbon (Figures 4-4 and 4-5). As for retrofit materials, insulation is the largest source of impact followed by metal in duct works (Figure 4-6).

Table 4-6 Summary of embodied environmental impact

Embodied environmental impact	Initial	Retrofit 2010	Increment (%)
Energy (kWh)	133,000	68,000	51
Carbon (kg)	34,000	15,000	45
EF (gha)	31	12	39

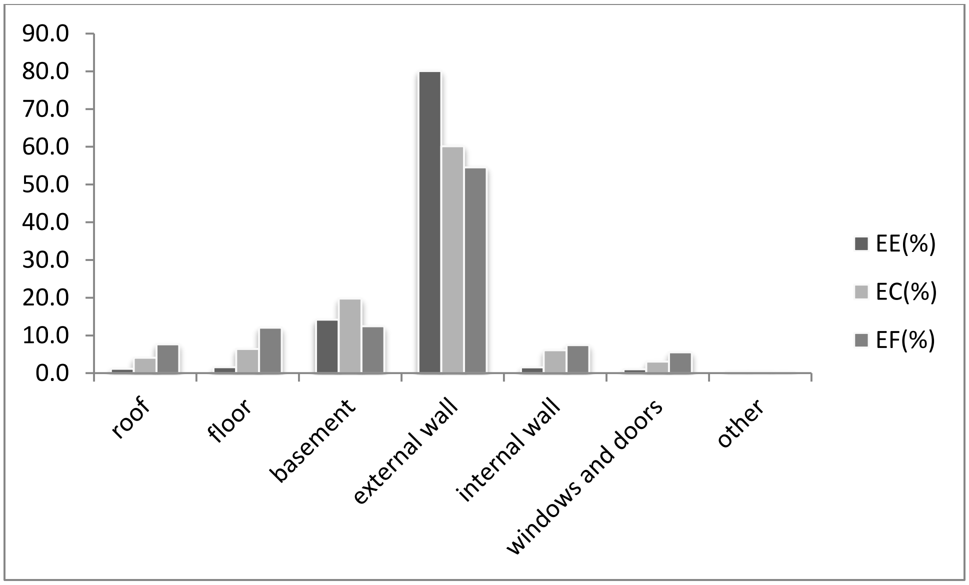

Figure 4-4 Initial embodied energy, carbon and EF by building assembly

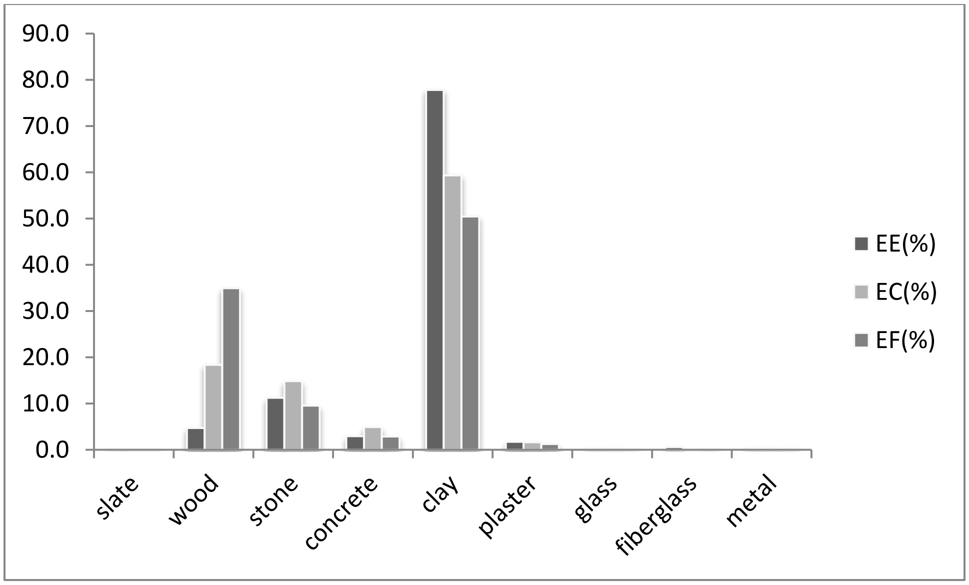

Figure 4-5 Initial embodied energy, carbon and EF by material

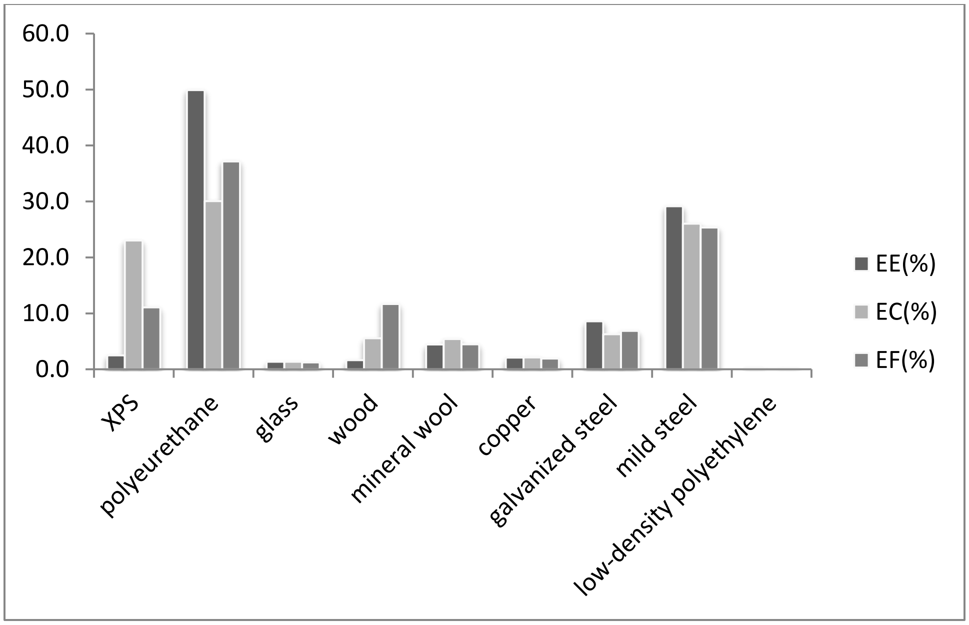

Figure 4-6 Retrofit-induced embodied energy, carbon and EF by material

What difference would it make if all the materials were produced locally or far away from the construction site? Table 4-7 compares several scenarios. As can be seen, if all the materials were produced within a 100km radius, the associated environmental impact would be very small compared to the total embodied environmental impact. As the distance increases, the absolute value can be significant; however, it remains a minor part of the total embodied impact (4%) in this case study.

Table 4-7 Transportation impact comparison of gate-to-site scenarios

Distance (km)	**Energy (kWh)**	**% of total**	**Carbon (kgCO2e)**	**% of total**	**EF (gha)**	**% of total**
100	223	<1	57	<1	0.04	<1
1000	2230	3	567	4	0.39	3
Reality	2453	4	624	4	0.43	4
2000	4461	6	1134	7	0.77	6
4000	8922	12	2269	13	1.55	12

The major renovations include substantial embodied energy, carbon and EF. How long will the savings from upgrades take to pay off their environmental cost? The answer is summarized in Table 4-8.

Table 4-8 Environmental cost, saving and payback for retrofits

	Cost	Saving/yr	Payback period (yr)
Energy (kWh)	68,000	55,000	<2
Carbon (kg)	15,000	10,000	<2
EF (gha)	12	7.4	<2

As can be seen, the payback periods are all estimated to be less than two years; thus, deep residential energy efficiency retrofits are found to be environmentally sound in the life cycle of the REEP House. However, it should be pointed out that the reason for the attractive payback is the huge difference between the poor initial environmental performance of this house before the renovation and extremely high performance after. When it comes to new houses, payback periods are expected to be longer because the savings are smaller.

Despite the fact that this renovation was beyond the level of normal home renovations, the increase in embodied impact was not large and is offset by annual savings as expected. As can be seen, the increment in embodied energy caused by the 2010 set of retrofits is approximately equal to one year’s operating energy in the previous period of poor performance. Figure 4-7 compares the consequence in energy; carbon and EF follow the similar pattern. The long period of poor energy performance results in operating energy impact dwarfing the embodied impacts of initial construction and the advanced renovations (Figure 4-8).

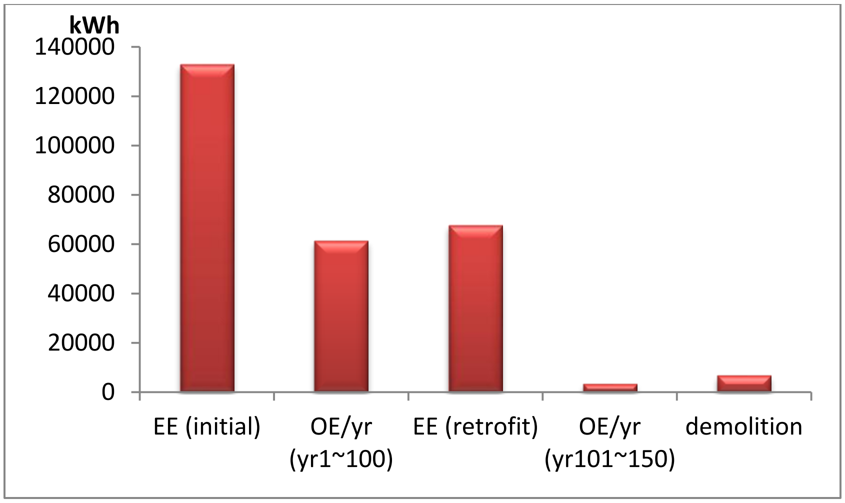

Figure 4-7 Embedded energy (EE) and operating energy (OE) by stage of life

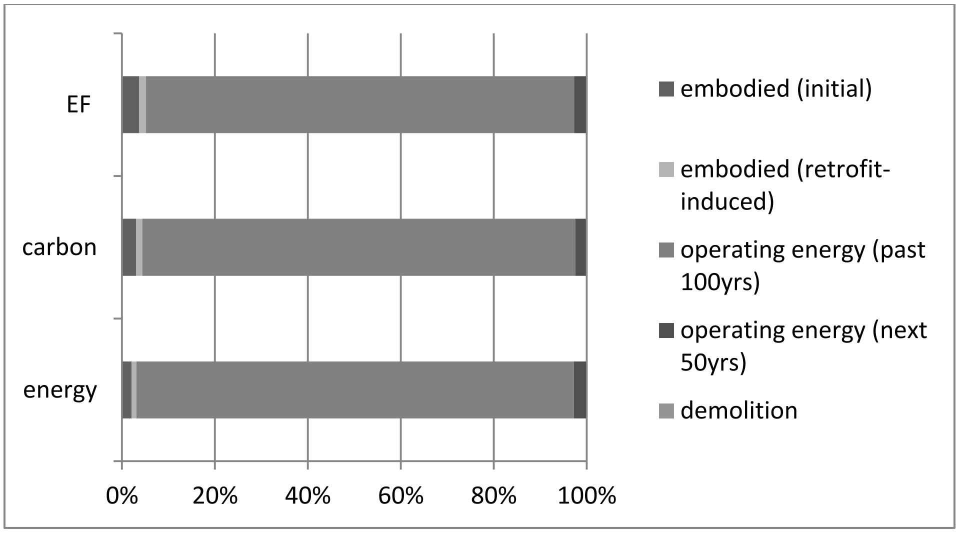

Figure 4-8 Energy, carbon and EF by stage of life

4.5 Discussion

Although the REEP House was built a century ago when society still used manual work and horse transportation (low grade energy) extensively, its embodied energy is not as low as one might expect. This finding is reasonable, given that this is a brick house, and brick making is energy-intensive due to the firing process. However, brick houses are less energy-intensive than concrete or steel framed houses (Suzuki, et al., 1995).

Equally notable is that it takes a small amount of fertile arable land to make traditional clay bricks, which results in an EF in the form of arable land loss. However, this part of the EF can hardly be recovered by natural regeneration in a short period; thus, losing arable land to brick making is a concern. Thus, traditional bricks have been phased out in favour of environmentally sound wall materials in many countries such as China, which once lost arable land at the rate of 80,000 hectares per year due to traditional clay brick manufacturing.

This result shows that the operational impact accounts for a major part of the total impact. However, that is because of the previous long period of poor performance which is rarely seen in other LCA studies. If year 2010 is seen as a starting point and the REEP House is seen as a newly built house with high efficiency, in its 50-year life span, its embodied impact will account for approximately 70% of the total impact, operating impact approximately 30% and demolition 1%. This is in line with the findings of most residential LCA studies of highly efficient buildings. The resulting savings and short pay-back period make renovations a wise environmental decision.

The environmental impact induced by gate-to-site transportation is only a small fraction (4%) of the total. That is because the materials are primarily sourced in Ontario, which entails transportation of relatively short distances. Regardless as to whether the materials were all sourced locally or from a distance of 2000km by diesel fuelled truck, the proportion of transportation related emissions would not change by much. The reason is that, compared to the transportation mode of diesel fuelled truck, the manufacturing processes of building materials are far more energy intensive. Thus, it is important to choose products that pose smaller environmental impacts during their cradle-to-gate or manufacturing stage. However, if less energy-intensive products and more energy-intensive transportation modes are selected, this conclusion may not stand.

The implications of these findings for sustainability are straightforward. The embodied EF of the century-old REEP House was 31 global hectares (gha) initially, and increased by 12gha as a result of deep renovations to improve energy efficiency. Given that the current global biocapacity per person (global biological benchmark) is only 1.8gha, during its construction, this house consumed the equivalent capacity of nature that could have supported 17 to 23 average people for a year. The durable nature of the house enabled it to provide shelter for a century. The annual share of initial impacts is thus 0.3gha/yr. If three occupants are assumed, the annual share is 0.1gha/cap/yr. This forms only a small fraction of EF associated with the contemporary Canadian overconsumption lifestyle (6.4gha/cap/yr). Although the upfront embedded impact seems significant, it is greatly reduced when considered over the long lifespan of the product.

There are several limitations to the study. First of all, the coefficients of embodied energy and carbon come from multiple sources; thus, inaccuracy and inconsistency exist. However, using these sources seems to be the best solution because there is only poor documentation of LCAs for particular products and processes of old houses. Second, only the building envelope and its associated heat loss are taken into account in this study. Therefore, changes in major electrical appliances are not included, nor is the EF stemming from the occupants' material consumption reduction considered. As a result, heating energy and the associated electricity consumption (e.g., ventilation) is treated as operating energy. It would be methodologically more complete if these appliances and products were incorporated. However, they are currently excluded due to the lack of data on particular appliances, devices and their life expectancies. Future detailed studies are required. Third, this study includes no further renovation or replacement analyses for the next 50 years of the house life. Thus, future studies on the life spans of house components and resulting renovation or replacement consequences are recommended.

4.6 Conclusion

In this case study, most of the embodied environmental impact is caused by bricks, which require an energy-consuming firing process, as well as direct consumption of land. Thus, more environmentally sound alternatives (e.g., wood) are recommended as wall construction materials.

Examining the life cycle energy, carbon and EF of the REEP House reveals that after renovation, the environmental upfront cost of energy retrofits will be offset within two years. Therefore, enhancing energy performance by renovation is an environmentally sound action for houses with decades remaining in their service life. This conclusion remains valid for more recent as well as century old houses which can easily achieve reductions in energy consumption by renovation. The 90 percent reduction in energy consumed for space heating in the REEP House is an extreme example of the savings that can be achieved. Given how quickly the carbon embodied in retrofit materials is offset by the carbon savings from improved efficiency, the results support the promotion of residential retrofits as a means to mitigate rising atmospheric CO_2 levels and the associated climate change.

Chapter 5 CONCLUSION AND DISCUSSION

As indicated in Chapter 1, the overall research objective of this thesis is to integrate the EF and LCA measures to provide an enhanced tool to measure the sustainability implications of residential energy retrofit decisions. This thesis has achieved its objective and shown the validity of such a methodology through a case study.

The usual performance approach to measuring operational impacts is enhanced by measuring embedded energy and carbon as well. As has been indicated in the case study findings, the REEP House is not low in embodied energy, because its major wall material, bricks, has an energy-intensive manufacturing procedure due to the firing process. Given that other popular building materials such as concrete and steel are even more energy-intensive than bricks (Suzuki, et al., 1995), the difference caused by the age of a house will not be significant, unless it is stone or wood framed, which requires much less energy during manufacturing.

For a highly energy efficient house, its embodied energy usually accounts for a major part of its energy consumption during its entire life cycle; if it is low in energy efficiency, its operational energy is normally the major part. In the case study, the first 100 years of the REEP House is an example of a low efficiency house. However, since the 2010 retrofit, it has turned into a high performance home, and its embodied impact will account for approximately 70% of the total impact, with operating impact being approximately 30% and demolition 1% in an assumed 50-year life span. This is in line with the findings of most residential LCA studies of highly efficient buildings. The resulting savings and short pay-back period make renovations a wise environmental decision.

Sourcing energy-intensive materials locally only reduces embodied impacts a little. In the case study, the environmental impact induced by gate-to-site transportation is only a small fraction (4%) of the total. That is because the materials are primarily sourced in Ontario, which entails transportation of relatively short distances. Even if the materials were sourced from a long distance, the proportion of transportation related emissions (12%) would not change by much, as indicated in the case study section.

The EF is able to interpret a conventional life cycle inventory, and provide a better way of examining the impact of our behaviour on sustainability. The embodied EF of the century-old REEP House was 31 global hectares (gha) initially, and increased by 12gha as a result of deep renovations to improve energy efficiency. Given that the current global biocapacity per person (global biological benchmark) is only 1.8gha, the construction of this house consumed the equivalent capacity of nature that could have supported 17 to 23 average people for a year. The durable nature of the house enabled it to provide shelter for a century. The annual share of initial impacts is thus 0.3gha/yr. If three occupants are assumed, the annual share is 0.1gha/cap/yr. This forms only a small fraction of EF associated with the contemporary Canadian overconsumption lifestyle (6.4gha/cap/yr). Although the upfront embedded impact seems significant, it is greatly reduced when considered over the long lifespan of the product.

Examining the life cycle energy, carbon and EF of the REEP House reveals that after renovation, the environmental upfront cost of energy retrofits will be offset within two years. Therefore, enhancing energy performance by renovation is an environmentally sound action for houses with decades remaining in their service life. This conclusion also remains valid for more recent houses which can easily achieve reductions in energy consumption by renovation. The 90 percent reduction in energy consumed for space heating in the REEP House is an extreme example of the savings that can be achieved. Given how quickly the carbon embodied in retrofit materials is offset by the carbon savings from improved efficiency, the results support the promotion of deep or extensive residential retrofits as a means to mitigate rising atmospheric CO_2 levels and the associated climate change.

There are several limitations to the study as well as potential aspects for future refinement and research. First of all, the coefficients of embodied energy and carbon come from multiple sources; thus, inaccuracy and inconsistency exist. However, using these sources seems to be the best solution because there is only poor documentation of LCAs for particular products and processes of old houses. Second, only the building envelope and its associated heat loss are taken into account in this study. Therefore, changes in major electrical appliances are not included, nor is the EF stemming from the occupants' material consumption considered. As a result, heating energy and the associated electricity consumption (e.g., mechanical ventilation) is treated as operating energy. It would be methodologically more complete if appliances and products were incorporated. However, they are currently excluded due to the lack of data on particular appliances, devices and their life expectancies. Future detailed studies are required. Third, this study includes no further renovation or replacement analyses for the next 50 years of the house life. Thus, future studies on the life spans of house components and resulting renovation or replacement consequences are recommended. Fourth, this study does not include EROI. It is necessary to watch EROI in future studies given current declining trends. Another possible aspect to work on is the comparison of retrofit scenarios.

This study only examines the environmental consequences of an advanced home renovation project, which is not frequently carried out because of its high standards and upfront cost. As an alternative, for instance, people can choose to insulate only the attic or the walls. Energy auditors usually inform home owners of their potential home renovation options and give advice to help them make a decision. Thus, future studies can take this project to a higher level and examine the EF consequences of various retrofit options, which will facilitate improved decision making at the household level. As a result, the thesis offers an improved technique to include embodied impacts in the environmental assessment of retrofit energy projects.

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APPENDIX I: EF-RELATED COEFFICIENTS

Factor	**Description**	**Value**	**Unit**	**Source**
Annual CO_2 sequestration rate of forest	Global average	3.66	ton/ha	Coto-Millán, et al., 2008
Production of timber	Global average	2.36	m^3/ha/yr	Brad Ewing, et al., 2008
Equivalence factor	Forest	1.24	gha/ha	Brad Ewing, et al., 2008
	Built-up land	2.39	gha/ha	Brad Ewing, et al., 2009
	Cropland	2.39	gha/ha	Brad Ewing, et al., 2009
	Pasture	0.51	gha/ha	Brad Ewing, et al., 2009
	Fishing ground	0.41	gha/ha	Brad Ewing, et al., 2009
	Fossil fuel land	1.24	gha/ha	Brad Ewing, et al., 2009
Energy production rate	Liquid fuels	14167	kWh/ha/yr	Coto-Millán, et al., 2008
	Solid fuel - coal	10278	kWh/ha/yr	Coto-Millán, et al., 2008
	Gas	18194	kWh/ha/yr	Coto-Millán, et al., 2008
	Average	14213	kWh/ha/yr	

APPENDIX II: FUEL-RELATED COEFFICIENTS

Category	**Factor**	**Description**	**Value**	**Unit**	**Source**
Natural gas	Energy content	Amount of energy in primary fuel	10.342	kWh/m^3	Natural Resources Canada, 2010
	GHG emission	Industrial combustion	1.902	$kgCO_2e/m^3$	Matin, et al., 2004
			0.184	$kgCO_2e/kWh$	
	Source-site ratio	US case	1.047		US EPA, 2009
	Furnace Efficiency	REEP House old furnace	80%		
		REEP House new furnace	96%		
Electricity	GHG emission	Ontario average in 2002	0.258	kg CO_2e/kWh	Matin, et al., 2004
	Source-site ratio		2.556		Ontario Ministry of Energy, 2007
Diesel (road)	Fuel intensity	Diesel-powered truck	0.33	kWh/ton/km	The ATHENA Sustainable Materials Institute, 1994-2005
	Energy content		10.74	kWh/L	The ATHENA Sustainable Materials Institute, 1994-2005
	GHG emission		0.254	kg CO_2e/kWh	The ATHENA Sustainable Materials Institute, 1994-2005
Diesel (rail)	Fuel intensity		0.067	kWh/ton/km	The ATHENA Sustainable Materials Institute, 1994-2005
	GHG emission		0.254	kg CO_2e/kWh	The ATHENA Sustainable Materials Institute, 1994-2005
Oil	GHG emission		0.266	kg CO_2e/kWh	The ATHENA Sustainable Materials Institute, 1994-2005
	Heat content		115.7	kWh/L	The ATHENA Sustainable Materials Institute, 1994-2005
Coal	GHG emission	Central Canada	0.315	kg CO_2e/kWh	The ATHENA Sustainable Materials Institute, 1994-2005
	Heat content		5.650	kWh/kg	The ATHENA Sustainable Materials Institute, 1994-2005

APPENDIX III: LCA-RELATED COEFFICIENTS

Material	**Category**	**Description**	**Value**	**Unit**	**Source**
Slate	EE		0.05	kWh/kg	Hammond & Jones, 2011, ICE v2.0
	EC		0.01	kgCO$_2$e/kg	Hammond & Jones, 2011, ICE v2.0
Timber	EE		383.3	kWh/m^3	Canadian Architect
	EC		0.72	kgCO$_2$e/kg	Hammond & Jones, 2011, ICE v2.0
Stone	EE		563.9	kWh/m^3	Canadian Architect
	EC		0.079	kg CO$_2$e/kg	Hammond & Jones, 2011, ICE v2.0
Concrete (30mpa)	EE		883.333	kWh/m^3	Canadian Architect
	EC		0.159	kg CO$_2$e/kg	Hammond & Jones, 2011, ICE v2.0
Brick	EE		2.105	kWh/kg	The ATHENA Sustainable Materials Institute, 1994-2005
	EC	coal-fired kiln	0.394	kg CO$_2$e/kg	The ATHENA Sustainable Materials Institute, 1994-2005
Plaster	EE		0.5	kWh/kg	Hammond & Jones, 2011, ICE v2.0
	EC		0.12	kg CO$_2$e/kg	Hammond & Jones, 2011, ICE v2.0
Glass	EE		10430.556	kWh/m^3	Canadian Architect
	EC		0.91	kg CO$_2$e/m^3	Hammond & Jones, 2011, ICE v2.0
Fiberglass	EE		7.78	kWh/kg	Hammond & Jones, 2011, ICE v2.0
	EC		1.35	kg CO$_2$e/kg	Hammond & Jones, 2011, ICE v2.0
Polyurethane foam	EE		22.86	kWh/kg	Franklin Associates, 2010
	EC		3.1	kg CO$_2$e/kg	Franklin Associates, 2010
Low-density polyethylene	EE		24.61	kWh/kg	Franklin Associates, 2010
	EC		1.705	kg CO$_2$e/kg	Franklin Associates, 2010
Mineral wool	EE		4.61	kWh/kg	Hammond & Jones, 2011, ICE v2.0
	EC		1.28	kg CO$_2$e/kg	Hammond & Jones, 2011, ICE v2.0
Steel tubing	EE		9.083	kWh/kg	The ATHENA Sustainable Materials Institute, 1994-2005
	EC		1.8	kg CO$_2$e/kg	The ATHENA Sustainable Materials Institute, 1994-2005
Galvanized steel	EE		10.593	kWh/kg	The ATHENA Sustainable Materials Institute, 1994-2005
	EC		1.75	kg CO$_2$e/kg	The ATHENA Sustainable Materials Institute, 1994-2005
Copper	EE		11.7	kWh/kg	Hammond & Jones, 2011, ICE v2.0
	EC		2.71	kg CO$_2$e/kg	Hammond & Jones, 2011, ICE v2.0
XPS	EE		450	kWh/m^3	Owens Corning Company, 2007
	EC		953.4	kg CO$_2$e/m^3	Owens Corning Company, 2007

Note: EE=Embodied Energy, EC=Embodied Carbon

APPENDIX IV: CALCULATION OF INITIAL EMBODIED IMPACTS

Assembly	Material	Volume (m^3)	Density (kg/m^3 or kg/m^2)	Weight (kg)	%	Embodied energy (kWh)	%	Embodied carbon (kg)	%	EFm	%	EFe	%	EFc	%	EF	%
Roof																	
south gable	slate	17.32	49	849	0.6	42	0.0	8	0.0		0	0.00	0.03	0.00	0.03	0.01	0.02
east and west gables	slate	71.88	49	3522	2.4	176	0.1	35	0.1		0	0.02	0.13	0.01	0.10	0.03	0.09
roof deck	pine	2.25	540	1215	0.8	862	0.6	875	2.6	1.18	14.1	0.08	0.65	0.30	2.58	1.55	4.94
rafter	pine	1.04	540	562	0.4	399	0.3	404	1.2	0.55	6.5	0.03	0.30	0.14	1.19	0.72	2.28
plates	pine	0.155	540	84	0.1	59	0.0	60	0.2	0.08	1.0	0.01	0.04	0.02	0.18	0.11	0.34
Floor																	
joists	pine	1.33	540	718	0.5	510	0.4	517	1.5	0.70	8.3	0.04	0.38	0.18	1.53	0.92	2.92
joists	pine	1.33	540	718	0.5	510	0.4	517	1.5	0.70	8.3	0.04	0.38	0.18	1.53	0.92	2.92
floor board	pine	2.33	540	1258	0.9	893	0.7	906	2.7	1.22	14.6	0.08	0.67	0.31	2.67	1.61	5.11
floor finish	pine	0.47	700	329	0.2	180	0.1	237	0.7	0.25	2.9	0.02	0.14	0.08	0.70	0.34	1.09
Basement																	
stone wall	stone	26.52	2400	63648	43.8	14955	11.2	5028	14.8		0.0	1.30	11.24	1.70	14.84	3.01	9.56
concrete floor	concrete	4.43	2370	10499	7.2	3913	2.9	1669	4.9		0.0	0.34	2.94	0.57	4.93	0.91	2.88
Wall (external)																	
brick	clay	30.43	1436	43697	30.1	91063	68.4	16991	50.1	0.024	0.3	7.94	68.45	5.76	50.14	13.73	43.63
brick	clay	4.17	1436	5988	4.1	12479	9.4	2328	6.9	0.003	0.0	1.09	9.38	0.79	6.87	1.88	5.98
plaster external walls	plaster	3.61	849	3061	2.1	1531	1.2	367	1.1		0.0	0.13	1.15	0.12	1.08	0.26	0.82
lathe	pine	1.35	540	730	0.5	518	0.4	526	1.6	0.71	8.5	0.05	0.39	0.18	1.55	0.93	2.97
lathe supports	pine	0.43	540	230	0.2	163	0.1	165	0.5	0.22	2.7	0.01	0.12	0.06	0.49	0.29	0.93
insulation	fiberglass	4.00	25	100	0.1	778	0.6	5	0.0			0.07	0.58	0.00	0.02	0.07	0.22
Wall																	

(internal)																	
main floor																	
stud	pine	0.60	540	323	0.2	229	0.2	232	0.7	0.31	3.7	0.02	0.17	0.08	0.69	0.41	1.31
lathe	pine	0.39	540	210	0.1	149	0.1	151	0.4	0.20	2.4	0.01	0.11	0.05	0.45	0.27	0.85
plaster	plaster	0.62	849	529	0.4	265	0.2	63	0.2		0.0	0.02	0.20	0.02	0.19	0.04	0.14
second floor																	
stud	pine	1.04	540	559	0.4	397	0.3	402	1.2	0.54	6.5	0.03	0.30	0.14	1.19	0.71	2.27
lathe	pine	0.76	540	410	0.3	468	0.4	295	0.9	0.40	4.8	0.04	0.35	0.10	0.87	0.54	1.71
plaster	plaster	1.22	849	1037	0.7	519	0.4	124	0.4		0.0	0.05	0.39	0.04	0.37	0.09	0.28
basement																	
double brick interior wall	clay	2.39	1436	3426	2.4	5	0.0	796	2.3	0.002	0.0	0.00	0.00	0.27	2.35	0.27	0.86
windows and doors																	
frame																	
basement	pine	0.17	540	93	0.1	66	0.0	67	0.2	0.09	1.1	0.01	0.05	0.02	0.20	0.12	0.38
1st	pine	0.46	540	249	0.2	177	0.1	180	0.5	0.24	2.9	0.02	0.13	0.06	0.53	0.32	1.01
2nd	pine	0.52	540	282	0.2	200	0.2	203	0.6	0.27	3.3	0.02	0.15	0.07	0.60	0.36	1.15
4 mm glass																	
basement	glass	0.00	2580	12	0.0	48	0.0	11	0.0		0.0	0.00	0.04	0.00	0.03	0.01	0.02
1st	glass	0.02	2580	50	0.0	203	0.2	46	0.1		0.0	0.02	0.15	0.02	0.13	0.03	0.11
2nd	glass	0.02	2580	53	0.0	213	0.2	48	0.1		0.0	0.02	0.16	0.02	0.14	0.03	0.11
doors	pine	0.61	540	330	0.2	234	0.2	237	0.7	0.32	3.8	0.02	0.18	0.08	0.70	0.42	1.34
trim (doors)	pine	0.14	540	74	0.1	53	0.0	53	0.2	0.07	0.9	0.00	0.04	0.02	0.16	0.09	0.30
trim (windows)	pine	0.11	540	59	0.0	42	0.0	43	0.1	0.06	0.7	0.00	0.03	0.01	0.13	0.08	0.24
skirting boards/base boards	pine	0.40	540	218	0.1	155	0.1	157	0.5	0.21	2.5	0.01	0.12	0.05	0.46	0.28	0.88
other																	
metal	metal	0.01	8000	50	0.0	585	0.4	135.5	0.4		0.0	0.05	0.44	0.05	0.40	0.10	0.31
sum				145172	100	133037	100	33885	100	8.37	100	11.61	100.00	11.48	100.00	31.46	100.00

APPENDIX V: CALCULATION OF RETROFIT-INDUCED IMPACTS

Assembly	Material	Volume (m^3)	Distance (km)	density (kg/m3 or kg/m2)	Weight (kg)	Gate-to-site energy (kwh)	Gate-to-site carbon (kg)	Gate-to-site EF (gha)	Embodied energy (kWh)	%	Embodied carbon (kg)	%	Efm	Efe	Efc	EF	%
building envelope panels	XPS	3.71	300	42.5	157.9	15.52	3.95	0.00	1687	2.49	3546	23.03	0	0.15	1.20	1.35	11.08
insulation	polyeurethane	34.15	700	32	1092.9	250.75	63.77	0.04	25234	37.22	3452	22.42	0	2.20	1.17	3.37	27.71
window (kitchen)	glass	0.02	100	2580	43.6	1.43	0.36	0.00	178	0.26	40	0.26	0	0.02	0.01	0.03	0.24
kitchen side x2	glass	0.02	100	2580	55.7	1.83	0.46	0.00	227	0.34	51	0.33	0	0.02	0.02	0.04	0.31
basement x4	glass	0.01	100	2580	28.9	0.95	0.24	0.00	118	0.17	27	0.17	0	0.01	0.01	0.02	0.16
kitchen side x2	glass	0.04	100	2580	99.1	3.25	0.83	0.00	404	0.60	91	0.59	0	0.04	0.03	0.07	0.54
studs	wood	1.97	1000	540	1063.3	348.52	88.63	0.06	1103	1.63	854	5.55	1.03	0.10	0.29	1.42	11.67
flooring	wood	1.06	25	540	573.8	4.70	1.20	0.00	5	0.01	1	0.01	0	0.00	0.00	0.00	0.01
roofing	polyeurethane	9.21	800	40	368.5	96.63	24.58	0.02	8521	12.57	1167	7.58	0	0.74	0.40	1.14	9.36
ROXUL	mineral wool	5.06	100	128	648.2	21.25	5.40	0.00	3009	4.44	835	5.42	0	0.26	0.28	0.55	4.48
communication wiring	copper	230m	120		4.1	0.16	0.04	0.00	48	0.07	11	0.07	0	0.00	0.00	0.01	0.07
electrical wiring	copper	200m	120		3.6	0.14	0.04	0.00	42	0.06	10	0.06	0	0.00	0.00	0.01	0.06
duct (hot air)	galvanized steel	0.02	70	7850	155.3	3.56	0.91	0.00	1649	2.43	273	1.77	0	0.14	0.09	0.24	1.94
duct (cold air)	galvanized steel	0.04	70	7850	276.3	6.34	1.61	0.00	2933	4.33	485	3.15	0	0.26	0.16	0.42	3.45
ERV piping	galvanized steel	0.01	1600	7850	110.9	58.17	14.79	0.01	1233	1.82	209	1.36	0	0.11	0.07	0.18	1.47
heatpump	mild steel	0.25	2500	7850	1996.6	1636.08	416.08	0.28	19770	29.16	4010	26.04	0	1.72	1.36	3.08	25.34
solar thermal	copper	0.01	100	8930	113.4	3.72	0.95	0.00	1330	1.96	308	2.00	0	0.12	0.10	0.22	1.81
	polyeurethane	0.16	100	24	3.9	0.13	0.03	0.00	89	0.13	12	0.08	0	0.01	0.00	0.01	0.10
PEX (Cross-linked Polyethylene) pipe	low-density polyethylene	0.01	100	930	8.8	0.29	0.07	0.00	218	0.32	15	0.10	0	0.02	0.01	0.02	0.20
sum		55.77			6804.7	2453.41	623.94	0.43	67798	100.00	15396	100.00	1.03	5.91	5.22	12.17	100.00