EMBODIED ENERGY CALCULATION: METHOD AND GUIDELINES FOR A BUILDING AND ITS CONSTITUENT MATERIALS

A Dissertation

by

MANISH KUMAR DIXIT

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Approved by:

Chair of Committee,	Charles H. Culp
Co-Chair of Committee,	José L. Fernández-Solís
Committee Members,	David E. Claridge
	Mark J. Clayton
	Wei Yan
Head of Department,	Ward Wells

December 2013

Major Subject: Architecture

ABSTRACT

The sum of all energy embedded in products and processes used in constructing a building is known as embodied energy. According to the literature, the current state of embodied energy research suffers from three major issues. First, there is little agreement on the definition of embodied energy. Second, the existing embodied energy data suffers from variation and are regarded as incomplete and not specific to a product under study. Third, there are various methods for calculating embodied energy with varying levels of completeness and accuracy. According to the literature, the input-output-based hybrid method is the most appropriate method but it needs further improvements. Some of the studies also found a positive and strong correlation between the cost and embodied energy of a building but this correlation needs to be analyzed at a building material or product level.

This research addressed the three issues identified by the literature. First, using a rigorous literature survey, it proposed an embodied energy definition, a complete system boundary model, and a set of data collection, embodied energy calculation, and result reporting guidelines. The main goal of proposing the guidelines was to streamline the process of embodied energy calculation to reduce variations in embodied energy data. Second, three improvements were carried out in the current input-output-based hybrid approach, which included process energy data inclusion, human and capital energy integration, and sectorial disaggregation to calculate material-specific embodied energy. Finally, the correlation between the embodied energy and cost and price was analyzed at a material level.

The study concluded that an input-output-based hybrid method was the most appropriate method for calculating the embodied energy of a building material in a complete manner. Furthermore, incompleteness in the results of a process-based method was significant (3.3 to 52% of the total). The energy of human labor and capital inputs was up to 15% of the total embodied energy. It was also found that the sectorial disaggregation could provide results specific to a material under study. The results of this study indicated a strong and positive correlation between the embodied energy and cost (and price) of building materials under study.

DEDICATION

Dedicated to

Krishna

and countless ***scientists*** *and unnoticed* ***activists*** *around the globe working to fight* ***global warming*** *and* ***climate change***

ACKNOWLEDGEMENTS

First and foremost I would like to thank my committee chair Dr. Charles H. Culp for the continuous support and guidance during my five years' of Ph.D. program. Dr. Culp has extensive experience researching the field of energy optimization in buildings. I am grateful to him for providing his ideas, knowledge, and resources to complete this research. He inspired me to improve not only the quality and content of my Ph.D. research, but also my writing and presentation skills. I would also like to express my sincere gratitude to my committee co-chair Dr. José L. Fernández-Solís, who originally motivated me to pursue this research during my master's program. His constant guidance, enthusiasm, and immense knowledge enabled me to research this complex but stimulating topic. Dr. Solís is a pioneer in the research demonstrating that the construction is rapidly approaching the threshold of becoming unsustainable. I would also like to thank my committee members Dr. David E. Claridge, Dr. Mark J. Clayton, and Dr. Wei Yan for their guidance, patience, and enthusiasm throughout the course of my Ph.D. research. Dr. Claridge has published extensively in the field of building energy conservation and Continuous Commissioning. He provided candid comments and asked hard questions that helped me refine my research. I appreciate Dr. Yan for his guidance to write programming codes for the research calculations. My sincere thanks to Dr. Clayton for valuable discussions and ideas, which helped me, contemplate my future research plans.

I want to thank Dr. Sarel Lavy, who not only provided his guidance and financial support, but also inspired me to maintain an excellent publication and conference presentation record. I had a great time traveling and attending conferences with him. I also express my sincere gratitude to Dr. John Penson and Dr. Rebekka Dudensing from the Department of Agricultural Economics for answering questions instrumental to my research. They helped me understand and construct the complex economic input-output models, which formed the basis of this research. I also thank Bonita Culp for reviewing not just this report but also other research papers I submitted for publication. To me, she is the most meticulous editor I have ever met. Her reviews helped me tremendously in refining my writing style.

I would like to thank the Department of Construction Science, Department of Architecture, and Energy Systems Lab for their financial, technical, and academic support to complete my Ph.D. program. I particularly appreciate Professor Joe Horlen and Dr. James Smith for their motivation and for giving me the opportunity to teach independently in the Department of Construction Science. Teaching and interacting with freshmen and undergraduate students was truly a unique learning experience. I also acknowledge the Texas A&M University, particularly the University Libraries, for all of their technical and literature support. The University Writing Center really helped me refine my writing skills during the final year of my Ph.D. program. I am thankful to their kind and supportive staff and consultants.

I acknowledge my friends and fellow postgraduate students who really made my time at Texas A&M University a unique and enjoyable experience. I also want to extend my thanks to the American Council for Construction Education (ACCE), International Facility Management Association (IFMA), and the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) for their generosity in providing prestigious scholarships.

Last but not least, I would like to thank my wife Madhavi and my son Savyasachi for their constant personal support, unconditional love, and great patience during the course of my postgraduate studies. My sincere thanks to my hard-working parents, in-laws, and loving family in India for their support and constant encouragement.

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CHAPTER I
INTRODUCTION

The natural capital of the earth is shrinking due to constant and unrestricted anthropogenic resource consumption as a result of population growth and increased affluence. Resources such as raw materials, fuels, biomass, and water are being drawn at a rate that has outrun the earth's capacity to replenish them. Among the major impacts of this increased resource consumption are increased levels of pollution, greenhouse gas emission, waste generation, and land depletion (Hacker et al., 2008; Malla, 2009; Kofoworola and Gheewala, 2009). The increased concentration of greenhouse gases in the atmosphere, according to experts, has caused severe environmental problems such as global warming leading to phenomenon of climate change (Fernández-Solís, 2008). According to some researchers (Nordhaus, 2010; Mendelsohn et al., 2012), among the most pronounced impacts of climate change on the atmosphere is the increased frequency of extreme weather events such as hurricanes, tornedos, flash floods, and storms, which not only are life-threatening but also have economic, social, and environmental consequences. One of the main constituents of greenhouse gases is carbon dioxide (CO_2) resulting from resource consumption and waste generation (Dietz and Rosa, 1997; Jiang et al., 2008; Alcott, 2012). The consumption of energy in activities such as transportation, construction, and building operations is the major cause of global CO_2 emission. According to UNDESA (2011), the global population is projected to reach 10 billion by the end of 2050. It is crucial to note that most of this growth will occur in countries which are currently among the top contributors to the global CO_2 emissions (Marland et al., 2010; EPI, 2010).

The construction industry consumes enormous amounts of energy (40%) and nonenergy resources such as building materials, water (16%), fuels, electricity, and labor annually (Ding, 2004; Langston and Langston, 2008). As a result, it also contributes to the CO_2 emissions and waste generation. Every year, nearly 40% of the global raw stone, sand and gravel supply, and 25% of the virgin wood supply is depleted by the construction activities (Ding, 2004; Dixit et al., 2010). The construction and demolition waste represented the largest share (40 - 50%) of the total annual waste generated in the United States (USEPA, 2009a). The construction sector, particularly the building sector, is responsible for more than 39% of the United States' annual carbon emission (USEPA, 2009a).

Buildings consume energy in their life cycle stages of construction, operation, maintenance, renovation, and demolition. The energy is consumed when building materials are manufactured. Construction materials extensively used in building construction such as cement, steel, aluminum, and insulation are very energy intensive (Chen et al., 2001; Dixit et al., 2010). When a building is constructed, energy is consumed directly in construction processes and indirectly in its constituent materials. The total energy consumed in all products and processes that are used in constructing the building is known as the initial embodied energy (Cole and Wong, 1996; Kernan, 1996; Ding, 2004). When the building is occupied it is also maintained, renovated, and some of its components are replaced periodically. Such processes also consume energy directly and indirectly, which is termed the recurring embodied energy (Ding, 2007; Khasreen et al., 2009; Vukotic et al., 2010; Dixit et al., 2010). At the end-of-life phase, the building is demolished and its materials are salvaged for reuse, recycling or disposal, consuming direct and indirect energy. This fraction of energy is called the demolition energy (Cole, 1996; Cole and Wong, 1996; Vukotic et al., 2010). The total life cycle embodied energy is the sum of the building's initial, recurring, and demolition embodied energy (Cole and Wong, 1996; Vukotic et al., 2010). The total life cycle energy use of the building constitutes embodied and operating energy. The operating energy is consumed in lighting, air-conditioning, and powering building appliances. In the literature (Treloar, 1998; Crawford, 2004; Pullen, 2007; Dixit et al., 2010), it has been highlighted that for a comprehensive reduction in building energy use, a whole life cycle energy accounting should be performed including not only the operating but also the embodied energy. Until recently, the focus of building energy research was on operating energy assuming that the embodied energy is insignificant. However, recent studies have invalidated this assumption and have clearly underscored the significance of embodied energy in the whole building energy optimization (Ding, 2004). Due to an increased focus on operating energy, highly advanced and energy efficient building systems, controls, appliances, and envelope materials have been developed. As a result, the operating energy use of buildings is going down gradually (Ding, 2004; Sartori and Hestnes, 2007; Plank, 2008). However, no concrete efforts were made to substantially reduce the embodied energy (Dixit et al., 2010). Among the major reasons cited for this by literature (Ding, 2004; Pullen, 1996; Miller, 2001; Lenzen, 2000; Dixit et al., 2010) include the unavailability of consistent and complete embodied energy data and a lack of an established and standard embodied energy calculation method.

Current embodied energy data of building materials differ across studies. Moreover, these data are regarded as incomplete, inaccurate, and inconsistent (Fernandez, 2006; Burnett, 2006; Dixit et al., 2010). These issues with embodied energy data make them questionable and practically unusable (Khasreen et al., 2009). There are parameters related to embodied energy calculation and energy data quality that cause serious variations in embodied energy data. Some of these parameters such as system boundary definition, energy inputs, and the embodied energy calculation approach are methodological issues. Completeness, inaccuracy, and representativeness of used energy and nonenergy data are among the major data quality parameters (Raynolds et al., 2000; Khasreen et al., 2009; Dixit et al., 2012).

System boundary is a demarcation of a system under investigation (IFIAS, 1975; Peuportier, 2001; Dixit et al., 2013). It defines what is included and excluded from a study performing an embodied energy calculation. For instance, if the embodied energy of a building is being quantified, a system boundary would delineate all the life cycle stages covered in the calculation. According to literature (Suh et al., 2004; Dixit et al., 2012a), studies around the globe have been selecting the system boundaries subjectively making their calculation results incomparable. Some of the studies performed embodied energy calculations and reported their results in primary energy terms, whereas some did it in delivered energy terms (Sartori and Hestnes, 2007; Gustavsson and Joelsson, 2010; Ramesh et al., 2010). The primary energy, which is the energy extracted from the earth, is quite different from the delivered energy. To deliver an energy source for the end use, it is extracted, processed, transported, and distributed. During these processes, energy is consumed and lost. Hence, to distribute one unit of delivered energy, more than one unit of primary energy is either used or lost (Treloar, 1998; Deru and Torcellini, 2007; Dixit et al., 2012). For instance, to deliver one unit of electricity, more than three units of primary fuel are burnt. If the embodied energy results of the two studies are given in primary and delivered energy forms, they cannot be compared before making appropriate adjustments. Another issue that causes significant variations in embodied energy values is related to the calculation methods. There are two established methods to compute the energy embodied in a building or its materials. The process-based method is accurate and provides results specific to the product under study but it is incomplete. The input-output-based method is complete but lacks specificity (Plank, 2008; Khasreen et al., 2009; Optis and Wild, 2010). The two methods have also been combined to develop hybrid approaches that are complete and more specific to the study. However, there is still no method that is standard and globally accepted. The results of these methods differ causing variations to embodied energy data (Nebel, 2007; Dixit et al., 2010).

If no reliable data were available, studies applied secondary data to calculate the embodied energy (Dixit et al., 2012). In some cases, the data were sourced from a region entirely different from the region of the study. Sometimes, the data sourced is old and does not represent the study temporally (Khasreen et al., 2009). These issues of data quality also contributed to the variations in embodied energy values. To resolve these issues, the literature (e.g., Pears, 1996; Menzies et al., 2007; Frey, 2008; Khasreen et al., 2009; Dixit et al., 2012a) has clearly pointed out a need to establish a set of guidelines that governs the quality of data (representativeness) being used for the energy calculation. A need to propose a globally accepted definition and a standard embodied energy calculation method has also been highlighted by studies such as Dixit et al. (2012).

The input-output-based hybrid method is regarded as the most appropriate approach to calculate the embodied energy in a complete manner. This method was improved earlier by Treloar (1998) and recently by Crawford (2004). They proposed inserting more reliable process data into an input-output model by extracting and replacing the comparable monetary data. These approaches are very useful especially when reliable energy use data are not available for all industry sectors. However, there is still a margin for improvement in the current form of input-output-based approach (Treloar, 1998; Crawford, 2004; Acquaye, 2010).

A positive and strong relationship of embodied energy and cost has been underlined by the literature (e.g. studies such as Bullard and Herendeen, 1975; Costanza, 1980; Cleveland et al., 1984; Ding, 2004; and Langston, 2006). The cost of a building is actually found to have a strong positive correlation with its embodied energy. This correlation, however, weakens if the analysis is performed at a more detailed level. This research focuses on streamlining the process of embodied energy calculation and proposing a method to calculate the energy embodied in a building material completely. It also investigates the correlation of embodied energy and cost at the individual material level. If a material's cost or price is positively and strongly correlated to its embodied energy, a user-friendly and less resource-consuming approach based on cost may be developed in the future.

CHAPTER II

LITERATURE REVIEW*

2.1 STATE OF RESOURCE CONSUMPTION: DRIVERS

2.1.1 Context

Our home, the planet earth, holds finite resources such as raw materials, minerals, fresh water, and fossil fuels, which are either shrinking with time or facing a complete depletion in the future (Cairns, 2003; Wackernagel et al., 1999). These resources are collectively called the *natural capital* (Wackernagel et al., 1999). The question of when these resources will be depleted depends on the current and future rate of anthropogenic consumption. The resource consumption is a transformative process in which a resource undergoes through physical and chemical changes (e.g. fuel combustion and food digestion). Each process of consumption (input) results in an end product (output) such as waste and emissions (Lehmann, 2011). For instance, use of raw materials for construction results in construction waste and using fossil fuels for energy purposes causes harmful emissions (Hacker et al., 2008; Malla, 2009; Kofoworola and Gheewala, 2009). An increase in resource consumption could mean more waste, discharge, and emission to land, water, and air (Lehmann, 2011; Bruce, 2012).

Nature has an inherent capacity called the *biocapacity* to deal with the resource depletion and the resulting waste, discharge, and emission (Wackernagel et al., 1999). It replenishes the consumed resources by processing the waste through a series of natural cycles. There used to be a balance between the rate of consumption and replenishment (Wackernagel et al., 1999; Holdren and Eherlich, 1974), which has been disturbed. Currently, the rate of consumption has outrun the rate of replenishment (Wackernagel et al., 1999; Bruce, 2012). Nature also has an ability to recuperate from an adverse environmental impact as a

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result of anthropogenic activities. Brand (2009) discussed the concept of *ecological resilience* that is nature's ability to return to equilibrium after an environmental disturbance has happened. Nature's ability to absorb and process waste and emissions closely relates to the concept of *ecological resilience*.

2.1.2 Drivers

The two main determinants of the exponentially growing resource use are population and affluence (Holdren and Eherlich, 1974; Dietz and Rosa, 1997; Bruce, 2012; Fernández-Solís, 2008; Alcott, 2012). The consumption of resources increases with the growing number of people. Also, when people manage to afford a higher standard of living due to increased affluence, they consume more goods and services. The increased demand for goods and services exerts pressure on the *natural capital* (Holdren and Eherlich, 1974; Dietz and Rosa, 1997; Bruce, 2012; Alcott, 2012). Holdren and Eherlich (1974) examined the relationship between population growth and environmental burden and proposed an equation to determine the environmental disruption caused by anthropogenic activities. According to the equation:

$$Environmental\ disturbance\ = Population\ \times Per\ capita\ consumption \times Environmental\ burden\ per\ unit\ of\ consumption$$

Equation 2-1

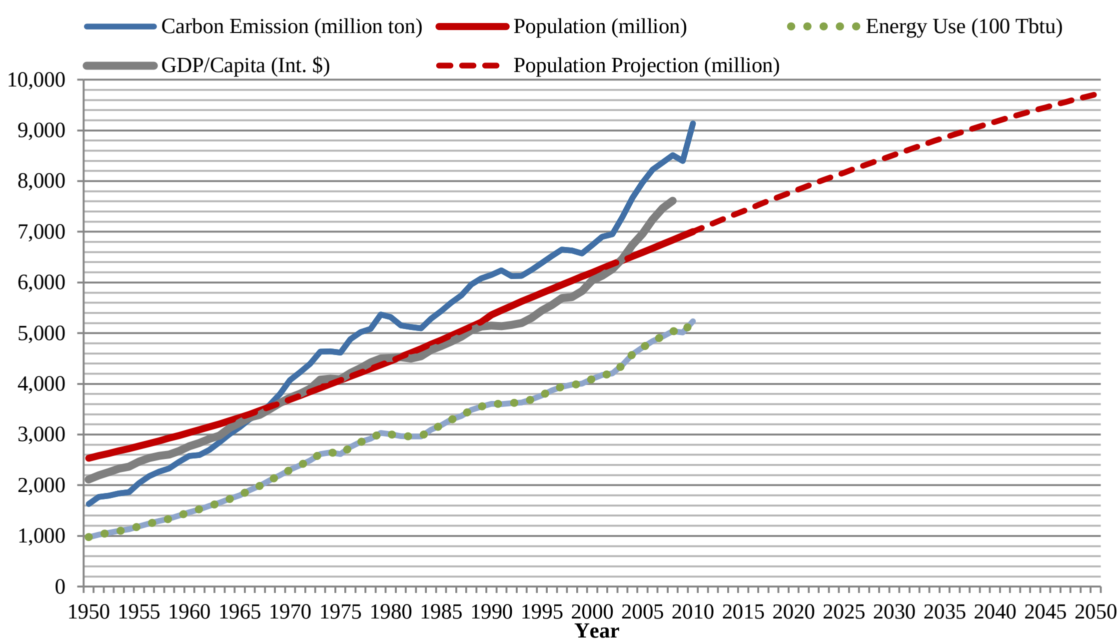


Figure 2-1: Growth in population, GDP, energy use, and resulting carbon emission

Dietz and Rosa (1997), Bruce (2012), and Alcott (2012) also supported the relationship of environmental disturbance to population growth and affluence as indicated by the above equation. The equation also highlights global population and increased affluence as the main drivers of environmental disturbance. Figure 2-1shows the growth in global population between 1950 and 2010 based on the data sourced from the United Nation's Department of Economic and Social Affairs (UNDESA, 2011). It is evident that a steady growth in global population resulted in an increased energy consumption primarily from fossil fuel sources. The emission of carbon mainly due to fossil fuel combustion closely followed the energy use curve. It is interesting to note how a steady growth in per capita Gross Domestic Product (GDP) also followed the population growth curve closely. A growing GDP indicates an increased demand of goods and services (a rise in affluence) resulting in mounting emissions as seen in Figure 2-1.

The UNDESA also provided the population projections for the future as shown in Figure 2-1. The global population, which is over 7 billion currently, is expected to reach 9-10 billion by the end of 2050 (Bruce, 2012; UNDESA, 2011). With nearly 10 billion people on the earth in 2050, one can imagine the grave situation of resource consumption and emission. The most important aspect of the future global population is that most of its growth will occur in developing and underdeveloped countries (Bruce, 2012). The economy of the world's most populated countries such as India and China is developing at a faster rate and the affluence level is also increasing (Bruce, 2012; Mendelsohn et al., 2012). Imagine how much resources would be consumed once the people in these countries attain the same standard of living as the developed countries (Fernández-Solís, 2008; Bruce, 2012). Figure 2-2 shows the historic carbon emission trends (1950-2009) for four of the top ten carbon emitters of the world (based on Marland et al., 2010; EPI, 2010). It is scary to see the exponential increase in carbon emission in countries where the maximum population growth is projected to occur.

2.1.3 Greenhouse Gas Emissions

Among the major impacts of global population increase and rising affluence is the growing concentration of anthropogenic greenhouse gases (GHG) such as CO_2, methane, and nitrous oxide in the atmosphere (Dietz and Rosa, 1997; Jiang et al., 2008; Alcott, 2012). A fraction of the emitted carbon is absorbed by the ocean and biomass (e.g. plants) and the remaining fraction is released to the atmosphere in a naturally occurring carbon cycle. Although the carbon cycle remained mostly balanced in the distant past, after the industrial revolution a significant rise in CO_2 levels (36%) has disturbed its equilibrium (USEPA, 2011p). One of the major impacts of an increased level of GHG, particularly CO_2, in the atmosphere is global warming leading to the phenomenon of climate change (Nordhaus, 2010; Mendelsohn et al., 2012; Bruce, 2012).

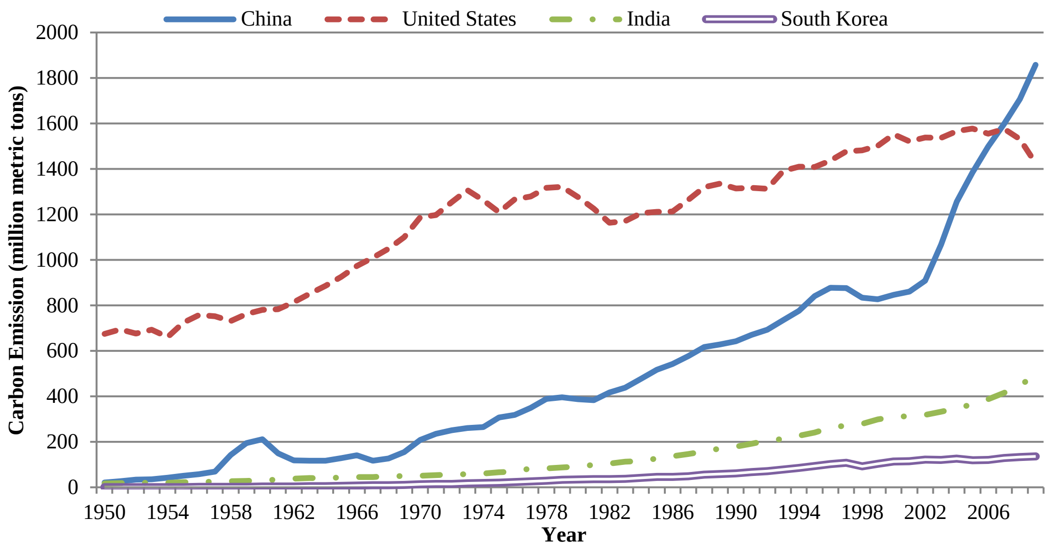


Figure 2-2: Top carbon emitters of the world and carbon emissions

IPCC (2007a) reported that the global CO_2 concentration in the atmosphere has increased from 280 ppm in the preindustrial era to 379 ppm in 2005. Three signs of global warming are evident. First, the surface temperature of the earth has increased by 1.33^{o}F (± 0.32 ^{o}F) in the last century (IPCC, 2007a). Second, an increase of 1.8 and 3.1 mm per year in the average sea level of the globe has been recorded between 1961 to 2003 and 1993 to 2003 respectively (IPCC, 2007b). Third, an annual average decrease of 2.7% (7.4% in summer) in Arctic sea ice has been recorded (IPCC, 2007b). These evidences are enough to suggest a slow but steady warming of the planet. The current trend of global warming if it continues would cause intense ecological, social, and economic damages in the future (Urge-Vorsatz and Metz, 2009). According to Mendelsohn et al. (2012) and Nordhaus (2010), increased occurrences of extreme weather events such as hurricanes and storms were mainly due to the climate change. They also warned that these weather events would be more intense and frequent in the future.

2.1.4 Energy Use and Carbon Emissions

The primary source of CO_2 emission is the use of fossil fuels for energy purposes (IPCC, 2007a). As reported by USEPA (2011p), nearly 95% of the United States' total CO_2 emissions, between 1990 and 2009, were a result of fossil fuel combustion for electricity production, transportation, residential and commercial operation, and manufacturing purposes. In 2009, nearly 42% and 33% of the total CO_2 emissions was attributed to electricity production and transportation, respectively. Malla (2009) revealed that the share of electricity production in the total global CO_2 emissions has increased from 36% in 1990 to 41% in 2005. Moreover, this share was projected to reach 45% by the end of 2030. These values clearly underlined power generation as the major source of carbon emissions. The population projection, as shown in Figure 2-1, clearly demonstrated that with the growing population and affluence, the demand for electricity and fuel (mostly fossil fuel) would also build up leading to more carbon emissions to the atmosphere.

How do we address the issue of mounting CO_2 concentration in the atmosphere? The answer lies in the equation proposed by Holdren and Eherlich, (1974). A controlled population growth, optimized per capita consumption, and improved levels of efficiency in production could bring in significant environmental benefits. In order to control the current and future rate of environmental degradation, it is critical that a balance between *natural capital* consumption and replenishment is gradually restored and the earth's *ecological resilience* is reinforced.

2.2 CONSTRUCTION INDUSTRY AND ENVIRONMENT

2.2.1 Raw Material Consumption

The construction industry is one of the largest consumers of renewable and nonrenewable resources (Palit, 2004; Horvath, 2004; Holtzhausen, 2007; Dixit et al., 2010). It depletes 40% of global energy and 16% of global water annually. Every year, nearly two-fifths of the global raw stone, sand and gravel supply, and one-fourth of world's total virgin wood supply is consumed in construction activities (Ding, 2004; Langston and Langston, 2008; Dixit et al., 2010). In the United States, between 1975 and 2003, the use of construction materials such as steel and cement increased by 108 and 57%, respectively (USGS, 2013). Table 2-1 lists the percent growth in the use of common construction materials in the United States. According to a study (Matos, 2009) conducted by the United States Geological Survey (USGS), the use of total raw materials reported in 2006 was over 26 times the consumption in the year 1900. This increase was 4.7 times more than the growth of the United States' population in the last century (CSS, 2012). Figure 2-3 illustrates the exponential rise in raw material consumption in the United States in the last 106 years. It is evident that construction materials held the largest share of the total raw material use. It is interesting to note that the only time the raw material use actually declined was during the events of adverse economic impacts such as a war, energy crisis, or an economic recession. Nearly 12% of the total material consumed annually was discharged as trash and 40% was released to the atmosphere (CSS, 2012). Disappointingly, only 5% of the total material consumption was recycled (CSS, 2012).

Table 2-1: Percent increase in the use of common construction materials

Duration	Percent Increase in Consumption: United States Construction Industry						
	Gypsum	Aluminum	Steel	Cement	Lime	Sand & Gravel	Copper
1975-2003	223.0%	12.1%	74.2%	76.8%	114.5%	67.9%	148.9%
1991-2003	107.3%	18.2%	107.7%	56.6%	112.7%	63.8%	33.0%

A comparable growth in building construction was also recorded. A 94% increase is reported in the total number of building permits issued in the United States between 1990 and 2006 (USCB, 2012). Likewise, the value of total construction put in place rose by over 140% between 1993 and 2006 (USCB, 2013).

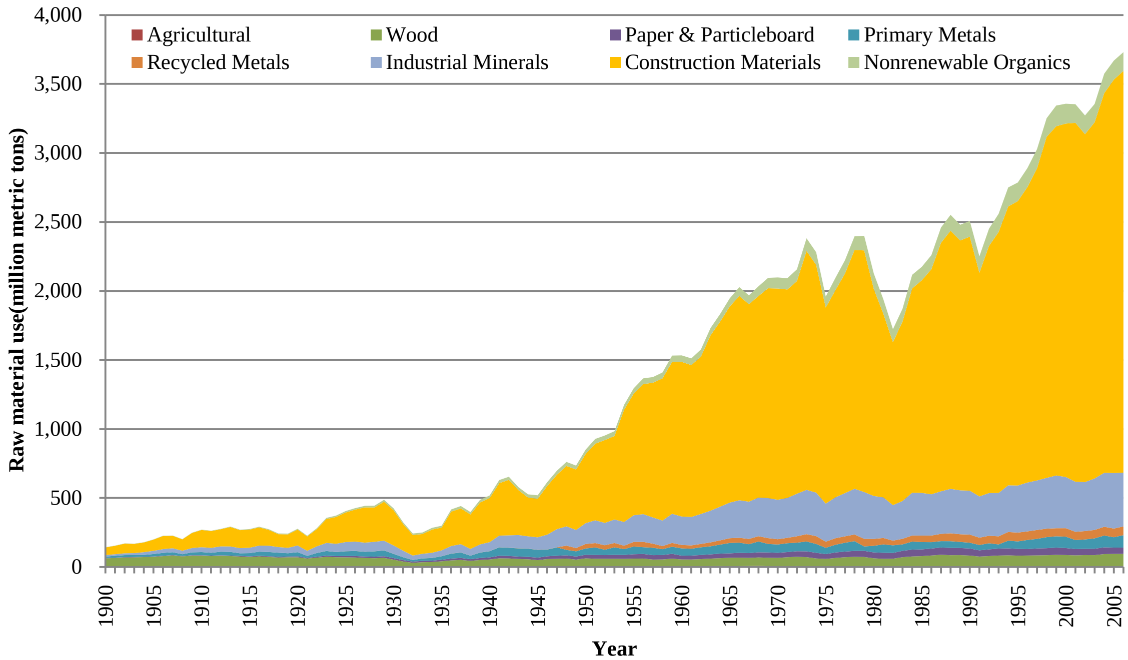


Figure 2-3: Total raw material use in the United States by categories

Table 2-2: Composition of building-related C&D waste

Material	Fraction in the total C&D waste
Concrete and rubble mix	40-50%
Wood	20-30%
Drywall	5-15%
Asphalt (roofing)	1-10%
Metals	1-5%
Bricks	1-5%
Plastics	1-5%

2.2.2 Waste Generation

Use of raw materials in such enormous quantities also resulted in construction and demolition (C&D) waste. Most of the C&D waste came from the building and non-building sectors (e.g., heavy civil, transportation, energy). Table 2-2 provides a composition of building-related C&D waste generated each year (USEPA, 2012).

On an average, a total of 160 million tons of building-related C&D waste is accumulated each year in the United States (USEPA, 2009a). Approximately half (48%) of the total C&D waste comes from building demolition activities. Building renovation and new construction activities constitute 44% and 8% of the total building-related C&D waste, respectively (USEPA, 2009a). Table 2-3 presents the amounts of building-related C&D waste reported by the USEPA for 1998 and 2003. The yearly estimate of the total C&D waste was not available, and the USEPA reported estimates for only 1998 and 2003 (Cochran and Townsend, 2010). Each year roughly 170,000 buildings are constructed and 45,000 buildings are demolished in the commercial sector (USEPA, 2009a). In the residential sector, nearly 245,000 buildings are demolished annually (USDOE, 2001). According to an online article by Granger (2009), the total building and non-building-related C&D waste could add up to 300 million tons each year.

Table 2-3: 1998 and 2003 building-related C&D waste (USEPA, 1998 and 2009b)

Study Year	Type of Building	Construction (lb/ft2)	Renovation (million tons)	Demolition (million tons)
1998	Residential	3.89	19.70	31.90
	Non-residential	4.27	45.10	28.04
2003	Residential	4.39	19.00	38.00
	Non-residential	4.34	65.00	29.00

2.2.3 Greenhouse Gas Emission

The building sector alone is responsible for 33% of the total global carbon emissions (Urge-Vorsatz and Novikava, 2007; Marszal et al., 2010). In the United States, buildings alone release roughly 39% of the total CO_2 emission 21% of which comes from residential buildings (USEPA, 2009a). Levermore (2008) reported that, between 1971 and 2002, the annual growth rate in building-related carbon emissions was 1.4 and 2.2% for the residential and commercial sectors, respectively. By the end of 2030, the emissions from building sector were projected to grow by nearly 72% from its 2002 levels (Levermore, 2008). Most of the carbon emission released by a building came from fossil fuel combustion. on-site. The total greenhouse gas emission resulting from a construction site in 2002 was 131 million tons of CO_2 equivalent and 100 million tons of that was attributed to fossil fuel combustion (USEPA, 2008; Zhu et al., 2010). Figure 2-4 illustrates the pattern of CO_2 emissions from various energy sources used in the residential and commercial sectors. As mentioned earlier, a decreasing trend in the emissions was probably due to the reduced energy use and economic activities during the economic meltdown.

According to the 2002 Economic Census (USCB, 2005), the use of electricity and natural gas in the United States' construction industry has increased by 130% and 23%, respectively between 2002 and 2007. As the electric power sector still remains the biggest contributor (33-34%) to the nation's total CO_2 emissions, any increase in electrical demand would raise carbon emission proportionally (USEPA, 2013). For instance, in 2006, a 2.5% increase in electricity demand resulted in a 3% increase in CO_2 emissions from the electric power sector (USDOE, 2008). Most of the values provided in the literature discussed so far included emissions resulting from only the direct use of energy (e.g., air-conditioning, lighting, powering building appliances). The indirect use of energy (e.g. energy of building materials and products) is seldom included in the calculation of emissions.

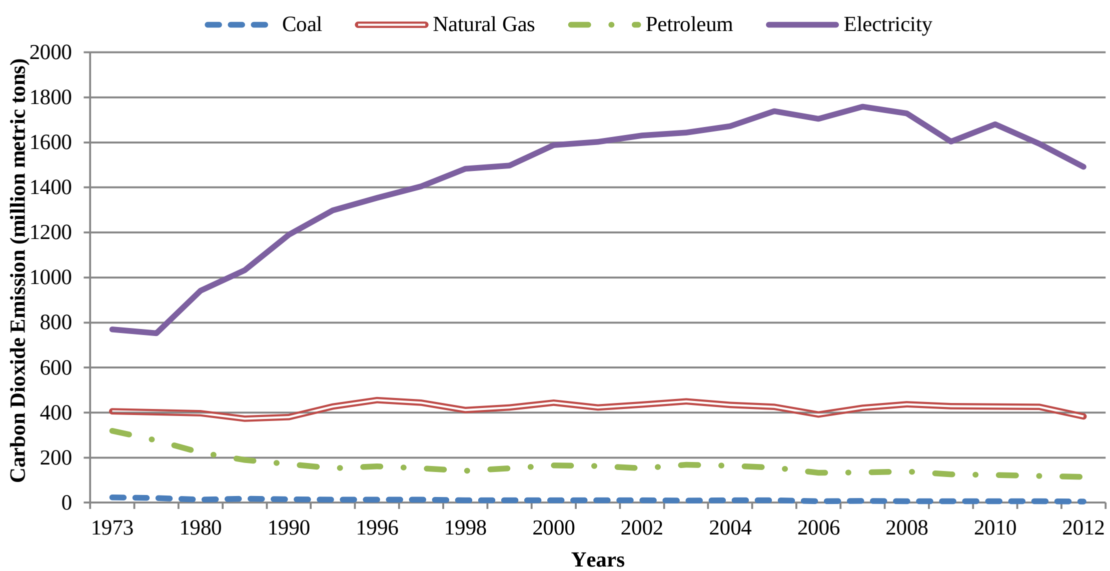


Figure 2-4: Carbon emissions from various energy sources

2.3 ENERGY USE IN BUILDINGS

Buildings consume nearly 40% of global energy annually in their life cycle stages of construction, use, maintenance, and demolition. The energy is consumed by buildings directly or indirectly in a primary (e.g., natural gas, oil) or delivered (e.g. electricity) form (Dixit et al., 2010; Marszal et al., 2010). In the United States, the residential structures deplete an average 55% of the total primary energy consumed by the entire building sector each year (Otto et al., 2010). In the developing countries, the situation of energy consumption is grave. In China, the residential building sector is responsible for 20-27% of the nation's total energy consumption and if the building material production and construction processes are included, this figure reaches up to 37% (Xie, 2011). Gupta (2009) has revealed that the energy consumed in operating a building in the United Kingdom represented roughly 50% of the nation's energy. This figure for a rapidly developing country such as India could be roughly 30% of the total national energy consumption. However, the situation could turn grave when the percentage of population currently living in urban areas jumps from 28% to 40% by the end of 2020 (Gupta, 2009). Moreover, the construction industry in India is currently growing at a 9.2% rate annually, which is nearly two times the global growth rate of 5.5% (Gupta, 2009).

2.3.1 Life Cycle Energy Components: Embodied and Operating Energy

The total energy consumed by a building over its service life is known as life cycle energy. The total life cycle energy is composed of two primary components: operating and embodied energy (Treloar, 1998; Hegner, 2007). During the use phase when the building is occupied, energy sources such as electricity and natural gas are used in the processes of space conditioning, lighting, and powering building appliances. This fraction of energy is called operating energy (Crowther, 1999; Hegner, 2007; Dixit et al., 2010). Electricity and fuels such as oil, natural gas, and coal are also consumed when not only the building but also its constituent materials are manufactured and delivered. This fraction of energy remains sequestered in the final product when the product is delivered for the end use. The total energy embedded in all products and processes that are used in constructing a building is known as embodied energy.

2.3.1.1 Embodied Energy: Definition and Interpretation

Buildings are constructed with a variety of building materials, each of which consumes energy throughout its life cycle stages of manufacture, use, deconstruction, and disposal. The energy consumed in these stages is known as the embodied energy of a building material (Vukotic et al., 2010; Dixit et al., 2010). Similarly, each building also consumes energy during its life cycle stages such as initial construction, use and maintenance, renovation, demolition, and disposal. Energy is also expended in various administration and transportation processes during the preconstruction phase. Post construction phases such as maintenance, renovation, demolition, and disposal also consume energy. The total energy consumed in all of these life cycle stages is collectively interpreted as the life cycle embodied energy of a building (Cole and Kernan, 1996; Vukotic et al., 2010).

According to Miller (2001), the term "embodied energy" is subject to numerous interpretations rendered by different authors and its published measurements are found to be quite unclear. Table 2-4 presents embodied energy definitions given by various research studies. Studies such as Hegner (2007) and Upton et al. (2008) defined embodied energy as the nonrenewable fraction of the total embodied energy. Clearly, current embodied energy definitions represent differences of opinion about the material and energy inputs to be included in an energy analysis (Hegner, 2007; Nebel, 2007). The embodied energy of a building is made up of two major components: direct energy and indirect energy (Treloar, 1998; Crawford and Treloar, 2003; Crawford et al., 2006; Khasreen et al., 2009; Dixit et al., 2010).

Table 2-4: Embodied energy definitions

Source	Embodied Energy Definition Provided
Crowther (1999)	"The total energy required in the creation of a building, including the direct energy used in the construction and assembly process, and the indirect energy, that is required to manufacture the materials and components of the buildings."
Treloar et al. (2000)	"Embodied energy (EE) is the energy required to provide a product (both directly and indirectly) through all processes upstream (i.e. traceable backwards from the finished product to consideration of raw materials)."
Dewick and Miozzo (2002)	"The total amount of energy used in the raw materials and manufacture of a certain quantity of material."
Sartori and Hestnes (2007)	"The sum of all the energy needed to manufacture a good. It may or may not include feedstock energy. Generally expressed in term of primary energy."
Li et al. (2007)	"Embodied energy is the total energy embodied in construction materials during extraction, manufacturing, transportation, assembly, maintenance, demolition, and final disposal processes."
Crawford et al. (2006)	"The embodied energy of an entire building, or a building material or product in a building, comprises of indirect and direct energy. Indirect energy is used to create the inputs of goods and services to the main process, whereas direct energy is the energy used for the main process."
HUB (2009)	"Embodied energy is the sum total of the energy used in a product from raw material extraction and transport to manufacturing, installation, use, disassembly, recycling and disposal and/or decomposition."
Crawford et al. (2010)	"Embodied energy accounts for the energy associated with the manufacture of products and materials including those resulting from the manufacture of goods and services used during this process."
Uzsilaityte and Maitinaitis (2010)	"Embodied energy is the amount of energy consumed to create a product, material or service."
Ramesh et al. (2010)	"Embodied energy is the energy utilized during manufacturing phase of the building. It is the energy content of all the materials used in the building and technical installations, and energy incurred at the time of erection / construction and renovation of the building."

Direct Energy*:* Energy consumed directly in on-site and off-site operations such as construction, prefabrication, assembly, transportation, and administration is termed direct energy (Fay and Treloar, 1998; Ding, 2004; Dixit et al., 2010). For instance, electricity consumed by stone cutters and drilling machines and oil used by earthmovers and other heavy equipment is a direct consumption of energy. When a building is occupied it is also maintained, and some of its components are replaced periodically (Cole, 1996; Ding, 2007; Dixit et al., 2012b). For example, carpet change, repainting of walls, repair of any physical damage, and building system maintenance are maintenance and replacement activities. Direct energy is used when these activities are performed during a building's service life (Chen et al., 2001; Ding, 2007; Utama and Gheewala, 2009). At the end-of-life stage, when the building is dismantled and its materials and products are salvaged, electricity and fuels are consumed as direct inputs (Crowther, 1999;

Miller, 2001; Dixit et al., 2010; Vukotic et al., 2010). All of these energy inputs that are used directly are categorized as direct energy.

Indirect Energy*:* Energy used indirectly by a building through nonenergy inputs is known as an indirect component. For instance, energy spent in manufacturing the building materials, assemblies, and equipment installed in the buildings is considered an indirect component (Boustead and Hancock, 1978; Treloar, 1998; Crawford, 2004; Dixit et al., 2010; Marszal et al., 2010). A fraction of manufacturing energy of machines, equipment, and apparatus utilized to manufacture materials is also accounted for as an indirect energy component (Buchanan and Honey, 1994; Fay, 1999; Hammond and Jones, 2008; Hammond and Jones, 2010; Dixit et al., 2012a). Major quantities of materials, assemblies, and equipment are mainly utilized during a building's initial construction. However, during the use phase, these products may also be consumed in the processes of maintenance and replacement. Therefore, a considerable portion of the indirect energy component may be spent during a building's the use phase (Cole, 1996; Dixit et al., 2013).

2.3.2 Life Cycle Energy Model

The total life cycle energy used by a building includes direct and indirect components of embodied and operating energy. This energy use is distributed among three major stages of the life cycle: construction, use, and end-of-life stage. Figure 2-5 shows an embodied energy model and illustrates the energy use associated with each of the three stages. The energy used in manufacturing building materials, assemblies, and equipment and in processes such as construction, installation, fabrication, transportation, and administration during a building's construction stage is collectively termed the Initial Embodied Energy (IEE) (Cole, 1996; Cole and Wong, 1996; Dixit et al., 2010; Vukotic et al., 2010; Dixit et al., 2013). The Recurrent Embodied Energy (REE) includes energy used in maintenance and replacement activities during the use phase of a built facility. At the end of its service life, when a facility is demolished and its materials are transported for reuse, recycling, and disposal, the total energy consumed is known as Demolition Energy (DE) (Cole, 1996; Cole and Wong, 1996; Dixit et al., 2010; Vukotic et al., 2010; Dixit et al., 2013). The total life cycle embodied energy (LCEE) of a building is the sum of its initial, recurrent, and demolition energy. The total life cycle energy (LCE) of a built facility includes LCEE and operating energy (OE) (Cole, 1996; Cole and Wong, 1996; Dixit et al., 2010; Vukotic et al., 2010; Dixit et al., 2013).

2.3.2.1 Initial Embodied Energy (IEE)

The IEE is composed of the total energy used during the building material production and building construction phase (Cole, 1996; Cole and Wong, 1996; Vukotic et al., 2010; Dixit et al., 2010). In the material production phase, the upstream processes such as raw material extraction, treatment, and transportation to production unit are quite energy intensive. The main production process involves use of both the electricity and fuels. Fuels are used both as an energy source and as a feedstock material. In the downstream, energy is expended when the final product is delivered to a construction site or a material supplier. During construction phase, on-site and off-site processes such as material delivery, storage, construction, fabrication, administration, and project closeout also consume energy. The sum of all energy spent in delivering a building as a final product is known as IEE (Cole, 1996; Cole and Wong, 1996; Vukotic et al., 2010; Dixit et al., 2010).

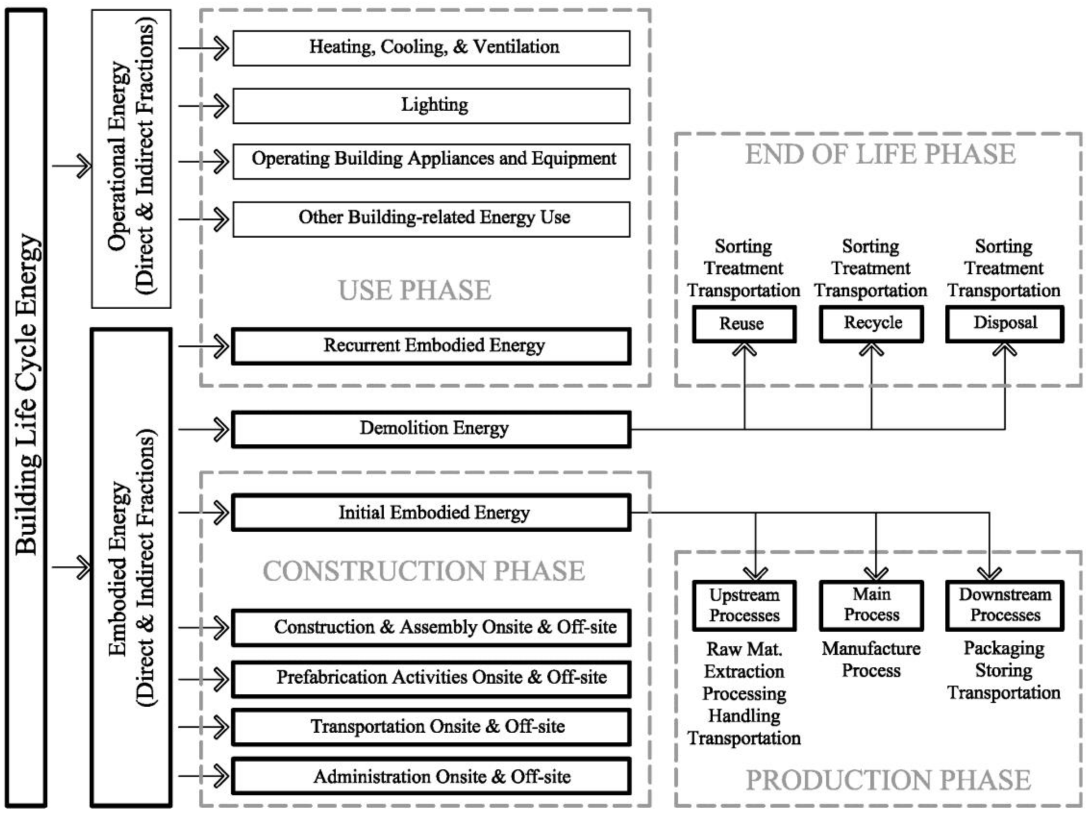


Figure 2-5: Embodied energy model for a building

Building Material Production Stage: The process of manufacturing building materials and products consumes energy and nonenergy inputs such as electricity, fuel, raw materials, and water (Thormark, 2000; Dixit et al., 2013). The overall manufacturing is completed in three main stages: main manufacturing, upstream, and downstream. In the main production stage, direct (energy inputs) and indirect energy (nonenergy inputs) are used both as an energy source and as a feedstock material (Trusty, 2006; Sartori and Hestnes, 2007; Ardente et al., 2008). Petroleum products such as oil and natural gas are utilized not only for energy purposes but also as a raw material in producing, for instance, petrochemical and plastic products. All of the on-site and off-site transportation related to manufacturing is also considered a direct energy input (Ding, 2004; Dixit et al., 2013). In the upstream stage, the processes of raw material extraction, treatment, handling, storage, and transportation to the manufacturing unit also deplete energy and nonenergy sources that are counted as well (Cole, 1996; Ding, 2004; Vukotic et al., 2010). In the downstream of the main production process, when a finished product is packaged, labeled, stored, and transported to a construction site or a material supplier, energy is consumed directly and indirectly (Cole, 1996; Cole and Wong, 1996; Ding, 2004; Dixit et al., 2013). In some cases, the delivery of finished building materials to their destination could be quite energy intensive depending on the distance and mode of transport (Ding, 2004).

The sum of all energy used up directly and indirectly in the main production, upstream, and downstream processes until the final product reaches its destination is considered building materials' production energy. The energy of material production represents the largest share of a building's total LCEE (Chen et al., 2001; Scheuer et al., 2003; Vukotic et al., 2010). In an analysis of two high-rise residential buildings in Hong Kong, Chen et al. (2001) concluded that the manufacturing energy shared up to 90-92% of a building's total LCEE. In a similar study of a six-story university building done by Scheuer et al. (2003), the total energy embodied in material production was found to be nearly 94% of the total LCEE (excluding construction and transportation). In Sweden, a study by Adalberth (1997b) found that nearly 64-65% of the total LCEE (over 50 years' service life) of three prefabricated single-family dwellings came from building materials' production. Similarly, Leckner & Zmeureanu (2011) studied a base case and a net-zero energy version of a two-floor house in Canada and found the share of building materials as 70% of the total LCEE over 40 years' service life. They used embodied energy data from Athena Impact Estimator developed by the Athena Sustainable Materials Institute. The proportions of building material manufacturing energy in the total LCEE calculated by Chen et al. (2001) and Scheuer et al. (2003) are higher than the ones calculated by Adalberth (1997b) and Leckner and Zmeureanu (2011). The value calculated by Scheuer et al. (2003) also included building materials used during replacement and maintenance processes over 75 years' service life, whereas Chen et al. (2001) did not include building systems in the maintenance and replacement phase. As mentioned earlier, the most commonly-used materials such as aluminum, steel, and plastics have a higher embodied energy. Table 2-5 shows the energy embodied in some of the commonly used building materials. Building materials such as cement (7.8 MJ/kg), glass (16-17 MJ/kg), plastics (70 MJ/kg), and insulation materials (16-105 MJ/kg) are quite energy intensive and contribute significantly to a building's IEE (Chen et al., 2001; Dimoudi and Tompa, 2008).

It can be seen that there is a considerable variation in the reported values of embodied energy. Energy intensive materials such as aluminum and polystyrene insulation have a wider embodied energy range of 130-379 MJ/kg and 58-116 MJ/kg, respectively. The embodied energy of one of the most widely used materials such as timber, ranged from 1.7-22.6 MJ/kg. According to Dixit et al. (2010), the embodied energy of most building materials differed across studies even within the same geographic location and time.

Table 2-5: Embodied energy of commonly used building materials as reported in literature

	Embodied Energy in MJ/kg of Building Material													
	Virgin Steel	Primary Aluminum	Cement	Glass	PVC	Fiberglass Ins.	Gypsum/Plasterboard	Bricks	Concrete	Plywood	Timber	Aggregates	Cellulose Ins.	Polystyrene, Exp.
Honey & Buchanan (1992)	34.9	129.5	8.9	31.5	96.0	23.0			3.1	18.9	1.7	0.3		100.0
Kernan (1996)	28.0	274.0		18.7			9.8	2.5	0.8		9.9	0.3		105.0
Adalberth (1997a)	32.0			26.0	88.7		8.6		2.0		5.2			106.7
Blanchard & Reppe (1998)	37.3	207.8		18.4	77.4	24.5	3.8	4.5	1.6	8.3	5.8	0.9	3.2	100.3
Eaton Et al. (1998)	25.5	200.0					2.7	5.8	0.8		13.0			
Chen et al. (2001)	32.0	191.0	7.8	16.1	70.0	30.3	8.6	2.5	1.0	18.9	5.2	0.1	3.3	105.0
Alcorn (2003)	31.3	192.0	6.2	15.9	60.9	32.1	7.4	2.7	0.9	11.9	2.8	0.4	4.3	58.4
Scheuer et al. (2003)	30.6	207.0	3.7	6.8	60.7	17.6	0.9	2.7			10.8	0.2		94.4
Reddy (2004)	42.0	236.8	4.2					1.4						
Almeida et al. (2005)	10.1	160.2		18.4			4.0		1.1		0.7			100.4
Yohanis & Norton (2006)	42.0	236.8	5.9	25.8										
Pullen (2007)	55.5	378.5	6.6	83.6	121.5		13.3	5.4	2.4	11.9	22.6	1.7		
Crawford (2004)	97.5	259.1	14.5		141.8									
Huberman & Pearlmutter (2008)	35.0	211.0		18.0					1.2					116.0
Hammond & Jones (2008)	35.3		4.6	15.0					1.0	15.0	8.5			
Hammond and Jones (2011)	31.3	218.0	5.2	15.0	70.6	28.0	3.5	3.0	2.9	13.6	7.1	0.1	3.3	100.1
Ramesh et al. (2013)	28.2	236.8	6.7	25.8	158.0									

The energy embodied in building materials is also dependent upon the type of construction such as a wood, steel, or concrete frame. Table 2-6 shows a comparison of embodied energy of various types of residential construction in different environments across the globe. According to the studies presented in Table 2-6, a reinforced concrete construction with brick masonry is the most energy intensive construction. It is critical to note that in the most populated regions of Asia, the conventional type of construction is a reinforced concrete frame with brick masonry (Ramesh et al., 2013). In an analysis of a conventional multi-family residential building in India, Ramesh et al. (2013) found that steel (34%), cement (25%), and bricks (24%) accounted for most of the building's total embodied energy. It is also interesting to note that the dwellings constructed in a vernacular style and with locally available materials tend to have a smaller embodied energy value. Most of the vernacular materials produced locally involve more human labor than mechanical energy.

A comparative analysis of steel and concrete frame buildings performed by Guggemos and Horvath (2005) revealed that the embodied energy of material production can be up to 77 - 86% of their LCEE. In a recent study, Vukotic et al. (2010) analyzed the structure of steel and timber frame buildings and calculated the embodied energy of building materials as 79 - 88% of the total LCEE.

Table 2-6: Residential buildings' embodied energy in different locations and environments

Study	Location	Environment	Material	EE (MJ/m^2)
Almeida et al. (2005)	Portugal	Heating & Cooling Dominated (Temp Range: -3.5 to 35^{o}C)	Concrete & Timber with Sun-space & Trombe Wall	5.3
Almeida et al. (2005)	Portugal	Heating & Cooling Dominated (Temp Range: -3.5 to 35^{o}C)	RC & Brick with Sun-space & Trombe Wall	9.9
Huberman & Pearlmutter (2004)	Israel	Desert	Soil-cement Bricks with Insulation	1.1
Huberman & Pearlmutter (2004)	Israel	Desert	Fire Bricks with Insulation	3.8
Renping & Zhenyu (2006)	China	Hot-humid, Earthquake Prone	Vernacular: Stone, Wood, & Concrete	1.9
Renping & Zhenyu (2006)	China	Hot-humid, Earthquake Prone	Vernacular: Wooden Log House	0.2
Renping & Zhenyu (2006)	China	Hot-humid, Earthquake Prone	Vernacular: Brick & Concrete	3.1
Fossdal & Edvardsen (1995)	Norway	Cold	Timber Frame House	2
Fossdal & Edvardsen (1995)	Norway	Cold	Log House	1.8
Reddy & Jagdish (2003)	India		RC Frame & Burnt Brick	4.2
Reddy & Jagdish (2003)	India		Brick Masonry & RC Slab	2.9
Reddy & Jagdish (2003)	India		Stabilized Mud Blocks	1.6

Note: RC indicates reinforced concrete, EE denotes embodied energy

Table A1-26 in Appendix A1 provides values of building material embodied energy reported by studies across the globe. As expected, embodied energy values differed considerably not only across different regions but also within the same region owing to a wide range of building and environmental parameters. The values calculated by Treloar et al. (2001b) and Duell and Martin (2005) are higher possibly due to a more comprehensive calculation method. Both the studies utilized data from the input-output-based hybrid approach proposed by Treloar (1998), which is considered relatively complete than the available process-based approaches. Utama and Gheewala (2008) calculated smaller embodied energy due to a narrow scope of study that covered only building enclosure in the calculation. This points out differing scopes of studies and different calculation methods as other parameters that may cause variation in a building's embodied energy.

Strategies such as reuse and recycling could significantly lower the energy of manufacturing building materials (Chen, 2001; Thormark, 2001; Gao et al., 2001; Worth, 2007; Dixit et al., 2013). According to Chen et al. (2001), the use of recycled steel (EE: 10 MJ/kg) and aluminum (EE: 8 MJ/kg) can save up to

70 - 96% of the manufacturing energy of virgin steel (EE: 32 MJ/kg) and primary aluminum (EE: 191 MJ/kg). Two types of recycling occur at this stage. A material can be recycled through a postconsumer or pre-consumer recycling. A postconsumer recycling involves obtaining a recycled material from a source external to the industry meaning the material is recycled after a consumer has already used it. Such a recycling across industries is also known as what Treloar et al. (2003) and Thormark (2002) have defined, an open loop recycling. In the pre-consumer recycling, recycled materials are sourced within the manufacturing industry. In this case, the material has not reached its final consumer before being recycled. Pre-consumer recycling is also termed closed loop recycling (Thormark, 2002; Treloar, 2003; Meil et al., 2004). At least 60% of the total manufacturing energy can be conserved by using recycled materials (Chen et al., 2001).

Transportation Energy: The finished building materials are transported from the manufacturing unit to a construction site or material supplier, which may be located in the same country or overseas. Hence, building materials could be distributed locally, imported from a foreign country, or exported to other locations involving a variety of transportation modes and consuming a wide range of energy sources (Peuportier, 2001; Chen et al., 2001; Miller, 2001; Lucuik et al., 2006). Building materials and products may be hauled to their point of use by surface (road and rail), water (boats and ships), or air transportation depending on the destination (Peuportier, 2001; Chen et al., 2001). According to Fay (1999), the energy used by sea vessels may be just 10% of the energy used in air transportation. Studies such as Chen et al. (2001) reported that energy use in domestic surface transportation of building material could be negligible, whereas exporting or importing building products could be very energy intensive. However, in an analysis of a modular home, Kim (2008) found that the energy consumed in domestic transportation of materials was nearly 8% of its total embodied energy. Peuportier (2001) questioned whether a return trip should be counted in the calculation, particularly in the case of a one-way trip delivery, as it is most likely that the delivery vehicle (e.g. trucks) may return empty. Eventually, only half of the return distance was included, as chances of trains and ships returning empty are highly unlikely. Miller (2001) reported that if the return distance and road infrastructure are considered, the energy embodied in transporting building materials may increase drastically.

The fraction of energy embodied in material transport is widely debated in the literature. Fay (1999) cited Miller (1996) who determined that the transportation energy consumed in a building was roughly 6% of the total LCEE. Later, Miller (2001) determined that the transportation energy was 1 - 1.5% of the total life cycle embedded energy (based on published data) and it could increase if the energy of return trips, vehicle manufacture, construction of roads, and other transport infrastructure were included. Whether to include the indirect fraction of energy associated with the transport infrastructure, automobile production, and labor in the transport energy calculation is still a contentious issue. Chen et al. (2001) found a larger value of transportation energy (7% of the LCEE) due to inclusion of surface and sea transportation of imported building materials. They also concluded that the energy embedded in surface transportation was negligible. This is particularly true in the case of Hong Kong where most raw materials come from overseas. Worth et al. (2007), on the other hand, excluded the transport energy of imports from the embodied energy calculations. Kim (2008) found a higher energy of transport as 7% of the total LCEE due to inclusion of both the material and employee transportation. This opens a new topic of debate, whether energy of transporting materials should be mixed with the transportation energy spent during the construction stage (Vukotic et al., 2010).

Fay (1999) concluded that the amount of transportation energy depends on a variety of factors such as travel distance, type of vehicle and fuel, number of trips, truck payloads, traffic conditions, road conditions, and competence of vehicle drivers. According to Vukotic et al. (2010), energy of transport for materials such as sand and gravel could be much higher than their production or procurement energy. Vukotic et al. (2010) cited a study performed by Reddy and Jagdish (2003), who determined that in the case of some construction materials, the transportation energy was considerably higher. Figure 2-6 illustrates production and transportation energy embodied in some of the construction materials. It can be seen that for materials such as sand and aggregates, the energy embodied in transportation was much higher than the production energy. Even for materials such as burnt clay bricks, the energy of transport was 4 - 8% of its manufacturing energy. Note that the production energy of burnt clay bricks, Portland cement, and steel was much higher and it is not shown completely in Figure 2-6 in order to show relatively lower transportation energy. Another reason for the differing energy of transportation is that some materials such as sand, gravel, stone, and bricks (70-100 km) may be sourced locally using trucks, whereas materials such as aluminum, steel, insulation, and plastic may be delivered from a long distance using rail transport (400-500 km) (Reddy and Jagdish, 2003). Trucks consuming diesel to haul much smaller quantities of materials than a train usually consume more energy per unit of material delivered (Reddy and Jagdish, 2003). Transportation energy can be much higher in the case of reused or recycled material due to relatively lower manufacturing energy (Chen et al., 2001; Vukotic et al., 2010). Chen et al. (2001) found that the fraction of energy of transporting recycled steel and aluminum was much higher.

Figure B1-1 in Appendix B1 shows values of transportation energy as a percentage of the total material's embodied energy calculated by various studies around the globe. As discussed earlier, transportation energy values associated with building material transport vary considerably (actual and percent values with a standard deviation of 0.2 and 7.8, respectively). Table 2-7 lists average transportation energy values calculated by published literature. The average values vary with a range of 0.01 - 0.66 GJ/m^2 and a standard deviation of 0.18.

Construction Energy: The construction energy is consumed mainly in on-site and off-site construction, installation, fabrication, transportation, and construction administration activities (Cole, 1999; Pullen, 2000a; Vukotic et al., 2010; Dixit et al., 2013). Resources such as labor, materials, equipment, and construction vehicles that are transported, maintained, and used during the construction phase deplete energy directly and indirectly (Cole, 1999; Vukotic et al., 2010). For instance, diesel burnt by an earth moving machine is a direct energy use, whereas the energy consumed in manufacturing the machine represents the indirect energy component. The food consumed by labor is a direct consumption, whereas the energy used to prepare the food and to keep the human body fit for work is an indirect consumption (Cleveland and Costanza, 2008; Alshboul and Azoubi, 2008; Dixit et al., 2013). In some geographic locations, conventional construction processes are labor intensive involving considerable amount of human energy (Huberman and Pearlmutter, 2008; Alshboul and Azoubi, 2008). Therefore, the total construction energy should be calculated as a sum of human and mechanical energy (Dixit et al., 2013). However, Gao et al. (2001) mentioned that human energy may be much smaller than mechanical energy. They also quantified that one liter of diesel is equivalent to two laborers working over six days. Pullen (2000a) found that at least 3% of construction energy can be attributed to labor and 28% to equipment. Current embodied energy methods fail to include the human energy component of total embodied energy (Langston and Langston, 2007) into the calculations. Moreover, a clear and straightforward method to estimate human energy is still lacking (Langston and Langston, 2007; Pulselli et al., 2009).

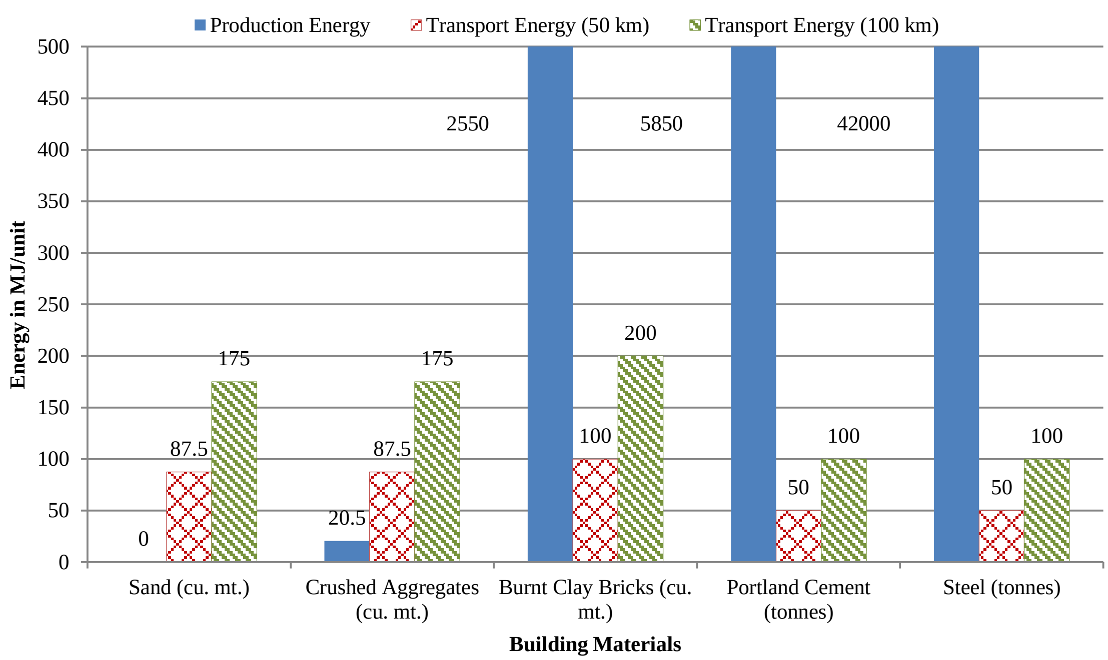


Figure 2-6: Higher transportation energy of some construction materials

Table 2-7: Average embodied energy of materials and transportation energy

	Energy Values in GJ/m^2	
Study	Materials Embodied Energy	Transportation Energy
Adalberth (1997b)	3.00	0.13
Sattler & Sperb (2000)	1.21	0.07
Chen et al. (2001)	4.48	0.51
Chulsukon et al. (2002)	3.04	0.17
Thormark (2002)	5.17	0.20
Scheuer et al. (2003)	5.40	0.31
Almeida et al. (2005)	7.59	0.66
Thormark (2006)	3.85	0.21
Johnson (2006)	0.77	0.20
Nassen et al. (2007)	3.10	0.65
Thormark (2007)	3.85	0.26
Kim (2008)	3.84	0.19
John et al. (2008)	2.98	0.11
Fridley et al. (2008)	8.64	0.05
Utama & Gheewala (2009)	0.88	0.01
Shiu et al. (2009)	3.11	0.12
Sobotka & Rolak (2009)	0.74	0.22
Vukotic et al. (2010)	2.49	0.19
Leckner & Zmeureanu (2011)	3.30	0.06
Ramesh et al. (2013)	6.94	0.27
Average		**0.23**

Most studies have a tendency to use a fixed value for determining the energy embodied in construction processes (Vukotic et al., 2010). One problem with that approach is that all of the building and construction types are assumed to use a similar amount of energy, which may not be the case. For instance, a residential and a commercial building would certainly have different construction energy values. The amount of construction energy involved in a building depends to some extent on the type of construction. Cole (1999) determined that steel structures consumed the least amount of construction energy (3 - 7 MJ/m2), whereas a concrete structure used higher construction energy (20 - 120 MJ/m2). Surprisingly, wood framed buildings, in Cole (1999), held more construction energy (8 - 20 MJ/m^2) than the steel framed buildings. Recently, Vukotic et al. (2010) calculated construction energy as 6% and 8.5% of the IEE of steel and timber structures, respectively. These values substantiated the results of Cole (1999), who calculated more construction energy in wood than the steel frame buildings. Cole (1999) and Pullen (2000a) also asserted that construction energy is considered insignificant as compared to materials' embodied energy. In addition, little information is available in the literature on how to quantify construction energy.

According to Cole (1999), three types of energy use during a construction process are significant: energy use by construction equipment, transportation, and by space conditioning equipment. On-site and off-site construction-related transportation includes moving building materials as well as labor and equipment. According to a study by Pullen (2000a), transportation of equipment and labor accounted for 69% of the total construction energy. Construction workers and administrative staff commute to construction sites and other places such as regional and corporate offices using mostly individual or sometimes shared vehicles (Cole, 1999). Heavy and light construction equipment such as cranes, loaders, and forklifts are also moved during the course of construction. Usually, the transportation of workers involves the use of gasoline, whereas moving and operating heavy equipment consumes fuels such as diesel. Fay (1999) cited studies by Stein et al. (1981), Baird et al. (1983) and Viljoen (1995), which determined the construction energy within a range of 6 - 17% of the total LCEE. In a similar study, Pullen (2000a) referred to studies by Ballantyne (1980), Lord (1994), and Lawson (1996) who found the construction energy within the range of 7 - 15% of the total LCEE. Cole (1999) included transportation of heavy equipment and workers in the calculation and found higher construction energy (7 - 10% of IEE). Much like Cole (1999), Vukotic et al. (2010) also counted the transportation of materials and labor during the materials' production and construction stages.

Figure 2-7 shows the average values of construction energy in various types of construction reported by studies mentioned in Table 2-8. Table 2-8 provides the average values of materials' embodied energy and construction energy reported in the literature. The average results in Figure 2-7 further support the findings of Cole (1999) and Vukotic et al. (2010) that the steel frame buildings required less construction energy than the wood frame. In addition, concrete frame is the most energy intensive type of construction. Increased need of labor, equipment, and formwork for concrete construction may be among the possible reasons for its higher energy requirement. The average reported values ranged from 0.01 - 1.18 GJ/m^2 and varied with a standard deviation of 0.34.

A large amount of waste is generated when building materials are moved, installed, and transformed during the construction process (Chen et al., 2001; Treloar et al., 2003). Energy embedded indirectly in construction waste could be significant, and would be lost if not recovered by reuse and recycling (Vukotic et al., 2010; Treloar et al., 2003). Construction waste may be hazardous and may also carry adverse environmental impacts if not handled properly. The amount of waste generated in the construction processes depends on a waste factor, which is the percentage of a material that may be wasted during the material's use (Worth et al., 2007; Treloar et al., 2003; Adalberth, 1997b; Blengini, 2009). Studies have derived different waste factors for different building materials. Table 2-9 presents the waste factors calculated by various studies. Materials can also be reused in the construction process without changing their current forms (Chen et al., 2001; Thormark, 2001). Building products that are made of materials such as wood and metals can be reused for the same or different purposes. The C&D debris that includes mostly concrete and brick can be reused as gravel in the construction of buildings (Thormark, 2001).

Figure 2-7: Construction energy as a percent of building materials' embodied energy

Table 2-8: Construction energy as a fraction of embodied energy of building material production

Study	Construction Type	Material EE GJ/m^2	Construction EE GJ/m^2	Fraction %
Treloar (1993)	Concrete	8.30	0.47	5.64
Treloar et al. (2001e)	Brick	9.86	0.88	8.88
Chen et al. (2001)	Steel	4.48	0.12	2.59
Chulsukon et al. (2002)	Brick	3.04	1.13	37.17
Scheuer et al. (2003)	Steel	5.40	0.31	5.74
Junnila et al. (2006)	Concrete	5.10	1.18	23.06
Randolph et al. (2006)	Brick	6.86	0.88	12.83
Johnson (2006)	Steel	0.77	0.12	15.82
Johnson (2006)	Concrete	0.76	0.15	19.13
Nassen et al. (2007)	Generic	3.10	0.35	11.29
Haines et al. (2007)	Wood	2.59	0.14	5.27
Utama & Gheewala (2008)	Brick	0.84	0.17	20.53
Utama & Gheewala (2008)	Concrete	0.82	0.15	17.83
Fridley et al. (2008)	Generic	9.24	0.07	0.74
Yang et al. (2008b)	Concrete	3.81	0.58	15.22
Kahhat et al. (2009)	Concrete	3.23	0.27	8.21
Kahhat et al. (2009)	Wood	2.91	0.26	8.85
Kahhat et al. (2009)	Steel	3.00	0.25	8.35
Utama & Gheewala (2009)	Brick	0.88	0.01	1.14
Gustavsson et al. (2010)	Wood	3.22	0.29	9.01
Leckner & Zmeureanu (2011)	Wood	3.30	0.20	6.06

Note: EE denotes embodied energy

2.3.2.2 Recurrent or Recurring Embodied Energy (REE)

After a building is occupied and used, the processes of maintenance, replacement, and management consume energy and also nonenergy inputs such as building materials, assemblies, and equipment. Also, if any part of the building is refurbished or a system is retrofitted, considerable amount of energy and material is expended. Sum of the energy spent directly and indirectly in the use phase maintenance, replacement, and renovation is termed recurrent or recurring embodied energy (REE) (Cole, 1996; Cole and Wong, 1996; Ding, 2007; Khasreen et al., 2009; Vukotic et al., 2010; Dixit et al., 2010). As the maintenance and replacement works occur periodically, the amount of REE depends mainly on the service life of a building, its materials, assemblies, and systems. It also depends on the maintenance requirements of products used in the building (Cole, 1996; Chen et al., 2001; Winistorfer et al., 2005; Chau et al., 2000). For instance, if a poor quality paint is applied on the walls to save the initial construction cost, more frequent repainting may be needed resulting in more use of material and energy. Similar to the construction phase, the maintenance and replacement activities require resources such as building materials, labor, and equipment. The processes of construction (e.g. repair), transportation, and management are also needed at this stage.

Table 2-9: Waste factors for construction materials reported in literature

Building Materials	Adalberth, 1997a	Chen et al., 2001	Treloar et al., 2003	Worth et al., 2007	Chau et al., 2007	Blengini, 2009
Steel	5%	5%	5%	6% [a]	5%	7%
Aluminum	-	2.5%	10% [a]	6% [a]	5%	5%
Copper	5%	2.5%	10% [a]	6% [a]	5%	5%
Concrete	10%	2.5%	5%	-	3%	7%
Glass	0	0	3%	-	5%	7%
Brick		-	5% [b]	-	3%	10%
Insulation	5-10%	5%	-	6%	8%	7%
Finishes e.g. paints	5%	-	5%	0	5%	7%
Plaster	-	-	10%		5%	10%
Timber	10%	2.5%	10%	11%	-	7%
Plastic	-	5%	10%		3-5%	7%
Equipment	-	-	0	-	-	-

[a] % indicated for metals in actual study; [b] % indicated for masonry/clay in actual study

According to Cole and Kernan (1996), a building material or component replaced 100% falls in the category of replacement and any replacement less than 100% is covered under maintenance. Building materials and components may not possess the same service life as the building, and may require one or multiple replacements over the building's service life (Chen et al., 2001; Chau et al., 2007; Winistorfer et al., 2005; Cole, 1996). These replacements, as in the building erection phase, involve building material use and construction processes (Utama and Gheewala, 2009). Each of these products and processes contributes to the total REE (Thormark, 2007; Chen et al., 2001; Ding, 2007; Pullen and Perkins, 1995). A replacement factor, which is the ratio of service life of a building to average service life of a building material or a component, is decisive in determining the amount of REE (Chen et al., 2001; Chau et al., 2007). Table 2-10 presents the replacement factors for some of the building materials and components determined by various studies.

Table 2-10: Replacement factors for various building components reported by literature

Building Component	Treloar et al., 1999	Fay et al., 2000	Chen et al., 2001	Keoleian et al., 2001	Scheuer et al., 2003	Chau et al., 2007	Ding, 2007
Structure	1		1		1	1	
Ext./Int. Walls	1.1		1		1	1	1-2.4
Doors			1.3		1.5		1.5-2
Windows		2	1.3	2	1.9		1.5
Wall/Roof Tiles		2-4	1.3	2	3.75**	2.5**	2.4
Paints and Coat.	8	10	5	5	15	5	6-8.6
Carpet			2.4	6.2	6.25	3.3	5
Ceiling Finishes	2		2		3.75	2.5**	4
Floor Finishes	4		3	2.5*	4.16*	2.5*	3*
Insulation					1	1	

* indicates vinyl flooring; ** denotes acoustical tiles

Functional, aesthetical, and end of service life of associated components are the most common reasons for replacements occurring in a building (Winistorfer et al., 2005). For instance, a window at the end of its service life needs to be assessed for its physical condition and replaced if required. If not replaced, it could adversely affect the annual energy consumption possibly due to an increased rate of heat transfer. An increased heat load due to the bad window eventually may exert pressure on the building's heating and cooling systems. Aesthetics is also seen as one of the main reasons for replacements particularly in the case of tenancy change or office redesign (Cole, 1996). In such cases, modification of interior walls, floor and wall finishes, ceiling, electrical and plumbing fixtures, and furniture is seen as a common practice. Fashion is also seen as a major reason behind frequent replacements of building elements such as furniture, fixtures, and fittings (Treloar et al., 1999).

In the case of maintenance, there are two types of maintenance activities: scheduled and unscheduled. The scheduled maintenance is also known as preventive maintenance that is performed to prevent a sudden breakdown of any building system or component (Lavy et al., 2013). The unscheduled maintenance, which is also termed corrective maintenance, is done when a system or a component has failed and now requires immediate repair (Lavy et al., 2013). Conventionally, both the types of maintenance activities occur in a building consuming labor, material, and energy (Chan et al., 2001; Shohet, 2006). According to Cole (1996), the LCEE should be updated periodically based on the completed maintenance and replacement works.

In 50 years of service life, a building's REE could equalize its IEE (Cole, 1996). In the case of Australian Secondary Schools, Ding (2007) found that the REE, over a 60-year service life, was 72% of the school buildings' total LCEE. Building components such as envelope, finishes, and services, which may not hold higher embodied energy initially, require a significant recurring energy (3.2 times the initial embodied energy in a 50-year service life) (Cole, 1996). Similarly, Cole (1996) determined that for a service life of 25, 50, and 100 years, the REE of these components was 1.3, 3.2, and 7.3 times their IEE, respectively. Treloar et al. (2000) and Adalberth (1997b) calculated recurring embodied energy as 45% (50-year service life) and 32% (30-year service life) of IEE, respectively. Pullen (2000a) determined an annual REE of 1% of the total IEE. This value is in accordance with the values suggested by Adalberth (1997b) and Treloar et al. (2000). In a study of 15 houses in the Adelaide region of Australia, Pullen and Perkins (1995) found the recurring embodied energy (for an 80-year service life) within a range of 36 - 84% of the total IEE (average 57%).

A building's REE increases with its service life. Factors such as durability, long service life, low maintenance requirements, functional suitability, and recycling and reuse potential of products installed in a building could significantly lower the amount of REE (Dixit et al., 2012b). Dixit et al. (2012b) conducted a rigorous analysis of 64 single and multi-family residential and 100 commercial case studies published in the literature. As buildings had differing service lives, for a fair comparison, REE values were annualized and expressed in MJ/m^2/year (Dixit et al., 2012b). In the case of residential buildings, Dixit et al. (2012b) found a moderate and positive correlation of REE with the buildings' service life (r^2 = 0.50) but a strong positive correlation with their total LCEE (r^2 = 0.94) and LCE (r^2 = 0.73). Figure B1-2 and Figure B1-3 in Appendix B1 illustrate the correlation of REE with the buildings' total LCE and LCEE, respectively. This means that the REE influences the LCE and LCEE more than any other life cycle embodied energy component. In the case of commercial buildings, the correlation of REE with the total LCEE (r^2 = 0.96) and LCE (r^2 = 0.83) was very strong and positive indicating a strong influence of REE over LCEE. The correlation of commercial buildings' REE with their service life was moderate and positive (r^2 = 0.68). According to Dixit et al. (2012b), the residential buildings conventionally do not involve very complex, modernized, and large size building systems and components requiring a greater degree of maintenance and replacements (Scheuer et al., 2003). This may be one of the reasons why REE of residential buildings showed a weaker correlation than the commercial buildings (Dixit et al., 2013).

Figure B1-4 in Appendix B1shows the variations in the reported values of REE. The annual REE requirements for the residential buildings vary from 8 to 213 MJ/m^2/year with an average of 62.3MJ/m^2/year. The REE values calculated by Barnes and Rankin (1975) were the lowest among the referred residential facilities. One reason for this may be the fixed percentage (0.9% of IEE) considered calculating the REE in the study. Fay and Treloar (1998) calculated a higher REE value (188 - 213 MJ/m^2/year) due to the inclusion of maintenance and replacement requirements for not only the building and its components but also the landscaping and major building appliances (stove, microwave oven, dishwasher, clothes washer and dryer, heater etc.). The REE values ranged from 1.7 to 470 MJ/m^2/year for commercial facilities with an average REE value of 157 MJ/m^2/year. The lower annual REE values (1.7 - 3.6 MJ/m^2/year) calculated by Page (2006) are due to the fact that only exterior walls and roof paint were included under the maintenance and replacement works. The annual REE values reported by Langston and Langston (2007) were significantly higher (up to 470 MJ/m^2/year), as they included the building, its components, services, fittings, site works and external services. They, like Fay and Treloar (1998), also used the input-output-based hybrid method to calculate the energy embodied, which usually results in higher energy values (Crawford et al., 2002).

2.3.2.3 Demolition Energy (DE)

At the end of its service life, a building is demolished and its constituent materials are sorted, treated, and transported for reuse, recycling, or disposal to landfills or incinerators. Both the electricity and fuel are consumed directly and indirectly in the demolition and disposal processes. The sum of total energy consumed is termed demolition energy (DE) (Cole, 1996; Cole and Wong, 1996; Vukotic et al., 2010; Dixit et al., 2010). Energy is consumed in four stages at the end-of-life phase of a building. The first stage involves complete demolition and disassembly of the building, and utilizes heavy equipment such as hydraulic hammers and hydraulic loaders consuming fuels such as oil (Miller, 2001; Blengini, 2009). In the second stage, on-site secondary demolition occurs, the purpose of which is to separate building materials and reduce their size for easy handling and sorting. Waste as well as salvaged materials are then transported to either landfills or to reuse and recycling facilities in the third stage. Finally, equipment such as jaw crushers and magnetic separators are used to separate and salvage reusable and recyclable materials at the recycling facilities. Sorted reusable or recyclable materials are then transported to manufacturing facilities or construction sites by means of trucks and trains (Blengini, 2009). One important activity at this stage includes recycling and reuse processes that could recover a major fraction of initial energy embodied in the building (Crowther, 1999; Tingley et al., 2012). Recycling and reuse may be an open loop or a closed loop type process (Tingley et al., 2012). In an open loop materials are recycled or reused between industries or life cycle stages of a building, whereas closed loop involves recycling and reuse within the same industry or life cycle stage (Thormark, 2002; Treloar et al., 2003).

Studies (e.g., Cole and Kernan, 1996; Scheuer et al., 2003; Adalberth, 1997b; Kernan, 1996; Kofoworola and Gheewala, 2009; Shu-hua et al., 2010) performed detailed life cycle assessment of buildings and derived a percentage of IEE that could be used for demolition energy calculation. Adalberth (1997b) and Cole and Kernan (1996) calculated the demolition energy as 4% and 1 - 3% of a building's total IEE, respectively. Scheuer et al. (2003) reported a higher demolition energy that was 12% of the total IEE of the study building. This higher value was probably due to the inclusion of the decommissioning of all nonstructural building components (e.g. mechanical, electrical, plumbing, finishes etc.) in addition to the structural components. The higher fraction could also be due to accounting for differing transport distances. Recently, Kofoworola and Gheewala (2009) and Shu-hua et al. (2010) calculated the demolition energy equivalent to 2.5% and 4% of the total IEE, respectively. Figure B1-5 in Appendix B1illustrates the values of demolition energy reported by various studies involving both the residential and commercial buildings. The values ranged from 0.03 to 0.80 GJ/m^2 and varied with a standard deviation of 0.2. The demolition energy as a fraction of the total IEE was in the range of 0.84 - 13.11%. On an average, the demolition energy represented nearly 4% of the total IEE. This value is very close to the values calculated by Cole and Kernan (1996), Adalberth (1997b), Kofoworola and Gheewala (2009), and Shu-hua et al. (2010). Table 2-11 lists average values calculated by some of the referred case studies. In the case of a wood frame building, the energy of demolition represented up to 2.7% of building's total IEE, whereas this reaches 5.1% in the case of concrete buildings. This could be expected, as concrete building demolition would certainly require more use of heavy equipment in the initial demolition, debris removal and sizing, sorting, and hauling. It is also important to note that most of the concrete buildings were commercial buildings that are typically larger, more complex, and involve a wide variety of materials than a residential building.

Table 2-11: Demolition energy as a fraction of embodied energy of building material production

Study	Building Type	Construction Type	Service Life (years)	Building Material EE (GJ/m^2)	Demolition Energy (GJ/m^2)	Fraction of Building Material EE (%)
Kohler et al. (1997b)	Residential	Brick	100	9.00	0.15	1.67
Adalberth (1997b)	Residential	Wood	50	3.37	0.12	3.56
Blanchard & Reppe (1998)	Residential	Wood	50	4.14	0.14	3.29
Lippke et al. (2004)	Residential	Wood	75	3.13	0.04	1.20
Winistorfer et al. (2005)	Residential	Wood	75	3.00	0.03	1.03
Leckner & Zmeureanu (2011)	Residential	Wood	40	3.56	0.03	0.84
Johnstone et al. (2001)	Residential	Wood	60	2.75	0.14	5.09
Haines et al. (2007)	Residential	Wood	60	2.73	0.04	1.47
Lippke et al. (2004)	Residential	Steel	75	3.36	0.04	1.19
Lippke et al. (2004)	Residential	Concrete	75	1.98	0.04	1.77
Winistorfer et al. (2005)	Residential	Concrete	75	2.20	0.04	1.59
Humphrey et al. (2004)	Residential	Concrete	50	7.38	0.07	0.94
Citherlet & Defaux (2007)	Residential	-	50	3.25	0.40	12.31
Kernan (1996)	Commercial	Concrete	100	4.74	0.05	0.99
Suzuki & Oka (1998)	Commercial	Concrete	40	8.95	0.49	5.47
Citherlet & Hand (2002)	Commercial	Concrete	80	6.10	0.80	13.11
Junnila et al. (2006)	Commercial	Concrete	50	6.27	0.47	7.42
John et al. (2008)	Commercial	Concrete	60	3.38	0.32	9.33
John et al. (2008)	Commercial	Steel	60	4.36	0.16	3.72
John et al. (2008)	Commercial	Wood	60	2.31	0.12	4.97

Note: EE denotes embodied energy

ACHP (1979) proposed a demolition energy figure of 136.3 MJ/m^2 for a 5000 m^2 concrete building. These energy values accounted for 1 - 3% of IEE as demolition energy (Cole and Wong, 1996; Cole and Kernan, 1996). Table 2-11 provides the demolition energy values presented by ACHP (1979).

2.3.3 Life Cycle Embodied Energy Components: Reported Values

Among the three major life cycle embodied energy components are initial embodied energy (IEE), recurrent embodied energy (REE), and demolition energy (DE). Among them, according to the reported results in the literature, the most influential energy components are REE and IEE. As discussed earlier, the REE showed a strong and positive correlation to a building's LCEE and LCE. This section of the literature review discusses and synthesizes various studies and their results in order to derive a range of proportions each component shares in the total LCEE. A rigorous review of literature was performed that included embodied energy case studies from 1976 through 2011.

Figure 2-8 shows the breakup of IEE, REE, and DE in total LCEE reported by case studies that calculated all three components. The variation in the proportions of the energy components is due to the presence of both the residential and commercial type of buildings with brick, wood, steel, and concrete construction. Table A1-1, Table A1-2, Table A1-3, and Table A1-4 in Appendix A1 provide the life cycle energy breakup in terms of total IEE, REE, OE, and DE for brick, concrete, steel, and wood frame buildings. In the tables, IEE, REE, OE, and DE denote initial embodied energy, recurrent embodied energy, operating energy, and demolition energy, respectively.

In the case of brick construction, the average value of REE was nearly half of the IEE values. It can be seen that for a 100 years' service life, a building's REE could be over 1.5 times its IEE as calculated by Kohler et al. (1997). This further supports the notion that REE and LCEE are dependent on a building's service life. In the case of concrete construction, the annualized REE values calculated by Cole and Kernan (1996), Kernan (1996), Eaton et al. (1998), Citherlet and Hands (2002), and Humphrey et al. (2004) were considerably higher (1.3 - 1.6 times) than IEE. In the case of brick buildings, the average REE was 46% of the buildings' IEE and it increased to 61% for concrete buildings. Similarly in the case of wood and steel frame buildings, the REE calculated by Jacques (1996), Cole and Kernan (1996), and Eaton et al. (1998) easily surpassed the IEE values within a service span of 50 - 60 years.

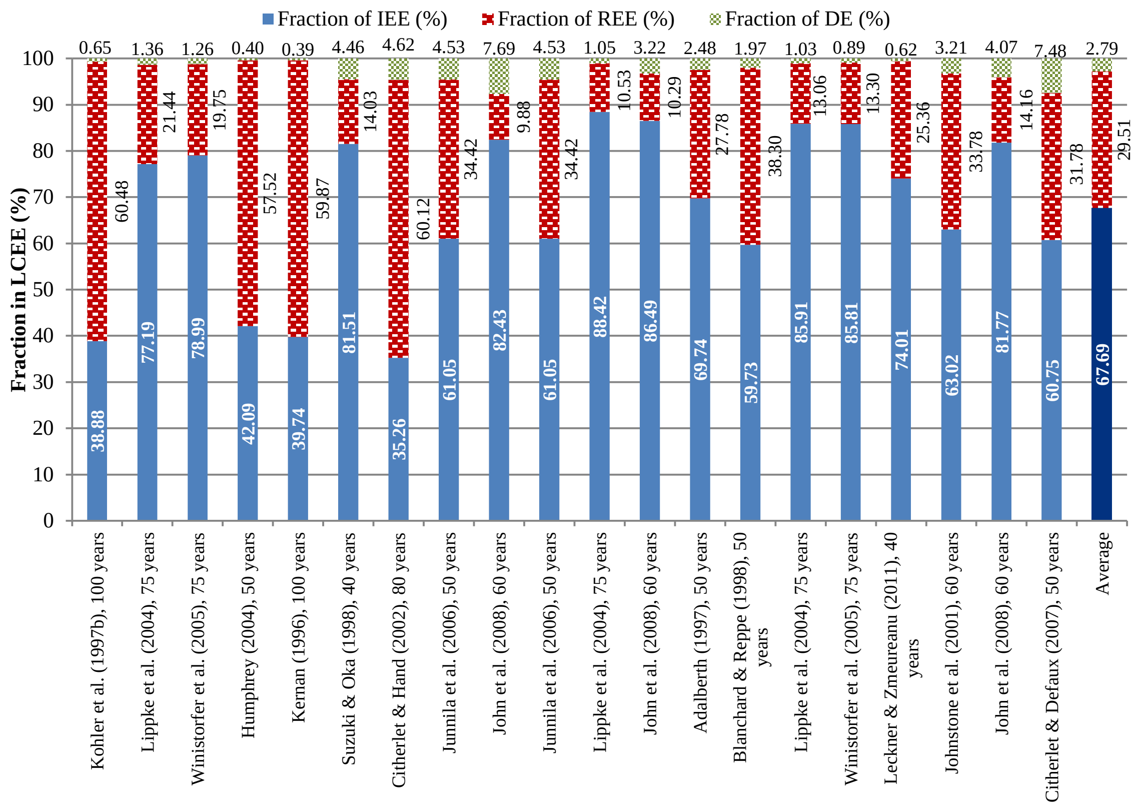


Figure 2-8: Fraction of the three life cycle embodied energy components in total LCEE

2.4 PROBLEM OF VARIATION IN EXISITNG EMBODIED ENERGY DATA

Embodied energy values in building materials and buildings vary considerably across research studies and this variation could be up to 30 - 50%. Furthermore, some studies pointed out the inaccuracy and incompleteness of existing embodied energy data of building materials. These problems with energy data make the comparison of building materials and products difficult in embodied energy terms (Khasreen et al., 2009). Inaccurate, incomplete, and inconsistent data cannot be used for environmental decision-making by building professionals such as designers, engineers, project managers, and contractors while selecting a low energy building material (Fernandez, 2006; Burnett, 2006). There are parameters that cause embodied energy values to differ across research studies (Dixit et al., 2010). Most of these parameters are related to embodied energy calculation methods, some of them are actually data quality-related issues. In this paper we categorize them into the two categories: methodological parameters and data quality parameters.

2.4.1 Methodological Parameters

Parameters such as system boundary, methods of embodied energy measurement, and type and form of energy to be included relate closely to embodied energy calculation methodology.

2.4.1.1 System Boundary: Problem of Incompleteness

The system boundary demarcates a system of various products and processes related to the manufacturing of a product under study. A system boundary also determines the number and type of energy and material inputs included in the calculation of embodied energy (IFIAS, 1975; Peuportier, 2001). Miller (2001) and Khasreen et al. (2009) asserted that research studies often do not describe the system boundary adopted in their study clearly and it becomes difficult for the readers to determine what is included and excluded from the energy calculation. Suh et al. (2004) stated that studies often select the system boundary of the energy analysis subjectively and results of such studies cannot be compared. Raynolds et al. (2000) emphasized the need for a system that ensures consistent system boundary selection across different studies. System boundary definition differs across studies, which leads to variations in the calculated embodied energy values (Dixit et al., 2010).

2.4.1.2 Method of Embodied Energy Calculation

Among the major embodied energy calculation methods are input-output-based, process-based, hybrid and statistical analysis (Fay and Treloar, 1998; Lenzen, 2000; Crawford and Treloar, 2003; Ding, 2004; Plank, 2008; Khasreen et al., 2009; Optis and Wild, 2010). Each of these methods has limitations and varying levels of accuracy. Consequently, results of these methods differ and affect their comparative evaluation (Miller, 2001; Crawford and Treloar, 2005; Nassen et al., 2007; Plank, 2008; Khasreen et al., 2009; Optis and Wild, 2010). Another method that is called hybrid analysis includes both the process and the input-output data and is considered relatively complete and accurate. Research studies have applied different calculation methods and their embodied energy results differ significantly (Nebel, 2007; Dixit et al., 2010).

Nassen et al. (2007) performed a detailed analysis of input-output and process-based energy calculation methods and found that the results of an input-output-based analysis could be 90% higher than a process-based analysis. Crawford and Treloar (2003) calculated embodied energy in a residential and a commercial building as 6.6 GJ/m^2 and 9.0 GJ/m^2, respectively using a process-based analysis. Furthermore, they also found that embodied energy in the same buildings could decrease by 14.5 - 23% if an input-output-based analysis is used. Crawford and Treloar (2005) later studied a commercial building and concluded that when an input-output-based calculation was performed, the calculated values increased by 56% from the building's process-based values (8.0 GJ/m^2). Optis and Wild (2010) concluded that nearly 78% of published studies failed to provide an accurate and clear description of the calculation methodology adopted making interstudy comparisons difficult.

2.4.1.3 Energy Inputs

Primary and Delivered Energy: Energy embodied in buildings and building materials is reported in primary or delivered energy terms. Delivered energy (e.g. electricity) is the energy used by a consumer. It is also known as "end use," "site," or, "final" energy. Primary energy is the energy of fossil fuel extracted from the earth. Primary energy is extracted, processed, and converted to a form (delivered energy) that is usable for a range of purposes (Dixit et al., 2010). Primary energy varies from delivered energy (and is usually more) owing to factors such as fuel types (e.g. electricity, natural gas, oil, etc.) and the means of delivered energy production (e.g. coal fired, natural gas fired, nuclear or hydro power plants) (Fay et al., 2000; Thormark, 2002; Sartori and Hestnes, 2007; Hernandez and Kenny, 2010). Each of these power plants holds differing efficiencies and uses relatively more primary energy to generate delivered energy. For example, as reported by Fay et al. (2000), for every single unit of electricity 3.4 units of primary energy is burnt in Australia. This factor of 3.4 is known as the "conversion factor" or "primary energy factor" and differs across countries and energy carriers (Fay et al., 2000; Sartori and Hestnes, 2007). While delivering end use energy to consumers, energy is also consumed and lost that also contributes to differences in primary and delivered energy values (Thormark, 2002; Sartori and Hestnes, 2007; Gustavsson and Joelsson, 2010). For instance, to move dry natural gas through pipelines, compressors are used that run on electricity and natural gas. Figure 2-9 illustrates a generic process of generating electricity from primary fuels. It can be seen that the efficiency of energy conversion and the type of fuels are the two key aspects that affect the amount of delivered energy generated and supplied to the end users.

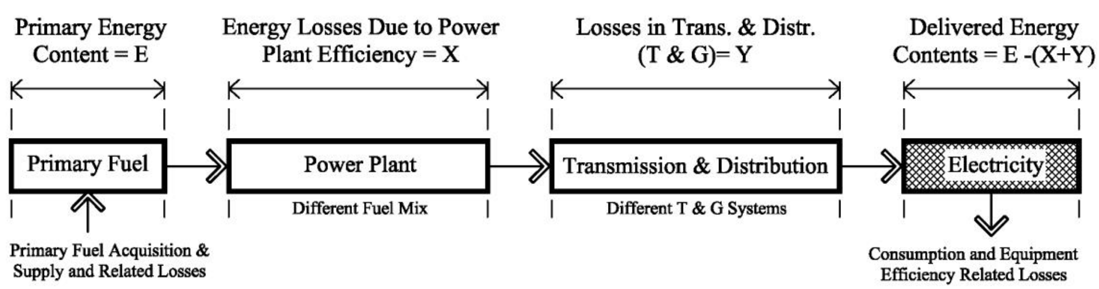


Figure 2-9: Process of electricity generation and related losses

If embodied energy of a building is reported in delivered energy terms, there is a strong possibility that these values would be nearly similar across different countries for the same building (Sartori and Hestnes, 2007). Such data cannot be compared globally, as the actual amount of primary energy consumed and true environmental impacts remain covered under delivered energy values (Fay and Treloar, 1998; Thormark, 2002; Sartori and Hestnes, 2007). Embodied energy presented in primary energy terms can portray a true picture of environmental burden, as primary energy values could provide a relatively accurate estimate of resulting greenhouse gas emissions (Pullen, 2007; Fridley et al., 2008; Gustavsson and Joelsson, 2010; Hernandez and Kenny, 2010). Studies have reported energy embodied in buildings and building materials either in a primary or delivered energy term or have not provided any indication of the energy term (Sartori and Hestnes, 2007; Gustavsson and Joelsson, 2010; Ramesh et al., 2010). Results of such studies differ considerably and cannot be compared. Pears (1996) revealed that embodied energy values could increase by 30 - 40% (from delivered energy term) if reported in a primary energy form.

Feedstock Energy: ISO 14040 (2006) defined feedstock energy as "heat of combustion of a raw material input that is not used as an energy source to a product system, expressed in terms of higher heating value or lower heating value." Feedstock energy is the heat of combustion or energy content of raw material input (e.g. wood and petrochemicals, such as oil and gas) used as ingredient in the process of manufacturing a product (e.g. wood components, plastics and rubber) (Trusty, 2006; Sartori and Hestnes, 2007; Ardente et al., 2008).

Embodied energy includes feedstock energy and the nonrenewable fraction of all direct and indirect energies consumed in manufacturing a product (Lucuik et al., 2006; Hegner, 2007; Krogmann et al., 2008; ASMI, 2009). Research studies have concluded that the feedstock energy could constitute a major fraction of the total embodied energy. Sartori and Hestnes (2007) argued that the embodied energy may or may not include the feedstock energy. However, studies such as Thormark (2002 and 2006), Lucuik et al. (2006), Trusty (2006), Ardente et al. (2008), Blengini (2009) and Gustavsson et al. (2010) accommodated feedstock energy into the total embodied energy calculations. Some of these studies (Thormark, 2002; Trusty, 2006; Thormark, 2007; Ardente et al., 2008) have presented the values of feedstock energy separately to highlight their importance. Thormark (2001) and (2007) found the feedstock energy as 27 - 94% of the materials' embodied energy (released materials). Ardente et al. (2008) conducted a "cradle to gate" LCA of the Kenaf-fiber insulation boards and revealed that nearly 50% of the total embodied energy was attributed to the material's feedstock. In a similar study, Lazzarin et al. (2008) quantified the feedstock energy of stone wool, expanded polystyrene foam, expanded polyurethane foam, and cork panels as 16%, 48%, 59%, and 88% of the material's total embodied energy, respectively. The feedstock component is the largest contributor to the total energy embodied in construction materials such as asphalt (Trusty, 2006).

Feedstock energy is significant and hence, needs to be considered in the embodied energy calculation (Thormark, 2006; Nassen et al., 2007; Ardente et al., 2008; Hammond and Jones, 2008 and 2010).

Inclusion or exclusion of feedstock energy in embodied energy calculation could cause variations in embodied energy values (Pullen, 2000b; Nassen et al., 2007). Nassen et al. (2007) noted that calculation methods such as input-output-based analyses do not accommodate feedstock energy of raw material inputs. Furthermore, they had to exclude feedstock energy values from total embodied energy values rendered by referred studies in order to make genuine comparisons in their study.

Nonrenewable Energy: Hegner (2007) presented an interesting explanation of embodied energy, citing Kasser and Poll (1998). According to them, only energy that is available in a limited amount should be considered embodied energy. Here, they relate the phenomenon of embodied energy to greenhouse gas emissions because a major fraction of primary energy available in a limited amount comes from fossil fuels. Recent studies (Citherlet and Hand, 2002; Holtzhausen, 2007; Upton et al., 2008; Fernandez, 2008; Verbeeck and Hens, 2010; De Meester et al., 2009; Pittet and Kotak, 2009; Black et al., 2010; Aste et al., 2010; Leckner and Zmeureanu, 2011) presented their energy results separately in nonrenewable energy terms to emphasize the environmental significance of embodied energy as an evaluation parameter. Studies (Hegner, 2007; Joseph and Tretsiakova-McNally, 2010; Ramesh et al., 2010) also claimed that embodied energy (in nonrenewable terms) becomes a vital environmental indicator of the greenhouse gas emission impacts of manufacturing a product.

Human Energy: In some geographic locations, conventional manufacturing processes of building materials and certain construction processes are labor intensive and involve considerable amount of human energy (Huberman and Pearlmutter, 2008; Alshboul and Alzoubi, 2008; Utama and Gheewala, 2008). Langston and Langston (2007) noted that some of the building’s life cycle activities such as maintenance and repair are more labor intensive than the initial construction and this fraction of human energy is often excluded from the embodied energy analysis. Studies (Langston and Langston, 2007; Pulselli et al., 2009) underscored a need to incorporate human energy in embodied energy analysis. However, it is often not accomplished due to the lack of a clear human energy calculation method. Dias and Pooliyadda (2004) discussed the importance of human energy but could not accommodate it in their calculations owing to the complexity and ambiguity involved in its analysis.

One significant study that calculated human energy was done by Alshboul and Alzoubi (2008) who performed embodied energy analysis of the natural-dimensioned stone in Jordan. They measured human energy using work duration and metabolic rates. However, they found that the variability of individual metabolic rates poses difficulty in consistently calculating the human energy. Another important work by Cleveland and Costanza (2008) discussed human labor and identified three components, which should be accounted for while quantifying the human energy. These are: 1. the calorific value of food consumed by workers, 2. the embodied energy of food, and 3. fuel purchased with salaries or wages of workers.

Current embodied energy methods fail to include the human energy component of total embodied energy (Langston and Langston, 2007; Ulgiati et al., 2010). In developed countries such as the United States, a significant amount of energy is consumed in growing, harvesting, transporting, marketing, storing, and preparing human food (Cleveland and Costanza, 2008). Grondzik et al. (2009) noted that some building materials are more human energy intensive than others that consume more mechanical energy. This further adds to the variability of materials' embodied energy.

2.4.2 Data Quality Parameters

Data quality is one of the key parameters, which differ within and across databases (Szaley and Nebel, 2006; Optis and Wild, 2010). Ardente et al. (2011) discussed a Data Quality Index (DQI) to determine the quality of data on the basis of age and representativeness of data. Quality of data used governs the reliability of energy analysis (Menzies et al., 2007; Khasreen et al., 2009). According to Optis and Wild (2010), about 20% of the studies do not mention data sources clearly, making it difficult for researchers to use or analyze their results. The following factors affect the quality of data used in an energy analysis:

2.4.2.1 Primary and Secondary Data

Khasreen et al. (2009) and Crawford and Treloar (2005) argued that the success or failure of an embodied energy analysis depends upon the quality and source of the data referred. Studies applied different techniques to acquire data. Some studies utilized primary data sources such as economic input-output tables, process data, and datasets attached to software, whereas some sourced secondary data from other published studies (Dixit et al., 2010). Goggins et al. (2010) claimed that the accuracy of embodied energy data depends upon the methods of embodied energy measurement. Often, embodied energy is also calculated using Life Cycle Assessment (LCA) tools and datasets such as Athena, BEES 4.0, Ecoinvent, Eco-Quantum, Envest 2, OPTIMIZE, LICHEE, and SimaPro. However, some of these tools do not cover all stages of a building's life cycle and lack the capability to perform a full life cycle assessment (Ting, 2006; Itard, 2007; Haapio and Viitaniemi, 2008; Khasreen, 2009). Plank (2008) also warned that most of these available tools act as a "black box", as they lack transparency and flexibility. According to Hammond and Jones (2008), if it is difficult to discern the system boundary adopted by the secondary data sources, such data should not be trusted.

2.4.2.2 Data Incompleteness

According to Menzies et al. (2007) and Peereboom et al. (1998), research studies often do not have access to primary data sources and rely on secondary data sources that may or may not be complete. The incompleteness of data stems from either the lack of data, limitations of the calculation methods, or a subjective selection of system boundaries (Menzies et al., 2007; Reap et al., 2008; Goggins et al., 2010; Monahan and Powel, 2010). Studies that performed embodied energy calculations based on process analysis often suffered from data incompleteness, as accounting for nearly all processes would have been a difficult task (Menzies et al., 2010; Hammond and Jones, 2010; Goggins et al., 2010). As a result, process analysis outcomes are underestimated and include data gaps (Menzies et al., 2007; Hammond and Jones, 2010). Existing LCA and embodied energy inventories are seriously incomplete and poor in data quality (Reap et al., 2008; Khasreen et al., 2009). Researchers ignore, assume, or estimate missing data whenever they encounter data gaps in the inventory and often end up inferring data from the literature (Reap et al., 2008; Monahan and Powel, 2010). Data incompleteness should be verified when choosing one material dataset over another (Alcorn, 1996; Crawford et al., 2006; Nebel, 2007; Khasreen et al., 2009).

2.4.2.3 Data Representativeness

Data representativeness is an important quality, which if lacking could make data irrelevant to the study and could change the direction of the analysis (Pittet and Kotak, 2009; Khasreen et al., 2009; Optis and Wild, 2010). Most of the current LCA studies used data that did not represent the local conditions (Huberman and Pearlmutter, 2008). According to literature, data should have the following representativeness:

Geographical Representativeness: Geographic relevance of data is the only factor causing the largest variation in LCA or embodied energy results (Khasreen et al., 2009; Optis and Wild, 2010). Countries around the globe differ in terms of use of construction materials, construction and fabrication processes, mode of transportation, and transportation distances (Menzies et al., 2007; Pittet and Kotak, 2009; Rule et al., 2009; Goggins et al., 2010). Moreover, the technology of construction material production and construction also differs in terms of efficiency (Menzies et al., 2007; Pittet and Kotak, 2009; Goggins et al., 2010). The fuel and technology used for electricity production, electricity mix (renewable and nonrenewable), and economic systems vary significantly around the globe (Sartori and Hestnes, 2007; Menzies et al., 2007; Monahan and Powell, 2010; Hammond and Jones, 2010). According to Buchanan and Honey (1994), differing energy supply assumptions could cause embodied energy and carbon results to vary by a factor of three. Energy tariffs paid by material manufacturers and material prices are also different in various locations causing an error up to 2.5% in the calculations (Pullen, 1996).

Temporal Representativeness: Studies often apply data that is obsolete and lacks temporal representation (Reap et al., 2008). In a paper focused on energy embodied in historic buildings, Frey (2008) discussed that old and outdated data should not be used directly for current situations. If possible, data should be modified to suit the current time. Studies based on input-output analysis often lacked the temporal relevance, as the analysis was based upon economic input-output tables, which most countries do not publish in a timely manner (Menzies et al., 2007). Technology of electricity production as well as construction material manufacturing could change over time and old data, if used, may not represent the study in current time (Buchanan and Honey, 1994; Pullen, 2000b; Crawford and Treloar, 2005; Menzies et al., 2007).

Technological Representativeness: Different technologies of material manufacture consume a varied amount of energy, as the new advanced technologies are relatively more efficient than the older ones. A downward trend was also observed in the energy consumption of process energy involved in construction material manufacturing (Menzies et al., 2007). This indicates that the technology of manufacture is getting energy efficient over time. Pittet and Kotak (2009) noted that the low income countries tend to use less efficient technology (of manufacture and construction) than the developed countries. In the same geographic location and time period, two studies could generate different results if they are extracting information from two different manufacturers (Pears, 1996).

2.5 EMBODIED ENERGY: SIGNIFICANCE

2.5.1 Embodied Versus Operating Energy

In the past, the main focus of building energy efficiency research was on operating energy and the relative fraction of embodied energy in the total life cycle energy was considered insignificant. However, recent research has revealed that embodied energy may account for a larger fraction of the total life cycle energy (Ding, 2004). Due to increased emphasis on operating energy research, the life cycle operating energy is getting optimized. In addition, a rise in readily available energy efficient appliances, advanced insulating materials, and the equipment of building performance optimization indicate that measures to optimize operating energy are already in place (Ding, 2004; Sartori and Hestnes, 2007; Plank, 2008). For example, data from the Building Energy Data book published annually by the United States Department of Energy clearly showed an increase in the number of Energy Star approved building appliances indicating a gradual decrease in operating energy use (USDOE, 2012) (see Figure 2-10). Reducing embodied energy, however, requires a careful selection of low energy intensive materials and products at pre-design, design, and use phases.

The proportion of embodied and operating energy in the total LCE varies depending on numerous factors such as geographic location, climate, socio-economic conditions, and energy sources used in the production of buildings (Nebel et al., 2011). Figure B1-6 and Figure B1-7 in Appendix B1 demonstrate the proportion of embodied energy in the total LCE of residential and commercial buildings, respectively on four geographic regions: North America, Asia, Europe, and Oceania. The data are collected by a rigorous literature review of published case studies of residential and commercial buildings across the globe. A description of the referred case studies can be found in Table A1-5 in Appendix A1.

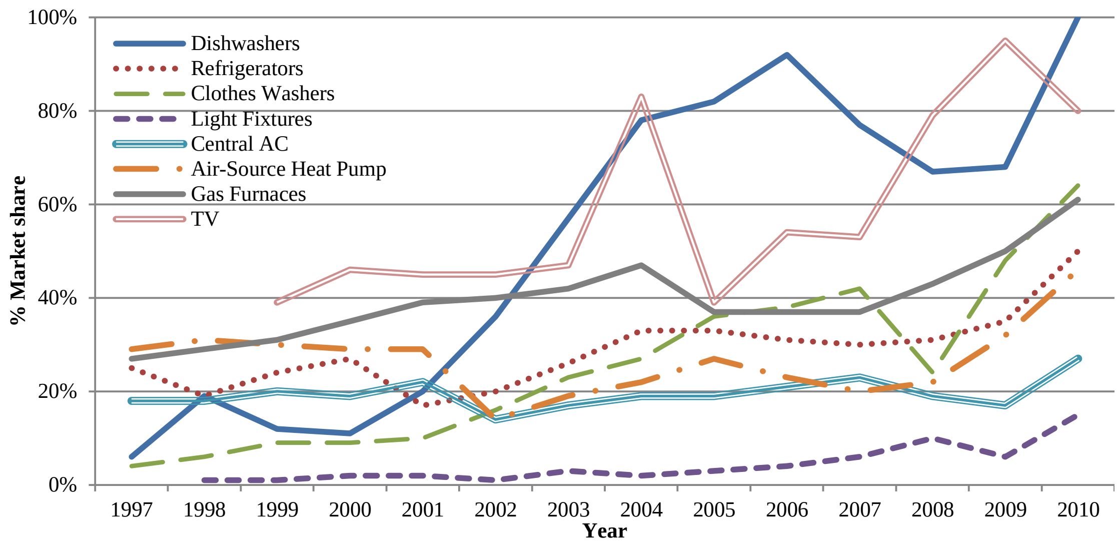


Figure 2-10: Number of Energy Star approved building appliances (based on USDOE, 2012)

The main purpose of the data presented in Figure B1-6 and Figure B1-7 is to show the variation in the relative proportion of embodied and operating energy that, as mentioned earlier, is contingent upon location, time, construction, and socio-economic parameters of the case study buildings. These data should not be taken as a thumb rule for estimating proportion of embodied and operating energy. The values of embodied energy fractions in total LCE of residential and commercial buildings reported by various studies are given in Table A1-5 in Appendix A1. The lowest value of embodied energy among the referred residential case studies is 1.1% of the total LCE calculated by Dodoo et al. (2010). There could be several reasons for this including the location of the study building in the heating dominated region. The study building is a multi-family structure having an electrical resistance type heating system that may increase the total life cycle operating energy use radically. Pearlmutter et al. (2007) calculated the highest proportion of embodied energy because no cooling load was included in the operating energy calculation. In addition, as the building was located in an arid region, the envelope construction with high thermal mass could result in a higher embodied energy. In a recent study, Huberman and Pearlmutter (2008) concluded that the embodied energy of a building designed with passive heating and cooling measures in the Negev desert region of Israel could be up to 60% of the total LCE (over 50 years' service life). However, in a heating dominated region of the United Kingdom, Plank (2008) found that the total embodied energy shared only 10% of the total LCE. According to Nebel et al. (2011), in heating dominated cold regions embodied energy shared a smaller fraction of the total LCE, which might be higher in a region with moderate climate because of a low operational energy use. The relative proportion of embodied and operating energy is still debated and due to a building's large size, complex nature, and custom design, there is a greater chance that it would differ across studies (Frey, 2008).

Due to an increased focus on operating energy optimization, the amount of operating energy is going down over time, and as a result, the proportion of embodied energy in the total LCE is growing (Crowther, 1999; Nebel et al., 2011; Plank, 2008; Frey, 2008; Gustavsson and Joelsson, 2010; Optis and Wild, 2010). Sartori and Hestnes (2007) reviewed and compared 60 case studies of conventional and energy efficient designs and determined that the energy embodied in an energy efficient building could be as high as 46% of its total LCE. According to Thormark (2007), the energy embodied in an energy efficient house could be as high as 40-60% of its total LCE. In the case of a conventional house, Buchanan and Honey (1994) calculated the total embodied energy as 38% of the total LCE. When they improved the operating energy performance, the fraction of embodied energy reached 84%. Similarly, in an energy analysis of a house in a heating dominated region of Norway, Winther and Hestnes (1999) found that if operating energy is optimized the fraction of embodied energy in the total LCE increased from 5% to 28%.

2.5.2 Embodied Energy and Carbon Emission

More than 80% of global and the United States' energy demands are still satisfied by fossil fuel combustion (IEA, 2009; EIA, 2010). The fossil fuels such as gasoline and natural gas are organic compounds made of mainly carbon and hydrogen and created by the anaerobic decomposition of buried organisms. Among the top fossil fuel consuming sectors are electricity production, transportation, industrial, residential, and the commercial sector (USEPA, 2011). As discussed earlier, the production of building materials includes consumption of fossil fuels and electricity and involves considerable transportation (Treloar, 1998; Crawford, 2004; Dixit et al., 2010). Hence, the amount of energy embodied in a building material primarily comes from fossil fuels (Hegner, 2007; Black et al., 2010; Upton et al., 2008). Figure 2-11 illustrates the fraction of fossil fuels in the total energy consumption in the United States. It is evident that we still depend mostly on fossil fuels for fulfilling our energy requirements.

2.5.2.1 Energy and Carbon Content

The process of fossil fuel combustion is a chemical reaction involving oxygen that results in release of water, carbon dioxide (CO_2), and heat. For instance, combustion of isooctane (gasoline) and methane (natural gas) results in the following reactions:

$2C_8 H_8 + 25O_2 \rightarrow 16CO_2 + 18H_2O + \text{Heat}$

$C H_4 + 2O_2 \rightarrow CO_2 + 2H_2O + \text{Heat}$

It can be seen from the above equations that carbon content in gasoline is more than the natural gas. Each fossil fuel possesses a different amount of carbon content (IPCC, 2006; USEPA, 2005). The process of fuel combustion is optimized to produce a maximum amount of energy per unit of fossil fuel combusted. The efficiency of fuel combustion relates to the oxidation of the maximum amount of carbon contained in the fuel. Hence, the amount of CO_2 released depends on the carbon content of a fuel rather than the combustion process (IPCC, 2006; USEPA, 2005). Not all of the carbon contained in a fuel is oxidized during the combustion process. A minute fraction (<1%) of the contained carbon escapes the oxidation process. However, IPCC guidelines assume 99 - 100% oxidation of the contained carbon in most of the fossil fuels (USEPA, 2005; IPCC, 2006). The CO_2 emission factors published by the IPCC provide the amount of CO_2 released per unit of energy produced. It is the emission factor that links the concept of embodied energy and embodied carbon (carbon content).

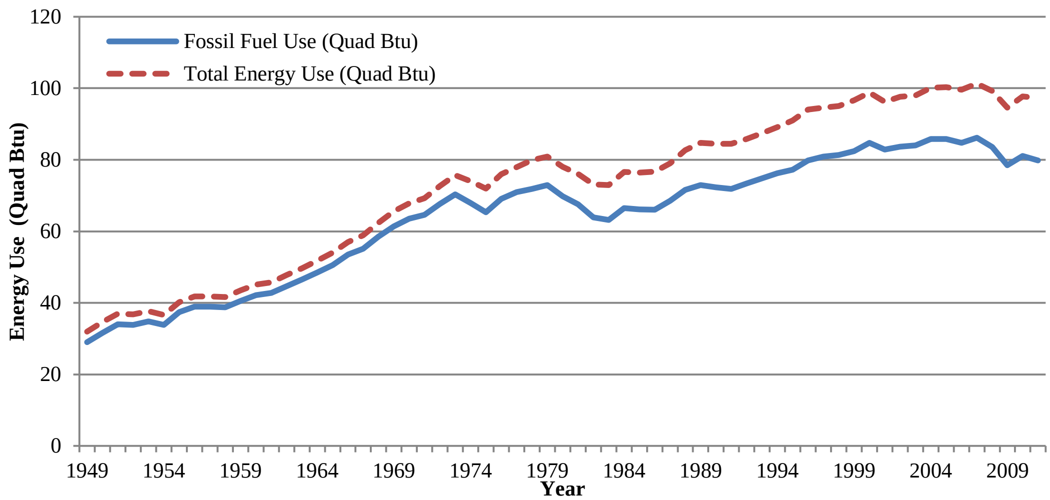


Figure 2-11: Share of fossil fuels in the United States' total energy supply

Embodied energy includes the consumption of both the nonrenewable primary and secondary energy, which involve fossil fuel combustion (Hegner, 2007; Black et al., 2010). In addition, electricity is consumed in the production processes that may have come from both the renewable and nonrenewable energy sources (Hegner, 2007; Black et al., 2010). Embodied energy also includes the feedstock energy, which is the energy of fossil fuels used as a raw material rather than as an energy source (Thormark, 2002; Thormark, 2006). The feedstock energy remains stored in the product with carbon that is not oxidized. However, in a life cycle term, whenever such material is burnt (e.g. in an incinerator) at the end of its service life, the stored carbon is oxidized and CO_2 is released. Literature (e.g. Alshboul and Alzoubi, 2008; Huberman and Pearlmutter, 2008) also suggested to include not only mechanical energy (equipment) but also human energy (of labor) used in material manufacturing. Human labor also consumes energy and has its own share in the total carbon emission.

From the concept of fossil fuel combustion, it can be expected that the amount of embodied energy is correlated to the resulting carbon emission. Figure 2-12 demonstrates a strong positive correlation (r^2 = 0.90 - 1.00) between the values of embodied energy and embodied carbon reported by Hammond and

Jones (2008) and Gonzalez and Navarro (2006). This correlation indicates that both the embodied energy and carbon can be used as an effective parameter for the environmental evaluation of various products (Hegner, 2007; Acquaye, 2010).

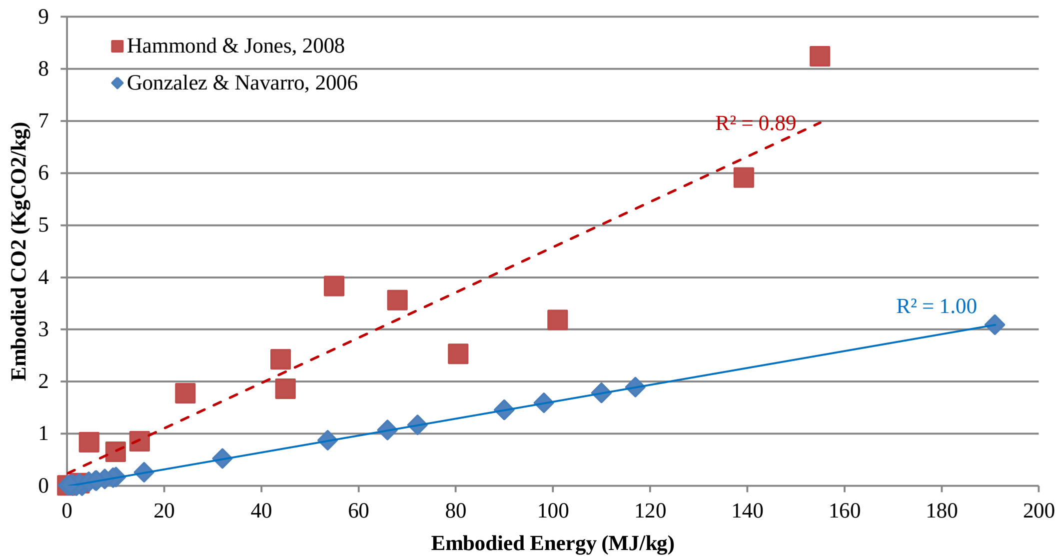


Figure 2-12: Correlation of embodied energy and carbon

2.6 EMBODIED ENERGY CALCULATION

Two issues are very important to discuss in the context of the embodied energy calculation process. The first issue is related to system boundary, whereas the second issue is associated with the existing embodied energy calculation methods.

2.6.1 System Boundary Definition: Major Issues and Need for Improvement

2.6.1.1 System Boundary Definitions in the Literature

A system boundary demarcates a system of various products and processes used in the manufacturing of a product under study. The system boundary also determines the number and type of energy and material inputs and waste and emission outputs that are included in the embodied energy calculation (Peuportier, 2001; IFIAS, 1975). A system boundary for a product can range from raw material extraction for its manufacturing in distant upstream to demolition and its disposal furthest downstream. Among common system boundaries for buildings and building products are “cradle to gate,” “cradle to site,” and “cradle to grave.” The cradle to gate system boundary includes upstream processes such as raw material extraction through a point where the finished product leaves the factory gate (excluding transport of material to the building site) (Frey, 2008, Goggins et al., 2010). The cradle to site covers, in addition to the cradle to gate boundary, transportation of finished product to the construction site, on-site construction and assembly processes, wastage disposal, etc. (Hammond and Jones, 2008). The cradle to grave system boundary takes also into account the use phase with operations and maintenance, renovation and refurbishment, and retrofit activities. The end-of-life phase with processes such as building demolition, waste sorting and hauling, recycling and reuse, and disposal of discarded waste to landfills is also included (Hammond and Jones, 2010; Hammond and Jones, 2008). The cradle to grave boundary provides a whole life cycle perspective, which is important for a complete and accurate environmental assessment (Plank, 2008; Hammond and Jones, 2010; Khasreen et al., 2009; Vukotic et al., 2010). Figure B1-8 in Appendix B1 provides an illustration of various boundary definitions discussed in the literature.

The International Federation of Institutes of Advanced Studies (IFIAS) organized a workshop on the relationship of energy and economic analysis that included 27 economists and scientists from ten countries around the globe (IFIAS, 1975). The IFIAS workshop provided a simplified system boundary model with four levels of regression to include most of the energy and material inputs to a process under study. Figure 2-13 illustrates the system boundary model as proposed in the IFIAS workshop. Level I regression included only direct inputs of primary and delivered energy to the main process. Materials and energy (e.g. electricity) involved in the main process might also have consumed energy in their acquisition and production which was accounted for in Level II regression. Level III analysis included production energy of direct energy input at Level II and also of capital equipment used in the main process. A Level IV regression covered the production energy of equipment that produced the capital equipment used in level III processes. Each of these levels also included the transportation energy of materials and equipment (IFIAS, 1975). Similarly, studies such as Hammond and Jones (2010), Hammond and Jones (2008), Buchanan and Honey (1994), and Fay (1999) also discussed multi-level system boundary definitions applicable to a building.

Buchanan and Honey (1994) and Hammond and Jones (2010) discussed the four levels of system boundary regression. The first level of regression covered all direct energy inputs into the processes of a building’s life cycle such as construction, prefabrication, maintenance, replacement, demolition, and disposal. Energy embedded in the main production and all upstream and downstream processes of a building material were counted in the second level of regression. Nearly 90% of the energy inputs could be tracked and determined by a second level of regression (Hammond and Jones, 2010; IFIAS, 1975). Furthermore, analysis of inputs beyond this level becomes time and effort consuming, and as a result, studies conducting analyses beyond this level are rare (Hammond and Jones, 2010; Hammond and Jones, 2008). A third regression level covered the energy embedded in production, delivery, and installation of machines used in building materials’ manufacturing and on-site and off-site construction processes.

Finally, the manufacturing energy of machines utilized to produce the machines of third level regression was covered in a fourth level of regression. The fourth regression level, however, is the most difficult one and is hard to achieve (Hammond and Jones, 2010; Buchanan and Honey, 1994). Likewise, Fay (1999) also proposed a multi-level system boundary model.

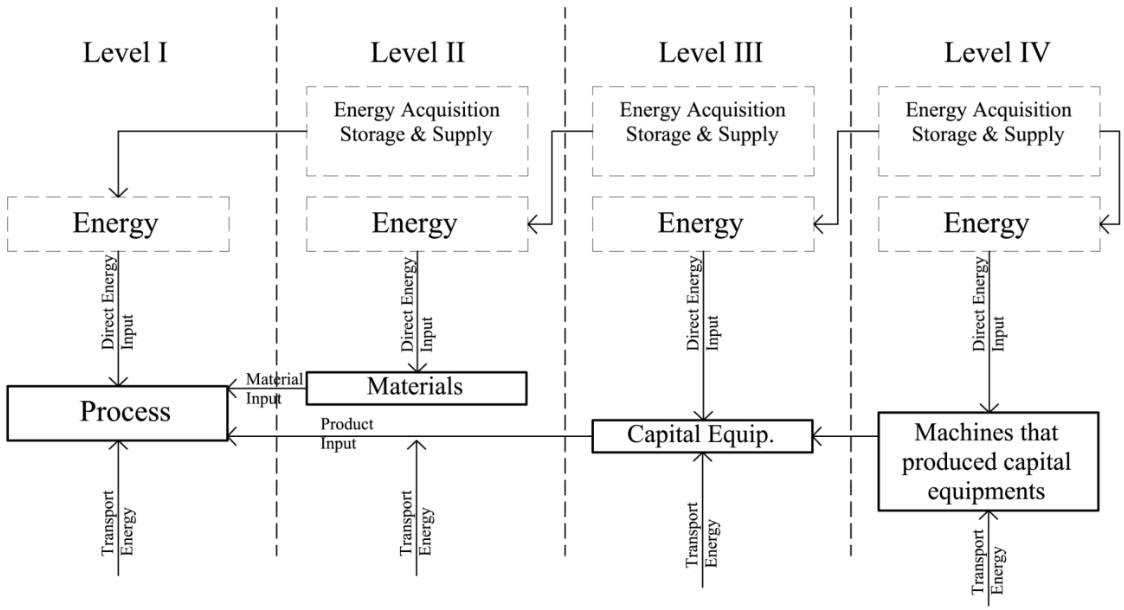


Figure 2-13: System boundary model proposed by IFIAS, 1975

Similar to the other models proposed, Atkinson (1996) suggested tracking all energy and nonenergy inputs to a building from its manufacturing stage back and forward to the biosphere (nature) as shown in Figure 2-14. Each phase of the building's life cycle involved the output of solid, liquid, or gaseous waste and emission affecting the ecosystems (Atkinson, 1996). Tracking inputs from the main production process back and forward to the biosphere actually depicted the upstream and downstream processes. Edwards and Bennett (2003) proposed a product system, which covered all water, primary and delivered energy inputs, and their acquisition in the upstream. Resulting wastes and emissions were shown in the downstream (see Figure 2-15). Likewise, Ries and Mahdavi (2001) defined a boundary that incorporated land use in addition to the energy embodied in the capital infrastructure (see Figure 2-16).

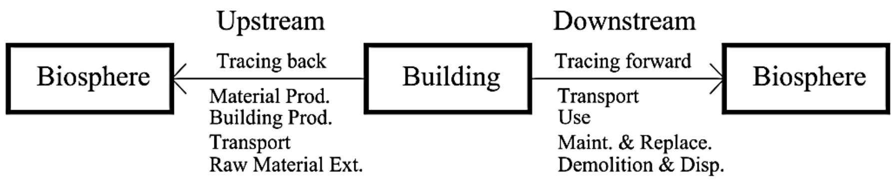


Figure 2-14: A simplified system boundary suggested by Atkinson, 1996

Herendeen (1998) illustrated a similar system boundary model by stating an example of car production. According to the study, the 10% of the total car production energy was consumed during car manufacturing, whereas the remaining 90% of energy was expended in acquiring, processing, producing, and delivering its other constituent materials such as steel, plastic, glass and fabric. Koskela (2000) translated a production model to the construction industry, which included the production components such as transformation (e.g. of input to output), flow (e.g. storage, transportation and handling), and value (e.g. final product). This model also demonstrated a system boundary that covered all of the products (value component) and processes (transformation and flow component) involved in a building's production.

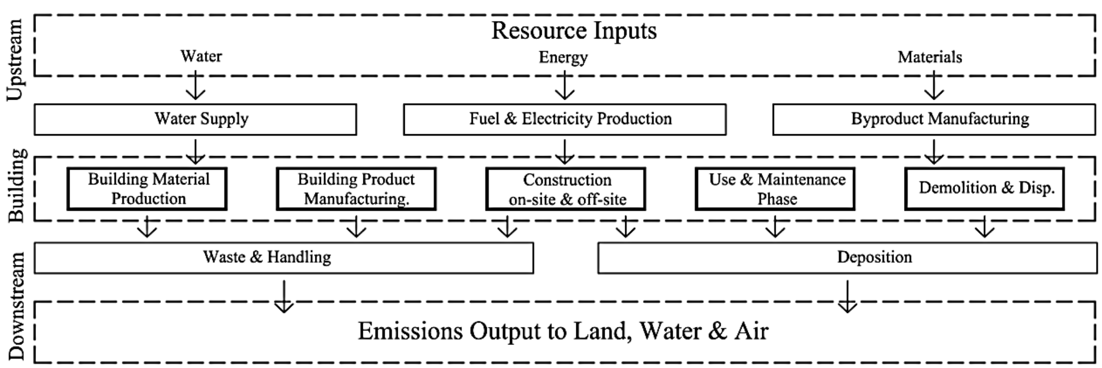


Figure 2-15: System boundary proposed by Edwards and Bennett, 2003

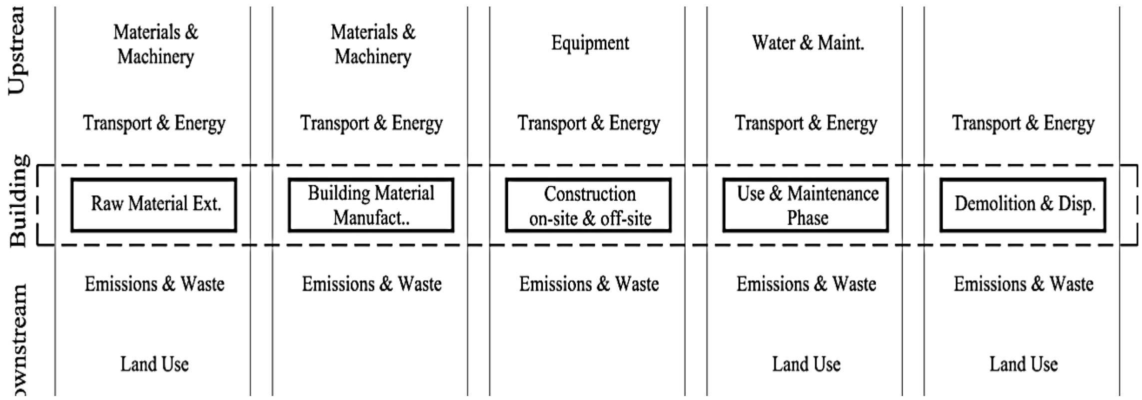


Figure 2-16: System boundary definition provided by Ries & Mahdavi, 2001

A model proposed by Chang et al. (2012) included the embodied impacts of materials, equipment, transportation, and construction used to deliver a building as a finished product. Interestingly, Deng et al. (2011) proposed a system in which all of the energy and material flows culminated into a stage that dealt with waste reuse, recycle, and treatment. Moreover, their model accounted for inputs such as food, human travel, and consumables that were used in the process building production. Murphy et al. (2011) suggested a multi-dimensional model incorporating five levels (inputs under study, energy inputs, material inputs, human labor, and other supportive activities). Figure 2-17 illustrates the system boundary model suggested by Murphy et al. (2011). An "extended system boundary" was another interesting definition of a system boundary proposed by Kua and Wong (2012), which also included the impacts of managing waste produced during a building's operation. Studies such as Kua and Wong (2012) and Matthews et al. (2008) also recommended expanding system boundaries beyond a building to its immediate surroundings.

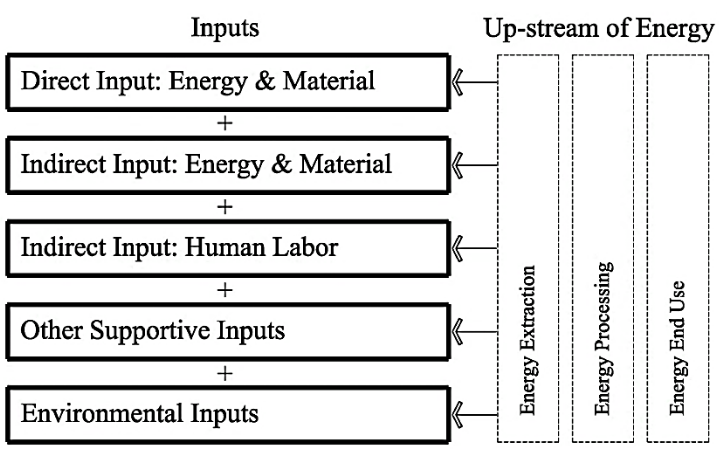


Figure 2-17: Model suggested by Murphy et al., 2011

2.6.1.2 System Boundary Definition: Difference of Opinion

System boundary definition has been an important issue of discussion in existing literature (Horvath, 2004). Studies such as Atkinson (1996), Ries and Mahdavi (2001), Ulgiati et al. (2010), Hammond and Jones (2010) exhibited differences of opinion on the extent of the system boundary. Furthermore, which energy and material inputs to include in the analysis is not always clear and consistent, and as a result, studies often select boundary definitions subjectively (Capper et al., 2012; Mpakati-Gama et al. 2011; Suh et al., 2004; Weidema et al., 2008; Zamagni et al., 2008; Heijungs et al., 2009; Abanda et al., 2012).

System boundaries proposed by published studies differed in three ways. First, studies often included only one or few life cycle stages of a building in the embodied energy analysis (Edwards et al., 1994; Ding, 2004). The transportation and transformation processes between two consecutive life cycle stages were seldom considered in the calculation. Second, how far in the upstream and downstream of each life cycle stage a study should go was unclear (Horvath, 2004; Weidema et al., 2008; Heijungs et al., 2009). Finally, not all studies considered the whole building in the embodied energy calculation and covered one or more building components such as building structure, envelope, finishes, services and site features (Ding, 2004; Edwards et al., 1994; Optis and Wild, 2010). These differences in boundary definition caused variation and incompleteness in embodied energy data due to the exclusion of important life cycle stages or building components (Ding, 2004; Khasreen et al., 2009). Literature (e.g., Hegner, 2007; Krogmann et al., 2008) repeatedly pointed out issues such as inclusion of human energy, capital energy, feedstock energy, and renewable energy need clarifications. Some studies (Crowther, 1999; Thormark, 2002; Worth et al., 2007) covered energy and resource recovery at the end of life in their energy analysis, some did not. Only few studies (e.g., Cole, 1999; Vukotic et al., 2010) incorporated processes such as transportation for materials, equipment, and labor. Others were limited to materials' transportation only. Raynolds et al. (2000) emphasized a need for a system that ensures consistent system boundary selection across different studies. Capper et al. (2012), Abanda et al. (2012), Chang et al. (2012) and Deng et al. (2011) also suggested building a consensus on the issue of a consistent system boundary definition.

2.6.2 Embodied Energy Calculation: Major Issues and Need for Improvement

Among the main methods of embodied energy analysis are process analysis, statistical analysis, input-output analysis and hybrid analysis (Treloar, 1998; Crawford and Treloar, 2003; Ding, 2004; Langston, 2006). In the statistical analysis, the embodied energy is calculated using the total energy supply to a particular industry sector and its total output (Alcorn, 1996; Treloar, 1998; Langston, 2006). This type of analysis is similar to the process analysis and has the same limitations as the process analysis (Alcorn, 1996; Treloar, 1998; Langston, 2006). Hence, the statistical analysis is not discussed separately in this section. The following sections discuss the most commonly used methods.

2.6.2.1 Process-based Embodied Energy Analysis

Process-based analysis is one of the most widely used methods of embodied energy (EE) analysis, as it delivers more accurate (Ding, 2004) and reliable results (Alcorn and Baird, 1996; Pullen, 2000b; Crawford and Treloar, 2003). The process commences with the building material as a final product and works backward in the upstream of the main process, taking into account most of the direct and indirect energy inputs embodied in each constituent material (Treloar, 1998; Alcorn and Baird, 1996). As discussed in Section 1.3, the embodied energy of a product is the sum of directly and indirectly consumed energy in its production. Hence, for a complete calculation both the direct and indirect energy data are required (Treloar, 1998; Crawford, 2004).

However, in the case of a process-based energy analysis, it is difficult to track most indirect energy inputs. For instance, take a generic example of using concrete and steel in a structure. Figure 2-18 illustrates the generic example. The construction of the structure shown in Figure 2-18 involves direct (E_{di}) and indirect energy use (spread over Stage 1 through *n* as marked in Figure 2-18). The direct energy requirements represent the construction energy consumed in operating construction vehicles, cranes, earthmovers, and power tools and in temporary space conditioning at the construction site. The indirect energy requirements account for the energy embedded in materials (e.g., concrete, rebar as shown in Figure 2-18) and services (architectural and engineering services as shown in Figure 2-18) used in building construction (Treloar, 1998; Crawford, 2004; Acquaye, 2010). In the case of a process-based analysis, energy embodied in concrete can be calculated if the embodied energy of Portland cement is known. Similarly, the embodied energy of Portland cement can be determined if the data about energy contents of clinker are available. By going in the upstream of, for instance concrete, one can track most of the indirect energy inputs. However, after a certain point in the upstream, the tracking of energy inputs is truncated due to the unavailability of data (Treloar, 1998; Crawford, 2004; Acquaye, 2010) or enormous efforts required to identify and quantify each material and energy input to the complex upstream processes (Alcorn and Baird, 1996; Treloar et al., 2001b; Ding, 2004; Crawford and Treloar, 2005). This causes a truncation error, which is actually an issue of incompleteness. Technically, this is called a system boundary truncation. Even downstream truncation of system boundary occurs in a process-based analysis (Acquaye, 2010). For instance, in the case of steel mills, downstream processes of fabricating rebar are truncated because the weight of rebar is multiplied by the embodied energy coefficient of steel to calculate the embodied energy of rebar. This excludes the direct energy consumed by manufacturing units fabricating rebar and other structural shapes. Other services such as banking, insurance, architectural and engineering consultancy, construction management, and commissioning are mostly excluded from the calculation causing a complete truncation of services.

A process-based embodied energy intensity, which is also known as the embodied energy coefficient (E_i), is calculated or sourced for each building material. At Stage 1 all material quantities, represented by Q_i, used in constructing the structure are quantified and multiplied by the materials' waste factors to make adjustment for waste. The embodied energy coefficients of the materials are then multiplied to material quantities to cover some indirect requirements as shown in the Equation 2-2. The indirect requirements are then added to the total direct energy consumed during the construction. Assuming a waste factor for a material as W_i, the total energy embodied in a building is calculated as (Treloar, 1998; Crawford, 2004; Acquaye, 2010):

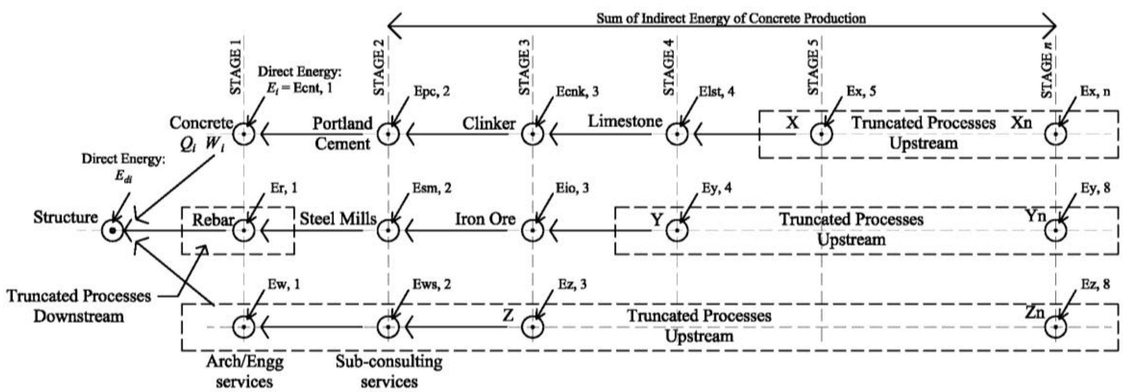


Figure 2-18: Process-based analysis and system boundary truncation

$$E_{Process-based} = E_d + \sum_{i=0}^{n} Q_i \times W_i \times E_i \qquad \text{Equation 2-2}$$

Where E_d, Q_i, and E_i, represent the direct energy use, quantity of material, material's embodied energy coefficient, and material, respectively. The term "*i*" denotes the materials used in the structure.

Process-based embodied energy analysis is data-intensive and time-consuming and in order to ensure completeness, all major and minor inputs need to be tracked and recorded (Crawford, 2004; Acquaye, 2010; Mattila et al., 2010). As huge efforts are required for collecting the energy data, a boundary is drawn to define the significant energy inputs for which data is available. However, it is assumed that all other inputs are insignificant and need not be included in the calculation (Treloar, 1998; Crawford, 2004; Acquaye, 2010). The process analysis is accurate but due to truncation of system boundary it suffers from the issues of incompleteness (Ting, 2006; Khasreen et al., 2009; Dixit et al., 2010). The magnitude of system incompleteness and error in process analysis results is estimated to be as high as 50% and 10%, respectively (Lenzen, 2000). According to Mattila et al. (2010), the impact of truncating a system boundary could be up to 20% or more, particularly in sectors dominated by capital investments. Pullen (2000b) stated that the process analysis fails to capture not only some of the downstream processes but also the capital energy inputs (e.g. plants and equipment) required for building material production. If a system boundary model is developed based on the IFIAS recommendations (see Figure 2-13), it is more likely that the calculation remains incomplete if a process-based analysis is used. Even inventories based on a detailed and extensive process analysis failed to attain a reasonable completeness (Treloar et al., 2001b; Crawford, 2004; Crawford and Treloar, 2005). Crawford (2004) also discussed a sideways truncation that occurred because of inputs to the main process extending sideways.

According to literature (e.g., Treloar, 1998; Crawford, 2004; Acquaye, 2010), most process-based studies could go up to Stage 2 if extensive data is available. According to Baird et al. (1994), Stage 1, which mainly covered direct energy inputs, represented less than 50% of the total energy requirements. At Stage 2, nearly 40% energy use was covered, whereas beyond Stage 2, only 10% of energy inputs were left. This meant that if an analysis was conducted up to Stage 2 completely, nearly 90% of the gross energy requirements of a building could have been covered.

2.6.2.2 Input-output-based Embodied Energy Analysis

An input-output-based analysis is conducted on the basis of economic data and it utilizes the monetary flows among different industry sectors to determine energy embodied in a particular product (Treloar, 1998; Crawford, 2004; Acquaye, 2010). These economic data are published periodically by the governments in the form of input-output tables. An economic input-output table presents monetary flows among various industries of a given economy. An economy on the globe can be divided into numerous sectors that produce a variety of products. These sectors represent one industry or a group of industries that produce a similar product (e.g. steel products). Each sector that manufactures a product also consumes goods and services produced by other sectors (Carter et al., 1981; Miller and Blair, 2009). This creates an interindustry flow of inputs and outputs where the sum of the inputs of a sector equals the sum of its outputs to other sectors. An input-output table demonstrates these interindustry transactions as well as consumption and purchases made by the final consumers and government. The input-output table contains sectors that produce goods and services and also consume goods and services produced by other sectors.

An economic input-output table is always in equilibrium meaning that the inputs and the outputs of the industry sectors are balanced (Miernyk, 1965; Carter et al., 1981; Miller and Blair, 2009). This means that if an industry sector increases its output by one dollar, then by the input-output theory, it will require inputs worth one dollar more from its supplying sector. The demand from its supplying sector is known as the direct requirement. Each supplying sector also needs to buy more to meet the demand of this increased output. Hence, the impact of increasing output by one dollar can be felt throughout the economy. This impact represents the indirect requirements. The sum of direct and indirect requirements is termed the total requirements (Miernyk, 1965; Miller and Blair, 2009). In an input-output-based energy analysis, the total impact of a one dollar increase in the output of an industry sector on the energy providing sectors is calculated from the total requirement coefficients. After determining the monetary inputs required from the energy sectors per dollar output, energy tariff can be used to derive the total energy consumption in energy units. The direct and total requirement coefficients are converted to direct and total energy requirement coefficients using fixed or variable energy prices. The input-output tables have been used to transcribe economic flows into energy flows by applying average energy tariffs (Fay and Treloar, 1998; Crawford and Treloar, 2003; Ding, 2004). Thus, in an input-output analysis, the cost of a product and its energy intensity (in MJ/$) are multiplied to compute its embodied energy (Crawford and Treloar, 2005).

The input-output-based analysis accounts for most direct and indirect energy inputs used in the process of building material production and thus is considered complete (Fay and Treloar, 1998). Figure 2-19 illustrates the same generic example in an input-output context. As the total requirement coefficients represent the sum of direct and indirect requirements, this method is assumed to be comprehensive and complete as it embraces nearly the entire system boundary as shown in Figure 2-19. If T_i and D_i represent the total and direct requirement coefficient in $ input/$ output of an industry sector "i", the total and direct energy requirements are given by:

$$TE_i = T_i \times F_p$$

$$DE_i = D_i \times F_p$$

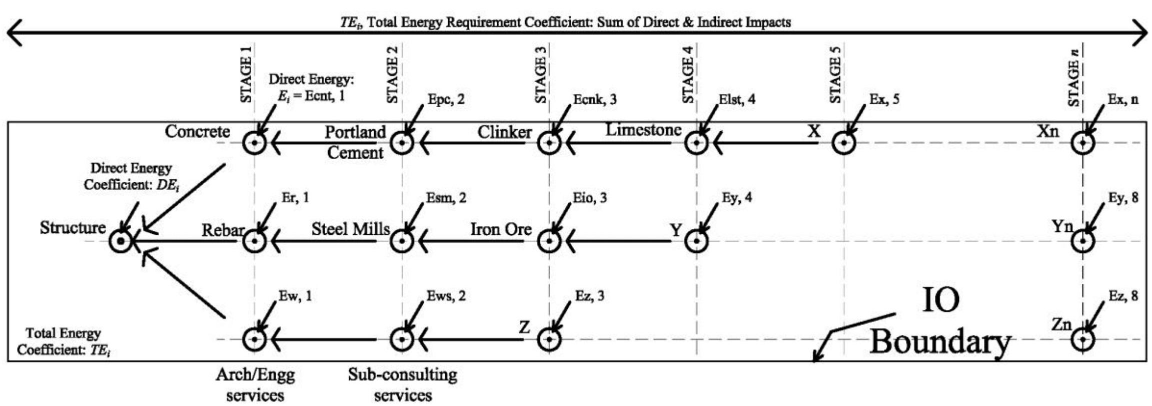


Figure 2-19: Input-output analysis and system boundary coverage

Where F_p is the energy price in MJ/$. The calculated energy coefficients provide total and direct energy use in MJ/$ industry output. The total energy requirements can be calculated by multiplying the TE_i and total industry output O_t ($).

$$T_e = TE_i \times O_t \qquad \text{Equation 2-3}$$

Although this method is considered complete, it also suffers from inherent problems such as errors and uncertainties of economic data (e.g. energy tariff and product cost) and aggregation of industry sectors. The issue of aggregation makes the end results less specific to the product under study. For example, a residential construction sector may represent all residential buildings including low-rise, high-rise, custom-designed, and mass housing. As per the input-output theory, all of them would have the same energy intensity as the residential sector, which may not be true. Although the results of an input-output-based analysis are less study-specific than the process-based analysis, it is still considered straightforward, accessible, and representative (Langston, 2006; Pullen, 1996). Among the major limitations of input-output-based methods include:

Age of Data: The input-output tables are not published in a timely manner due to extensive efforts involved in collecting, analyzing, and balancing the economic data. Usually, economic input-output tables are five or more years old making its data nonrepresentative in time (Crawford, 2004; Langston, 2006; Miller and Blair, 2009). For instance, the United States' detailed input-output accounts are published every seven years. The latest benchmark data that are available are from 2002 (USBEA, 2008). Two types of anomalies could arise due to the use of old data. First, the structure of the domestic and foreign monetary transaction might have changed over time. Second, the composition of labor and machine in the production function might have altered as a result of improved technology.

National Average and Fixed Energy Tariff: To convert monetary transactions into energy terms, national average prices are used that may not represent the actual energy prices paid by the industry sectors. The fuel mix for electricity production and input composition for material production also differ with geographic location (Crawford, 2004) within the same country. Some industries pay real-time electricity prices, whereas some end up paying peak rate charges. Also, energy buyers usually negotiate while purchasing energy in bulk. Using a national average price to convert monetary flows into energy flows may not be representative (Treloar, 1998; Crawford, 2004; Miller and Blair, 2009; Acquaye, 2010). Instead of using variable prices, fixed energy tariffs are used to derive a national average by converting monetary data to energy data. In reality, sectors may be paying different prices for different energy types such as oil, natural gas, and coal (Langston, 2006; Crawford et al., 2002; Carter et al., 1981; Crawford, 2004).

Proportionality Assumptions: The cost of the product of each sector in an input-output table is directly proportional to the amount of goods and services consumed by that sector. For instance, if 50 kilograms of steel is needed to manufacture a refrigerator then 100 kilograms of steel would be needed to produce two refrigerators of the same cost (Langston, 2006; Crawford, 2004; Crawford et al., 2002). In energy terms, for instance, if 1 MBtu is consumed to produce 1 lb of steel then to produce 5 lbs. of steel, 5 MBtu of energy would be required. This may not hold true, as manufacturing industries use different production technologies and their energy and material input could be quite different from one another (Acquaye, 2010).

Homogeneity Assumptions: Input-output tables are built assuming that the same mix of inputs (product and services) is required by each product manufactured by an industry sector. This means that all products covered under the aluminum sector are manufactured using the same mix of inputs (e.g. bauxite, electricity, accounting services, etc.), which may not be true, especially for a sector that is highly aggregated (Langston, 2006; Crawford, 2004; Treloar, 1998; Crawford et al., 2002). Aluminum cans, for instance, would require a different mix of inputs than a cooking utensil of the same weight. According to the homogeneity assumption, the aluminum cans could be substituted for the cooking utensil, which may be accurate in monetary terms but may not be in physical terms (Treloar, 1998; Crawford, 2004)

Aggregation Problem: Input-output tables are composed of sectors that are highly aggregated. These sectors represent more than one product and each product may have a different energy intensity and price (Langston, 2006; Crawford, 2004; Treloar, 1997). For instance, an industry sector manufacturing plastic goods would represent, in energy terms, all plastic products related to construction, medical supply, packaging, machinery, electronic items, etc. Given this assumption, each of these plastic products would share the same energy intensity as the industry sector as a whole. In reality, this assumption is not true, as each of the listed products has a different energy intensity (Crawford, 2004; Acquaye, 2010).

Double Counting: According to Treloar (1998) and Langston (2006), energy may be double counted while using input-output data for energy providing sectors. For instance, if 1 GJ of electricity is produced using 2 GJ of oil then the energy embodied in electricity would be 3 GJ as per input-output theory (Treloar, 1998). Another example of double counting is the energy intensity of an energy providing sector. For example, in the United States, the dry natural gas is distributed by the *Natural Gas Distribution* sector. If an industry sector purchased natural gas from the *Natural Gas Distribution* sector, the purchased natural gas would be double counted as an indirect impact because the *Natural Gas Distribution* sector also bought natural gas from the *Oil and Gas Extraction* sector.

Exclusion of Inputs: Inputs such as capital goods are not purchased or replaced frequently. Such goods may not show up in the input-output tables for a given year (Treloar, 1998; Crawford, 2004; Langston, 2006). In addition, since household expenditure is treated as a final demand component, the use of human energy by manufacturing sectors remains excluded from the input-output calculations.

The assumptions and various issues with economic input-output data make results of an input-output-based analysis erroneous and unreliable (Fay and Treloar, 1998; Crawford and Treloar, 2003; Ting, 2006; Pearlmutter et al., 2007; Khasreen et al., 2009). The resulting error in the measurement could be up to 50% (Treloar et al., 2001a).

2.6.2.3 Hybrid Analysis

The process-based analysis is specific to the study but lacks completeness. The input-output-based analysis is complete but lacks specificity (Dixit et al., 2012a). A hybrid analysis is devised by unifying the benefits of the two methods to eliminate the fundamental errors and limitations of both the process and input-output-based analyses (Mattila et al., 2010; Acquaye, 2010; Dixit et al., 2012a). However, the results of a hybrid method also need to be compared and validated (Crawford and Treloar, 2003).

The hybrid method starts with process analysis of readily available energy input data of the final production stage and likely one stage more in the upstream. In later upstream stages when it becomes difficult to achieve reliable and consistent information about complex upstream processes, the process analysis is substituted by the input-output-based analysis (Alcorn and Baird, 1996; Lenzen, 2000). There are many ways in which the two methods can be combined. The ultimate aim is to improve specificity, accuracy, and completeness of the method. Literature (e.g., Crawford, 2004; Treloar, 1998; Dixit et al., 2010; Acquaye, 2010) categorized hybrid methods as:

Process-based Hybrid Analysis: This method applies input-output-based analysis to complex parts of upstream processes of material production and thus, obviates the incompleteness inherent in process analysis. In this method, the material quantities used in a building are quantified using the process data (e.g. bill of quantities). According to Treloar (1998), the calculated material quantities are then multiplied by input-output-based energy intensities of each material. The input-output -based energy intensities that are in energy unit per $ (e.g. MJ/$) are converted into physical quantities using the price of the material (Treloar, 1998). Treloar (1998) also warned that if material prices are underestimated or overestimated, the embodied energy values would be grossly affected. However, using this method for a complex product, which is made of more than one material, could pose problems, as the manufacturing energy of the complex product is mostly excluded. Figure 2-20 illustrates this issue by an example of open web joists. For quantifying the energy embodied in an open web joist, the quantity of steel (Q_i) is derived and multiplied by the input-output -based embodied energy coefficient of steel. However, in the process, other upstream inputs (as marked in the dashed box) are left behind. Also, as only steel quantities are used, the direct energy (E_{di} as shown in Figure 2-20) consumed in fabricating open web joists is also excluded from the calculation. According to Treloar (1998), incompleteness due to this issue could be 0-100%.

Input-output-Based Hybrid Analysis: This method involves substitution of input-output data by process data in an input-output model in order to improve reliability of the energy calculation (Treloar, 1998;

Crawford and Treloar, 2003; Langston, 2006). In this method, the process-based direct energy use is derived first, data of which are readily available. These process-based direct energy data are then incorporated in an input-output -based model (see Figure 2-21). The assumption is that the more the inclusion of process data, the more reliable the model. The process data can be inserted in the input-output -based model in many ways. For instance, if energy use data are available for all industry sectors, they can be incorporated directly into the input-output model (Carter et al., 1981). If direct energy data are available only for a few sectors, then incorporating them into the input-output model may cause unwanted indirect impacts (Treloar, 1998). Treloar (1998) proposed a method for integrating energy use data into the economic model. This method involves the identification and extraction of direct energy paths from the input-output model in order to integrate the study-specific process data to avoid any unwanted indirect effects (Treloar, 1998). This method is discussed in detail in Section 2.6.2.4. According to Treloar (1997), the incompleteness or error in typical embodied energy calculation and analysis is approximately 20% and thus, no method is available that is fully efficient. However, an input-output-based hybrid analysis is considered better than other existing methods (Alcorn and Baird, 1996; Crawford and Treloar, 2003; Langston and Langston, 2008).

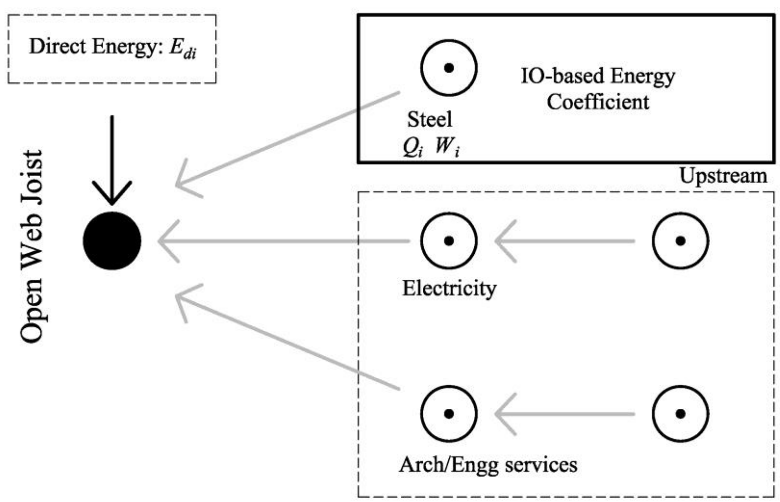


Figure 2-20: Process-based hybrid analysis example

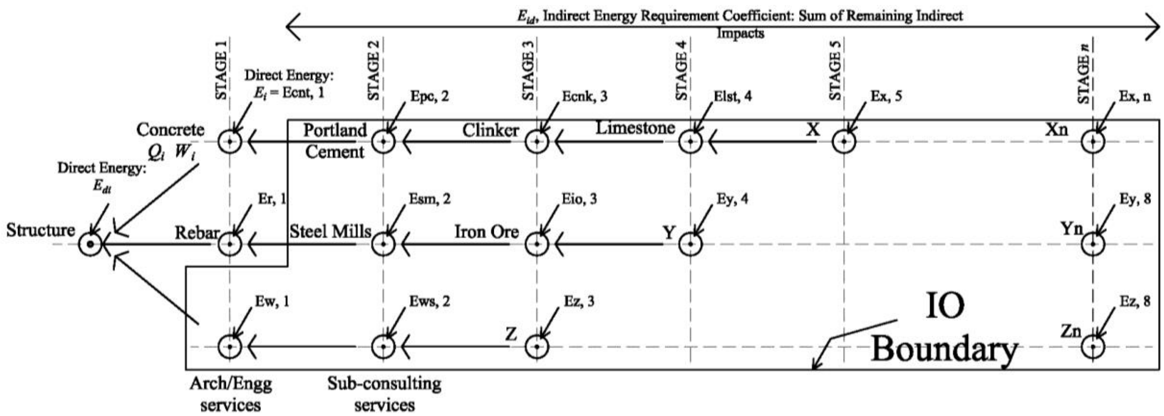


Figure 2-21: Input-output-based hybrid analysis

2.6.2.4 Embodied Energy Path Extraction by Treloar (1998)

Treloar (1998) proposed a unique way to extract significant energy paths (paths with energy values more than an arbitrarily selected value of 0.0001 GJ/$1000) from the input-output model and replace them with reliable process data. According to Treloar (1998), there are three ways to improve reliability of an input-output-based energy analysis. First, process-based direct requirement coefficients are inserted into the input-output matrix. This approach was found to be problematic, as it may cause unwanted indirect impacts, particularly if the process data are not available for all sectors. Second, a separate column of process-based coefficients could be added to the direct requirement matrix. According to Treloar (1998), in this method, efforts were more focused on quantifying smaller inputs at an early stage ignoring potentially larger inputs in distant upstream. The third approach, that Treloar (1998) adopted, included tracing and extracting direct energy paths for which process data are available, calculating the total energy of the extracted path, and substituting the energy of the path by process data. The input-output-based hybrid analysis that was further improved by Treloar (1998) is currently considered one of the most appropriate methods to calculate embodied energy (Langston, 2006). Crawford (2004) commented by citing Lenzen (2000) that an input-output-based hybrid method is “complete, more elegant, less data and labor intensive and easier to perform.”

According to Crawford (2004), in spite of newly developed and improved hybrid methods, data uncertainty remains a major limitation. As the hybrid methods are a combination of process and input-output data, these methods also carry the limitations and inaccuracies associated with these data. The method developed by Treloar (1998) also had certain limitations and errors (Crawford, 2004). For instance, while extracting a significant path for a product (e.g. metal deck roof), other paths (e.g. other types of roof products in the same category) remained in the input-output model. These paths should have been deleted if these products were not used in the study building (Crawford, 2004). Crawford and Treloar

(2003) demonstrated an approach to carefully extract all paths that were used or not used in the study building and then insert relevant process data. Treloar et al. (2000) also warned that even if significant energy paths were extracted and replaced with reliable process data, unimportant energy paths remained in the model that still acted as a "black box." The input-output-based hybrid method proposed by Treloar (1998) requires process data, which may not be representative, accurate, or complete. For instance, Treloar (2001c) utilized the same method to calculate energy embodied in office buildings and obtained process data from a variety of sources. Although care was taken not to select process data that are more than five years old, the sourced process data may not be complete or representative. In addition, if process energy data are available for most of the industry sectors, it would be much easier to modify a column of an input-output model without unwanted indirect effects as shown by Carter et al. (1981). According to Treloar (1998), energy use data are only available for 25 industry sectors out of the total 113 sectors of the Australian economy. Hendrickson et al. (1997) concluded that life cycle assessment at a more refined level may not be meaningful given the uncertainty of life cycle data. Crawford (2004) (by citing Crawford et al., 2003) believed that efforts to improve reliability and completeness are "still worthwhile."

2.6.2.5 Improvements in Treloar's Method by Crawford (2004)

Some of the problems identified in the embodied energy path extraction approach proposed by Treloar (1998) were resolved by Crawford (2004). Crawford's approach was useful in calculating the embodied energy of particularly complex products that are made of multiple basic materials. For instance, in quantifying the energy embodied in concrete that is composed of cement, aggregates, steel, and water, this method ensured the inclusion of all direct and indirect inputs associated with a ready-mix plant in addition to the collective embodied energy of its constituent materials. The approach proposed by Crawford (2004) involved three main steps:

Step I: Calculation of the process-based hybrid energy intensity of each constituent material (e.g. in the case of the concrete example, cement, aggregates, steel, and water) by adding the process-based energy intensity and extracting the total energy of the total energy path representing each constituent material from its input-output sector:

$$E_{ph,i} = E_{p,i} + (T_{s,i} - T_i) \times P_i \qquad \text{Equation 2-4}$$

Where:

i Representing a constituent material (e.g. cement)

$E_{ph,i}$ Process-based hybrid energy intensity of the constituent material

$E_{p,i}$ Process-based energy intensity of the constituent material

$T_{s,i}$ Total energy intensity of input-output sector manufacturing the constituent material

T_i Total energy of the total energy path representing the constituent material

P_i Price of the constituent material

Step II: The process-based hybrid embodied energy of a complex product "p" is calculated as:

$$E_{ph,p} = M_i \times W_i \times E_{ph,i} + (D_{s,p} \times P_p) \qquad \text{Equation 2-5}$$

Where:

p Representing a complex product (e.g. concrete)

$E_{ph,p}$ Process-based hybrid energy intensity of the product

M_i Quantity of the constituent material

W_i Waste factor of the constituent material

$E_{ph,i}$ Process-based hybrid energy intensity of the constituent material

$D_{s,p}$ Direct energy intensity of input-output sector manufacturing the product

P_p Price of the product

Step III: The IO-based hybrid embodied energy of a complex product is calculated as:

$$E_{ioh,p} = M_i \times W_i \times E_{ph,i} + \left(T_{s,p} - T_p\right) \times P_p \qquad \text{Equation 2-6}$$

Where:

p Representing a complex product (e.g. concrete)

$E_{ioh,p}$ IO-based hybrid energy intensity of the product

M_i Quantity of the constituent material

W_i Waste factor of the constituent material

$E_{ph,i}$ Process-based energy intensity of the constituent material

$T_{s,p}$ Total energy intensity of IO sector manufacturing the product

T_p Total energy of the total energy path representing the product

P_p Price of the product

2.6.2.6 Issue with the Proposed Hybrid Methods

The input-output-based hybrid methods proposed by Treloar (1998) and Crawford (2004) were very useful, especially when determining the embodied energy of a complex product in an economy where process energy data are available for some of the industry sectors. However, there was an assumption that the process-based energy intensities were calculated in a complete and accurate manner. For instance, inputs such as human energy might not be included in the available process data. It is still not clear how to incorporate human and capital inputs in the calculation. In addition, while calculating the process-based hybrid energy intensity of a constituent material (Step I in the Crawford's method), when the energy of the total energy path (T_i) was extracted, both the direct and indirect energy were excluded. However, the energy replaced by the process-based value ($E_{p,\,i}$) might not include the indirect energy of the constituent material. Also, if a sector is highly aggregated, the calculated indirect impacts may not be representative. For calculating the upstream indirect impacts, both hybrid approaches proposed by Treloar (1998) and Crawford (2004) still depend on product prices, which, according to Treloar (1998), could distort the end results.

Another variation of an input-output -based hybrid approach provided by Acquaye (2010) (based on Crawford, 2004) seemed more appropriate in which the energy of direct energy paths rather than the total energy paths were extracted. In Equation 2-7 - Equation 2-9, it can be seen that instead of extracting the total energy paths, as done by Crawford (2004), Acquaye (2010) extracted the direct energy paths. Acquaye (2010) also warned about a dual price error in Crawford's method that may arise due to the use of energy, material, and product prices multiple times. According to Acquaye (2010):

$$PHC_i = PC_i + \left(TC_{s,i} - DC_i\right) \times P_i \qquad \text{Equation 2-7}$$

$$PHC_p = \sum_{i=1}^{M} (M_i \times W_i \times PHC_i) + (DC_p \times P_p) \qquad \text{Equation 2-8}$$

$$IOHC_p = PHC_p + \left[\left(TC_{s,i} - \sum_{m=1}^{M} DC_i\right) - DC_p\right] \times P_p \qquad \text{Equation 2-9}$$

Where:

p	Representing a complex product (e.g. concrete)
PHC_i	Process-based hybrid carbon intensity of the constituent material
PC_i	Process-based carbon intensity of the constituent material
$TC_{s,i}$	Total carbon intensity of IO sector manufacturing the constituent material
DC_i	Direct carbon of the direct energy path representing the constituent material
P_i	Price of the constituent material
M_i	Quantity of the constituent material
W_i	Waste factor of the constituent material
PHC_p	Process-based hybrid carbon intensity of the product
DC_p	Direct carbon intensity of IO sector manufacturing the product
P_p	Price of the product
$IOHC_p$	IO-based hybrid carbon intensity of the product

2.6.3 Proposed Improvements to Input-output Model

As discussed in the embodied energy calculation section, the input-output-based energy calculations are affected by the limitations of the economic input-output data and models. Although these limitations were emphasized quite regularly in the literature (Treloar, 1998; Crawford, 2004; Acquaye, 2010), solutions to reduce or eliminate their impacts were also proposed. This section discusses briefly what solutions have been proposed and how they should be applied.

2.6.3.1 Aggregation of Industry Sectors

One major problem that has been repeatedly pointed out was that of highly disaggregated economic sectors. Although some countries around the globe have recently started publishing their economic accounts at a more detailed level (e.g. United States commodity-by-commodity requirement matrices), there are sectors that still represent multiple different products. One way to get results specific to a product under study is to disaggregate the product sector. As suggested by Joshi (1998) and (1999), a direct requirement matrix **a** (*n by n size*) can be broken down into matrix **A** *(n+1 by n+1 size*) in such a way that the added sector represents the product under study. Consider **a** and **A** as:

$$\mathbf{a} = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & a_{i\,k} & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} \;;\; \mathbf{A} = \begin{bmatrix} A_{1\,1} & \dots & A_{1\,n-1} & A_{1\,n} & A_{1\,n+1} \\ \vdots & A_{i\,k} & \vdots & \vdots & \vdots \\ A_{n-1\,1} & \dots & A_{n-1\,n-1} & A_{n-1\,n} & A_{n-1\,n+1} \\ A_{n\,1} & \dots & A_{n\,n-1} & A_{n\,n} & A_{n\,n+1} \\ A_{n+1\,1} & \dots & A_{n+1\,n-1} & A_{n+1\,n} & A_{n+1\,n+1} \end{bmatrix}$$

Where "*i*" indicates the sector from which sector *n* purchases its inputs. If X_{in} and X_{in+1} represent the output of sector *n* and the newly added sector *n+1*, respectively, then from the input-output theory (based on Joshi, 1998; Joshi, 1999):

$$a_{in} \times (X_{in} + X_{i\,n+1}) = A_{in} \times X_{in} + A_{i\,n+1} \times X_{i\,n+1}$$

$$a_{in} = A_{in} \times (X_{in} \div (X_{in} + X_{i\,n+1})\,) + A_{i\,n+1} \times (X_{i\,n+1} \div (X_{in} + X_{i\,n+1})\,) \qquad \text{Equation 2-10}$$

Where $(X_{in} \div (X_{in} + X_{i\,n+1})\,)$ and $(X_{in} \div (X_{in} + X_{i\,n+1})\,)$ denote respective share of sectors *n* and *n+1* in the total output of the original aggregated sector. Similarly, purchases made by a sector *k* from the original aggregated sector would be equal to the sum of purchases from sector *n* and *n+1*.

$$a_{nk} = A_{nk} + A_{n+1\,k}$$

$$a_{nn} = (A_{n\,n} + A_{n+1\,n}) \times (X_{in} \div (X_{in} + X_{i\,n+1})\,) + (A_{n\,n+1} + A_{n+1\,n+1}) \times (X_{i\,n+1} \div (X_{in} + X_{i\,n+1})\,)$$

Equation 2-11

If the breakup of the total output of an industry sector is known, it can be disaggregated into two or more sectors of interest.

2.6.3.2 Double Counting of Energy Inputs

As mentioned earlier, a conventional input-output model, if applied as it is, involves double counting of inputs especially in the case of energy providing sectors that purchase, process, and distribute energy (e.g., electricity production, natural gas distribution) (Treloar, 1998; Crawford, 2004; Acquaye, 2010; Mo et al., 2010). Treloar (1998) proposed using a factor that converts a delivered energy quantity into a primary energy quantity. The factor is known as the Primary Energy Factor (PEF), and it takes into account all process energy consumed (human and mechanical energy), energy losses incurred, and energy used indirectly (e.g. embodied energy of materials, plants, equipment, and other services used) in extracting, processing, transmitting, and distributing energy such as oil, gas, or electricity (Treloar, 1998; Deru and Torcellini, 2007; Mo et al., 2010). However, the basic assumption is that the calculated value of PEF takes into account all direct and indirect consumption related to a delivered energy source. Therefore, if PEF does not cover all the energy inputs, the final energy calculation may remain inaccurate or incomplete. According to Treloar (1998), all energy and nonenergy inputs to energy providing sectors are kept at zero meaning there is no direct and indirect consumption by the energy providing sectors. However, the output of the energy providing sector still goes to other industry sectors. The calculated direct and total requirements are then multiplied by PEF of each energy source in order to make adjustment for all direct and indirect energy use.

2.6.3.3 Fixed Energy Tariff

There are multiple energy providing sectors in an economy delivering energy sources such as oil, natural gas, coal, and electricity. Each industry sector of the economy pays a different price to these energy providing sectors for purchasing energy. One alternative to use and integrate variable price data into an input-output model is given by Carter et al. (1981). If the actual physical quantities of energy consumed by industry sectors are known, they can be inserted into an input-output model to derive the direct and total requirement coefficient in energy units (e.g. MJ/$). One big advantage of this approach is that energy prices are not used to convert monetary flows into energy flows. Any issues resulting from energy price variations would not affect the results of this approach. Weber et al. (2010) also created a vector of actual physical quantities of electricity use in order to determine the carbon emission intensities of various industry sectors. However, information of actual physical quantities of energy consumed by each industry sector may not be readily available (Weber et al., 2010).

2.6.4 Embodied Energy Calculation: Energy and Cost Relationship

In spite of many efforts to define a system boundary and derive an appropriate method to calculate embodied energy, studies such as Pears (1996), Ding (2004), Crawford et al. (2002), Frey (2008), Dixit et al. (2010) concluded that a reliable, consistent, and accurate embodied energy information is not readily available. An embodied energy analysis in its current form is expensive and time-consuming and is based on a number of assumptions (Langston, 2006). In addition, the energy analysis is still not well integrated into current design and construction practices and decisions are still made based on solely the capital cost. The following studies are worth discussing in the context of energy and cost relationship:

2.6.4.1 Costanza (1980)

According to Costanza (1980), the linkage between the economic and energy flows across an economy can be utilized to determine the energy embodied in a product. In addition, it is claimed that efforts to save energy may mean saving one form of energy at the cost of other. The calculation approach proposed by Costanza (1980) was based on the energy balance of an economic system in which the energy embodied in energy and nonenergy inputs to a sector was balanced by the embodied energy of its total output. The system boundary proposed by Costanza (1980) included the household and government sector as endogenous to the intermediate transaction matrix. What this means that the energy embodied in human and government inputs were also accounted for. Costanza (1980) analyzed four types of economic systems that included a conventional system and three modifications to cover household sector, government sector, and solar energy inputs. Costanza (1980) differentiated the various energy forms. For instance, the electricity was considered higher quality energy than the fossil fuels, which was of higher quality than the solar energy. Costanza (1980) demonstrated a strong relationship between the energy embedded in a product and monetary output of its production sector. Literature (e.g., Costanza, 1980; Cleveland et al., 1984) revealed a strong relationship of the nation's energy to the Gross Domestic Product (GDP) and derived a ratio of energy to GDP. Costanza (1980) concluded that assuming appropriate system boundaries, "market determined dollar values" are proportional to the embodied energy values with an exception of the primary energy sector.

2.6.4.2 Langston (2006)

The research performed by Langston (2006) was inspired by the fact that current embodied energy calculation approaches are not only tedious but also time and resources-consuming. The difficult embodied energy calculation process hindered its wide-spread application as an important indicator of the energy and environmental impacts of production. Langston hypothesized that a building's capital and recurring cost (operating and maintenance costs) had a strong and positive correlation with its embodied and operating energy. If a strong correlation was found, the estimation of embodied energy from the cost of a building could be possible. Langston used the approach proposed by Treloar (1998) to calculate the embodied energy of the study buildings. Cost data were collected from the study buildings' bill of quantities. Langston (2006) found that there is a strong and positive correlation between the total energy (embodied and operating) and total cost (capital and recurring) of the buildings under study. However, when analysis was done at a more detailed level (individual work and material level) this correlation was positive but weak.

Bullard and Herendeen (1975) also emphasized the relationship of product consumption and energy consumption by stating "when you consume anything, you are consuming energy." Likewise, Costanza

(1980) and Langston (2006) both concluded that there was a strong and positive correlation between the cost and embodied energy of a building at the project level.

2.7 RESEARCH GAPS

The review of relevant literature about embodied energy modeling and analysis revealed several gaps in the current state of research, which are discussed in this section.

2.7.1 Embodied Energy Definition and System Boundary Model

The topic of energy embodied in a building and its constituent materials has been discussed widely in the literature. However, a consensus on its definition is still lacking. As the interpretation of embodied energy is tied to what is included in the calculation, a consistent and complete system boundary modeling becomes a crucial issue. Issues such as the extent of the system boundary in the upstream and downstream of a product are still not clearly defined. As mentioned in the literature (e.g. Raynolds et al., 2000), a model to define a system boundary consistently and completely needs to be developed in order to introduce comparability to embodied energy data. Differing system boundaries, due to their subjective selection, is a major methodological issue with the embodied energy research.

2.7.2 Calculation Guidelines

In spite of some remarkable efforts by researchers such as Treloar (1998), Crawford (2004), and Langston, (2006), the variation in embodied energy values is still an unresolved issue. There is no protocol that could be used to standardize the energy calculation in order to reduce some of these variations (Menzies et al., 2007; NIST, 2010). The International Standardization Organization (ISO) developed standards (ISO14040 and ISO 14044) for performing the Life Cycle Assessment (LCA) of a manufactured product. However, these standards have been criticized for not being able to provide the required guidance to streamline the LCA process (Zamagni et al., 2008; Weidema et al., 2008; Heijungs et al., 2009; Jeswani et al., 2010). Some of the parameters responsible for variations have been identified. These parameters can be used to develop a set of guidelines to streamline the process of embodied energy calculation (Dixit et al., 2010).

2.7.3 Calculation Method

The field of embodied energy research lacks a standard methodology to accurately and completely determine the energy embodied in a building (Ting, 2006; Menzies et al., 2007; Langston and Langston, 2008; Frey, 2008; Khasreen et al., 2009). The existing methods are either incomplete or not specific to a product under study, and hence, produce different results. According to Ting (2006), current methods need to be improved in order to consistently measure the energy embodied in a product. Some of the improvements suggested include inclusion of process data, insertion of human and capital energy, sectorial disaggregation for increased specificity, and avoiding double counting (Treloar, 1998; Joshi, 1998; Crawford, 2004; Langston and Langston, 2007; Ulgiati et al., 2010).

2.7.4 Energy and Cost Relationship

Langston (2006) performed research on the relationship between embodied energy and cost and found that a building's embodied energy is highly correlated with its capital cost. However, it was found that this correlation is weak if the correlation analysis is performed at a material or process level (Langston, 2006). This relationship of building components and their cost needs more research. In addition, Langston (2006) suggested that the energy and cost relationship research needs to be extended to other geographic locations and to other building types.

2.8 SUMMARY

In CHAPTER II , we discussed the current state of research in the field of embodied energy of buildings. The review of literature revealed four major issues that need attention. First, the current interpretation of embodied energy is not clear and there is a little consensus on embodied energy definition. Second, the definition of system boundary was not consistent across studies. Studies proposed various models to define a system boundary in a complete manner but there were difference of opinion. According to the review of literature, it was important to derive a system for consistently and completely defining a system boundary. Third, the analysis of existing embodied energy calculation methods revealed that the most appropriate method that was currently available had issues that need to be resolved. In addition, an urgency to develop a user-friendly approach for calculating the embodied energy was underlined. Finally, the current embodied energy data exhibited significant variations, and hence, were not comparable. To reduce the variations in embodied energy data due to methodological and data quality parameters, a need to standardize the embodied energy analysis process was also emphasized. The review of literature revealed some research gaps in the current embodied energy research.

CHAPTER III

RESEARCH DESIGN AND METHODS

3.1 RESEARCH METHODOLOGY

3.1.1 Aim and Objectives

The review of relevant literature indicated that a large number of studies have been performed on topics such as embodied energy calculation, system boundary model, variations in embodied energy data, and relationship of energy and economic flows. This research collected, analyzed, and used relevant information from these studies in order to fill the identified research gaps. The aim of this study was to derive a less data-intensive and streamlined method to consistently calculate the energy embodied in a building and its constituent materials. This aim was achieved by meeting the following objectives:

Objectives

- Propose a set of guidelines for the embodied energy calculation for a building and its materials
- Develop a comprehensive system boundary model for embodied energy analysis of a building and its materials
- Develop a method to consistently and completely calculate the embodied energy of a building material based on the energy-cost relationship
- Identify any correlation between the cost and price of a building material and its embodied energy

3.1.2 Research Hypotheses

After defining a consistent and complete system boundary model, an input-output-based hybrid method was developed and the energy embodied in commonly-used building materials was quantified. Table 3-1 lists the study materials.

Table 3-1: Building materials under study

Virgin steel	Stone	Glass
Primary aluminum	Gypsum	Paints & coatings
Copper	Wood, lumber	Adhesives
Cement	Plywood & veneer, hardwood	Plastic pipes & fittings
Bricks	Plywood & veneer, softwood	Carpets & rugs
Ceramic wall & floor tiles	Mineral wool insulation	Lime
Polystyrene insulation	Vitrified clay sewer pipes	Concrete

Once the embodied energy of the above-mentioned materials was quantified, it was analyzed for its correlation with the cost and price of the study materials. The following hypotheses were tested using the calculated embodied energy values and the collected cost and price data:
Hypothesis I: There is a strong positive correlation (r^2>0.7) between the cost and the embodied energy of a product.

Hypothesis II: There is a strong positive correlation (r^2>0.7) between the price and the embodied energy of a product.

The cost of a product was defined as the amount of money required to produce the product, whereas the amount of money paid by a consumer to buy the product was the price. The product, in the context of this study, was a building material.

3.1.3 Scope and Limitations

This research was solely focused on embodied energy and did not address any issue related to operating energy. Although the amount of embodied energy and embodied carbon in a product were found to be strongly related, this research aimed to determine only embodied energy. The scope of the research was limited to commonly-used building materials (see Table 3-1). As mentioned in the literature (e.g. Hegner, 2007), the selection of a material based on its low embodied energy could affect a building's operating energy. Any such analysis was out of the scope of this research.

Because the United States' economy was used as a basis for the development of the embodied energy calculation method, the results should be applied to a foreign economy with a caution. However, the steps proposed in the calculation method could be replicated with or without modifications if comparable data were available. When input-output tables are used for calculating the embodied energy, the definition of system boundary is conventionally assumed as "cradle to gate." However, as most of the transportation among the various sectors of the United States' economy was included in the input-output model, a "cradle to site" system boundary can be assumed for the calculated embodied energy values.

The economic data used for developing the input-output model and the calculation method were sourced from the latest 2002 Benchmark Input-output Accounts published in 2008 by the United States Bureau of Economic Analysis (USBEA, 2008). All other relevant data collected, treated, and used were also from year 2002. Therefore, the results of the research need to be adjusted for economic and technological changes before being applied to a different time period.

3.1.4 Research Methods

A Literature-Based Discovery (LBD), an input-output-based hybrid method, and a correlation and regression analysis were performed to accomplish the research goals. The research methods adopted are discussed in four sections that are tied to the four study objectives. The first two sections discuss the method used for deriving a set of guidelines to streamline the embodied energy calculation process and to develop a comprehensive system boundary model. The third section provides a stepwise approach to developing the embodied energy calculation method and to quantifying the study materials' embodied energy. The last section explains the evaluation of the embodied energy results and the process of hypothesis testing.

3.1.4.1 Deriving a Set of Guidelines for Embodied Energy Calculation

The process commenced with a survey of relevant literature to understand the current state of research and to identify the research gaps. The conclusions were derived by referring to various peer-reviewed bibliographic sources. This method is called Literature-Based Discovery (LBD), proposed by Dr. Don R. Swanson from the University of Chicago and widely used in the realm of biomedical science. In 1986, Swanson adopted the LBD in biomedical science studies, and was successful in creating new knowledge (Weeber et al., 2001). Kenneth A. Cory from Wayne State University, Detroit, demonstrated that this method of creating new knowledge was valid outside of the biomedical science field (Weeber et al., 2001; Kostoff, 1999).

In the next step, a set of guidelines for calculating embodied energy was proposed using the process of LBD. A previously developed matrix (Dixit et al., 2010) of embodied energy parameters was particularly referenced for developing the guidelines. Three types of literary sources were referred. First, peer-reviewed papers on embodied energy methods and data quality issues were referred to seek literature opinion on how to standardize the calculation process. A survey of existing international standards (e.g., ISO 14040 & 14044 and SETAC: Code of Practice) was also conducted to comprehend the current state of standardization in the field of embodied energy analysis. The critical reviews of existing international standards were referred in order to identify the potential areas of improvements.

3.1.4.2 Developing a System Boundary Model

Extensive literature is available that provided guidance to select a system boundary for embodied energy calculation. From the review of literature, it was evident that various system boundary models were proposed with a varying degree of coverage. For instance, a model covered only a few stages of a building's life cycle, whereas other models covered all but included only a few upstream processes. While some studies performed embodied energy analysis of an entire building, some only covered selected building components. All of these models were appropriate within the scope of their research. The process of LBD was used to collect, analyze, and synthesize these models to propose a comprehensive system boundary definition. The comprehensiveness and completeness of the proposed model relates to the extent to which energy and material inputs are covered by a proposed model (Treloar, 1998; Raynolds et al., 2000). The accuracy of the model is determined by the level of the details (Leedy, 2005) with which the proposed model covers each energy and material input.

3.1.4.3 Developing a Calculation Method and Quantifying Embodied Energy

Literature was also available on a chronological development of current embodied energy calculation methods. Although an input-output-based hybrid analysis was regarded as appropriate and complete, its limitations and problems were also highlighted. It was also discussed that an input-output-based hybrid method was complete but its results were less specific to a study material than a process-based method. However, a process-based method was grossly incomplete and, consequently, its results might be erroneous. It was also found that the impact of incompleteness of process-based analyses was greater than the effect of reduced specificity of an input-output-based analysis. Moreover, studies suggested various approaches (see Section 2.6.3) to make the results of an input-output-based analysis more product-specific.

The reliability of a measurement tool or a method is related to its accuracy (Leedy, 2005). The validity is more relevant to the end results and answers questions such as does the proposed method actually measure the energy embodied in a product. Most of the studies (e.g., Treloar, 1998; Crawford, 2004; Langston, 2006; Mo et al., 2010) have already discussed the reliability and validity of the input-output-based hybrid method and have regarded it as the most appropriate method currently available. The input-output-based hybrid method was used in this study. The following improvements were proposed in the input-output-based hybrid method:

- Calculating and using PEF for each type of delivered energy to avoid the double counting of energy inputs
- Disaggregation of sectors representing more than one product using a detailed output and input data sourced from the United States Census Bureau (USCB).
- Inserting the process data of energy use (including the feedstock use of fuel) in physical units into the input-output model
- Quantifying the energy embodied in labor and capital inputs and including them into the input-output model
- Deriving energy intensities of study materials by each energy source to have a better understanding of their environmental impacts

Figure 3-1 illustrates the approach to developing the calculation method and quantifying the embodied energy of study materials. The following steps were taken to develop the calculation method:

Step I: Developing commodity-by-commodity direct and total requirement matrices using the raw *make* and *use* data sourced from the 2002 United States Benchmark Input-output Accounts published by the USBEA (USBEA, 2008). The matrices were adjusted for scrap as suggested by Horowitz and Planting (2009). The final matrices were checked for consistency with the direct and total requirement tables provided on USBEA website (USBEA, 2008).

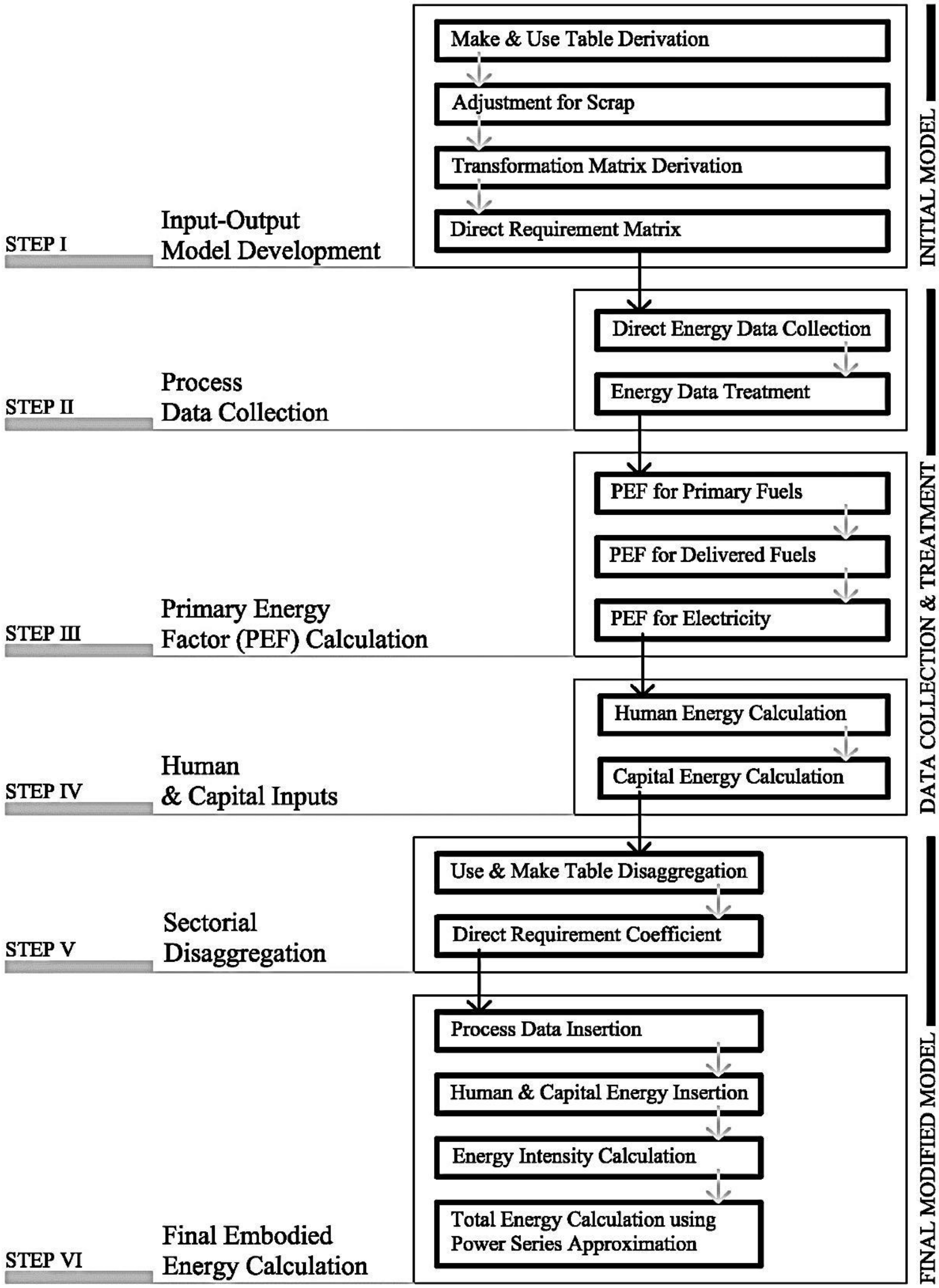


Figure 3-1: Approach to developing an input-output-based hybrid method

Step II: Collecting data on energy use by industry sectors in physical or energy units for 2002. If the data were available in monetary units, sector-specific energy prices were used to convert them to energy units. In addition, if the energy data were in aggregated form, they were decomposed into different fuel categories (e.g., coal, oil, and natural gas).

Step III: Quantifying PEF for each type of energy delivered for end use to industry sectors. Both the direct and indirect energy lost and spent in extracting, processing, transmitting, and distributing an energy source was included.

Step IV: Calculating the energy embodied in human labor and capital inputs using the method recommended by the literature (e.g. Joshi, 1998). The calculated values were then inserted into the input-output model as two separate columns similar to the five energy providing sectors of the United States' economy (based upon Penson, 2012 and 2013 and Dudensing, 2012 and 2013). All energy and nonenergy inputs to these two sectors were kept at zero to avoid double counting.

Step V: Disaggregating industry sectors manufacturing more than one product using detailed composition of industry sector inputs and outputs. The sector disaggregation was based on the approach suggested by Joshi (1998) and Joshi (1999). The disaggregation coefficient used for sectorial inputs are provided in Table A1-23, Table A1-24, and Table A1-25 in Appendix A1. The process of disaggregation was also discussed with Penson (2012 and 2013) and Dudensing (2012 and 2013).

Step VI: Applying Power Series Approximation approach to calculate the total embodied energy of study materials as recommended by Treloar (1998). This approach was preferred against the Leontief's Inverse Matrix because it allowed calculating the energy intensities by upstream stages. In addition, the energy intensities were also calculated fuel wise so that an analysis of the environmental impacts of fuel use can be performed in the future.

Main Assumptions

Although assumptions are mentioned in the relevant chapters, some assumptions are important to mention in this section.

- While calculating the human energy requirements, it was assumed that all of the energy of food consumed by an employee was allocated to the employment. It was assumed appropriate to derive input-output-based energy intensities for sectors producing capital goods in order to quantify capital energy. The fractions of various capital goods under the categories such as structures, automobiles, equipment, and software in the total capital investment were used to calculate weighted average energy intensities.
- While calculating the Primary Energy Factors (PEFs) for various energy sources except electricity, the indirect energy use was calculated using an input-output-based analysis. As most

of the energy providing sectors produce only energy goods, their energy intensities were assumed specific to their primary products. In addition, it was assumed that energy cannot be gained and any energy gain reported in the year 2002 was ignored.

- During the process of sectorial disaggregation, the total purchases of goods by each disaggregated sector were used to allocate the total input of goods of the aggregated sector. Similarly, the purchases of services were allocated using each disaggregated sector's total purchases of services. The use of commodity by industries was disaggregated based upon each disaggregated commodity's share in the total output of the aggregated commodity. In the make table, the make of disaggregated commodities was assumed same as the aggregated commodity.
- While inserting the human and capital inputs, it was assumed that the two represented energy commodities with no industry sectors producing them. All of the energy and nonenergy inputs to these commodities were kept at zero.

3.1.4.4 Hypotheses Testing and Result Evaluation

Hypotheses Testing: Three types of information were needed for hypotheses testing: material cost, price, and embodied energy intensities. As material prices were obtained from multiple sources, it was important to convert them to the same units. From the review of literature, it was clear that most energy intensities were given in energy units per mass of materials (e.g. MJ/kg). Some material prices were also given in units of mass. Therefore, it was decided to convert the embodied energy of each material into energy unit per unit of its mass. For some material such as steel, cement, and aluminum, the material quantities were available in mass units, whereas the quantities of materials such as carpets, paint, wood, and bricks were given in various units such as square foot, gallons, cubic foot, and also in numbers. Appropriate material density data were sourced and used. As material density was dependent on type of materials used, a weighted average was derived. For instance, in the case of saw wood, each species of hardwood and softwood had a different density and it became important to calculate a weighted average density. The average was weighted on each species' share in the total wood production. In some cases such as carpets, a material thickness of 3/8 inch was assumed while calculating the material density.

The cost of a material was interpreted as the total amount of expenditure incurred in manufacturing the material. Reliable cost data were not readily available and it was considered appropriate to calculate the material cost. One option to avoid the use of product prices was to gather the total commodity output or production quantity in physical units. The embodied energy per unit mass then can be calculated using the following equation:

$$E_{t,i} = \frac{e_{t,i} \times C_{o,i}}{C_{m,i}} \qquad \text{Equation 3-1}$$

Where $e_{t,\,i}$ and $C_{o,\,i}$ are the total energy intensity of a sector (e.g. MBtu/$) and total sectorial output ($), respectively. Term $C_{m,\,i}$ denotes the total commodity output in physical units (e.g. ton or cubic yards). The obtained values would provide the total embodied energy $E_{t,\,i}$ in energy units per mass of the product. To calculate the cost of a material, its material specific commodity output (in $) was divided by the material quantities (in physical units such as tons, cubit yards, square foot, etc.). As it avoids use of material prices, using cost to calculate embodied energy can be more reliable if the cost data are readily available. The total quantity of a material produced in 2002 was obtained from sources such as historical statistics provided by the USGS (USGS, 2013) and the Current Industrial Report series published by the USCB (2002b). However, material quantities were not available for all study materials.

The material prices are volatile and keep changing throughout the year. One way to obtain the average material prices was to use the material shipments' quantities and values. These data can be sourced from the Current Industrial Reports (USCB, 2002b) and also from the 2002 Economic Census (USCB 2002a). Material prices for most metals and minerals were also available in statistics provided by the USGS (2013). The missing data were obtained from the 2002 National Construction Estimator (Ogershok, 2002). Appropriate energy conversion factors were used to convert all prices to comparable units. Some of the material price and density data used in the study are provided in Table A1-12 and Table A1-15 in Appendix A1.

Correlation Analysis: The calculated values of embodied energy per unit of mass were analyzed for their correlation with material prices and costs. A coefficient of determination (r^2) less than 0.5, 0.5 - 0.7, 0.7-0.9 and more than 0.9 is considered to show a weak, moderate, strong, and a very strong positive correlation, respectively (Ding, 2004; Crawford, 2004; Langston, 2006). According to Taylor (1990) and Chan (2003), a correlation coefficient (r) less than 0.3 and more than 0.8 indicates a week and strong positive correlation, respectively. Based on the literature opinion, the following criteria were used in evaluating the correlation and testing the hypotheses:

Very Weak	Weak	Moderate	Strong	Very Strong
r^2 <0.3	0.3>r^2 <0.5	0.5>r^2 <0.7	0.7>r^2<0.9	r^2 >0.9

Once a strong correlation was observed, a regression analysis was performed to test the hypotheses. A regression analysis also helped in deriving an equation for an energy and cost relationship.

Result Evaluation: The input-output-based hybrid method in its current form was not comparable to other methods due to a varying degree of completeness and specificity. Crawford (2004) noted that evaluations such as sensitivity and Monte Carlo analysis were not suitable to analyze a method that is a combination of two entirely different approaches (input-output and process-based). It was also said that the Monte Carlo analysis is appropriate to evaluate inputs rather than the output (or results) (Crawford, 2004). It was important to assess the completeness and specificity of the proposed method by comparing its results to relatively incomplete methods such as process-based analyses. Treloar (1998) and Crawford (2004) recommended using a gap analysis to evaluate the completeness of an input-output-based hybrid method. The gap analysis assesses the completeness by determining the gap between the proposed method and a less complete method such as process-based analysis. To assess the reliability of the proposed method, a comparative analysis was appropriate because it analyzed the correlation between the replaced input-output values and the inserted process data. The gap and comparative analyses were used in this research to evaluate the developed method.

Gap Analysis: As the current form of input-output-based method was improved based on the literature recommendations (e.g., Joshi, 1998; Carter et al., 1981; Treloar, 1998), an input-output analysis was performed to create a benchmark. In addition, process-based values of embodied energy were collected from published studies. However, instead of using the process-based values, direct energy process data were used. As the system boundaries of most of the process data were not clear, it was more appropriate to analyze the gap with the direct energy intensities. Both the input-output-based and process-based values were analyzed for their gaps with the input-output-based hybrid values. The gap can be calculated as (based on Crawford, 2004):

$$G_{P\ to\ IOH} = \frac{(E_{IOH} - E_P) \times 100}{E_{IOH}} \qquad \text{Equation 3-2}$$

$$G_{IO\ to\ IOH} = \frac{(E_{IOH} - E_{IO}) \times 100}{E_{IOH}} \qquad \text{Equation 3-3}$$

Where:

$G_{P\ to\ IOH}$ Gap between an input-output-based hybrid and process-based embodied energy

E_{IOH} Input-output-based hybrid embodied energy

E_P Process-based direct embodied energy

$G_{IO\ to\ IOH}$ Gap between an input-output-based hybrid and input-output-based embodied energy

E_{IO} Input-output-based embodied energy

Comparative Analysis: As the process energy data were inserted into the input-output model, the inserted values were compared to the replaced energy values. The comparison was performed by plotting both values on an x-y plot or by creating a scatter plot. The values then were analyzed for their correlation. Such comparative analysis provided an assessment of whether or not the process values closely represented the comparable input-output values. The correlation analysis was performed between the total energy coefficients of the industry sectors calculated using original input-output data and the comparable process data. This analysis was also performed for the calculated values of the embodied energy of the study materials per unit of mass.

The calculated values were also compared with the published values of the embodied energy of the study materials. The purpose of this comparison was to identify if there was any unusual pattern in the calculated embodied energy values.

3.2 SUMMARY

The research was designed to address the four major issues identified as research gaps. To propose a complete and consistent system boundary model and a set of embodied energy guidelines, the research method of LBD was used. As the current version of the input-output-based hybrid method was regarded as the most appropriate method for calculating the embodied energy, it was used as a basis for making improvements suggested by literature. The PEF for each energy source used in the United States' economy was quantified. The method proposed by Treloar (1998) to avoid the double counting of energy inputs was used. The human and capital energy was calculated and inserted into the input-output model using the approach proposed by Joshi (1998). In addition, using the same approach (Joshi, 1998 and Joshi, 1999), the industry sectors were disaggregated to obtain more study-specific results.

CHAPTER IV

INPUT-OUTPUT MODEL DEVELOPMENT

4.1 INPUT-OUTPUT MODEL: BASIC FRAMEWORK

4.1.1 Input-Output Tables: Major Components

An economic input-output table shows monetary inflows and outflows among the various sectors of a nation's economy. Current input-output framework and methodology are based on the work of Wassily Leontief in the 1930s, who in 1973 won the Nobel Prize of economics (Guo et al., 2002; Perese, 2010). Leontief's work enabled the use of economic data for a wide range of purposes such as energy and environmental research. It soon became a tool to forecast not only economic indicators but also impact matrices of population and environmental degradation. The economy of a nation can be divided into numerous sectors that produce and consume a variety of products. These sectors also pay, for instance, taxes to government and receive payments from the buying sectors. There are three types of sectors in an economy: *processing sector*; *final demand sector*; and *value added sector* (Miernyk, 1965; Miller and Blair, 2009). These sectors are illustrated in Figure 4-1.

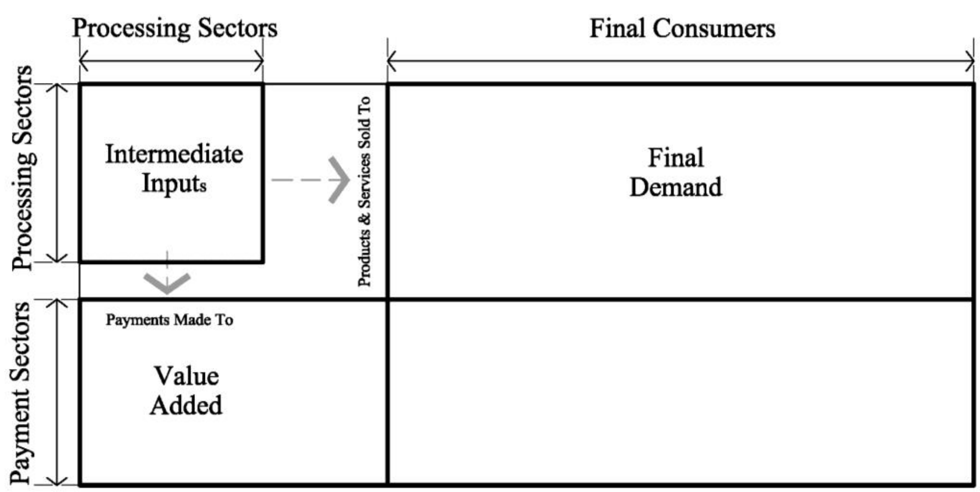


Figure 4-1: Basic framework of an input-output table

The *processing sector* may include one industry or a group of industries that produce a similar type of product (e.g. steel products). Each processing sector that manufactures a product also consumes goods and services produced by other processing sectors (Carter et al., 1981; Miller and Blair, 2009). This creates an interindustry flow of inputs and outputs among the sectors. In an input-output table, the processing sectors appear in both the rows and columns forming a symmetrical matrix. This matrix is a square matrix in which the number of rows equals the number of columns (Miernyk, 1965; Carter et al., 1981; Miller and Blair, 2009). The column sectors are the buying sectors and the row sectors are the selling sectors. In the symmetrical matrix, the rows of a column contain the values of inputs required from the row sectors to produce a unit output of the column sector. The column sum represents the total value of purchases made by the column sector. The sum of rows shows the total output of a row sector that is sold to the column sectors (Miernyk, 1965; Carter et al., 1981; Miller and Blair, 2009). Figure 4-1 shows the basic framework of an input-output table.

The final demand sector shows the total value of sales by the processing sectors to the final consumer such as private households and government agencies (Miernyk, 1965; Miller and Blair, 2009). It includes columns of gross inventory accumulation, personal consumption expenditure, gross private domestic investments, government purchases, and the total value of export (Miernyk, 1965; Miller and Blair, 2009) (see Figure 4-2). Some final consumers such as retailers maintain an inventory of goods. Any addition to the inventory is recorded in the column of gross inventory accumulation.

		Processing Sectors: Buying						Final Demand					
		1	2	3	4	5	Total Intermediate Output	Gross Inventory Accumulation	Personal Consumption Exp.	Gross Pvt. Domestic Investment	Government Purchases	Exports	Total Output
Processing Sectors: Selling	1	z_{11}	z_{12}	z_{13}	z_{14}	z_{15}							x_1
	2	z_{21}	z_{22}	z_{23}	z_{24}	z_{25}							x_2
	3	z_{31}	z_{22}	z_{23}	z_{24}	z_{25}							x_3
	4	z_{41}	z_{42}	z_{43}	z_{44}	z_{45}							x_4
	5	z_{51}	z_{52}	z_{53}	z_{54}	z_{55}							x_5
	Total Intermediate Input												
Value Added	Gross Inventory Depletion												ID
	Employee Compensation												EC
	Capital Consumption & Profit												CC
	Payments to Governments												GP
	Imports												M
	Total Gross Outlays	x_1	x_2	x_3	x_4	x_5		IA	PC	GDI	G	E	

Figure 4-2: Various components of an input-output table

The personal consumption expenditure includes purchases made by, for instance, residential consumers from the row sectors. The purchases of capital such as plants and equipment made for the purpose of replacement or addition are recorded as the gross private domestic investment. The industry sectors also sell their products and services to the government agencies. These transactions are reported in the government purchases column of the final demand sector. The total value of goods and services exported to foreign economies is listed in the column of total exports (Miernyk, 1965; Miller and Blair, 2009). The sum of all components of a final demand sector is known as the *total final demand*, whereas the sum excluding the value of exports is termed *domestic final demand* (Miller and Blair, 2009). The sum of domestic final demand and the net of exports (export minus import) represents the *Gross Domestic Product* (GDP) (Horowitz and Planting, 2009).

The payments such as salaries and wages to employees or taxes paid to the government by the column sectors to value added row sectors are recorded in the value added component (Miernyk, 1965; Miller and Blair, 2009). The value added sector is formed by rows showing values of gross inventory depletion, payments to private households, depreciation, payments to government, and the total value of imports (see Figure 4-2). Any subtraction from the inventory is recorded under the gross inventory depletion row. The salaries and wages paid by the column sectors to employees and workers are reported in the payments to private household rows. The capital payment row shows the value of depreciation of capital goods and also the interest paid towards such purchases. The taxes paid by the column sectors to the government are listed under the payment to government row. Finally the import row shows the purchases made by the column sectors from a foreign economy (Miernyk, 1965; Miller and Blair, 2009). Various components of a conventional input-output table are shown in detail in Figure 4-2. The totals of rows and columns are marked in the last column and last row. In a balanced economy, the sum of the total output column and the total gross outlays row is equal. Hence:

$$x_1 + x_2 \dots\dots + x_5 + IA + PC + GDI + G + E = x_1 + x_2 \dots\dots. + x_5 + ID + EC + CP + GP + M$$

Equation 4-1

Or

$$IA + PC + GDI + G + E = ID + EC + CP + GP + M$$ Equation 4-2

$$IA + PC + GDI + G + (E - M) = ID + EC + CP + GP$$ Equation 4-3

Where:

x	Total output and total outlays	*ID*	Gross inventory depletion
IA	Gross inventory accumulation	*EC*	Employee compensation
PC	Personal consumption expenditure	*CP*	Capital payments
GDI	Gross private domestic investments	*GP*	Government payments
G	Government purchases	*M*	Total value of import
E	Total value of export		

The terms x_1, x_2, x_3, and so on represent the total output and total outlays, which are equal in an input-output table. The left-hand side term represents the total domestic and net foreign consumption and is termed *Gross Domestic Product* (GDP). As total output and outlays are equal, Equation 4-1 can be written as Equation 4-3. In Equation 4-3, the right-hand side term denotes the income received and is known as *Gross National Income* (Miller and Blair, 2009; Horowitz and Planting, 2009).

The following sections provide a detailed explanation of direct and indirect requirements based on Miernyk, (1965), Carter et al. (1981), Horowitz and Planting (2009), Miller and Blair (2009), and Perese (2010).

4.1.1.1 Direct Requirements

According to an input-output theory**,** when a production sector increases its output by one dollar, it will require inputs worth one dollar more from its supplying sectors. The demand for inputs from its supplying sector is known as the direct or technical requirement. The direct requirement is quantified as a technical coefficient or direct requirement coefficient, which is the ratio of input from a selling sector to the output of a buying sector. For instance, assume a hypothetical economy with *n* number of sectors such that z_{ij} represents the amount of input required from sector "i" to produce the output of sector "j." In other words, z_{ij} shows intermediate sales from industry "i" to "j." If the total output of sector "j" is denoted by x_j then the technical coefficient:

$$\boldsymbol{a_{ij}} = \frac{z_{ij}}{x_j} \qquad \text{Equation 4-4}$$

		Processing Sectors: Buying						Final Demand					
		1	2	3	4	5	Total Intermediate Output	Gross Inventory Accumulation	Personal Consumption Exp.	Gross Pvt. Domestic Investment	Government Purchases	Exports	Total Output
Processing Sectors: Selling	1	z_{11}	z_{12}	z_{13}	z_{14}	z_{15}	Z_1	Total final Demand $= f_1$					x_1
	2	z_{21}	z_{22}	z_{23}	z_{24}	z_{25}	Z_2	Total final Demand $= f_2$					x_2
	3	z_{31}	z_{22}	z_{23}	z_{24}	z_{25}	Z_3	Total final Demand $= f_3$					x_3
	4	z_{41}	z_{42}	z_{43}	z_{44}	z_{45}	Z_4	Total final Demand $= f_4$					x_4
	5	z_{51}	z_{52}	z_{53}	z_{54}	z_{55}	Z_5	Total final Demand $= f_5$					x_5
	Total Intermediate Input												
Value Added	Gross Inventory Depletion												
	Employee Compensation												
	Capital Consumption & Profit												
	Payments to Governments												
	Imports												
	Total Gross Outlays	x_1	x_2	x_3	x_4	x_5							

Figure 4-3: A typical input-output matrix with intermediate transactions

In a square matrix of *n* sectors, each cell contains direct requirement or technical coefficients that represent the amount of inputs required from row industry by industry at the top of the column to produce one dollar of column industry's output. The square matrix shows the interindustry transactions or intermediate sales of intermediate sectors as shown in Figure 4-3. These sectors buy and sell goods and services to each other for delivering their outputs to the final demand sector.

It can be seen in Figure 4-3 that the total output of an industry sector is the sum of its total intermediate sales and its sales to final demand sectors. If inputs from sector "i" to sector "j" are denoted by z_{ij} then a square matrix **Z** of *n* sectors would represent the intermediate sales. If **x** and **f** represent a column vector of total output x_j and total final demand f_j then:

$$\mathbf{Z} = \begin{bmatrix} z_{11} & \cdots & z_{1n} \\ \vdots & \ddots & \vdots \\ z_{n1} & \cdots & z_{nn} \end{bmatrix}; \quad \mathbf{f} = \begin{bmatrix} f_1 \\ \vdots \\ f_n \end{bmatrix}; \quad \mathbf{x} = \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix}$$

$$\mathbf{x} = \mathbf{Z} \times \mathbf{i} + \mathbf{f} \qquad \text{Equation 4-5}$$

Where "**i**" is a column vector of only 1s and it is used for summing up the intermediate sales.

4.1.1.2 Indirect Requirements

When an industry sector raises its output by one dollar, it needs to buy more inputs from its supplying sectors. Each supplying sector also needs to buy more to meet the demand of increased output. Similarly, supplying sectors of supplying sectors also need to meet the increased demand of their outputs. One can keep on calculating the increased requirements of inputs by infinite times tracking each input of a supplying sector. Hence, the impact of increasing output by one dollar can be felt throughout the economy. This impact represents the indirect requirements. The sum of all requirements due to indirect impact is known as the indirect requirement, and the respective coefficient is known as the indirect requirement coefficient. The sum of direct and indirect requirements is the total requirement of a single dollar increase in a sector's output. The indirect requirements can be quantified using two approaches: Leontief's Inverse Matrix and Power Series Approximation method. In both of the approaches, the direct requirement coefficients are used as a carrier of indirect impacts.

4.1.2 Leontief's Inverse Matrix: Direct and Total Requirement Matrix

Equation 4-4 provides the calculation of the direct requirement coefficient. Consider an *n*-sector square matrix of direct requirement coefficients:

$$\mathbf{A} = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix}$$

If **Z** and **x** denote a square matrix of intermediate sales and a vector of total outputs, respectively, then one can write:

$\mathbf{A} = \mathbf{Z} \times \mathbf{x}^{-1}$ Equation 4-6

Or

$\mathbf{Z} = \mathbf{A}\mathbf{x}$

From Equation 4-5 we can write

$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{f}$

$\mathbf{f} = \mathbf{x}(\mathbf{I} - \mathbf{A})$

$\mathbf{x} = \mathbf{f}(\mathbf{I} - \mathbf{A})^{-1}$ Equation 4-7

Where "**I"** represents a square identity matrix of *n* sectors. Here, the right-hand side term $(\mathbf{I} - \mathbf{A})^{-1}$ is known as the Leontief's Inverse Matrix representing the total requirements of increasing the output of an industry sector by one dollar. To find out the indirect requirements, the direct requirements are subtracted from the total requirements. Using Leontief's Inverse Matrix for calculating the total requirements is easy, quick, and straightforward. If Leontief's Inverse Matrix is denoted by **L** then:

$\mathbf{x} = \mathbf{f}\boldsymbol{L}$ Equation 4-8

4.1.3 Power Series Approximation

If a modification to indirect requirements is needed or a more detailed account of indirect requirements is sought, a Power Series Approximation approach provides a better option. For instance, consider a two-sector hypothetical economy as shown in Table 4-1. There are two sectors: construction and manufacturing. If the construction sector increases its final demand by one dollar, it will force itself and the manufacturing sector to increase their output by 0.2 and 0.35 dollars, respectively. So the increased output for the construction and manufacturing sectors in round one would be 1.2 and 0.35, respectively. Similarly, an increased output of the manufacturing sector (+0.35) would cause manufacturing and construction sectors to raise their output by 0.25 X 0.35 and 0.1 X 0.35, respectively. Table 4-2 shows the indirect requirements for round 1 through 5, which can go up to round infinity. It is important to note that each time the calculation goes back in rounds, the result of the previous round is multiplied by the direct requirement coefficient. This is the reason why with each round calculation the indirect impacts get smaller and become nearly zero at round infinity. The calculation of the indirect impact using this approach is known as the Power Series Approximation method.

Table 4-1: Hypothetical economy

Industry Sectors	Construction	Manufacturing
Construction	0.2	0.1
Manufacturing	0.35	0.25

Based on an *n*-sector economy, we can derive an expression that does require finding out an inverse of matrix (I – A) to calculate the total requirement matrix. According to the results of input demands of various rounds in Table 4-2, we can write:

$$(\mathbf{I}-\mathbf{A})\times(\mathbf{I}+\mathbf{A}^2+\mathbf{A}^3+\mathbf{A}^4\ldots\ldots\ldots\ldots\ldots\ldots\ldots+\ \mathbf{A}^{\mathrm{n}})=(\mathbf{I}-\mathbf{A}^{\mathrm{n+1}}) \qquad \text{Equation 4-9}$$

From the example in Table 4-2 we have seen that with each round going back to infinity, the indirect requirements get smaller and smaller. With $n = \infty$, we can assume that the indirect requirement for $\mathbf{A}^{n+1}$ would be zero. Hence:

$$(\mathbf{I}-\mathbf{A})\times(\mathbf{I}+\mathbf{A}^2+\mathbf{A}^3+\mathbf{A}^4\ldots\ldots\ldots\ldots\ldots\ldots\ldots+\ \mathbf{A}^{\mathrm{n}})=\mathbf{I}$$

Or

$$(\mathbf{I}-\mathbf{A})^{-1}=(\mathbf{I}+\mathbf{A}^2+\mathbf{A}^3+\mathbf{A}^4\ldots\ldots\ldots\ldots\ldots\ldots\ldots+\ \mathbf{A}^{\mathrm{n}})$$

Or

$$\mathbf{L}=(\mathbf{I}+\mathbf{A}^2+\mathbf{A}^3+\mathbf{A}^4\ldots\ldots\ldots\ldots\ldots\ldots\ldots+\ \mathbf{A}^{\mathrm{n}}) \qquad \text{Equation 4-10}$$

Table 4-2: Indirect requirements of the hypothetical economy

Input Demands $\longrightarrow$	**Construction**	**Manufacturing**
Round 0	1.0+0.2=1.2	0.35
Round 1	0.2*1.2+0.1*0.35=0.28	0.25*0.35+0.35*1.2=0.51
Round 2	0.2*0.28+0.1*0.51=0.11	0.25*0.51+0.35*0.28=0.23
Round 3	0.2*0.11+0.1*0.23=0.045	0.25*0.23+0.35*0.11=0.096
Round 4	0.2*0.045+0.1*0.096=0.019	0.25*0.096+0.35*0.045=0.04
Round 5	0.2*0.019+0.1*0.04=0.008	0.25*0.04+0.35*0.019=0.017
….		
….	$= C_i$	$= M_i$
Round ∞	0.2* C_i+0.1* M_i	0.25* M_i+0.35* C_i

Using the Power Series Approximation approach, the indirect requirement associated with each individual round can be calculated for a more detailed analysis of monetary flows. It can be seen that, with each stage in the upstream, the indirect impacts are carried by the direct requirement coefficient. In other words, going back in each stage involves multiplying by **A,** which is less than one. Therefore, in each upstream stage, the indirect impacts get reduced.

Conventionally, the input-output accounts are published with direct and total requirement tables. A discussion on open and closed input-output accounts is necessary before we proceed to discuss the United States industry accounts. The input-output tables are conventionally published with intermediate sectors as *endogenous sectors* and final demand sectors as *exogenous sectors*. The endogenous sectors are the producers that deliver goods and services to the final consumers of the exogenous final demand sectors. Such conventional tables are termed *open input-output accounts*. However, some final demand sectors such as private households could be interpreted as intermediate sectors providing labor in return for receiving salaries and wages. In some economies, one or more of the exogenous final demand sectors are moved to intermediate sectors, making them endogenous to the economy. Such tables are known as *closed input-output accounts*.

4.2 UNITED STATES INPUT-OUTPUT ACCOUNTS

The United States Bureau of Economic Analysis (BEA) reports economic statistics in the form of Annual Industry Accounts and the Benchmark Input-Output Accounts published every five years (Rassier et al., 2007; Horowitz and Planting, 2009). These accounts show monetary transactions between various sectors representing industries, net export (export minus import), value added, and final demand (GDP). According to Horowitz and Planting (2009), one main purpose of the economic input-output accounts is to calculate the GDP and Gross National Income of the country. According to Miernyk (1965), the input – output accounts are used as an “analytical tool” for “economic planning” and for resource allocation and income distribution. The input-output accounts also help government, industry, business, the research community, and the public in decision-making and in deriving strategies for the future. For instance, these accounts can be used for predicting the impact of an increased final demand on the entire economy in order to identify potential congestion in the input supply. These accounts are also widely used for quantifying energy flows and resulting greenhouse gas emissions (Miller and Blair, 2009).

The Annual Industry Accounts provide a more aggregated form (65 industries and commodities) of the flow of goods and services between various industry sectors. The Benchmark Input-Output Accounts that include 428 commodity sectors and 426 industry sectors present a more detailed form of the flows of goods and services (Stewart et al., 2007; Rassier et al., 2007). The benchmark accounts are published each year ending with 2 and 7 (e.g., 1992, 1997, and 2002). Such detailed and comprehensive economic statistics provide a strong and credible source of information that can be used for the purpose of economic planning, forecasting, and a variety of other research (Stewart et al., 2007; Rassier et al., 2007). The latest Benchmark Input-Output Accounts were released in 2007 by BEA for the year 2002 (Stewart et al., 2007). These accounts were updated in 2008. The BEA publishes the benchmark accounts at a summary and detailed level. The latest summary level accounts included 133 industries and 135 commodities, whereas the detailed accounts presented economic data for 426 industries and 428 commodities (Stewart et al., 2007).

4.2.1 North American Industry Classification System (NAICS)

The industry data are presented by a uniform code system known as the North American Industry Classification System (NAICS). To improve the comparability of the economic reporting and analysis, the United States, Canada, and Mexico developed the NAICS under the North American Free Trade

Agreement (NAFTA). The NAICS has replaced the earlier 1987 United States Standard Industrial Classification (SIC) system (Ambler, 1998). The NAICS categorized the industries based on their production methods. Each industry was denoted by a six-digit NAICS code reading left to right. The first two digits denoted the sector, the third digit represented the subsector, and the fourth and fifth digits indicated the industry group and the NAICS industry, respectively (Horowitz and Planting, 2009). Table 4-3 illustrates an example of NAICS classification for iron and steel manufacturing.

Table 4-3: NAICS code example

NAICS Code	Description
33	Manufacturing
331	Primary Metal Manufacturing
3311	Iron and Steel Mills and Ferroalloy Manufacturing
33122	Rolling and Drawing of Purchased Steel
331221	Rolled Steel Shape Manufacturing

It is evident from the NAICS that a double-digit classification is more aggregated than a four or six-digit classification. A six-digit classification is country specific and may not be comparable with other countries following the NAICS (Horowitz and Planting, 2009). It is also the most detailed categorization available in the NAICS. According to the NAICS, the United States' economy is composed of 20 sectors as shown in Table 4-4 (based on Horowitz and Planting, 2009; USCB, 2002c).

Table 4-4: Sectors of the United States economy as per NAICS

NAICS	Sector Description	NAICS	Sector Description
11	Agriculture, Forestry, Fishing and Hunting	53	Real Estate and Rental and Leasing
21	Mining	54	Professional, Scientific, and Technical Services
22	Utilities	55	Management of Companies and Enterprises
23	Construction	56	Administrative and Support and Waste Management and Remediation Services
31-33	Manufacturing	61	Educational Services
42	Wholesale Trade	62	Healthcare and Social Assistance
44-45	Retail Trade	71	Arts, Entertainment, and Recreation
48-49	Transportation and Warehousing	72	Accommodation and Food Services
51	Information	81	Other Services (except Public Administration)
52	Finance and Insurance	92	Public Administration

4.2.2 Establishments, Industries, and Commodities

According to NAICS, an *establishment* is a physical location where a group of industries are performing various industrial operations or providing a range of services. For example, the agriculture sector consists of various establishments such as farms, ranches, and dairies (USCB, 2002c). Horowitz and Planting (2009) warned that the terms "*establishment*" and "*enterprise*" should not be confused, as they are different. An *enterprise* could be a corporation, a company, or an organization that is a legal entity. In addition, an enterprise may contain one or more establishments (USCB, 2002c; Horowitz and Planting, 2009). An establishment contains one or more industries engaged in numerous activities and using a similar production method (Stewart et al., 2007; Horowitz and Planting, 2009). However, each industry is categorized according to its primary activity. The primary activity could be manufacturing a product or providing a service. The primary activity is determined by the industries' *primary product* (goods or services) that holds the largest share in the production cost, capital investment, or other information such as revenue, sales, or employment of an establishment (Horowitz and Planting, 2009). In addition to the primary products, industries also produce or provide other goods or services that are termed *secondary products* (Stewart et al., 2007; Horowitz and Planting, 2009).

The goods and services provided by the industries of an establishment are grouped in commodity groups based on product characteristics. The *commodity* represents a group of similar goods or similar services produced or provided by an industry. A commodity could be manufactured or provided by one or more industries and could be primary or secondary in those industries (Stewart et al., 2007; Horowitz and Planting, 2009). Hence, the output of a commodity code reports its total output regardless of whether the commodity is a primary or a secondary product in one or more establishments. In current NAICS, commodities are categorized by a six-digit NAICS code of industries in which they are primary (Horowitz and Planting, 2009).

4.2.3 Reclassification and Redefinition

As mentioned earlier, the establishments also produce secondary goods or provide secondary services other than the primary products. The USBEA treats the secondary products in three ways (based on Guo et al., 2002; Horowitz and Planting, 2009; Perese, 2010).

4.2.3.1 Reclassification

Under reclassification, the USBEA categorizes a primary product as a secondary product for the purpose of input-output accounts and reclassifies it to a commodity in which it is primary. Horowitz and Planting (2009) explained this using the newspaper industry as an example. The United States Census Bureau (USCB) assigns the newspaper and newspaper advertising both as a primary product. The USBEA, however, categorizes the newspaper advertising as a secondary product and reclassifies it as a primary product to advertising commodity. When a product is primary to more than one industry due to different production methods, it is reclassified to a commodity in which it is primary. In the case of reclassification, only the commodity output changes and the industry output remain unmodified.

4.2.3.2 Redefinition

When the input requirements and structure of a secondary product of an industry differs considerably from its primary product, the secondary product is redefined to an industry where it is primary. The main purpose of redefinition is to make the input-product relationship more homogenous. One problem identified in the past by Bullard and Herendeen (1975), Casler and Wilbur (1984), and Suh and Huppes (2004) was that of aggregation of primary and secondary products that have a different input structure. The process of redefinition resolved this problem. In the process of redefinition, only the industry output changes as the product output is moved across industries. The commodity output remains unchanged after redefinition.

4.2.3.3 Other Secondary Products

This categorization is done to secondary products that have a similar input structure as the primary product of an industry. In such a case, the secondary product is included in the output of the primary product. After this classification neither industry nor commodity output changes.

Two assumptions can be used in the treatment of the secondary product in input-output accounting. The first assumption is the *industry-technology assumption* under which a secondary product's input structure is identified by the industry that is producing it. Hence, both the primary and secondary products will have the same inputs under industry-technology assumption. The second assumption is termed the *commodity-technology* assumption. Under the *commodity-technology* assumption, the input structure of a secondary product is determined from an industry in which the secondary product is primary. Meaning under this assumption, the primary and secondary products of an industry would not have the same inputs. The USBEA uses both the assumptions. The *commodity-technology* assumption is used when secondary products are redefined, reclassified, or reallocated. The derivation of a symmetrical direct and total requirement matrix is done based on the industry-technology assumption (Guo et al., 2002; Horowitz and Planting, 2009; Perese, 2010).

4.2.4 The United States 2002 Benchmark Input-Output Accounts (USBEA, 2008)

The 2002 Benchmark Input-Output Accounts were released in two table formats: Standard and supplementary tables (Stewart et al., 2007; Horowitz and Planting, 2009). The standard tables provided industry accounts before redefinition, whereas the supplementary tables reported the industry accounts after redefinition in addition to other supplemental information. The input-output accounts consist of the flow of both the primary and secondary goods and services (Stewart et al., 2007; Horowitz and Planting, 2009). As supplementary tables provide industry accounts after redefinition, they are used for the purpose of creating a direct requirement matrix in this research. Three types of supplementary tables are used from the 2002 benchmark input-output accounts: *make table, use table*, and the total requirements table. The following sections describe the three tables (based on Guo et al., 2002; Horowitz and Planting, 2009; Perese, 2010).

4.2.5 Make and Use Tables

The *make table* is an Industry-by-commodity table (426 X 430 matrix) that presents production of commodities by each industry listed by their 6-digit NAICS codes. The rows of the *make table* show the industries producing one or more commodities listed at the top of the columns. Hence, the *make table* is composed of 426 industry rows and 430 commodity columns. Reading down a column, fractions of a column commodity produced by the row industries are listed. All of the commodities (of the column) produced by a row industry can be found reading across the rows. The basic framework of a *make table* is shown in Figure 4-4.

	Commodities 1 2 3 .... m	Industries 1 2 3 .... n	Final Demand	Total Output
Commodities 1 2 3 . . . m		Use Table		
Industries 1 2 3 . . . n	Make Table			
Value Added				
Total Gross Outlays				

Figure 4-4: The make and *use table* in input-output model

The *use table* provides a “recipe” for producing a product. It shows the consumption of commodities listed in rows by the column industries for producing their unit output. The *use table* is a commodity-by-industry matrix (430 X 426) of 430 rows and 426 columns. Reading down the column, a composition of input commodities (in rows) required to produce the output of industries (in columns) can be found. The consumption of a row commodity by column industries can be traced by reading across the rows. The industries and commodities are listed by their 6-digit NAICS codes.

As industries are conventionally engaged in production of more than one commodity, both the *make* and *use* tables are used to derive a more detailed commodity-by-commodity matrix. The *make* and *use table*s are published before and after redefinition. The 2002 Benchmark Input-Output Accounts were released with a *make table*, a *use table* and a total requirement coefficient table (after redefinition). The *total requirement coefficient table* is a commodity-by-commodity matrix (430 X 430) and it provides the total (direct and indirect) requirements of commodities to produce a unit of each commodity. Reading down the column, each cell shows the input of the commodity required to produce a unit of the column commodity. The input-output-based hybrid method of energy analysis requires a commodity-by-commodity direct requirement coefficient matrix. As the direct requirement matrix is not published with the benchmark accounts, it needs to be calculated using the raw *make* and *use tables*.

4.3 DIRECT REQUIREMENT COEFFICIENT CALCULATION

Guo et al., (2002), Horowitz and Planting (2009), and Perese (2010) provided an approach to calculate a symmetrical direct and total requirement matrix for the United States' economy. It is important to note that detailed *make* and *use tables* contain a total of 430 commodities. Unlike the other commodities, scrap, used and secondhand goods, non-comparable imports, and rest of the world adjustments do not have a corresponding industry. These commodities appear in the *use table* but, only scrap and used and secondhand goods commodities appear in the *make table*. According to Perese (2010), the rest of the world adjustments commodity indicates only adjustments to foreign transactions and can be removed from the calculation. The scrap is not produced by any industry and it is considered a by-product of the process of fulfilling demands of other industries. Horowitz and Planting (2009) suggested adjustment for scrap before creating a symmetrical direct requirement matrix so that a demand for scrap does not require an industry output. The following section explains the steps for creating a direct requirement matrix (based on Horowitz and Planting, 2009).

Assuming:

V: Industry-by-commodity make matrix (426 X 430)

U: Commodity-by-industry use matrix (430 X 426)

g: Industry output vector (426 X 1); $\hat{\mathbf{g}}$ indicates a diagonal matrix of industry outputs

q: Commodity output vector (430 X 1); $\hat{\mathbf{q}}$ indicates a diagonal matrix of commodity outputs

s: Scrap vector (426 X 1)

I: Identity matrix

First, a commodity-by-industry direct requirements matrix (use coefficient matrix) is calculated as:

$$\mathbf{D} = \mathbf{U}\hat{\mathbf{g}} \qquad \text{Equation 4-11}$$

Second, a matrix showing the market share of industries is derived. The market share matrix (make coefficient matrix):

$$\mathbf{B} = \mathbf{V}\hat{\mathbf{q}} \qquad \text{Equation 4-12}$$

Next, an adjustment is made to remove the scrap commodity. This is done by calculating industry outputs without scrap. A vector for the non-scrap ratio is calculated by dividing the industry output excluding scrap by the total industry output. Each coefficient in the rows of the market share matrix **B** is then divided by the non-scrap ratio to make adjustment for scrap. The resulting scrap-adjusted market share matrix is termed transformation matrix. The industry output vector without scrap:

$$\mathbf{g_s} = \mathbf{g} - \mathbf{s}$$

$$\mathbf{R_s} = \mathbf{g_s} \div \mathbf{g}$$

$$\mathbf{W} = \mathbf{B} \div \mathbf{R_s} \qquad \text{Equation 4-13}$$

Where $\mathbf{s}$, $\mathbf{g}$, $\mathbf{g_s}$, $\mathbf{R_s}$, and $\mathbf{W}$ terms are scrap value, industry output vector, industry output vector without scrap, scrap ratio, and transformation matrix, respectively.

The symmetrical commodity-by-commodity direct requirement matrix can be calculated as:

$$\mathbf{A} = \mathbf{D}\mathrm{X}\mathbf{W} \qquad \text{Equation 4-14}$$

The total requirement matrix can be created by using the Leontief's Inverse method. The symmetrical commodity-by-commodity total requirement matrix:

$$\mathbf{T} = (\mathbf{I} - \mathbf{A})^{-1} \qquad \text{Equation 4-15}$$

For a more detailed analysis of indirect requirements, the Power Series Approximation method can be applied using direct requirement coefficients.

4.4 SUMMARY

2002 Benchmark Input Output Accounts were used to create a commodity-by-commodity symmetrical matrix of the direct requirements. First, raw make and use tables were used to create make and use coefficient matrix, which were then used to derive the direct requirement matrix. All of the data referenced was after the process of redefinition. An adjustment for scrap was done in the symmetrical matrix as per the procedure given by Horowitz and Planting (2009).

CHAPTER V

ENERGY DATA COLLECTION AND TREATMENT

5.1 PROCESS DATA FOR ENERGY USE BY INDUSTRY SECTORS

The United States' economy is divided into 20 major sectors that provide goods and services to other industry sectors and also to final consumers (see also Table 4-4). These sectors are represented by 2-digit NAICS codes and contain other subsectors denoted by 3-6-digit NAICS codes. The data on energy used by these sectors were available either in monetary or energy units. Also, the energy consumption by some sectors was given in an aggregated form under the fuel use or purchased fuel category. Agencies such as the United States Department of Agriculture (USDA), United States Department of Energy (USDOE), USCB, and the USGS reported energy use by industry sectors periodically. All of the data available from diverse sources needed to be collected, disaggregated by fuel use, and converted into energy units.

All establishments classified by the 2002 Annual Energy Review under industrial and commercial sectors consumed primary (e.g., crude oil) and secondary fuel (e.g., natural gas). Electricity was also purchased to be used for commercial or industrial operations. The establishments also generated electricity on-site using the purchased quantities of primary or secondary fuel in Combined Heat and Power (CHP) or electricity generation plants. A fraction of this on-site generated electricity was consumed by the establishment itself, the remaining fraction was either sold out or transferred to other establishments within or across sectors. Figure 5-1 illustrates the energy input and output system of a typical industrial or commercial establishment. If the net energy consumed by an establishment was included in the calculation, potential for double counting could exist. For example, the net electricity demand of an establishment represented the total electrical energy used minus the energy transferred and sold out. As any on-site generation of energy utilized the purchased quantities of fuel, inclusion of the on-site generated electricity was avoided in calculating the total energy consumption. If only the purchased quantities of fuel and electricity are included in the calculation, a potential double counting of energy can be eliminated. In this study, only quantities that were purchased were included in the calculation. The following sections describe the energy use data collection and treatment for each major sector.

5.1.1 Energy Consumption: Agriculture Sector (NAICS 11)

The United States agriculture sector is comprised of subsectors involved in two primary operations: crop production, and animal production. Among the major products delivered by the United States agriculture sectors are crops, livestock, and poultry. The agriculture sectors consumed energy such as fuel and electricity directly and indirectly in farm operations related to crop and animal production. The direct energy use included mostly petroleum-based fuels and electricity, whereas the energy of fertilizers and chemicals used on farms was categorized as indirect energy (Schenpf, 2004). Most of the direct fuel use involved diesel, gasoline, natural gas, and liquid propane consumed in operating vehicles, crop dryers, and irrigation equipment. Electricity was mainly utilized in irrigation operations, dairy and poultry operations, and lighting and space conditioning of farm facilities such as barns, stores, and farm homes. The farm machinery also required use of oils and lubricants regularly.

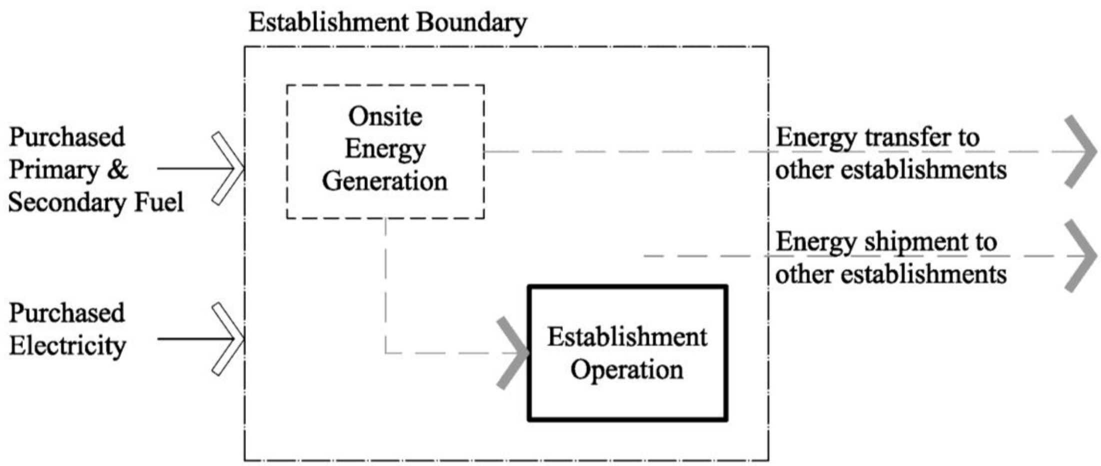


Figure 5-1: Energy flow to and from an establishment

For over 150 years, the agriculture statistics were published by the USCB under the Census of Agriculture. Since 1997, the Census of Agriculture data were published by the USDA, National Agricultural Statistics Service (NASS). There were two main sources of energy data in the agriculture sector: the Census of Agriculture, and agricultural statistics. The Census of Agriculture was conducted every five years (e.g., 1992, 1997, 2002 and 2007), whereas the agricultural statistics were published annually by NASS.

5.1.1.1 Data Collection and Disaggregation

The fuel and electricity consumption by the agriculture sectors was reported in the 2002 Census of Agriculture published by the USDA. The 2002 Census of Agriculture (NASS, 2004) also reported electricity consumption under the utilities category that also included telephone charges, internet charges, and purchased water. These data were provided in monetary units ($) and required energy prices in order to convert them to energy units. Energy prices paid by farmers for some fuels in 2002 are reported in NASS (2005). In addition, the fuel consumption was reported in aggregated form without providing the breakup by individual fuel such as diesel, natural gas, and gasoline. Although the USDA energy use was for the entire agriculture sector, it could be used to disaggregate the total fuel consumption into energy use by each fuel. The USDA website provides the Quickstat tool that reports the total energy use under the categories of gasoline, diesel, liquefied petroleum gas (LPG), and other fuels (kerosene, motor oil, grease etc.). There was no separate category for natural gas use and it was reported under the other fuels category in this dataset. The total natural gas and electricity use was reported in the 2002 farm fuel expenses category in the 2002 Agricultural Resource Management Survey (ARMS) (USDA, 2002). The ARMS and some additional data were also received through personal electronic communication with NASS representatives (personal communication, 6 November, 2012; 31 October, 2012; 23 October, 2012). The additional data included total fuel and electricity expenses by the animal and crop production sectors. The total electricity use for the entire agriculture sector was given in the 2005 Agriculture Statistics published by NASS (NASS, 2005). The total electricity use can be decomposed into electricity use by each individual agriculture sector on the basis of the 1997 census data (NASS, 1999). Table 5-1 lists all energy prices used in converting monetary values to energy units.

Table 5-1: Energy prices paid by farmers

Fuel/Energy	**Price ($/MBtu)**	**Source**
Diesel fuel	6.95	NASS (2005)
Gasoline, service station, unleaded	10.93	NASS (2005)
Gasoline, service station, bulk delivery	10.93	NASS (2005)
L. P. gas, bulk delivery	10.75	NASS (2005)
Natural gas	6.44	EIA, 2007
Other	8.97	Average value
Electricity	24.76	Miranowski (2004)

Figure 5-2 illustrates the total energy use and energy use by farm operation (animal and crop production) and Table 5-2 compares the calculated values (in primary energy units) to those provided in the literature. The total energy use by fuel category can be verified by comparing the calculated values to data provided by Miranowski (2004) and Schnepf (2004). According to these sources, the electricity use by the agriculture sector was 351 - 356 trillion Btu in 2002. However, it was not clear whether the electrical energy use was given in a primary energy term. If calculated using the electricity prices provided by Schnepf (2004), the electricity consumption was approximately 133 trillion Btu. This indicated a possibility of electricity use given in a primary energy term by Miranowski (2004) and Schnepf (2004). If the combustion energy factor (2.5 to 3.0) was applied, the calculated electricity use is comparable to the published values given in Table 5-2.

The total fuel use reported by NASS included the energy consumed by vehicles engaged in agriculture related transportation. Schnepf (2004) listed various fuels by their use. According to the list, gasoline was primarily used in operating small vehicles such as cars and pickup trucks and diesel was consumed by most farm machinery and irrigation equipment. As vehicle energy use was already accounted for in the transportation sector, the use of gasoline needed to be removed to avoid double counting. The final fuel use data used in this research excluded the quantity of gasoline consumed by the agriculture sector.

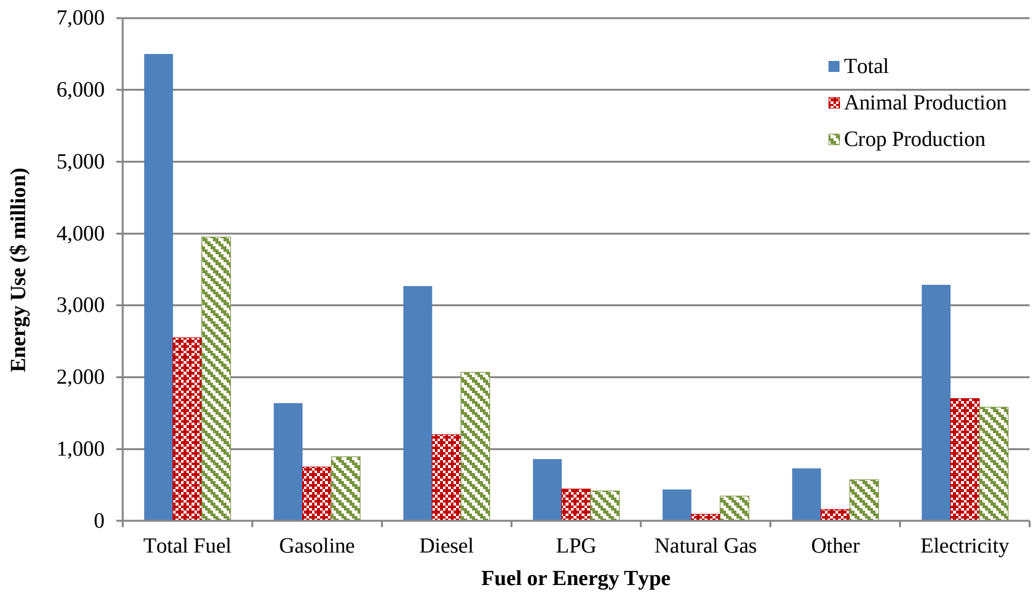


Figure 5-2: Energy expenditure in United States agriculture

Table 5-2: Comparison of calculated values of energy use to reported values

Fuel/Energy	Calculated Values (MBtu)	Miranowski, 2004 (MBtu)	% Diff	Schnepf, 2004 (MBtu)	% Diff
Diesel fuel	470,454,208.7	469,000,000.00	-0.3%	464,100,000.0	-1.4%
Gasoline	150,104,019.7	146,000,000.00	-2.8%	144,500,000.0	-3.9%
LPG	79,978,893.2	79,000,000.00	-1.2%	76,500,000.0	-4.5%
Natural gas	67,938,962.6	62,000,000.00	-9.6%	61,200,000.0	-11.0%
Electricity	132,681,943.6	356,000,000.00	3.0%	351,900,000.0	1.9%
Total	1,113,738,546.85	1,112,000,000.00	-0.2%	1,098,200,000.0	-1.4%

5.1.2 Energy Consumption: Mining Sector (NAICS 21)

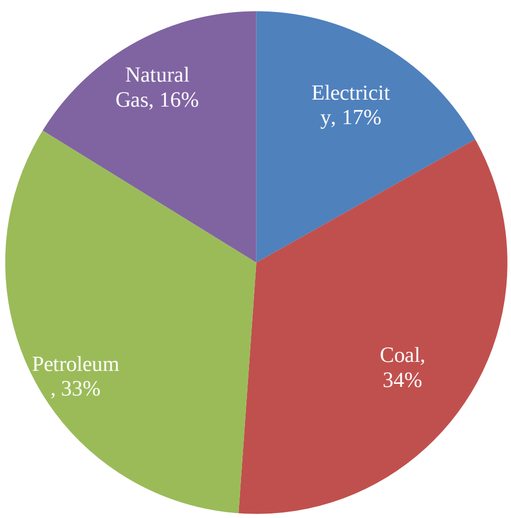
The United States' mining sector is comprised of subsectors that mine, process, and deliver a range of raw materials such as metals, minerals, gravel, sand, and stone. Some subsectors supply primary fuels such as coal, oil, and gas that are further processed, converted, or refined into delivered energy products (USDOE, 2007). Mining raw materials involves processes such as extraction, transport, handling, and beneficiation, which require considerable amount of energy. Most of the extraction processes include digging, drilling, blasting, ventilation, and dewatering. Material transport and handling processes consume mainly diesel in vehicle use and electricity in load haul dumps, conveyers, and pumps. Crushing and grinding equipment such as crushers and mills also use energy. The process of physical and chemical separation of raw materials is also quite energy intensive. Among the major primary and secondary fuels or energy sources consumed by the mining sectors are electricity, diesel, natural gas, gasoline, and a mix of other fuels such as lubricating oil, LPG, and coke.

The mining energy consumption was reported in the industry series of mining published by the Census Bureau (USCB, 2002a). The energy data were listed under the *purchased fuels* category for fuels such as coal, distillate oil, residual oil, gasoline, natural gas and other fuels. Electricity use was provided under *quantity of purchased electricity* and *quantity of electricity generated less sold* category. Mining sectors also generated electricity on-site and sold a fraction of it. The category of *quantity of electricity generated less sold* represented the fraction of on-site generated electricity used by a mining sector. As mentioned earlier, to avoid double counting, the on-site generated energy was excluded from the total energy calculation. The purchased fuel category of *other fuels* denoted a mix of fuels such as LPG and coke. Another category of purchased fuels was *undistributed fuels*, which indicated aggregated monetary data from those establishments that failed to provide detailed fuel use data. The fuel consumption data were reported either in physical quantity or in monetary units. The electricity use was provided in both physical and monetary units. The energy use information was published for 29 mining sectors that include metal, non-metal, fuel, and non-fuel sectors. Among the primary fuel sectors were the oil, gas, and coal extraction sectors.

The energy use was reported by fuel breakup but in some cases values were withheld due to confidentiality. The total fuel expenditure was given, which in some cases can be used to estimate the missing values. To decompose the total fuel expenditure or to derive the missing values, the previous year's data can be utilized (Weber et al., 2010). In some cases, data from 2007, 1997, 1992 and 1987 were used to decompose the total fuel purchased quantity (USCB, 1995; USCB, 1999; USCB, 2004; USCB, 2007). Only the fraction of a fuel as a percentage of the total fuel expenditure was calculated and used to estimate the missing values. After filling in the missing values using the disaggregation factors, any difference between the total fuel expenditures before and after filling the missing values was adjusted. The undistributed fuels were also decomposed using the calculated fractions. Some of the fuels (e.g. coal, natural gas, etc.) were extracted and used in the same plant. Such fuels were reported separately by the USCB (2004) and therefore not considered a part of the purchased fuels.

Table 5-3: Energy prices used for mining sector

Fuel/Energy	Price
Distillate oil ($/bbl.)	38.52
Residual oil ($/bbl.)	36.22
Gasoline ($/bbl.)	49.4
Coal ($/short ton)	36.97
Natural gas ($/1000 CF)	3.20
Other fuel ($/MBtu)	4.27
Electricity ($/kWh)	0.053



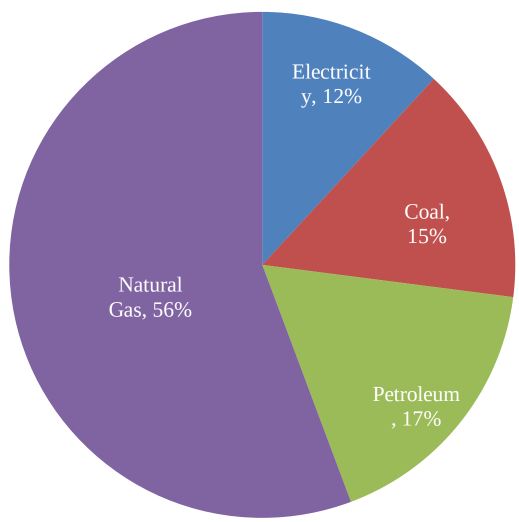


Figure 5-3: Energy use in mining (left: excluding oil & gas, right: including oil & gas)

The energy prices for fuels, data of which were given in both physical quantity and monetary terms, were calculated by dividing the monetary values by physical quantities. The fuel prices were found to differ across mining subsectors. Only monetary values of fuel consumption were provided in the case of some sectors. In such a case, an average value of fuel prices from all other mining sectors was used. Prices for petroleum products such as lubricants were sourced from the 2002 Annual Energy Review (EIA, 2002c). Table 5-3 lists energy prices of major energy sources as calculated and used in this study. The price paid for the purchased electricity was calculated using the electricity use data in kilowatt hour and in the United States dollars. The heat content of various fuels were sourced from the EIA publications such as 2002 Annual Energy Review (EIA, 2002c), Monthly Energy Review (EIA, 2012), and Electric Power Annual

2010 (EIA, 2011). Figure 5-3 provides the energy breakup for the entire mining sector (all fuel use) and for all subsectors excluding oil and gas extraction (only purchased fuel).

5.1.3 Energy Consumption: Utilities Sector (NAICS 22)

There are three major subsectors under the utilities sector supplying electricity, natural gas, steam, and water and treating and removing wastewater and sewage. The electric power is generated, transmitted, and distributed by the *Electric Power Generation, Transmission, and Distribution* subsector. The subsector *Natural Gas Distribution* includes establishments operating natural gas distribution system (e.g., meters and mains). The establishments are known as gas marketers or gas brokers and are mainly engaged in transmitting and distributing the consumer grade natural gas. Water is supplied to end users by the *Water, Sewage, and Other Systems* subsector using pumps, aqueducts, and distribution lines. This subsector also includes establishments that deliver steam, hot water and air, and chilled water. Establishments engaged in wastewater and sewage removal and treatment are also included in this subsector (USCB, 2002c).

The consumption of energy in *Electric Power Generation, Transmission, and Distribution* subsector includes fuels combusted to generate electricity and energy consumed in operating the power plants, transmission and distribution system, and related facilities. The transmission and distribution of consumer grade natural gas consumes natural gas and electricity to pressurize and move the gas through pipelines. The water supply and wastewater treatment plants also consume a considerable amount of energy in their operations. The sources of fuel consumption data for the subsectors delivering natural gas and electricity are discussed in detail in CHAPTER VI describing primary energy factor calculation. The electrical use for 2002 by the *Water, Sewage, and Other Systems* subsector was 50,000 million kWh (Weber et al., 2010). Other fuel use data for this subsector were not available and were calculated from the *use table* provided in the 2002 Benchmark Input-Output Accounts (USBEA, 2008). Table 5-4 lists the energy use by fuel for the three subsectors of the utilities sector.

Table 5-4 Primary and delivered energy consumption by utilities subsectors

NAICS & Subsector	Coal (Quad. Btu)	Electricity (Quad. Btu)	Natural Gas (Quad. Btu)	Petroleum (Quad. Btu)
2211: Electric Power Generation, Transmission, and Distribution	19.996	0.69	6.249	1.013
2212: Natural Gas Distribution	0.000	0.027	0.021	0.016
2213: Water, Sewage, and Other Systems	0.000	0.171	0.012	0.009

5.1.4 Energy Consumption by the Construction Sector (NAICS 23)

The construction sector is comprised of subsectors performing new construction, specialty construction, renovation, maintenance, and repair. The subsectors are also categorized by the type of construction such as residential, commercial, manufacturing, healthcare, and other nonresidential. Among the major products of this sector are various buildings (e.g., houses, apartments, malls, hospitals, schools, university buildings, public buildings etc.) and non-building construction projects (e.g., highways, crossovers, utility systems, power plants, dams, etc.) (USCB, 2002c).

Establishments engaged in construction activities are known as general contractors. Based on the contractual arrangements, general contractors are also termed design-builders, construction managers, turnkey contractors, and joint venture contractors. Establishments providing specific construction services or products are known as specialty contractors, trade contractors, or subcontractors. Subcontractors either work directly for the owner (e.g., renovation, maintenance, and repair work) or for the general contractors (USCB, 2002c). All of these establishments use electricity and fuels such as diesel, gasoline, and lubricants in operating on-site and off-site construction equipment and vehicles. The energy use data provided by the 2002 Economic Census (USCB, 2005) were listed by 31 subsectors represented by 6-digit NAICS codes (see Table A1-6). However, these subsectors were aggregated into only 7 subsectors in the 2002 Benchmark Input-output Accounts (see Table A1-6 in Appendix A1). The pie chart in Figure 5-4 shows the breakup of the total energy sources consumed in the construction sector in 2002 in monetary ($1000) and energy units (MBtu).

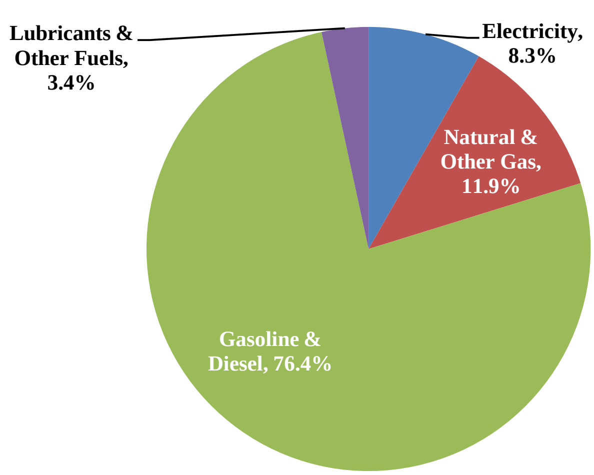


Figure 5-4: Energy use in the construction sector

No mapping was provided to relate the subsector classification of the economic census to benchmark input-output accounts. Sharrard (2007) made efforts to map the census bureau subsectors to the input-output subsector using the total value of construction put in to place. The value of construction put into place was provided under the three categories: new construction; additions, alterations, or reconstruction; and maintenance and repair. However, it became difficult to allocate the value of construction by specialty trade to input-output subsectors. According to Weber et al. (2010), the input-output data can be used to disaggregate the total fuel use by sector into fuel use by subsector. In this study, the total energy consumption of the construction sector provided by the USCB was disaggregated into consumption by input-output subsectors using the *use table* data from the benchmark input-output accounts (*use table* data from USBEA, 2008). The coefficients of energy use were calculated for each subsector and were used to disaggregate the total energy consumption. For calculating the disaggregation coefficient the monetary data were used, as the total energy consumption was also reported in monetary terms. It was assumed that the *use table* represented the actual use of energy commodity by industries. Table 5-5 provides the disaggregated energy use by input-output subsector.

Table 5-5: Disaggregated energy use in the construction sector

NAICS & Subsectors	Energy Use in MBtu			
	Natural Gas	On-highway Petroleum	Off-highway Petroleum	Electricity
230101 Nonresidential commercial & health care structures	29,663,924	118,101,369	44,023,480	25,774,598
230102 Nonresidential manufacturing structures	5,250,252	20,913,784	7,795,825	3,811,736
230103 Other nonresidential structures	91,091,873	513,002,823	191,226,993	55,905,465
230201 Residential permanent site single & multi-family structures	68,778,302	282,951,198	105,472,922	52,275,240
230202 Other residential structures	29,401,411	116,871,147	43,564,902	23,233,440
230301Nonresidential maintenance & repair	32,026,537	147,626,712	55,029,350	16,336,013
230302 Residential maintenance & repair	6,300,302	30,755,565	11,464,448	4,356,270

The calculated values of petroleum consumption as listed in Table 5-5 included both the on-highway and off-highway fuel use. To avoid the double counting, only off-highway petroleum use was included in the calculation.

5.1.5 Energy Consumption: Manufacturing Sectors (NAICS 31 & 33)

The manufacturing sectors are comprised of establishments such as plants, mills, and factories that are engaged in manufacturing a range of products by physically, chemically, or mechanically transforming raw materials. The raw materials are extracted, processed and supplied to the manufacturing sector by industry sectors such as agriculture, mining, forestry, and fishing. There are 21 subsectors indicated by 3-

digit NAICS codes in the manufacturing sectors producing a variety of products. These 21 subsectors are listed in Table 5-6. Each of the 21 subsectors is further divided into subsectors represented by 3 - 6-digit NAICS codes. The grouping is done on the basis of material inputs, outputs, production processes, production equipment, and skills of employees. Conventionally, establishments in each of 21 subsectors manufacture similar products. For instance, establishments under the *Food Manufacturing* (NAICS 311) subsector manufacture food items such as flour, starch, vegetable oil, sugar, chocolate, frozen food, etc. Similarly, subsector *Primary Metal Manufacturing* includes establishments that manufacture metals such as steel, aluminum, copper, and metal products such as steel pipes, steel bars, aluminum window sections, aluminum sheets, copper wire etc. (USCB, 2002c).

Table 5-6: Manufacturing subsectors in the United States economy

NAICS	Subsector	NAICS	Subsector
311	Food	326	Plastics and Rubber Products
312	Beverage and Tobacco Products	327	Nonmetallic Mineral Products
313	Textile Mills	331	Primary Metal
314	Textile Product Mills	332	Fabricated Metal Products
315	Apparel	333	Machinery
316	Leather and Allied Products	334	Computer and Electronic Products
321	Wood Products	335	Electrical Equip., Appliances, and Components
322	Paper	336	Transportation Equipment
323	Printing and Related Support	337	Furniture and Related Products
324	Petroleum and Coal Products	339	Miscellaneous
325	Chemicals		

All of the subsectors of the manufacturing sector consume a range of energy sources such as primary fuels, secondary fuels, and electricity. In 2002, the manufacturing sector consumed nearly 32.5 quadrillion Btu of total energy representing one third of the total United States' energy use. Energy is used in numerous transformation and transportation processes within and across the establishments. Some of the most energy intensive subsectors are petroleum and coal products, chemical, and primary metal manufacturing. The manufacturing sector consumes energy sources for both the fuel and nonfuel purposes. Under fuel purposes, fuels are burnt to produce heat or to operate a piece of equipment. Electricity is mostly used to produce heat (e.g., primary aluminum production) or to operate manufacturing machinery. Fuel such as coal, oil, and natural gas are also consumed as raw material for manufacturing products such as steel, rubber, plastic, and other synthetic products. The fuel and electricity use data are available from three major sources: the 2002 Economic Census (USCB, 2002a), the Annual Survey of Manufacturers (ASM) (USDOC, 2005), and the Manufacturing Energy Consumption Survey (MECS) (EIA, 2002b).

The fuel consumption for the manufacturing subsectors (by 6-digit NAICS codes) was reported in the 2002 Economic Census performed every five years by the United States Census Bureau. However, the fuel use was provided in an aggregated form and in monetary units as fuel purchased. The fuel and electricity use information was also published in the ASM by the United States Department of Commerce, Economics and Statistics Administration. The electricity use was reported in both the monetary units and physical units (kWh). ASM also reported the amount of net electricity generated on-site (total electricity generated less sold). It should be noted that only fuels that are purchased were reported in the ASM and any amount of energy (e.g., biomass, waste, by-product fuel) that is generated on-site may not be included in the reported value. Another source of fuel and electricity consumption data was the 2002 Manufacturing Energy Consumption Survey (MECS) administered by the United States Department of Energy (USDOE), Energy Information Administration (EIA) (EIA, 2002b). Although the MECS data were reported by individual fuel use in both the physical and energy units, energy use for only the major sectors (by 3, 4, 5, 6-digit NAICS codes) was reported.

Four types of energy data are published by the EIA in the 2002 MECS (EIA, 2002b). Table 5-7 illustrates the types of data with the energy components reported in the MECS data. The first type of energy data referred was *First Use for All Purposes*. In this type of energy data, all fuel and nonfuel use of energy was reported except the use of any energy produced on-site from energy inputs. It also reported the amount of energy shipped to other establishments. Energy data type *Energy Use for Fuel Purposes* listed quantities of all energy produced on-site or off-site from energy or nonenergy inputs consumed as a fuel. Consumption of energy produced off-site for nonfuel purposes was included in the third energy data type *Energy Use for Nonfuel Purposes*. It also included the nonfuel use of energy produced on-site from nonenergy inputs. The nonfuel use of energy generated on-site from energy sources was not reported in any of the three data types. If *Energy Use for Fuel Purposes* and *Energy Use for Nonfuel Purposes* are summed, the total would include all energy that is consumed on-site for fuel and nonfuel purposes. In order to estimate the amount of energy generated on-site from energy sources and used as a fuel, *First Use for All Purposes* should be subtracted from the total of *Energy Use for Fuel Purposes* and *Energy Use for Nonfuel Purposes.*

$$Energy\ generated\ on - site\ from\ energy\ inputs\ = (Energy\ use\ for\ fuel\ purposes + Energy\ use\ for\ nonfuel\ purposes) - First\ use\ for\ all\ purpose$$

For calculating the total energy use, the category *First Use for All Purposes* is used, as it excludes all on-site energy consumed on-site, transferred, or sold out.

Table 5-7: Various energy use components reported in the 2002 MECS

Energy Component Reported in 2002 MECS	Type of Energy Data		
	First Use, All Purposes	Energy Use, Fuel Purposes	Energy Use, Nonfuel purposes
Off-site generated energy used as a fuel	√	√	X
Off-site generated energy used as a nonfuel	√	X	√
On-site generated energy from nonenergy sources & used on-site as a fuel	√	√	X
On-site generated energy from nonenergy sources & used on-site as a non-fuel	√	X	√
On-site generated energy from energy sources & used on-site as a fuel	X	√	X
On-site generated energy from energy sources & used on-site as a non-fuel	X	X	X
On-site generated energy from energy sources & sold out to other establishments	√	X	X

5.1.5.1 Disaggregation of Fuel

The fuel and electricity consumption that was reported in aggregated form needed to be decomposed into energy uses by fuel type for each industry sector (USEPA, 2008). The decomposition of total fuel use into individual fuel use can be done on the basis of either MECS data or input-output data (USEPA, 2008; Upadhyaya, 2010; Weber et al., 2010). The 2002 *use table* published by the USBEA listed the amount of commodity purchases by each industry sector. The fuel purchase made by each lower level sector represented by a 6-digit NAICS can be compared with the total fuel purchases of the main sector represented by a higher level 3-digit NAICS code (Weber et al., 2010). According to Upadhyaya (2010), the total amount of value added by each manufacturing sector can also be used to disaggregate the total fuel purchases into purchases by fuel type. However, as the reported values (EIA, 2002b) of the energy price paid by each manufacturing sector differ considerably (with a standard deviation in the range of 0.2 - 30.4), using monetary data to decompose the total fuel was not considered accurate. Another approach to disaggregate the total fuel data was to use earlier or later years' data as a basis to decompose the total fuel into individual fuel. For instance, Weber et al. (2010) utilized the 1997 fuel breakup to decompose the 2002 aggregated fuel use in the agriculture sector.

The 2002 MECS data were used to disaggregate the total fuel use reported by the 2003 ASM for the year 2002. The purchased fuel data provided by 6-digit NAICS codes in the 2003 ASM were used to calculate the total fuel use (fuel and nonfuel use) for subsectors with 6-digit NAICS codes. Figure 5-5 illustrates the use of ASM and MECS data for deriving disaggregated fuel consumption by 6-digit NAICS code.

The MECS 2002 reported detailed energy use by seven fuel types (coal, natural gas, residual oil, distillate oil, LPG & LNG, coal & breeze and other) for some manufacturing subsectors (EIA, 2002b). These fuel types were categorized into three categories of coal, natural gas and petroleum that coincide well with the energy providing sectors of the economic input-output table. Table 5-8 presents the three categories with the included fuel types.

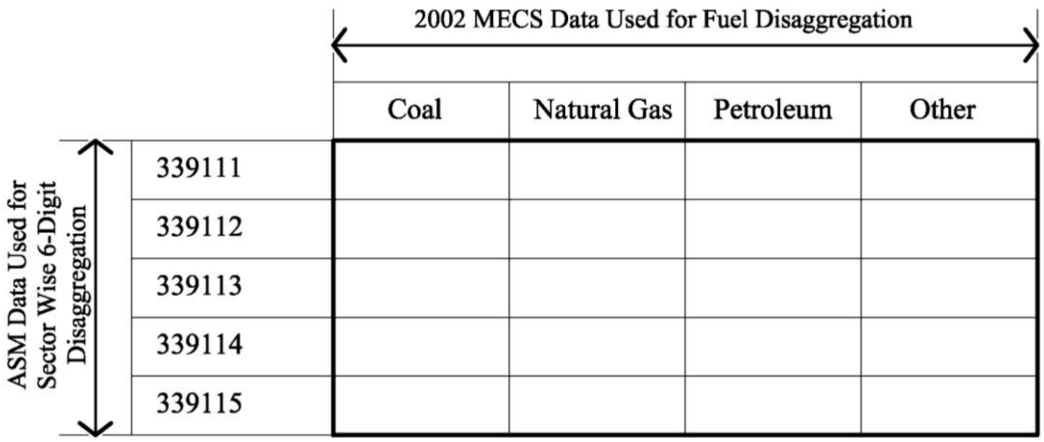


Figure 5-5: Disaggregation of fuel using the 2002 MECS and 2003 ASM data

Table 5-8: Fuel categorization by sectors

Categories	Relevant Input-output Sector	MECS 2002 Fuel Type (EIA, 2002b)
Coal	Coal mining	Coal
Natural gas	Oil & gas extraction, Natural gas distribution	Natural gas
Petroleum	Oil & gas extraction, Petroleum refineries	Residual & distillate oil, LPG & LNG, and Others

Weber et al. (2010) categorized the fuel type of coke and breeze under the petroleum category. As indicated by the MECS data (EIA, 2002b), coke is actually the coal coke, and hence, it should not be included under the petroleum category. The fuel category of coke and breeze was not included under any of the above three categories because none of the four energy providing sectors (column two of the above table) produced coke or breeze as a primary product. In addition, coal coke was produced using coal by manufacturing industries such as iron and steel mills. Counting coke and breeze use may result in double counting. To avoid the double counting, the fuel generated on-site and shipped to other establishments from coke producing subsectors was excluded from the calculation and use of coke and breeze was included. Other on-site generated energy such as oil-based fuels that were sold out to other subsectors was also excluded from the calculation. According to the MECS document (EIA, 2002a), the other category of fuel included a range of other energy sources such as asphalts, lubricants, naphtha, other oils, kerosene, motor gasoline, petroleum coke, still gas/waste gas, waxes, other nonfuel sources, biomass, steam etc. As nearly 80% of the energy of the other category came from petroleum or petroleum related products, the other category was included in the petroleum category. Weber et al. (2010) also included the category of others in petroleum.

5.1.5.2 Treatment of Missing Data

The 2002 MECS data of fuel, nonfuel, and first use for all purposes contained cells with missing values due to confidentiality or poor data quality. Row sums and column sums were used to calculate the missing values. According to Weber et al. (2010), previous years' data can be used to derive the disaggregation coefficients to estimate the missing values. Some cells were marked with an * meaning the values in the cells were less than 0.5. In such cases, an average value of 0.25 was assumed if the missing value could not be calculated. The 2006 (EIA, 2009a) and 1998 MECS (EIA, 1998) energy data were referred to derive the fractions to calculate the missing values.

Figure 5-6 shows that the ratio of total coal use to the total fuel use was consistent in 1998, 2002, and 2006. Ratios for other fuels can be seen in Figure B1-9, Figure B1-10, and Figure B1-11 in Appendix B1. These ratios can be used to estimate or interpolate the missing energy values. The ratios varied with a standard deviation in the range of 0 - 0.25.

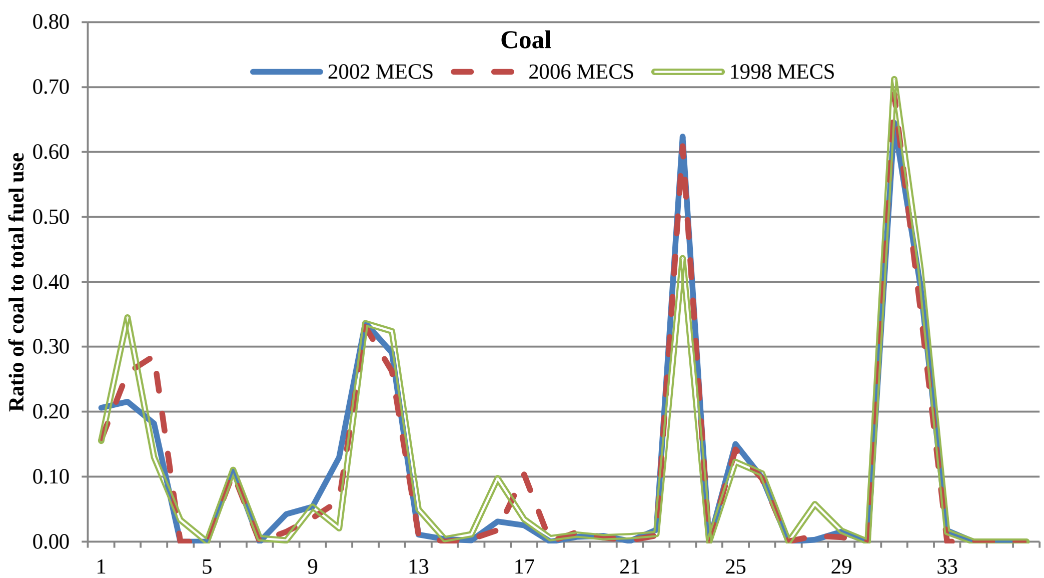


Figure 5-6: Ratio of coal use to total fuel use in selected manufacturing sectors

The amount of coal, natural gas and petroleum as a fraction of the total fuel is also found to have a strong to very strong correlation. The correlation can be seen in scatter plots provided in Figure B1-12, Figure B1-13, Figure B1-14, and Figure B1-15 in Appendix B1. The value of r^2 for correlation of 2002 fractions to 2006 and 1998 fractions for fuel used for all purposes was within the range of 0.86 - 0.97 and 0.91 - 0.99, respectively. These values showed a strong to very strong positive correlation.

Three types of electricity use data were available: purchased electricity, net electricity demand, and first use of electricity. The purchased electricity was the amount of electrical power bought from other sectors. The net demand of electricity equaled the total of purchases, on-site generation, and transfer (to the sector) of electrical power minus the electricity sold out to other establishments. As for on-site electricity generation, purchased fuels were consumed, only purchased electricity data (excluding any on-site electricity generation) were used to avoid double counting of energy inputs. The 2002 purchased electricity data of manufacturing sectors were provided in ASM 2003 and MECS 2002 in both the monetary ($) and in energy units (kWh). Some of the electricity data in the MECS 2002 were withheld due to confidentiality. The purchased electricity data from the ASM 2003 or MECS 2006 (EIA, 2009b) can be used as a basis to estimate the missing electricity data. The correlation of purchased electricity data in MECS 2002 to ASM 2003 was found to be very strong and positive (r2 value of 0.93) as shown in Figure 5-7 . However, as the ASM 2003 data were complete and given in energy units, they are used for final calculation.

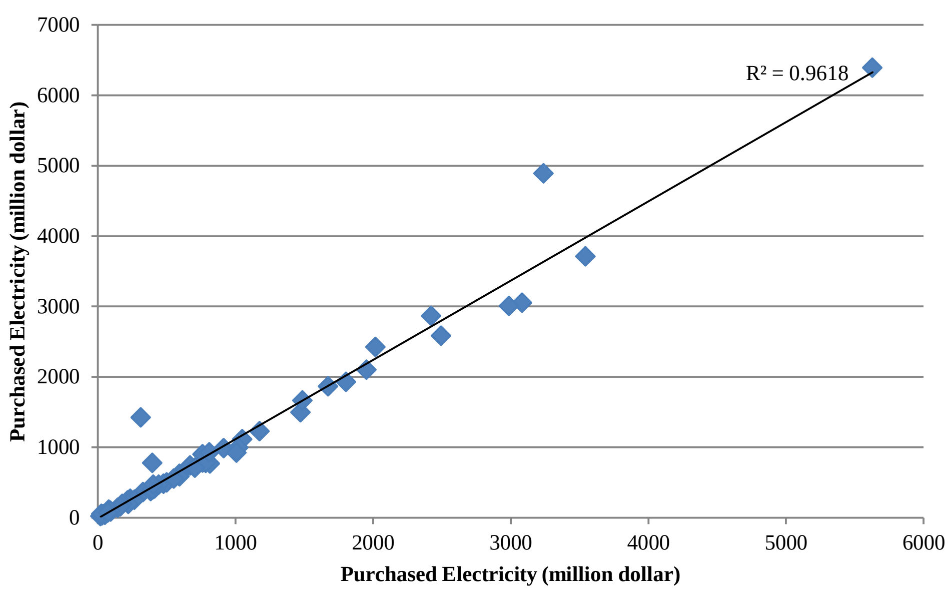


Figure 5-7: Correlation of 2002 MECS and 2003 ASM electricity data

After deriving the amounts of energy use by fuel type for all relevant subsectors with 6-digit NAICS, the total fossil fuel and electricity used by the manufacturing sector was equal to 19.8 and 2.8 quadrillion Btu, respectively. The calculated values of energy use for subsectors with 6-digit NAICS were disaggregated using the 2002 MECS data. The final disaggregated values of energy use are given in Table 5-9.

Table 5-9: Final disaggregated primary energy use in the manufacturing sectors

NAICS Subsector	Subsector Description	Final Disaggregated Fuel Use (Trillion Btu)		
		Coal	Natural Gas	Petroleum
311	Food	185.00	582.00	126.00
312	Beverage and Tobacco Products	17.00	46.00	16.00
313	Textile Mills	22.00	75.00	23.00
314	Textile Product Mills	7.00	29.00	7.00
315	Apparel	0.00	16.00	1.75
316	Leather and Allied Products	0.00	4.00	1.00
321	Wood Products	1.00	57.00	247.00
322	Paper	240.00	504.00	1395.00
323	Printing and Related Support	0.00	46.00	2.50
324	Petroleum and Coal Products	289.00	878.00	5505.00
325	Chemicals	350.00	2307.00	3285.00
326	Plastics and Rubber Products	22.00	128.00	20.00
327	Nonmetallic Mineral Products	320.00	422.00	176.00
331	Primary Metal	727.00	704.00	197.00
332	Fabricated Metal Products	4.75	210.00	12.25
333	Machinery	1.00	82.00	10.25
334	Computer and Electronic Products	0.25	65.00	5.25
335	Electrical Equip., Appliances, and Components	0.50	53.00	72.25
336	Transportation Equipment	10.00	203.00	44.00
337	Furniture and Related Products	1.00	25.00	13.25
339	Miscellaneous	0.00	32.00	4.25
Total		**2,196.00**	**6,468.00**	**11,165.00**

Table 5-10 documents the energy use by fuel type and by energy component as mentioned earlier in Table 5-7. As seen in the table, the nonfuel use of coal, natural gas, and petroleum comprised nearly 40%, 10%, and 55% of the total fuel use, respectively. This was critical to note, as most of the embodied energy calculations fail to account for the feedstock use of energy sources, which could be substantial. The first use of energy for all purposes was the same as the total fuel and nonfuel use of energy in the case of coal and natural gas. This, however, was different in the case of petroleum due to the use of on-site generated fuel from energy sources, which totals to 854 trillion Btu. As mentioned earlier, the use of on-site generated fuel (from energy sources) was not included in the first use of energy for all purposes. It is also important to note that the nonfuel use of on-site generated fuel from energy inputs was not included in any of the reported energy components. This energy component was not required to be counted, as it was produced using the purchased fuel.

Table 5-10: Energy use accounting by energy component

Energy Component (TBtu)	Coal & Coke	Natural Gas	Petroleum
Fuel Use: On-site & Off-site Generated Fuel	1,567	5794	5,036
Non-fuel Use: On-site & Off-site Generated Fuel	774	674	6715
First Use for All Purposes	2,341	6,468	11,751
Energy Shipments	143	0	587
Actual Energy Use (Without Double Counting)	**2,198**	**6,468**	**11,164**
Fuel Use: Energy Produced On-site from Energy Sources	0	0	854
Total	2,341	6,468	12,605
Nonfuel Use %	35%	10%	60%

Table 5-11: Comparison of disaggregated energy use with input-output data

NAICS Subsector	Subsector Description	Electricity Use Based on MECS & ASM Data (Trillion Btu)		Electricity Use Based on Input-Output Data (Trillion Btu)
		Net Demand	Purchased	Purchased
311	Food	251	230	264
312	Beverage & Tobacco Products	29	26	34
313	Textile Mills	87	86	54
314	Textile Product Mills	18	17	12
315	Apparel	12	12	11
316	Leather & Allied Products	2	2	2
321	Wood Products	77	72	60
322	Paper	391	223	157
323	Printing & Related Support	51	50	49
324	Petroleum & Coal Products	187	127	82
325	Chemicals	691	522	328
326	Plastics & Rubber Products	184	181	155
327	Nonmetallic Mineral Products	144	141	102
331	Primary Metals	514	493	227
332	Fabricated Metal Products	162	161	128
333	Machinery	84	84	74
334	Computer & Electronic Products	131	131	105
335	Electrical Equip., Appliances etc.	48	47	36
336	Transportation Equipment	181	172	139
337	Furniture & Related Products	27	24	26
339	Miscellaneous	35	35	34
	Total	**3,304**	**2,836**	**2,078**

The net electricity demand, which is the total use of electricity in the manufacturing sector, was calculated as 3.0 quadrillion Btu that includes the quantity of purchased, on-site produced, and transferred electricity less the quantity that was sold out to other establishments. The total amount of electricity purchased by the manufacturing sector was 2.84 quadrillion Btu. The difference between the net demand and purchased electricity denoted the quantity of electrical power generated on-site and/or transferred to the subsector. The quantities of net electricity demand and purchased electricity are tabulated in Table 5-11. The quantities of purchased electricity using input-output data are also listed in Table 5-11. A strong positive correlation (r^2 = 0.90) was found between the purchased electricity use calculated using the MECS data and the input-output data. This makes sense, as the input-output data represented only monetary transactions (energy sold or purchased). The value of r^2 rose to 0.95 when the net electricity demand was compared with the input-output-based data.

Figure 5-8 shows the strong positive correlation between the calculated values and the input-output-based values of purchased electricity and net demand of electricity. In this research, only the quantity of electricity that was purchased by the manufacturing establishments is included in the total energy calculation.

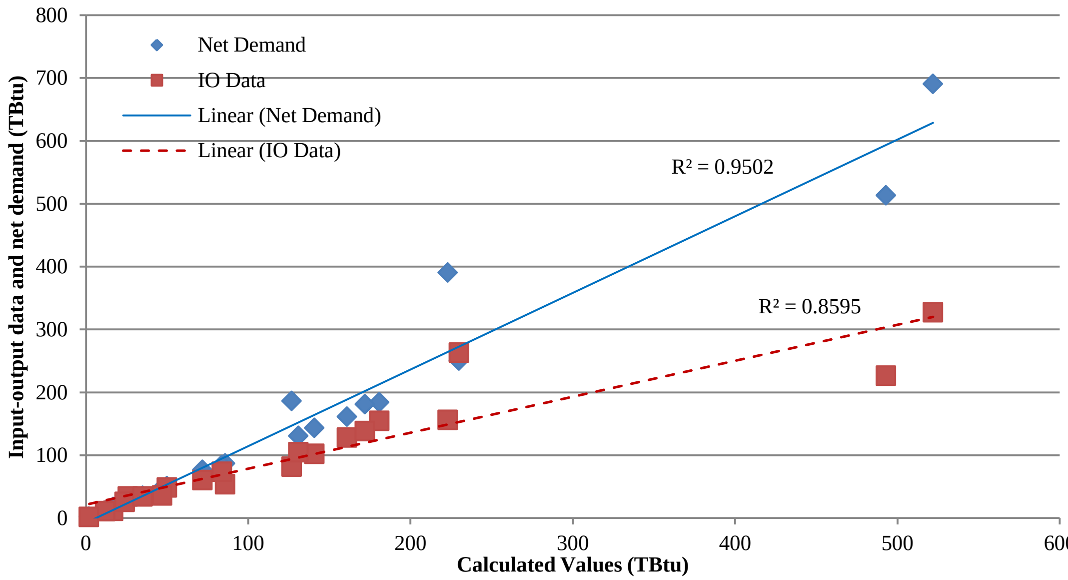


Figure 5-8: Correlation of disaggregated electricity use

5.1.6 Energy Consumption: Trade Sectors (NAICS 42-45)

Among the major trade sectors in the United States economy are the wholesale and retail trade sectors. The wholesale trade sector (NAICS 42) is comprised of subsectors engaged in the wholesaling of merchandise to other wholesalers or to retailers. The subsectors also provide incidental services related to the wholesale trade. The merchandise is usually a product of sectors such as agriculture, mining, manufacturing, and information (e.g., software, books, music CDs, etc.). Typically, wholesalers do not transform the merchandise and do not advertise their products to final customers. They operate from their warehouses or offices and use the telephone, in-person communication, internet, or other electronic means to reach their customers. Two types of wholesalers operate in the United States economy. Wholesalers selling merchandise on their account are merchant wholesalers. Establishments arranging the sales of products within wholesalers and between wholesalers and retailers are business to business electronic markets, brokers, agents, or commission merchants. Such establishments work for a fee or commission for facilitating a product's sale. Although wholesalers deal with sales of large volumes of capital and durable goods to wholesalers and retailers, they also sell non-consumer capital and durable goods such as farm equipment, industrial machinery, and vehicles used in the production and processing of goods and services.

The Retail trade sector is made of subsectors that sell their merchandise to the final consumers such as private households, institutional customers, and other commercial customers. They also provide incidental and after sales services such as maintenance and repair. The sales of products occur in small quantities from locations such as stores. Extensive advertising is used to promote their products and stores. Just like wholesalers, retailers mostly do not transform their merchandise. However, in some cases such as optical stores, the merchandise such as lenses may be grinded, cut, and transformed into another type of product (e.g., prescription and sunglasses). There are two types of retailers: store retailers and non-store retailers. The store retailers have a fixed point-of-sale location designed to handle a large crowd of customers. Such stores use extensive amount of display and advertising in and out of stores. The non-stores include retailers that are engaged in selling merchandise door-to-door and from portable stalls using electronic or print catalogues, home demonstration, and direct response marketing (USCB, 2002c).

Among the major energy uses in the trade sectors are fuel use for heating and generating electrical power and consumption of electricity in operating the business facilities such as warehouses, offices, stores, and other related buildings. Fuel is also consumed by automobiles involved in trade activities. Energy use in the wholesale and retail trade sectors was given in two categories: purchased fuel, and purchased electricity. The cost of purchased fuel and electricity was reported in the business expenses report published under the annual Economic Census by the United States Census Bureau. The fuel consumed by motor vehicles was not included in the purchased fuel category.

Two main issues were found in the business expenses data. First, some energy data were missing because the information was either unavailable or withheld due to poor data quality. In such cases, the known quantities of fuel use given by the lower level NAICS codes were subtracted from those provided by the higher level NAICS code. In some cases, where energy use for more than one subsector was missing, the input-output data were used to disaggregate the fuel use of a higher level subsector and derive the energy use for a lower level subsector. As mentioned earlier, the 2002 Benchmark Input-Output Accounts data can be used to disaggregate the total energy use. However, as wholesale and retail trade establishments may purchase energy to sell out to final consumers, using input-output data may be inaccurate. The 2002

Annual Energy Review provided fuel wise energy use data for the commercial sector, which included all the trade, service, government, nongovernment, and utilities sectors. This information can be used to decompose the total energy use. Using the commercial fuel use provided by the 2002 AER, the monetary quantities of purchased energy were decomposed into individual fuel use. The total quantity of each fuel was disaggregated into fuel use by subsector by utilizing the amounts of energy purchases made by the subsectors. Input-output data was used for those subsectors for which no process data was available. Commercial sector energy prices referred from the 2002 Annual Energy Review were used to convert the energy or fuel use from monetary units to energy units. After disaggregation, the amounts of energy consumed by the wholesale and retail trade sectors are shown in Table 5-12.

Table 5-12: Final disaggregated energy use in wholesale and retail trade

		Disaggregated Energy Use (MBtu)			
NAICS	Sector	Coal	Natural Gas	Petroleum	Electricity
420000	Wholesale Trade	9,404,104.38	231,887,424.22	51,723,801.54	199,380,301.07
4A0000	Retail Trade	10,804,289.02	266,413,328.84	59,424,999.85	728,662,715.77

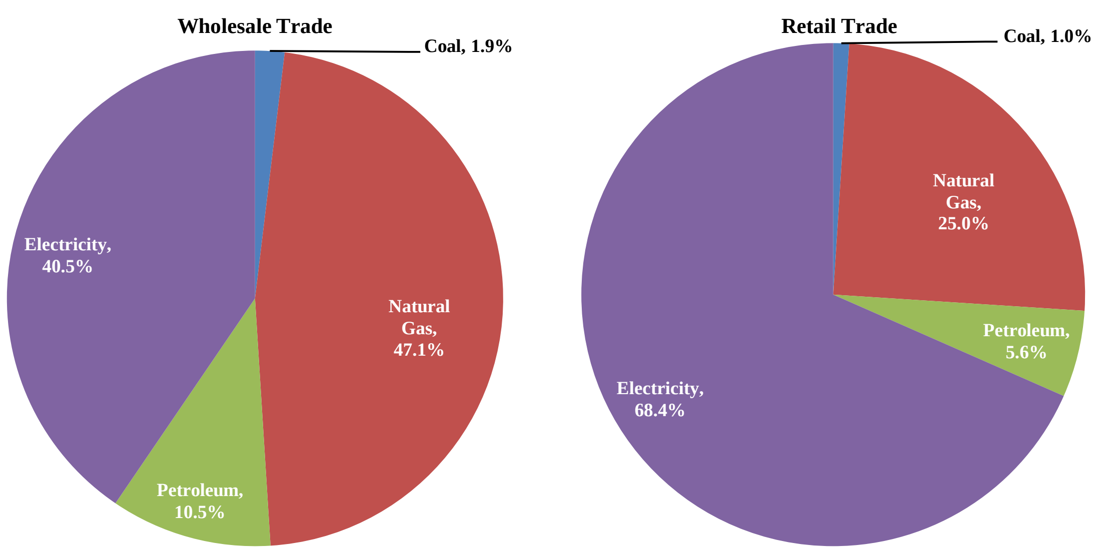


Figure 5-9: Final energy use in wholesale and retail sectors

Figure 5-9 provides a breakdown of fuel use by fuel type for the wholesale and retail sectors, respectively. It is evident from the pie charts that use of natural gas and electricity dominates the wholesale and retail sectors' total energy use, respectively. As most retail trade establishments maintain large size stores and use extensive use of electronic displays, dominance of electricity in total energy use seems reasonable.

5.1.7 Energy Consumption: Transportation and Warehousing Sectors (NAICS 48 & 49)

The transportation and warehousing sectors are made of subsectors involved in moving goods such as the final products of manufacturing, mining, agriculture, information, and service sectors across cities and states. These sectors also include scheduled and unscheduled human travel using rented vehicles such as cars, buses, taxicabs, and trucks or through public transportation such as mass transit rail and road systems. The transportation may be domestic or international. The subsectors are characterized by mode of transportation such as land, water, and air. Railroad and road transportation are among the major surface transportation modes. Airlines involved in passenger and cargo transportation are covered under air transportation. Transporting goods and human labor using ships, barges, and boats are included in lake, river, or deep seawater transportation. All travel activities for leisure, sightseeing, and recreational purposes are included in scenic and sightseeing transportation (USCB, 2002c).

In addition, to move liquids and gases such as crude and refined petroleum and natural gas products, a network of pipelines is used, which is categorized under pipeline transportation. Subsectors operating warehouses and storage facilities for general merchandise, refrigerated products, and other products such as equipment are represented by the warehousing and storage subsector. The warehousing and storage subsectors may provide logistic services to distribute merchandise. They do not, however, sell any product. All transportation subsectors require support activities such as vehicle maintenance and repair, which are covered by a representing subsector. The movement of goods or information also involves postal and courier services covered under subsectors: postal services, and courier and messenger services. Table 5-13 lists the major subsectors that are engaged in transportation across geographic regions (USCB, 2002c).

Table 5-13: Major transportation sub-sectors (USCB, 2002c)

NAICS	Sector and Subsector	NAICS	Sector and Subsector
481000	Air transportation	487000	Scenic and sightseeing transportation
482000	Rail transportation	488000	Support activities for transportation
483000	Water transportation	491000	Postal services
484000	Truck transportation	492000	Couriers and messengers
485000	Transit and ground passenger transportation	493000	Warehousing and storage
486000	Pipeline transportation		

The United States' transportation sector consumed over 27% (28.6 quadrillion Btu) of the nation's total energy in 2002. Among the major fuels consumed in transportation include gasoline, diesel, and jet fuel. Other energy sources such as LPG, natural gas, residual fuel oil, and electricity were also used in transportation activities. A significant amount of gasoline (95%) and diesel (68%) was used in highway transportation and represented nearly 75% of the total transportation energy in 2002.

Figure 5-10 illustrates the dominance of gasoline and diesel (in monetary units) in highway, non-highway, and off-highway transportation (in monetary units). Highway transportation included vehicles such as motorcycles, cars, light trucks, buses, medium trucks, and heavy trucks or trailers. The non-highway mode included all railroad, air, water, and pipeline transportation involving the use of pipelines and vehicles such as trains, aircrafts, ships, barges, and boats. Fuel used by vehicles or moving equipment used in personal and recreational activities (e.g., sports and leisure), and by the agriculture, construction, mining, industrial, and commercial sectors was covered under the off-highway mode of transportation.

Figure 5-10 shows the breakdown of total transportation energy consumption by energy types (in energy units). The transportation energy data were provided by the United States Department of Transportation (USDOT) and Department of Energy by the mode of transportation (USDOT, 2012). A major issue with these data was that no system was available for mapping the energy use by mode to energy use by NAICS codes. Although subsectors such as air, rail, truck, and pipeline transportation were easy to map, subsectors such as transit and ground passenger, scenic and sightseeing transportation, and support activities for transportation were difficult to map due to overlapping activities. For instance, light vehicles such as motorcycles, cars, and light trucks consumed a total of 16.2 quadrillion Btu of energy. These vehicles included personal vehicles as well as taxicabs, limousines, emergency vehicles, and rented cars and light trucks. All vehicles other than the personal ones needed to be mapped to the transit and ground passenger transportation subsector. Similarly, the total energy consumed in air, water, and ground transportation also included energy use in travel for sightseeing and scenic activities. This total energy was also required to be decomposed into transportation energy for general and sightseeing purposes. Energy use of support activities for transportation was not given in the transportation statistics provided by the USDOT.

The fuel use data from the transportation statistics data were mapped directly to the input-output sectors of air, rail, water, truck, and pipeline transportation. The passenger rail transportation was given by the breakdown of transit, commuter, and intercity travel. The transit and commuter travel was allocated to transit and ground passenger transportation. According to the 2002 vehicle fleet data from the National Transportation Statistics (USDOT, 2012), nearly 31 and 4% of the total cars and light trucks, respectively represented taxi or rental vehicles. Therefore, only 31 and 4% of the total fuel used by cars and light trucks was counted in transit and ground passenger transportation. Other transportation components such as transit and school buses were also mapped to transit and ground passenger transportation. Table 5-14 lists information provided by the USCB that was utilized to map the energy use to input-output subsectors.

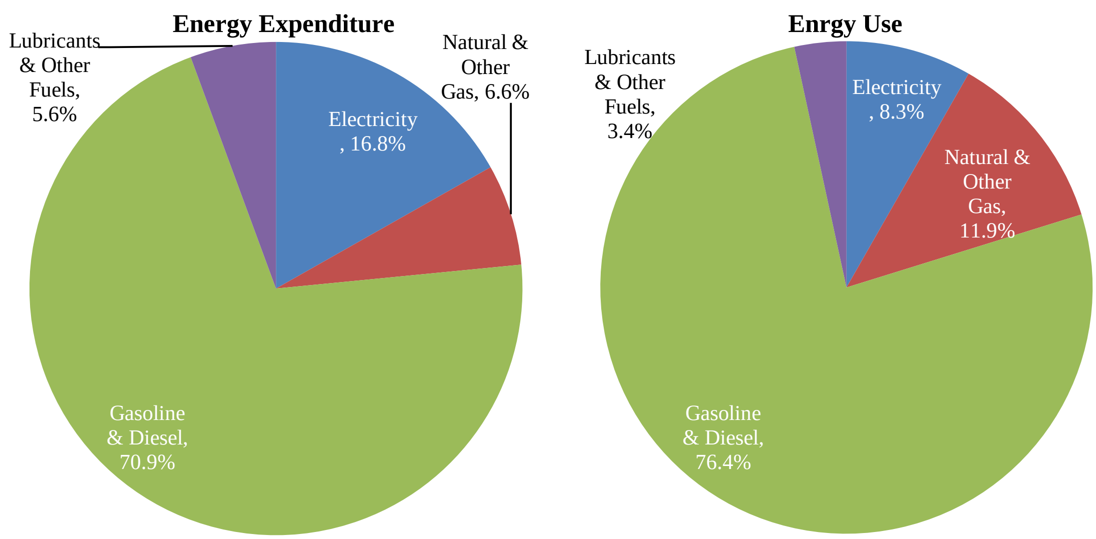


Figure 5-10: Energy use breakdown in monetary (left-hand) and energy units (right-hand) in the transportation sector

Table 5-14: Categorization of travel components

NAICS	Sector and Subsector	Transportation or Travel Component (USCB, 2002c)
481000	Air transportation	Air transportation of passenger and cargo by scheduled and unscheduled carriers excluding sightseeing & scenic transportation, air courier, and support activities for air transportation
482000	Rail transportation	Long and short rail transportation of passengers and cargo across cities excluding urban transit system, sightseeing & scenic transportation, and support activities for rail transportation
483000	Water transportation	Water transportation of passenger and cargo by ships, barges, and boats excluding sightseeing & scenic transportation, and support activities
484000	Truck transportation	Truck transportation of cargo using trucks and tractor trailers excluding support activities for truck transportation
485000	Transit and ground passenger transportation	A range of ground transportation (road, light rail, commuter rail, subway, and streetcars) of passengers including urban transit system, school buses, chartered buses, city bus services, taxicabs, limousine services, and other special ground transportation. Excluded are sightseeing & scenic transportation, and support activities
486000	Pipeline transportation	Transportation of crude and refined petroleum and natural gas products excluding water and steam supply
487000	Scenic and sightseeing transportation	Land, water, and other (air) transportation for sightseeing and scenic trips involving sightseeing buses, trolleys, steam train excursions, horse-drawn rides, cruises, aerial tramways, helicopter rides, hot air balloon rides, aerial cable cars, glider excursions and other similar activities.

To estimate the energy consumed by the *scenic and sightseeing transportation* and *support activities for transportation* subsectors, *use table* data from the benchmark accounts were used (USBEA, 2008). However, the *use table* provided energy data for both sectors together under one subsector: *scenic and sightseeing transportation and support activities for transportation (48A000)*. The 2002 Benchmark Input-output Accounts were published with a table outlining the detailed output of industries. For the subsector 48A000, the output was given by land, water, and other scenic and sightseeing transportation and support activities for transportation. The fraction of scenic and sightseeing transportation in the total output was used to disaggregate the total energy consumed by subsector 48A000. The energy consumed in sightseeing and scenic transportation was nearly 4% of the total energy use of subsector 48A000.

Table 5-15: Disaggregated energy use in transportation

NAICS	Commodity	Energy Use in Trillion Btu			
		Coal	Natural Gas	Petroleum	Electricity
481000	Air transportation	0.00	0.00	2,212.36	0.00
482000	Rail transportation	0.00	0.00	536.30	9.60
483000	Water transportation	0.00	0.00	995.07	0.00
484000	Truck transportation	0.00	0.00	5,026.80	0.00
485000	Transit and ground passenger transportation	0.00	11.60	3,292.85	65.70
486000	Pipeline transportation	0.00	687.70	0.00	247.70
48A000	Scenic and sightseeing transportation and support activities for transportation	0.36	58.28	289.24	13.45
	Total	**0.00**	**699.30**	**12,254.53**	**323.20**

As energy use of air, water, and ground transportation subsectors provided by the USDOT included all kinds of travel, energy use in sightseeing and scenic transportation was subtracted to avoid double counting. Table 5-15 provides the final energy use disaggregated by individual fuel and total electricity use by the transportation subsectors.

5.1.8 Energy Consumption: Service Sectors (NAICS 51-81)

This section discusses the energy consumed by various service providing sectors represented by NAICS 51 through 81. These sectors include subsectors providing a range of services as listed in Table A1-7 in Appendix A1. Energy is used in operating facilities, equipment, machinery, and in related transportation. Energy consumption data were published for most of the service subsectors by the USCB in the Annual Business Expense report under the categories of purchased fuel and electricity (USCB, 2006b). These data were in monetary terms and did not include motor vehicle fuel. Similar to the wholesale and retail trade sectors, energy data were decomposed and converted to energy units using 2002 AER data of commercial sector energy use and relevant energy prices. Energy use by postal services was sourced from 2002 AER (EIA, 2002c). Table 5-16 lists the final energy use by each service sector.

Figure 5-11 shows the breakup of total energy consumption of all service sectors. It was clear that the total energy use of this sector is dominated by natural gas and electricity. As most of the energy was consumed in operating the related facilities (e.g. lighting and air-conditioning), the dominance of natural gas and electricity seemed reasonable.

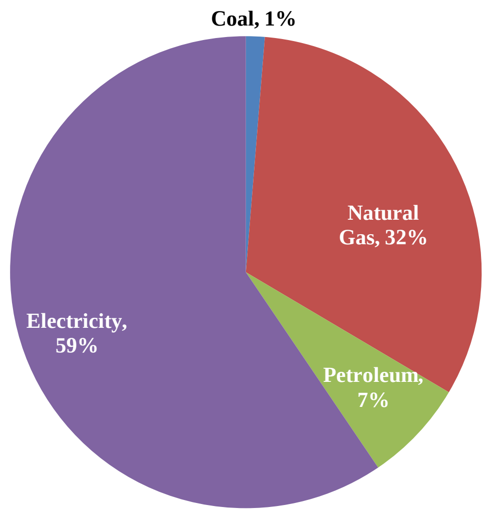


Figure 5-11: Final disaggregated energy use in the service sectors

Table 5-16: Disaggregated energy use in service sector

NAICS & Sector Description		Energy Consumption in MBtu			
		Coal	Natural Gas	Petroleum	Electricity
51	Information	1,828,071	45,302,941	10,036,032	209,002,843
52	Finance and Insurance	1,017,188	28,145,852	5,342,697	71,962,024
53	Real Estate and Rental and Leasing	2,055,416	55,249,716	10,929,470	712,117,851
54	Professional, Scientific, and Technical Services	2,254,402	55,589,280	12,399,503	105,758,789
55	Management of Companies and Enterprises	1,184,203	32,767,202	6,219,930	114,814,890
56	Administrative and Support, and Waste Management and Remediation Services	3,530,250	87,049,292	19,416,837	55,555,936
61	Educational Services	3,282,204	90,819,420	17,239,507	132,900,538
62	Healthcare and Social Assistance	12,787,557	315,316,968	70,333,233	342,213,717
71	Arts, Entertainment, and Recreation	3,332,853	82,181,844	18,331,125	125,386,129
72	Accommodation and Food Services	14,452,708	356,376,434	79,491,779	452,669,023
81	Other Services (except Public Administration)	8,049,990	198,861,742	44,246,045	166,521,999
	Total	**93,438,582**	**2,445,166,340**	**502,316,667**	**2,488,903,740**

5.1.9 Energy Consumption: Public Administration Sector (NAICS 91)

The public administration sector is composed of subsectors representing various federal, state, and local government agencies overseeing, managing, and administering public programs and providing executive, legislative, and judicial authority over a range of institutions. This sector includes establishments such as executive offices, legislative bodies, municipal authorities, police departments, courts, prosecution offices, correctional institutions, fire departments, public health offices, veteran's affairs, transportation, utilities, community development, housing authorities, national security, space program, and other national and international affairs departments (USCB, 2002c). Detailed energy use data for some of the federal government defense and non-defense agencies were reported in 2002 AER. Energy use data of the remaining subsectors were sourced from the 2002 input-output *use table*. The total energy purchases by all nondefense subsectors were decomposed using the energy use data from the 2002 AER for commercial sector category. It was assumed that the *general federal defense government services* subsector was not a part of the commercial sector as defined in the 2002 AER. Table 5-17 provides the decomposed energy use for the public administration subsectors.

Table 5-17: Disaggregated energy use in public administration sector

NAICS & Subsector Description		Energy Consumption in MBtu			
		Coal	Natural Gas	Petroleum	Electricity
S00101	Federal electric utilities	0	5,495,515	38,480,362	4,195,002
S00102	Other federal government enterprises	826,733	22,875,914	4,342,347	2,525,590
S00201	State and local government passenger transit	1,248,599	34,549,044	6,558,162	16,187,131
S00202	State and local government electric utilities	1,137,044,882	0	48,153,518	109,245
S00203	Other state and local government enterprises	1,699,825	47,034,590	8,928,191	48,799,247
S00500	General federal defense government services	28,000,000	78,000,000	579,000,000	102,200,000
S00600	General federal nondefense government services	9,100,000	45,900,000	46,000,000	68,600,000
S00700	General state and local government services	724,744	20,053,839	3,806,656	317,329,172

5.1.10 2002 Total Energy Flow: United States

The flow of energy through various industry sectors was reported in the 2002 Annual Energy Review published by the EIA. According to the 2002 AER, the residential sector included all household and personal energy use associated with living quarters. Energy was consumed mainly in lighting, heating, air-conditioning, and powering home appliances. Energy used by all equipment and facilities of service providing agencies; businesses; federal, state, and local entities; public and private organizations; institutional living quarters; and waste treatment agencies were covered under the commercial sector in the

2002 AER. The industrial sector included energy used to operate facilities and equipment of manufacturing sector; the agriculture, forestry, fishing, and hunting sector; the mining sectors (including oil and gas); the construction sector; the natural gas distribution sector; and the water supply and irrigation sector. All of the land, water, and air transportation (public and private) related energy consumption was covered under the transportation sector. The total energy use and individual fuel use provided by the 2002 AER was compared with the calculated values.

Figure 5-12 provides a breakup of the total energy consumption by fuel type as provided by the 2002 AER and as calculated using the process data. The total quantities of coal, natural gas, petroleum, and electricity use were within 0.2%, 4.3%, 9.7%, and 3.4% of the value reported in the 2002 AER, respectively. In the case of petroleum use, the other fuel category (manufacturing sector) also included wood, biomass, steam, and hot water energy. When this fraction was excluded, the total petroleum use came within 5.5% of the 2002 AER values. Another reason for an increased petroleum use was the fuel used by motor vehicles in sectors for which input-output data have been used. As motor vehicle energy use was already accounted for in the transportation sector, it needed to be removed from either the transportation sector or from the industry sectors. No information was available that could have been utilized to disaggregate the vehicle and non-vehicle fuel use. As the calculated values were within 5.5% of the reported values, they were assumed appropriate for the energy analysis. The reported and calculated value of the total electricity use is 12.55 and 12.98 quadrillion Btu, respectively.

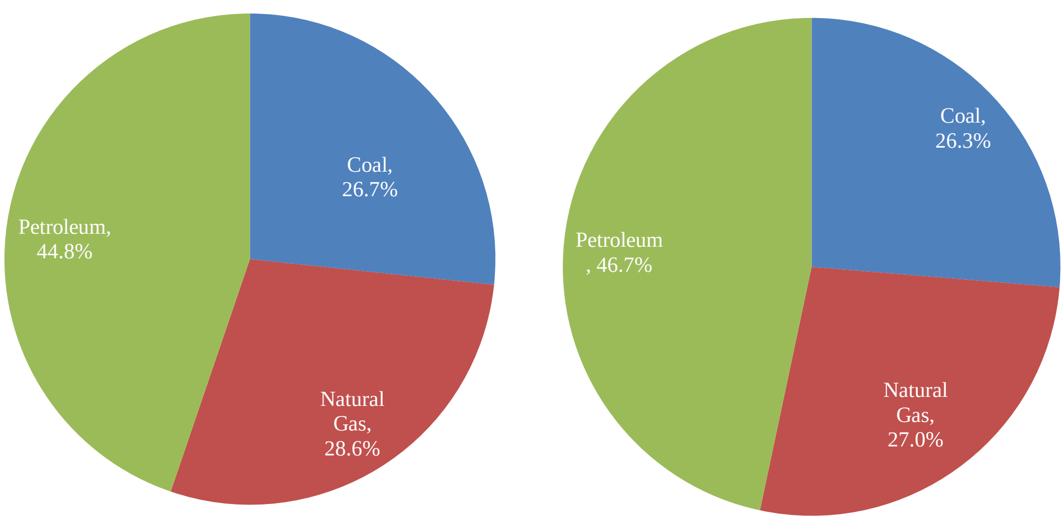


Figure 5-12: Total energy use in the United States reported by 2002 AER (left-hand) and as calculated (right-hand)

5.2 SUMMARY

The process data of energy used by energy sources were collected for nearly all industry sectors. Some data such as electricity use were given in energy units (kWh), whereas some data were provided in monetary units. Appropriate energy prices were used to convert the energy use from monetary data to energy units. Three primary fuels, namely coal, natural gas, petroleum dominated the total energy supply in the United States in 2002. According to the calculations of this study, nearly 22.8, 23.4, and 40.4 quadrillion Btu of coal, natural gas, and petroleum was consumed in the United States, respectively. The total fossil fuel based energy supply was calculated as 86.6 quadrillion Btu, which was within 1% of the value reported by the 2002 Annual Energy Review. The total consumption of electricity was calculated as 12.98 quadrillion Btu, which was within 3% of the 2002 Annual Energy Review. The energy used by each industry sector was calculated by energy source. Since some industry sectors purchased energy directly from the oil and gas sector, a separate energy row of such purchases was estimated.

The energy use data was available for more than half of the industry sectors in physical units. However, in the case of some industry sectors such as service industries, the data was in monetary units. Although, the monetary data was used only to proportionately allocate the total energy use, availability of detailed energy use data in energy units would have been better. In the future, one can expect an availability of detailed energy use data by each energy source for the service sectors.

CHAPTER VI

PRIMARY ENERGY FACTOR CALCULATION

6.1 PRIMARY AND SECONDARY ENERGY

The energy consumed by various economic sectors is either in a primary or a secondary energy form (Deru and Torcellini, 2007; Dixit et al., 2010). The primary energy is the energy of a fuel extracted directly from earth. Fossil fuels such as coal, crude oil, and gas are extracted directly from the earth and are known as primary fuels. The secondary energy (also known as delivered energy) is the energy that is generated by processing the primary fuels. For instance, gasoline that is processed and refined from crude oil is a secondary or delivered fuel, whereas the crude oil is a primary fuel. Another example of secondary energy is electricity, which is generated mostly by combusting primary fuels such as coal, petroleum, and natural gas. The primary and secondary energies are also known as source and site energy, respectively. It is important to distinguish primary energy from secondary energy, as the two are not comparable and represent different amounts of energy. For example, it will be inaccurate to compare the energy use of two buildings if one is expressed in a primary (source energy e.g. in Btu) and the other in a secondary energy term (e.g. electricity in kWh). The amount of electricity use could be significantly higher when converted to a primary energy term. It is due to the energy conversion and transmission and distribution (T&D) losses that incur while producing and distributing the electricity. The process of generating electricity could use 2 - 3 times more coal, oil, or natural gas in generating one unit of electricity. Similarly, the process of producing and distributing other secondary fuels such as consumer grade natural gas and gasoline also involves energy use and energy losses (or gains), which should also be accounted for when converting them to primary energy terms. All secondary energy use quantities should be converted to a primary or source energy term before a comparison is made.

6.2 PRIMARY ENERGY FACTOR (PEF)

In this research, the term primary energy means the sum of energy consumed by an economic sector and the energy that is required to extract, process, convert, transmit, and distribute the consumed energy. Both, the primary and secondary energy sources have consumed a significant amount of energy before they reach to the end users. In the process of their extraction and delivery, primary fuels such as coal also consume a considerable amount of energy. The ratio of the total amount of energy delivered to the end users to the total amount of energy consumed (including the delivered energy) in delivering that energy is termed the Primary Energy Factor (PEF). A PEF represents the total primary energy needed to produce a unit of energy delivered for end use. Hence:

$$\text{Primary Energy Factor (PEF)} = \frac{\text{Total Energy Delivered for End Use}}{\text{Total Primary Energy Consumed in the Delivery}} \qquad \text{Equation 6-1}$$

The above expression should be adjusted for the energy losses that incur during extraction, processing, and delivery of an energy source. The numerator in the above equation denotes the delivered energy, for instance, electricity or consumer grade natural gas. The denominator represents the total primary energy used and lost in the process of delivery (including the energy spent in extraction, processing, conversion, and distribution). This total primary energy used in the process of delivering the energy for end use is made of one or more of the three major components as shown in Figure 6-1. The following sections describe these components:

6.2.1 Primary Fuel Use

At this stage, a primary fuel is either burnt (e.g. in power plants) or used as a raw material (e.g. in oil refineries) to be processed or refined further. The total energy consumed at this stage has a direct and an indirect component. The direct fraction includes combustion energy, whereas the indirect energy fraction consists of pre-combustion energy.

Combustion Energy: The combustion energy represents the calorific value of a fuel or energy source that is released when the fuel is burnt. The process of fossil fuel combustion is a chemical reaction involving oxygen that results in release of water, CO_2, and heat. The amount of heat energy produced in the fuel combustion process represents the combustion energy of a fuel (see Figure 6-1).

Pre-combustion Energy: The pre-combustion energy is the energy consumed in extracting, processing, converting, and distributing a fossil fuel that is being combusted, processed, or refined. This fraction of energy covers all fuel and nonfuel inputs. The use of primary fuel as an energy input and as a feedstock material is included under the fuel input category. The nonfuel inputs cover the energy embodied in raw materials, equipment, and labor that are used in processing, refining, and delivering the energy for end use.

6.2.2 Energy Use in Plant or Lease Operation and Energy Delivery

The plants such as natural gas processing facilities, petroleum refineries, and power plants consume energy in their operations. Energy is also used when energy source or fuel is distributed to end users. Similarly, operations of oil and gas wells, coal and uranium mines, and related facilities also use a significant amount of energy. Such operations also need built structures, equipment, and raw materials, which also have consumed energy when they were manufactured or installed.

Direct Energy: The primary and secondary energy used by plants, lease operations, or mine facilities and equipment in their operations is accounted for in this fraction. The energy consumed in distributing the processed fuel is also added to the total operating energy. The energy of labor is also included (see Figure 6-1).

Indirect Fraction of Operating Energy: The amount of energy that is consumed in extracting, processing, converting, and distributing the operating energy is included in this fraction. In addition, the energy embodied in built facilities, materials, equipment, and labor is also accounted for (see Figure 6-1).

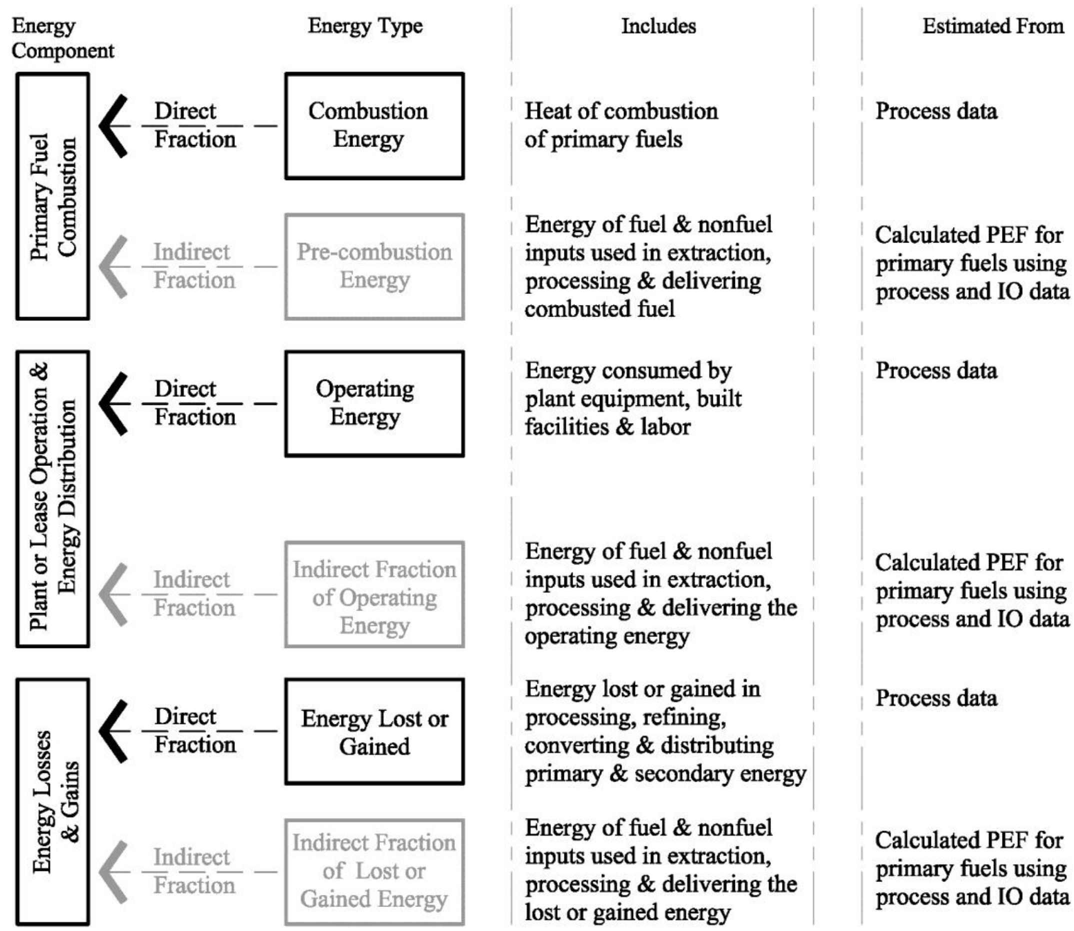


Figure 6-1: Energy components used in delivering energy for end use

6.2.3 Energy Lost and Gained

In the process of energy extraction, processing, refining, conversion, and distribution, a significant amount of energy is either lost or gained (in the case of petroleum refineries). Just like any other primary energy, this fraction of energy also has a direct and an indirect component.

Energy Lost or Gained: This direct component includes energy lost while extracting, processing, and distributing the energy. For instance, when oil and gas are extracted, a fraction of gas is vented or flared. Similarly, when primary fuels are processed or refined, some energy is either lost or gained. In 2002, petroleum refineries actually gained some energy while refining the crude petroleum. The losses due to transmission and distribution are also accounted for in this fraction. Electricity distribution involves significant transmission and distribution (T&D) losses (nearly 10%), which are also included in this fraction of energy.

Indirect Fraction of Lost or Gained Energy: This fraction includes the amount of energy that is consumed in extracting, processing, converting, and distributing the lost or gained energy including the energy embodied in structures, materials, equipment, and labor.

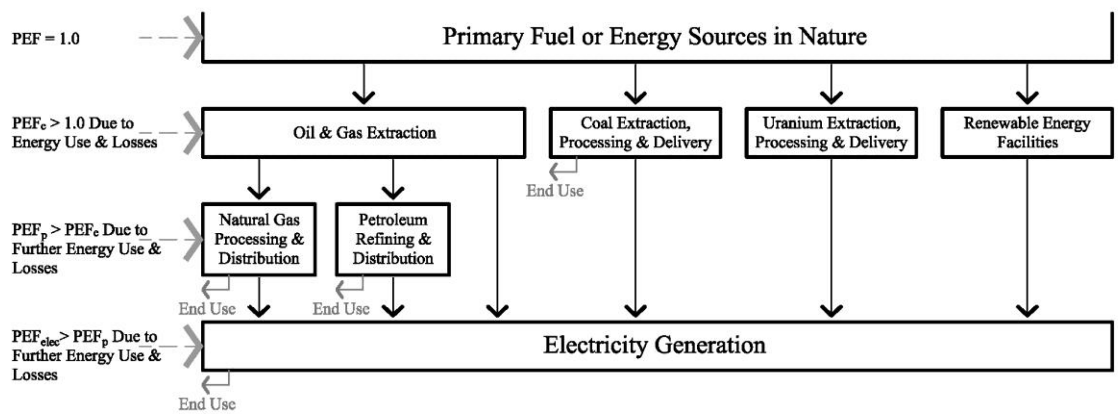


Figure 6-2: Primary to delivered energy and resulting PEFs

The PEF should be calculated for each category of primary and secondary fuels. When a primary fuel exists in its natural form in the earth, it has a PEF that equals nearly one representing only its energy of combustion. When this fuel is extracted from the earth, energy is consumed and lost in the process resulting in a PEF that is more than one (see Figure 6-2). It's further processing, refining, and distribution requires building facilities, installing equipment, and procuring labor in addition to the direct energy use. Therefore, any additional processing of an energy source in the downstream results in an increase in its PEF (see Figure 6-2). Each of the major primary fuels such as coal, natural gas, petroleum, and uranium oxide has a PEF greater than one. The process of electricity generation utilizes one of the major primary fuels mentioned earlier and should include their PEFs in the calculation of PEF for electricity.

6.3 ENERGY IN THE UNITED STATES' ECONOMY

Energy supply in the United States is dominated by three categories of fossil fuels: coal, oil, and natural gas. As per 2002 Annual Energy Review, nearly 86% (83.5 quads out of 97.4 quads) of the total energy use in the United States can be attributed to the three fossil fuels (see

Figure 6-3). Nearly 70% of the nation's total electricity supply came from fossil fuel-based power plants (see

Figure 6-3). There are mainly five energy providing sectors in the United States' economy (Mo et al., 2010; Mo et al., 2011):

- Oil and gas extraction
- Coal mining
- Electric power generation, transmission, and distribution
- Natural gas distribution
- Petroleum refineries

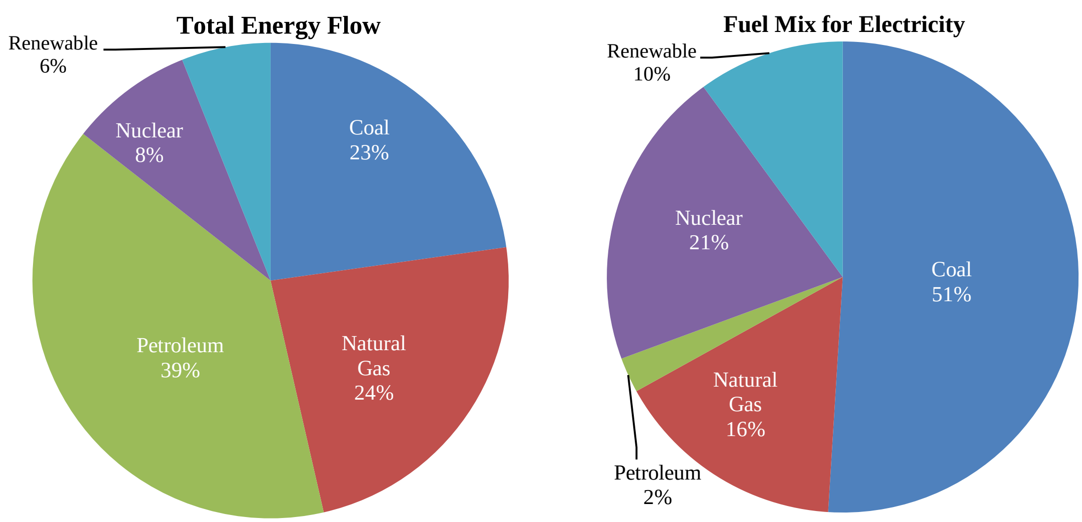


Figure 6-3: Fuel mix of the total energy use and electricity production

The first two sectors are primary energy sectors extracting, processing, and delivering coal, crude oil and gas, whereas the last three sectors are the secondary energy sectors supplying electricity, natural gas and refined petroleum to the end users as shown in Figure 6-4. Each of the energy sectors mentioned above supplies either primary or delivered energy to end users and other industry sectors of the economy. The primary energy sectors such as coal mining deliver their output for final use (e.g. residential and commercial use), for inter-industry use (e.g. industrial use in iron and steel mills), and for producing the electrical power. Other primary energy sectors such as oil and gas extraction distribute their products mostly to other industries, electric power plants, natural gas distribution, and petroleum refineries for further processing. In 2002, the United States imported over 66% of its crude oil supply from other countries (EIA, 2002c). The nuclear fuel is mined, processed, and delivered to power plants by subsector Uranium-Radium-Vanadium Ore Mining under the main mining sector Other Metal Ore Mining. In 2002, nearly 92% of the uranium loaded into nuclear power plants in the United States was imported from various countries around the globe (EIA, 2002c; EIA, 2004a).

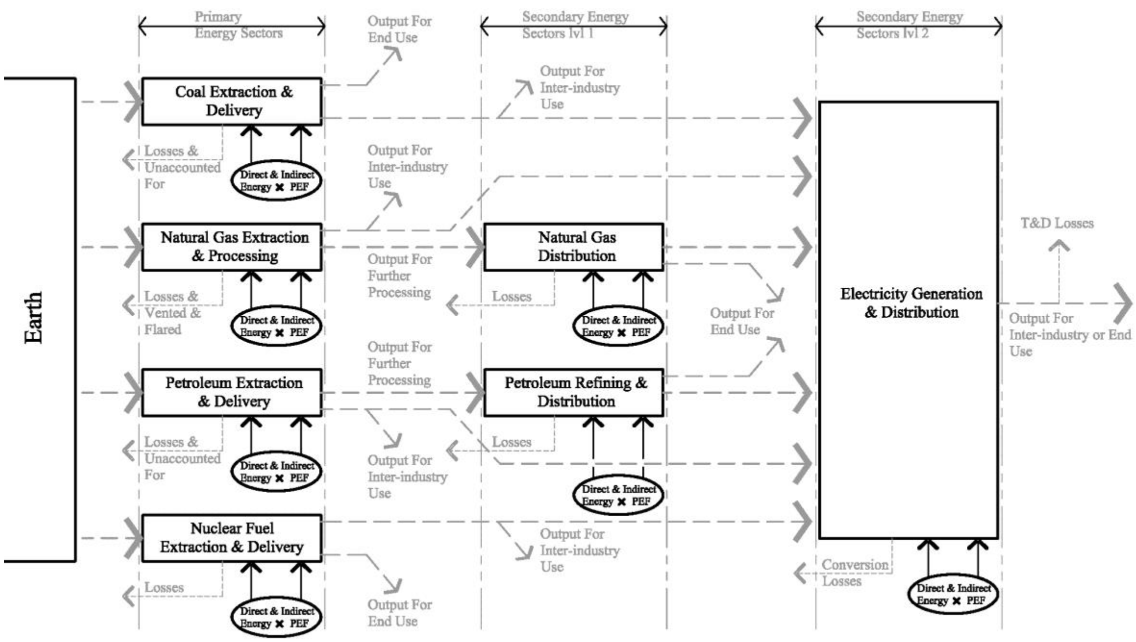


Figure 6-4: Primary and delivered energy flow in the United States' economy

6.4 PRIMARY ENERGY FACTOR CALCULATION FOR PRIMARY FUELS

If an input-output-based energy analysis is performed, particularly in an economy with a mix of primary and delivered energy, the energy inputs could be counted twice (Treloar, 1998). For example, if a delivered energy such as electricity (1 MBtu) is produced using amounts of coal (2 MBtu), natural gas (5 MBtu), and oil (4 MBtu), then as per the input-output theory the energy embodied in electricity would be the total of energy contents of all the fuels plus the energy contents of the produced electricity (1+2+5+4 MBtu). This is inaccurate because the actual amount of energy embodied would be the sum of all the fuels

(11 MBtu) that were consumed. One must be careful to do some adjustments to avoid double counting before using the input-output framework (Treloar, 1998). In addition, it is important to note that the indirect fraction of energy due to all energy and nonenergy inputs should not remain excluded from the calculation.

In this research, the PEFs for all major fuels were calculated using three approaches. In the first approach, the direct energy fraction was calculated on the basis of process data of energy use and losses. The indirect energy fraction was calculated and added using the input-output framework. The direct requirements were subtracted from the total requirements to estimate the indirect energy fraction. The direct energy process data and indirect energy input-output data were then totaled and adjusted for the energy losses. The PEFs for fuels such as coal, natural gas, petroleum, and nuclear fuel were calculated first. The PEF for electricity was then computed using the direct energy data and the calculated values of PEFs for the four fuels. There was no need to use the input-output data for electricity, as the PEFs represented the indirect impacts of its production. Both the human and capital energy inputs were included in the calculation. The following sections describe the first approach in detail, as the results of this approach were adopted in this research.

It is assumed that nearly all of the natural gas supplied to the end users was distributed through the natural gas distribution sector. Additionally, all refined petroleum products were assumed to come from the petroleum refineries sector. It is important to calculate the PEFs separately for oil and gas extraction, natural gas distribution, and petroleum refineries sectors, as some industry sectors made purchases directly from all three sectors. Hence, a set of PEFs representing each energy providing sector must be derived for those purchases. The PEFs of the coal mining, oil and gas extraction, natural gas distribution, petroleum refineries, and the uranium-radium-vanadium ore mining were used to compute the PEF of electricity production.

6.4.1 Oil and Gas Extraction

The fuel and electricity consumption data were sourced from the 2002 Economic Census (USCB, 2004) for the two sectors involved in oil and gas extraction. The sectors were:

- Crude petroleum and natural gas extraction
- Natural gas liquid extraction

This sector drew crude oil and natural gas from the earth and processed the natural gas into a dry and consumable form in order to distribute it for the end use. In the natural gas processing plants, dry consumer-grade natural gas was produced. To produce dry natural gas, the liquefiable hydrocarbons and non-hydrocarbon gases (e.g., water vapor, carbon dioxide (CO_2), helium, hydrogen sulfide and nitrogen) were removed from the extracted volume of natural gas (EIA, 2004b; NPC, 2011). There were only two components of total primary energy use in these sectors. First, the energy used in lease and plant operations and second, the energy lost while extracting and processing the oil and gas. The fuel consumption data were provided in energy and monetary terms. In the case of missing data in energy terms, appropriate energy prices were used to convert the monetary data to energy terms.

Total direct energy use ($E_{d,\,og}$) is the sum of the energies of all types of fuels consumed in the operations of oil and gas extraction facilities. The total energy consumed in processing and distributing dry natural gas included both the direct ($E_{d,\,og}$) and indirect fraction ($E_{in,\,og}$). The consumption of fuel from the energy providing sectors caused the other industry sectors to increase their production to meet the demand. This increase in production represented the indirect requirements. The 2002 Benchmark Input-output Accounts were referred (USBEA, 2008) and direct requirement coefficients are subtracted from the total requirement coefficients for estimating the indirect energy requirements ($E_{in,\,og}$) of the oil and gas extraction sector. The indirect requirements were in monetary units, and hence, converted to energy units by using energy prices. There are two options for using energy prices: the annual average wellhead price ($2.95/1000 CF) for natural gas and domestic first purchase price ($24.65/bbl.) for crude oil. According to the 2002 Annual Energy Review (EIA, 2002c), the wellhead price included all costs before shipping the natural gas from the lease. In addition, a United States average for consumer grade natural gas and refined petroleum could be derived and used. However, this was difficult, particularly in the case of refined petroleum that included multiple products with varying prices and varying levels of uses. Another option was to derive an average energy price as a ratio of the total monetary output to the total energy output of the energy providing sector. Such a price was assumed to be a better representative of the national energy economy.

Table 6-1 lists major energy parameters used for calculating the PEF for major energy sources. Human energy and the energy embodied in capital inputs is then added to the calculated direct and indirect energy values for coal, natural gas, petroleum, and electricity. The extraction of natural gas and oil also incurs production and processing losses. The production losses include the volume of natural gas that is vented and flared during the extraction process. The processing results in extraction losses. The extraction loss data were sourced from (EIA, 2002c; EIA, 2004b). The total amount of natural gas leakage was sourced from the California Air Resources Board report (ARB, 2009). The sum of all extraction and processing losses is termed total oil and gas loss (L_{og}).

If the combustion and pre-combustion energy factors are represented by $EF_{C,\,og}$ and $EF_{P,\,og}$, respectively, then:

$$EF_{C,og} = 1 \qquad \text{Equation 6-2}$$

$$E_{d,og} = \sum_{i=1}^{n} E_{i,d,og}$$

$$E_{in,og} = \sum_{i=1}^{n} E_{i,in,og}$$

$$EF_{P,og} = \frac{(E_{d,og} + E_{in,og})}{E_{o,og}} \quad \text{Equation 6-3}$$

The PEF for oil and gas extraction is calculated as:

$$PEF_{e,og} = (EF_{C,og} + EF_{P,og}) \times (1 + L_{og}) \quad \text{Equation 6-4}$$

Where:

$EF_{C,og}$ - Combustion energy factor for oil & gas extraction

$EF_{P,og}$ - Pre-combustion energy factor for oil & gas extraction

$E_{d,og}$ - Direct energy use by oil & gas extraction

$E_{in,og}$ - Indirect energy use by oil & gas extraction

$E_{o,og}$ - Total energy output of oil & gas extraction

$E_{i,d,,og}$ - Total direct energy consumed by oil & gas extraction including pipeline transportation

$E_{i,in,,og}$ - Total indirect energy consumed by oil & gas extraction including pipeline transportation

n - Number of energy sources or fuels used by oil & gas extraction

i - Represents an energy source or a fuel

L_{og} - Ratio of net energy loss or gain to the total energy output of oil & gas extraction

Table 6-1: Major energy parameters used for the PEF Calculation

Fuel	**Heat Contents**	**IO Price ($/MBtu)**	**Price ($/MBtu)**	**Source**
Crude oil	5.800 MBtu/bbl.	2.59	3.88	EIA, 2002c (AER)
Natural gas at wellhead: Marketed	1.105 MBtu/1000 CF	2.59	2.95	EIA, 2002c (AER)
Natural gas: Consumer grade, national weighted average	1.029 MBtu/1000 CF	4.04	5.05	EIA, 2002c (AER)
Coal, national weighted average	20.892 MBtu/short ton	0.92	1.05	EIA, 2002c (AER); EIA, 2002 (ACR)
Petroleum refined, national weighted average	5.322 MBtu/bbl.	5.02	6.21	EIA, 2002c (AER)
Electricity	---	20.03	21.07	EIA, 2002c (AER)

6.4.2 Coal Mining

In 2002, the total monetary output of the coal mining sector was 20,371.8 million dollars representing a total of nearly 1094 million short tons of coal. The processes of extracting, processing, and transporting coal are quite energy intensive and each unit of energy delivered by coal has some amount of embodied energy (EERE, 2002). Three ranks of coal are mined in the United States: anthracite, bituminous, and lignite. These ranks differ in hardness and the amount of fixed carbon and volatile matter in the coal (EERE, 2002). Coal is mined either by surface or underground mining depending on the depth of the coal seam. Coal beds that are below 100 - 200 feet were mined using the underground mining approach (EERE, 2002). Both of the approaches use equipment, materials, and labor extensively in mining, loading, and removing coal from a surface or underground mine. The quality of mined coal, termed run-of-mine, is not suitable for fuel use. The end users require pure and consistently sized coal. The process of coal beneficiation includes processing, washing, and sizing the mined coal. After the run-of-mine coal is extracted, its impurities are removed and it is sized consistently (EERE, 2002).

Over 92% of the total coal consumption went to electricity generation alone in 2002 (EIA, 2002c). Most of the remaining quantities were consumed by coke plants and other manufacturing plants. The processed coal was transported to end users by water, railroad, or road transportation. The transportation of coal by water was more economical than the railroad and road. Approximately 58% of the coal was transported by railroads in the United States (EERE, 2002; BESR, 2007). Waterborne and truck transportation carried roughly 17% and 12% of the total coal, respectively to end users.

The energy use data for coal mining sector were provided by the 2002 Economic Census (USCB, 2004) under purchased fuel, supplies, and electricity. The coal transportation energy use was calculated from the 2002 Benchmark Input-output Accounts (USBEA, 2008). The supply and disposition accounting of coal was provided by 2002 Annual Energy Review, which was used as a basis for identifying the quantities of coal produced, consumed, and unaccounted for. The total direct energy, indirect energy, and lost energy was calculated by summing the process and input-output data. Similar to the oil and gas extraction, the combustion energy factor for coal was also assumed as one. The pre-combustion energy factor and PEF for coal is calculated in the same manner as oil and gas.

6.4.3 Natural Gas Distribution

The natural gas processing consumed direct energy in natural gas transmission and distribution. The energy was consumed mainly in the process of compressing and moving the gas in the pipeline (NPC, 2011). As it is assumed that nearly the entire natural gas supply to the end users came from the natural gas distribution sector, the calculation of PEF for natural gas included the energy consumed and lost while extracting, processing, and distributing the natural gas. Figure 6-5 shows the flow of natural gas from its extraction to its delivery to the end users. In 2002, the oil and gas extraction sector yielded 57% and 43%

(in energy terms) of its output as natural gas and crude oil (including NGPL), respectively. Hence, 57% of the total energy (direct and indirect) used in the oil and gas extraction sector was allotted to natural gas in calculating its PEF. All of the natural gas loss from the oil and gas extraction sector was allocated to the calculation of PEF for the natural gas. The calculated value of PEF of natural gas represented the total energy consumed and lost in its extraction, processing, transmission, and distribution to the end users. Similar to the oil and gas extraction, the combustion energy factor for natural gas is assumed as one. The total electricity consumed in transmitting and distributing dry natural gas was sourced from USDOT (2012). The data were reported for both the oil and gas transportation together. The relative share of natural gas and oil in the total oil and gas supply was used to disaggregate the total pipeline transportation energy. The PEF for natural gas distribution was calculated in the following steps:

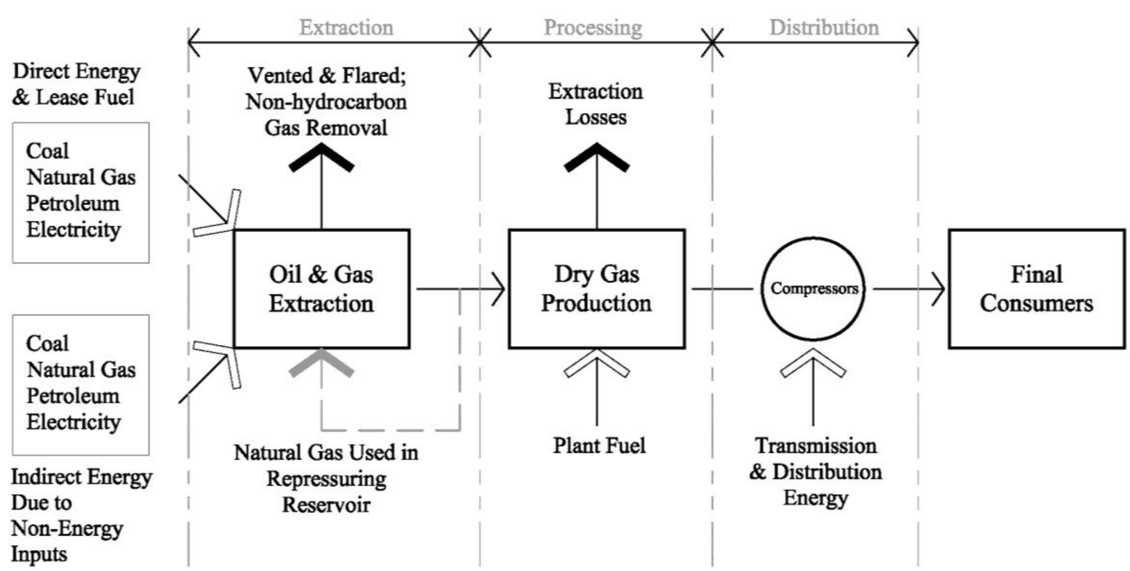


Figure 6-5: System boundary for PEF calculation for natural gas

$$EF_{C,ng} = 1 \qquad \text{Equation 6-5}$$

$$E_{d,ng} = \sum_{i=1}^{n} (E_{i,d,ng} + E_{i,d,og} \times F_{ng,og})$$

$$E_{in,ng} = \sum_{i=1}^{n} (E_{i,in,ng} + E_{i,in,og} \times F_{ng,og})$$

$$EF_{P,ng} = \frac{(E_{d,ng} + E_{in,ng})}{E_{o,ng}}$$ Equation 6-6

The PEF for natural gas is estimated as:

$$PEF_{e,ng} = (EF_{C,ng} + EF_{P,ng}) \times (1 + L_{ng})$$ Equation 6-7

Where:

$EF_{C,ng}$ - Combustion energy factor for natural gas

$EF_{P,ng}$ - Pre-combustion energy factor for natural gas

$E_{d,ng}$ - Direct energy use by natural gas

$E_{in,ng}$ - Indirect energy use by natural gas

$E_{o,ng}$ - Total energy output of natural gas

$E_{i,d,,ng}$ - Total direct energy consumed by natural gas including pipeline transportation

$E_{i,d,,og}$ - Total direct energy consumed by oil & gas extraction sector

$E_{i,in,,ng}$ - Total indirect energy consumed by natural gas including pipeline transportation

$E_{i,in,,og}$ - Total indirect energy consumed by oil & gas extraction sector

$F_{ng,og}$ - Natural gas as a fraction of total energy output of oil and gas extraction sector

n - Number of energy sources or fuels used by natural gas

i - Represents an energy source or a fuel

L_{ng} - Ratio of net energy loss or gain to the total energy output of natural gas

6.4.4 Petroleum Refineries

In 2002, the United States produced and imported 5.82 and 9.05 million bbl. of crude oil every day, respectively. Petroleum refineries used crude oil and produced a range of fuel and chemical products such as gasoline, kerosene, and naphtha. Petroleum refining is a complex process that involves separating, cracking, restructuring, treating, and mixing hydrocarbons to produce the refined products. These processes consume energy and also result in energy losses or gains. In 2002, the refining of petroleum resulted in 0.117 million bbl. of unaccounted crude oil. In addition, a total of 349.15 million bbl. of petroleum was reported as an energy gain. Similar to the natural gas sector, it was assumed that all of the petroleum products supplied to the national economy came only from the petroleum refineries sector. It means that all of the upstream energy use should also be taken into account in the PEF calculation. As nearly 43% of the oil and gas sector output consisted of crude oil, 43% of the energy use was allocated to petroleum products and added to the total direct and indirect energy use. The PEF was calculated in the same steps as the natural gas distribution.

6.4.5 Nuclear Fuel

In 2002, nearly 52.7 million pounds of uranium oxide was imported against 2.34 million pounds of domestic production. The total uranium purchases made by electric power plants from domestic suppliers in the United States totaled 22.7 million pounds. A total of 57.3 million pounds of uranium was loaded into the nuclear power reactors as a fuel in 2002 (EIA, 2004b). The uranium-radium-vanadium ore mining, a subsector of the gold, silver, and other metal ore mining sector, extracts the uranium used by the nuclear power plants. The total amount of uranium extracted, processed and consumed domestically for generating electricity can be used to disaggregate the sector to calculate the indirect energy use for nuclear fuel. It is assumed that the imported quantities of nuclear fuel were extracted, processed, and delivered domestically. Process data of energy required to extract, process, and deliver 1000 pounds of uranium were used to calculate the direct energy use. These data were sourced from the Oregon Department of Environmental Quality report (ODEQ, 2004). The indirect energy fraction was calculated using the input-output approach similar to other primary fuels. The energy contents of uranium were calculated using the amount of total nuclear energy consumed and the total quantity of uranium consumed in nuclear power plants in 2002.

6.4.6 Electricity

Electricity is produced in electric power plants using a range of nonrenewable fuels such as coal, natural gas, oil, and nuclear fuel. Most of the fossil fuel-based power plants burn fossil fuels for producing steam to run the turbines. In nuclear power plants, the fission process of nuclear fuel in nuclear reactors is used to generate steam. Renewable energy sources such as wind, solar energy, hydropower, biomass, geothermal, and tidal energy are also utilized to generate electrical power. The fuel mix used for generating the electricity differs in different regions depending on the availability of energy sources. The production of one unit of electricity from fossil fuel combustion usually requires 2 - 3 times more energy due to lower energy conversion efficiency. The combustion energy factor, which is assumed as one for primary fuel is more than one in the case of electricity production.

Approximately 50% of the electricity generated in the United States came from fossil fuel-based power plants in 2002. Figure B1-16 in Appendix B1 illustrates the trends in the use of energy sources for producing electrical power in the United States from 1949 through 2011. Fossil fuels clearly dominated the electricity generation sector in the country. Furthermore, a detailed look at the fossil fuel use for electricity production revealed the clear dominance of coal from 1949 - 2011(see Figure B1-17 in Appendix B1). In 2002, over 50% of electricity was produced using coal alone. Nearly 70% of the total United States' electricity generation was attributed to fossil fuels. It can be concluded that electricity generation is still primarily a fossil fuel-based process in the United States. The total quantities of fuel used in generating electricity in the United States for 2002 were sourced from EIA monthly data (EIA, 2002d). Each of the 50 states and the District of Columbia (D.C.) used different fuel mixes to produce electrical power. The quantity of electricity consumed in power plant operations and the total transmission and distribution losses were referenced from the 2002 Annual Energy Review (EIA, 2002c).

Figure 6-6 shows the fuel mixes used by the states and the D.C. for generating electricity in 2002. If calculated, each of the states and the D.C. would have a different combustion energy factor due to a varying fuel mix. However, an average combustion energy factor weighted by the states' share in the total national electricity production was calculated for the entire nation.

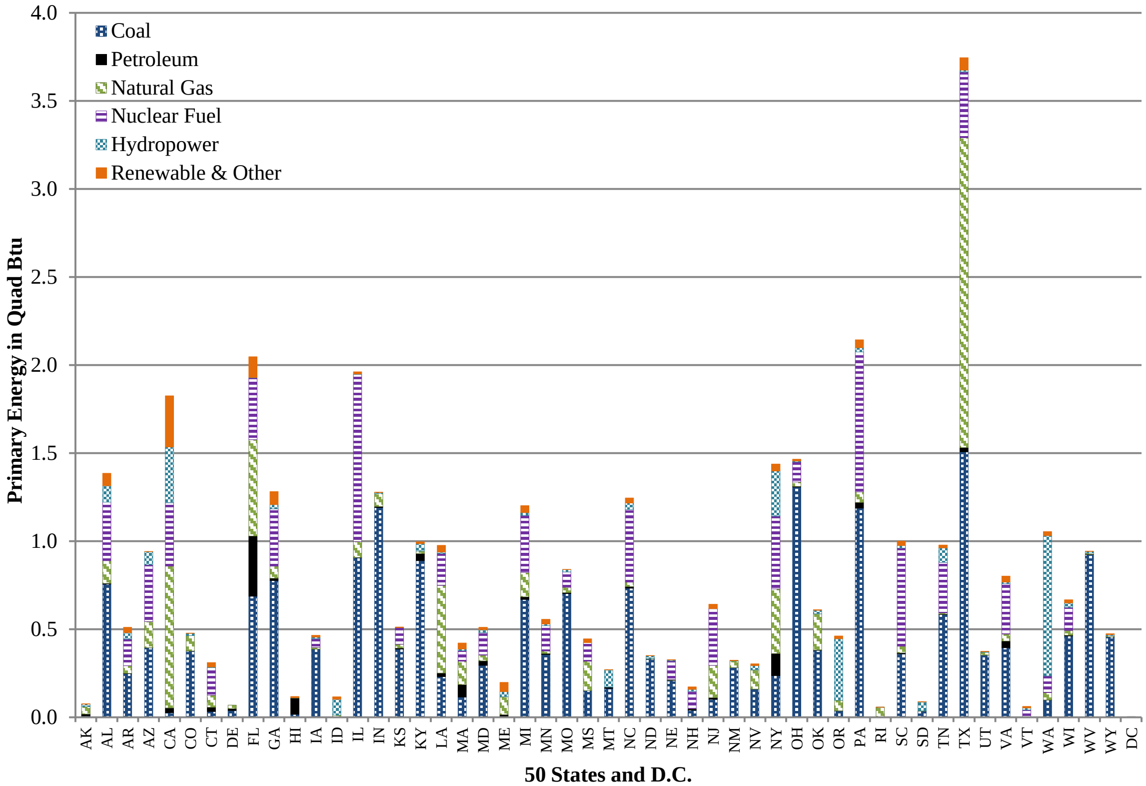


Figure 6-6: 2002 Fuel mix for electricity production in different states and the D.C.

The calculation of PEF for electricity included the direct and indirect energy of combusted fuel, energy used in power plant operations, and energy lost in energy conversion and electricity transmission and distribution. Figure 6-7 illustrates the system boundary for calculating the PEF for electricity. The calculation started from the primary fuel extraction, includes all direct and indirect energy use and loss during electricity production, and ended by covering the energy lost in transmission and distribution.

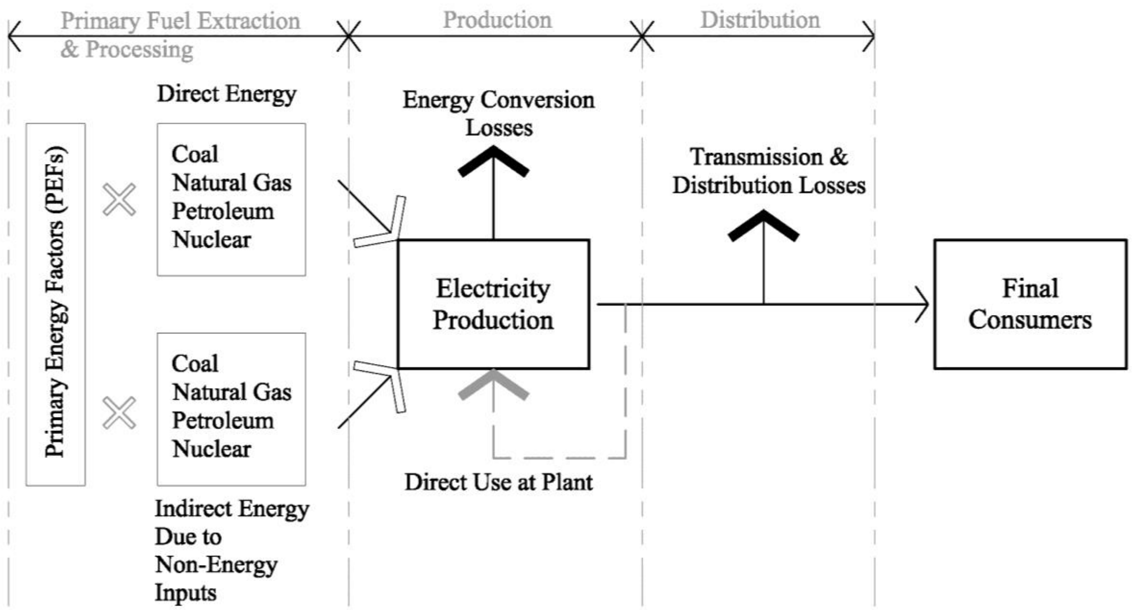


Figure 6-7: System boundary for PEF calculation for electricity

Deru and Torcellini (2007) proposed an approach for calculating the PEF of electricity in the United States. According to this procedure, three energy components, namely combustion energy, pre-combustion energy, and the total energy loss were included in the calculation of PEF. The combustion energy represented a direct energy component, which is the energy of fuel being combusted in a power plant. The pre-combustion energy included all energy consumed in the upstream processes of extracting, processing, converting, and delivering primary fuels to the power plant. Both of these energy components also had an indirect fraction that resulted from the energy and nonenergy requirements of the energy providing sectors. The total amount of energy lost in the process of transmission and distribution of electricity was also accounted for in the calculation. To calculate the combustion energy factor, the approach suggested by Deru and Torcellini (2007) was applied, whereas to calculate the indirect component, the calculated values of PEF of primary fuels were used. To compute the combustion energy factors, the following information and variables were used (based on Deru and Torcellini, 2007):

E_o - Total annual net generation of electricity in the United States

E_j - Total annual generation of electricity by states

$EF_{C,i,j}$ - Combustion energy factor by fuel or energy type and region

$EF_{C,j}$ - Combustion primary energy factor for electricity by region

L_{td} - Ratio of transmission and distribution losses to total electricity generation

PEF_{elec} - Total primary energy factor for delivered electricity

$Q_{i,j}$ - Quantity of energy of fuel used for electricity generation by fuel or energy type and region

$\delta_{i,j}$ - Fraction of total electricity generation by fuel or energy type and region

$\vartheta_{i,j}$ - Combustion energy factor for a unit of composite electricity by fuel/energy type and region

$\varepsilon_{i,j}$ - Electricity generation by fuel or energy type and region

ε_{pe} - Total plant energy used

CEF_e - Combustion energy factor for all fuels

CEF_{pe} - Combustion energy factor for plant energy

CEF_{elec} - Combustion energy factor for electricity

PCF_{elec} - Pre-combustion energy factor for electricity

$FRF_{in,i}$ - Indirect fuel requirement factor by fuels

Q_i - Quantity of energy of fuel used for electricity generation by fuels

L_{elec} - Energy loss factor for electricity

Q_{loss} - Energy of electricity lost during transmission and distribution

i - Represents an energy source or a fuel

j - Represents a region

6.4.6.1 Combustion Energy Factor Calculation: Electricity

Apart from four major fossil fuel sectors that provided primary fuels to the electricity generating sector, the gold, silver, and other metal ore mining sector consisted of a subsector that extracted the uranium used as nuclear fuel by the nuclear power plants. The total amount of uranium extracted, processed and consumed domestically for generating electricity was used to disaggregate the sector to calculate the indirect energy use for nuclear fuel.

$$\delta_{i,j} = \frac{\varepsilon_{i,j}}{E_j}$$

$$EF_{C,i,j} = \frac{Q_{en_{i,j}}}{\varepsilon_{i,j}}$$

$$\vartheta_{i,j} = \delta_{i,j} \times f_{i,j}$$

$$EF_{C,j} = \sum_{i=1}^{n} \vartheta_{i,j}$$

$$\mathrm{CEF_e} = \sum_{j=1}^{m} EF_{C,j} \times (\frac{E_j}{E_o}) \qquad \text{Equation 6-8}$$

$$CEF_{pe=} \frac{\varepsilon_{pe}}{E_o} \qquad \text{Equation 6-9}$$

$$CEF_{elec} = \mathrm{CEF_e} + CEF_{pe} \qquad \text{Equation 6-10}$$

6.4.6.2 Pre-combustion Energy Factor Calculation: Electricity

The pre-combustion energy of fuels combusted for electricity generation was calculated by multiplying their quantities to their indirect fuel requirement factor. The indirect fuel requirement factor of a fuel was equal to its PEF minus one (see Equation 6-11). No input-output data was used for the purpose of calculating the pre-combustion energy factor to avoid double counting of fuel inputs. Major fuels that were considered in the calculation included coal, natural gas, petroleum, and nuclear fuel, as these fuels together constituted over 94% of the energy used for generating electricity in 2002. It was assumed that the PEF for all other fuels including renewable energy sources was one. The following calculations were done to derive pre-combustion energy factor:

$$FRF_{in,i} = PEF_i - 1 \qquad \text{Equation 6-11}$$

$$Q = \sum_{i=1}^{n} FRF_{in,i} \times Q_i$$

$$PCF_{elec} = \frac{Q}{E_o} \qquad \text{Equation 6-12}$$

Q represents the total pre-combustion energy of electricity production.

6.4.6.3 Primary Energy Factor Calculation: Electricity

An energy loss factor for electricity was derived using the total transmission and distribution loss data for 2002. The calculated values of the combustion and pre-combustion energy factors were summed and multiplied by the energy loss factor to derive the PEF for electricity production.

$$L_{elec} = \left(1 + \frac{Q_{loss}}{E_o}\right) \qquad \text{Equation 6-13}$$

$$PEF_{elec} = (CEF_{elec} + PCF_{elec}) \times L_{elec} \qquad \text{Equation 6-14}$$

The calculation steps discussed so far were for the first approach. In the second approach, the monetary flows from the energy providing sectors to other industry sectors were replaced by the direct energy process data. The energy inputs to all five energy providing sectors were also replaced with the process data. As some energy uses (e.g., energy used in repressuring reservoir) and energy losses (e.g., T&D losses) did not show up in the input-output table, the calculated PEFs were adjusted to accommodate these inputs. The PEFs calculated for major fuels were used to compute the PEF for electricity. The third approach was purely input-output-based. In this approach, the total requirement matrix was used to estimate the energy requirement (in $) per $ output of the energy providing sector. Energy prices were used to convert the energy requirements from $ to energy units. The calculated values of PEFs for primary fuel was adjusted for energy use and losses not covered in the input-output table. Similar to the first two approaches, the calculated PEFs were used to quantify the PEF for electricity generation.

Table 6-2 shows the results of the three approaches. It was clear that the results of the primary fuel sector representing oil and gas extraction and coal mining are consistent. However, results of the PEF for natural gas distribution and petroleum refining were quite different. It can be seen that the PEFs calculated using the third approach were higher than the other two approaches. The main reason for this was the double counting of natural gas and crude oil that was supplied by the oil and gas extraction sector. The quantity of natural gas supplied to the natural gas distribution sector was not consumed entirely but pressurized and distributed to end users. Similarly, the entire crude oil quantity delivered to petroleum refineries was not consumed but refined to produce a range of petroleum products. It could be misleading to interpret any monetary flow as consumption in an input-output framework. The results from the first approach were used in this research.

Table 6-2: PEF values calculated using the three approaches

Fuel/Energy Type	Approach 1	Approach 2	Approach 3
Coal Mining	**1.04**	1.03	1.09
Oil & Gas Extraction	**1.23**	1.21	1.22
Natural Gas Distribution	**1.43**	1.53	1.90
Petroleum Refineries	**1.44**	1.27	2.55
Electricity Generation	**4.12**	4.22	4.64

6.5 SUMMARY

To avoid the double counting of delivered energy sources such as natural gas, refined petroleum, and electricity, a set of PEFs were calculated for each energy source. First, PEFs for primary fuels such as coal, crude oil, and natural gas were calculated. These PEFs were used to calculate the PEF for consumer grade natural gas, refined petroleum, and electricity. The calculation of PEF was done using the three approaches. In the first approach, direct energy was calculated using the process energy data, whereas to calculate the indirect energy, input-output data were used. The process energy data were inserted into an input-output matrix to calculate the direct and indirect energy in the second approach. The third approach was based on an input-output analysis. From the results, it was clear that the PEF values calculated using only the input-output data were high due to the double counting issue. The PEF values obtained from the first approach were adopted in the study.

CHAPTER VII

HUMAN AND CAPITAL ENERGY CALCULATION

7.1 HUMAN ENERGY

The process of manufacturing and construction are labor intensive and the energy embodied in labor needs to be included in embodied energy calculations. In some regions of the world, the industry sectors such as, manufacturing, construction, mining, agriculture, and business employ extensive labor due to low wages, high labor availability, and limited energy sources. If the final products are to be compared in embodied energy terms, it should be ensured that both the mechanical and human energy are accounted for. The energy requirements of human labor vary with factors such as age, sex, weight, lifestyle, and also the socio-economic conditions (FAO, 2001; Held, 2010). The energy requirements of labor can be categorized in three parts. The first part is the energy required to perform the basal metabolism that is a series of basic body functions such as respiration, brain function, body temperature maintenance, secretion of hormones and enzymes, and heart and lung functions. This fraction represents the threshold of energy that is required for the basic functioning of a human body and is termed *basal metabolic rate (BMR)*. According to FAO (2001), the BMR could represent up to 45-70% of the total daily energy requirements of a human body. The second part includes the energy required to eat and digest the food, and to absorb, transform, transport, and deposit essential nutrients. This fraction is known as the *metabolic response to food* and could constitute energy up to 10% of the BMR. The third part relates to the activity an individual is engaged in. Depending upon the activities such as exercising, biking, working in an office, loading and unloading, and working in a manufacturing unit, the energy requirement may vary. Human beings are engaged in physical activities that are either obligatory or discretionary. The obligatory activities can hardly be avoided due to the socio-economic and cultural settings. Discretionary activities are the activities an individual is not obligated to engage in due to social, economic, and cultural settings. In addition, other human body functions such as growth of tissues also need energy. The following definitions are important to know (FAO, 2001; Held, 2010):

Total Energy Expenditure (TEE): The average amount of total energy expended by an individual in 24 hours of a typical day.

Basal Metabolic Rate (BMR): The minimum energy rate required to support the basal metabolism, measured in an individual who is awake, immobile, thermo-neutral, mentally relaxed, is in a supine position, has rested for at least 8 hours, and fasted for a minimum 12 hours. The rate of energy required is derived per minute, per hour, or per day. The BMR is affected by factors such as body weight, sex, and age. FAO (2001) provides the following equations to calculate the BMR:

Males, age 18 - 30 years

$$BMR = 0.063 \times Wt_{bd} + 2.896 \qquad \text{Equation 7-1}$$

Males, age 30 - 60 years

$$BMR = 0.048 \times Wt_{bd} + 3.653 \qquad \text{Equation 7-2}$$

Females, age 18 - 30 years

$$BMR = 0.062 \times Wt_{bd} + 2.036 \qquad \text{Equation 7-3}$$

Females, age 30 - 60 years

$$BMR = 0.034 \times Wt_{bd} + 3.538 \qquad \text{Equation 7-4}$$

Wt_{bd} - Body weight of individual in Kg

BMR - Basal metabolic rate in MJ/day

Physical Activity Level (PAL): PAL indicates the lifestyle of individuals based on their 24-hour activity schedule. It is used to express the TEE in the multiple of BMR. According to FAO (2001), in the case of an adult, the PAL can be quantified based on 24-hour activities, as growth energy requirements, at his age, are nearly zero.

$$PAL = \frac{TEE}{BMR} \qquad \text{Equation 7-5}$$

The PAL can be categorized based on the duration and intensity of activities an individual is involved in. FAO provides three categories of PAL and respective ranges of PAL values as shown in Table 7-1.

Table 7-1: PAL values for different activities

PAL Category	PAL Range
Sedentary or light activities	1.40-1.69
Active or moderate activities	1.70-1.99
Vigorous activities	2.00-2.40

Physical Activity Ratio (PAR): PAR is the energy spent by a human body in performing an activity. It is usually expressed in energy units per minute or per hour. FAO (2001) lists PAR values for major activities that are routine such as personal care, transportation, cooking, domestic chores, and yard work. It also lists activities occurring in various sectors such as agriculture, business, mining, manufacturing, construction, and public administration.

7.1.1 Human Energy Requirement Calculation

Three types of data were required to quantify the TEE of an average working individual in the United States. First, the average range of weight and age by sex was needed to calculate the BMR values. Next, an hourly activity schedule of a typical day for a worker employed in sectors relevant to the United States' economy was to be derived. Finally, the PAR values of the activities were needed to calculate an average PAL value for the workers. Table 7-2 presents the demographics of employed individuals in 2002. These data were used to make assumptions about the age, sex, and weight characteristics of the employed population.

Table 7-2: Physical characteristics of the employed population in the United States in 2002

Age Group	Total Population Employed	% of Total	Source
16 years and over	136,485,000	100	BLS (2002)
20 years and over	130,154,000	95	BLS (2002)
25 years and over	116,802,000	86	BLS (2002)
45 years and over	51,261,000	38	BLS (2002)
55 years and over	19,980,000	15	BLS (2002)
65 years and over	4,306,000	3	BLS (2002)
Age adjusted Mean Body Mass (kg), 20 years and older:		87.3	Borrud et al., 2010
Full-time Wage & Salaried Workers, Female (% of total):		44	BLS, 2003
Full-time Wage & Salaried Workers, Male (% of total):		56	BLS, 2003

Based on statistics from Table 7-2, it is assumed that the two age groups, 18 - 30 years and 30 - 60 years represented the working population in the United States in 2002. Moreover, the mean weight of an individual employed in the mentioned age groups was 87.3 kilograms. Equation 7-1 and Equation 7-2 were used to calculate the BMR of an average employee in 2002.

The next step was to account for the average PAL values for individuals employed in different industry sectors. Table 7-3 illustrates the activity schedule of an average employee by sector derived for 2002. The hours and PAR values were based on FAO (2001) and the American Time Use Survey Data for 2003 (data for 2002 were not available) from the United States Bureau of Labor Statistics (USBLS) (BLS, 2004a). The computed values of PAL for each sector are also shown in Table 7-3. According to FAO (2001), a PAL value over 2.4 cannot be sustained for a long time. Hence, a PAL of 2.4 was selected for the agriculture sector instead of the calculated value of 2.7. The rest of the PAL values were used as calculated. The total energy requirement of an average American employee in 2002 was calculated as:

$$TEE = BMR \times PAL \qquad \text{Equation 7-6}$$

The TEE values were calculated for both the male and female employees separately and were then averaged using their percent share in the total employment (% share sourced from BLS, 2003). It was assumed that the entire day's activities may be required to sustain the employment and hence, the total energy requirement of one full day is allocated to work hours at the job. Finally, the value of TEE per hour per employee was calculated.

Table 7-3: Activity schedule of an average employee by industry sector

Activity	Activity Duration (Hrs.)		
	Agriculture Sector	Mining, Construction & Manufacturing Sector	Business & Government Sector
Sleeping	8	8	8
Personal care	1	1	1
Cooking and/or eating	2	2	2
Household work/ chores	1	1	1
Commute to work	1	1	1
Working at job	6	8	8
Support activities for work/job	2	0	0
Physical exercise/workout	0	0	1
Leisure	3	3	2
Mean PAL, Calculated	**2.7**	**2.2-2.4**	**1.7**

The total number of employees was sourced from the USCB (USCB, 2006c; USDOC, 2005; USCB, 2005), USBLS (BLS, 2012), and USDA (NASS, 2004) for each six-digit NAICS code. Although most of the numbers were available for industry sectors by 6-digit NAICS codes, some of the numbers were provided by 2 or 3-digit NAICS codes, particularly in the agriculture sector. These numbers were disaggregated to a six-digit NAICS code on the basis of criteria such as number of farms or total land area harvested. Table 7-4 lists the total number of employees in the United States in 2002 reported by various agencies and also the number calculated by this study. The number calculated in this research is within 2 - 6% of the numbers reported by various agencies.

Table 7-4: Comparison of the total number of employees in 2002

Source	Number of Employees, 2002	% Diff
National Income & Products Accounts, 2002, (USBEA, 2005)	137,306,000	-1.88%
Bureau of Labor Statistics, 2002 Data, (BLS, 2002)	142,297,000	1.70%
American Community Survey, 2002, (USCB, 2002a)	132,390,104	-5.66%
Calculated in this study	139,882,199	0.00%

It was important to make a distinction between the production workers and other staff due to their varying daily energy requirements. The USBLS reported the number of employees as well as the number of production workers (USBLS, 2012). The total energy requirements calculated on the basis of Table 7-3 should be applied to production workers only. The remaining employees were assumed as technical or managerial staff and their TEE was derived using a PAL value of 1.7. The total annual energy consumed by an individual employee was calculated by multiplying the per hour TEE values to the annual work hours data (per employee) provided by the USBLS by industry sector (USBLS, 2012).

The number of employees who worked for the industry also used private transportation to commute to work. The inputs and outputs used by private households were not a part of the direct and total requirement matrix. The private transportation used by individuals was not accounted for in calculating the energy use of various transportation sectors. Hence, the transportation energy consumed by each individual employee, who commuted to work using private vehicles, needs to be included in the total human energy. In addition, a fraction of the total expenditure of an average household belonged to the industry of employment. Expenses on items such as clothes, accessories, housing, appliances, automobile, and health should also be allotted to the employment industry (Cleveland and Costanza, 2008). How should we allocate these expenses to the industry of employment? Cleveland and Costanza (2008) suggested that the difference between the expenses of an earner and non-earner can be used to identify expenses incurred due to the employment.

The transportation energy data for 2002 were sourced from the USDOT (USDOT, 2012). The total energy consumed by cars and light trucks in 2002 was 21,410 trillion Btu. A fraction of this energy was consumed by taxicabs and other rental vehicles, which should be subtracted in order to estimate the energy specifically used by personal vehicles. The fraction of taxicabs and rental vehicles was calculated from the National Transportation Statistics data published by the USDOT (USDOT, 2012). The transportation energy of personal vehicles was estimated to be nearly 13 quadrillion Btu. Not all of the personal transportation was used for work related purposes. The Federal Highway Administration (USDOT) published data on work-related trips for the years 1983, 1990, 1995, 2001, and 2009 (Santos et al., 2011). Figure 7-1 shows the trends of work related trips by Vehicle Miles of Travel (VMT) and Person Miles of Travel (PMT). The percentage of total work-related trips was consistently between 22 - 30% of the total trips. For 2002, 27% of the total trips were considered work-related and 27% of the energy consumed in personal transportation was allocated to the industry of employment (Santos et al., 2011).

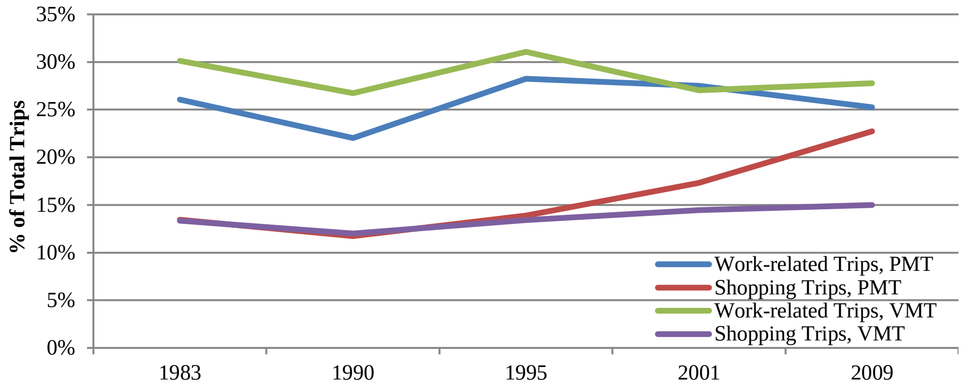


Figure 7-1: Work-related and other trips by average working population

The USBLS provided the consumer expenditure for single and more than 2 consumers under the category of no earner and one earner (USBLS, 2004b). Excluding the food and utilities expenses, the difference between the earner and non-earner for single and multiple consumers was in the range of 26 - 35%. An average 30% of the total personal consumption expenditure (excluding food, utilities, and transportation) was allocated to the industry of employment. The personal consumption expenditure data were sourced from the USBEA's 2002 Benchmark Input-Output Accounts. To account for the energy embodied in personal consumption items, the 2002 Benchmark Input-output direct and total requirements tables were used (USBEA, 2008). The collected process data was inserted into these tables and the total energy intensity was calculated for each industry sector. As the direct energy of food, transportation, and utilities was already quantified, the industry sectors related to these items were excluded from the personal consumption calculation. The indirect energy, however, for all the sectors was included in the calculation, as this was not counted while accounting for food, transportation, and utilities. As the human energy was added while calculating the PEFs, the PEFs published in the literature (Deru and Torcellini, 2007) were applied to the total energy use. The residential energy consumption data for electricity, natural gas, and petroleum were sourced from the 2002 Annual Energy Review to account for the household energy use.

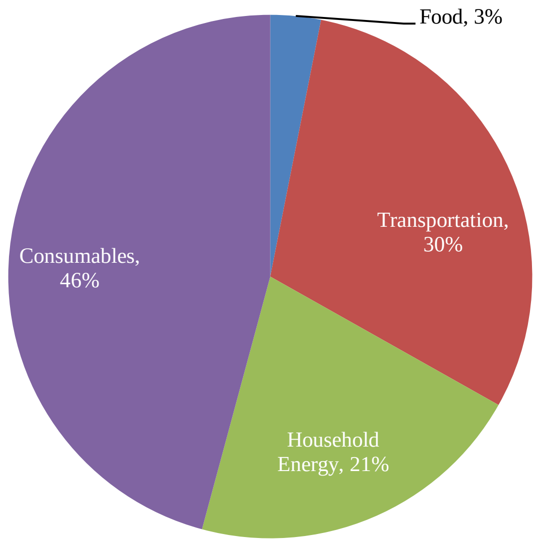


Figure 7-2: Breakup of calculated human energy

The total annual energy consumed by an employee that was allocated to the industry of employment was calculated as nearly 66.7 MBtu per year (excluding work-related transport). This energy use included energy of food, household energy, and all other nonenergy items such as consumables. The pie chart shown in Figure 7-2 presents the breakup of this total energy by various items consumed by an employee in 2002. The total energy embodied in human inputs consumed in 2002 was equal to 13.95 quadrillion Btu.

7.2 CAPITAL INPUTS

The national economy of the United States is divided into various industry sectors engaged in activities such as agriculture, mining, construction, utility distribution, manufacturing, trade, services, and public administration. Each of the industry sectors requires considerable investment in capital goods in addition to labor. The capital goods include all building and non-building structures such as administration buildings, warehouses, workshops, electrical yards, loading and unloading areas, etc. The construction of such built facilities is energy intensive and should be taken into account while calculating the capital energy. Industry sectors also make purchases of a range of equipment to be used in offices, manufacturing units, buildings, job sites, workshops, etc. Other capital inputs such as software purchases, office purchases, and building furniture are also a part of the total capital expenditure. Purchases of a range of automobiles form another significant portion of the capital inputs. All of these capital expenditures would have consumed energy during their installation, construction, or manufacturing.

The annual and benchmark input-output accounts conventionally include only transactions of goods and services that are consumed in the current year and do not include the capital flow in input-output tables (Horowitz and Planting, 2009). The capital inputs are treated as final purchases made as an investment and usually do not show up in the input-output tables (Horowitz and Planting, 2009; Treloar, 1998). Although the USBEA publishes capital flow data for the national economy as supplemental information to the benchmark accounts, the latest data available were for 1997, and hence, could not be utilized for quantifying capital inputs in 2002. Data relating to capital expenditures of various industries needed to be collected from diverse sources such as the USCB and USBLS. The USCB reported data on capital spending in the Annual Capital Expenditure Survey of non-farm businesses and include capital expenses in the category of used and new structures and equipment (USCB, 2002d). The 2003 Annual Survey of Manufacturers (USDOC, 2003) also reported detailed data on capital spending on structures and equipment. Additional information regarding capital spending was sourced from the Fixed Assets Accounts (under National Income & Products Accounts) published by the USBEA (USBEA, 2012; USBEA, 2011). The Fixed Assets Accounts also listed the current cost of the net stock of private fixed assets that helped derive the percent spent on capital inputs such as structures, equipment, software, and automobiles. Other capital expenditure related data were sourced from USDA (2004) and USCB (2002e).

Detailed data with breakup by capital inputs such as buildings, automobile, computer equipment, and other equipment were available for nearly the entire manufacturing sector. For most other sectors the capital input information was available only by the buildings and equipment categories. Some of the capital spending data was available by the 2 or 3-digit NAICS code and these numbers were disaggregated to a six-digit NAICS code on the basis of criteria such as number of establishments, annual capital expenses, annual revenue, or total annual output. Capital expenditure data of the USPS was difficult to obtain, as a freeze on capital commitment was put into effect in 2002. The total expenditure was estimated from a graph presented in USPS (2011) and the total value was disaggregated into the categories of buildings and equipment using the data for federal non-defense spending on capital.

Table 7-5: Various capital inputs in the building category and their average energy intensities

NAICS	Year-end Change in Fixed Assets: Structure Category, 2002	% of Total	Avg. Energy Intensity
230101	Nonresidential commercial and health care structures	12.4	0.0110 MBtu/$
230102	Nonresidential manufacturing structures	1.6	0.0089 MBtu/$
230103	Other nonresidential structures	17.1	0.0137 MBtu/$
230201	Residential permanent site single- and multi-family structures	56.5	0.0142 MBtu/$
230202	Other residential structures	12.4	0.0132 MBtu/$
	Average Energy Intensity: Structure Category		**0.0135 MBtu/$**

After gathering the capital spending data for all relevant sectors, the total capital spending was roughly 1204 billion dollars. This amount was verified by calculating the change in the fixed assets value from the USBEA's Fixed Assets Accounts (USBEA, 2011). The change in fixed assets at the end of 2002 was reported at roughly 1165 billion dollars, which is within 3.5% of the calculated value. The breakup of change in year-end fixed assets from 2001 to 2002 in the equipment and building categories was used to calculate the energy intensity for building and equipment category. The energy intensity was averaged on the basis of relative share of capital inputs in the total net change in the fixed assets' value at the end of 2002. Table 7-5 and Table 7-6 show the breakup of the structure and equipment categories with their average energy intensities and percent share in the total change in the value of fixed assets.

The total energy embodied in capital inputs at the end of 2002 was calculated as 16.3 quadrillion Btu. The share of equipment and structure in the total capital energy was equal to 8.4 and 7.9 quadrillion Btu, respectively. A more detailed account of capital flow was needed in order to quantify the capital energy more accurately and consistently. If the capital flow accounts were published concurrently with the national input-output accounts, it would be easier to accurately calculate the energy embodied in capital expenditure. It was interesting to know that the energy intensities of capital equipment and structure input were nearly the same. Although the economic input-output framework was used for the calculation, the input-output energy data were replaced by the process energy data.

Table 7-6: Other capital inputs and their average energy intensities

NAICS	Yearend Change in Fixed Assets: Equipment Category, 2002	% of Total	Avg. Energy intensity
334	Computer and Electronic Product Manufacturing	17.3	0.0110 MBtu/$
3391	Medical Equipment and Supplies Manufacturing	18.3	0.0103 MBtu/$
333293	Printing Machinery and Equipment Manufacturing	0.3	0.0141 MBtu/$
3332	Industrial Machinery Manufacturing	20.2	0.0149 MBtu/$
3334	Ventilation, Heating, Air-Conditioning, and Commercial Refrigeration Equipment Manufacturing		
3335	Metalworking Machinery Manufacturing		
3336	Engine, Turbine, and Power Transmission Equipment Manufacturing		
3339	Other General Purpose Machinery Manufacturing		
3353	Electrical Equipment Manufacturing		
3359	Other Electrical Equipment and Component Manufacturing		
336	Transportation Equipment Manufacturing	11.4	0.0141 MBtu/$
3331	Agriculture, Construction, and Mining Machinery Manufacturing	4.6	0.0153 MBtu/$
3333	Commercial and Service Industry Machinery Manufacturing	16.6	0.0145 MBtu/$
3351	Electric Lighting Equipment Manufacturing	1.0	0.0171 MBtu/$
3352	Household Appliance Manufacturing		
3371	Household and Institutional Furniture and Kitchen Cabinet Manufacturing	10.3	0.0170 MBtu/$
3372	Office Furniture (including Fixtures) Manufacturing		
	Average Energy Intensity: Equipment/Other Category		**0.0135 MBtu/$**

7.3 SUMMARY

The calculation of human energy involved three components, namely energy of food, energy of consumables, and household energy use. The amount of food energy consumed by an individual depends upon various factors such as age, gender, and body mass. To calculate the energy of food consumed by an average worker, a national average for age and body mass was derived. A schedule of activities was also established for various work categories such as farming, labor, office work, etc. Using the average physical parameters for the 2002 working population and its activity schedule, the energy of food was quantified. The energy embodied in other consumables was calculated using the 2002 personal consumption expenditure data and input-output-based energy intensities. The energy used by an average household was sourced from the 2002 Annual Energy Review. The fraction of the total energy consumed by an average working individual that can be attributed to the employment was calculated as 67 MBtu per year excluding transportation. The energy embodied in capital investments was calculated by gathering the capital investment data by categories such as structure, equipment, automobile, and software. Using the input-output-based energy intensities, the total energy embodied in capital goods was quantified. Overall, nearly 16 quadrillion Btu of capital energy was consumed in the United States in 2002. Although, the data on total capital investment was gathered from a variety of sources, availability of capital input accounts in a timely manner would certainly improve the quality of capital input data in the future.

CHAPTER VIII

EMBODIED ENERGY CALCULATION

8.1 DISAGGREGATION OF INDUSTRY SECTORS

8.1.1 Data for Disaggregation

The disaggregated industry sectors corresponding to the study materials are given in Table 8-1. Industry sectors such as *iron and steel mills and ferroalloy manufacturing* were disaggregated into two sectors. The first sector was *iron and steel mills* that produced one of the study materials. The second sector represented all other products manufactured by the aggregated sector. Based on the recommended approaches discussed in the research method section, the industry sectors were disaggregated. Two types of data were required for disaggregating an aggregated industry sector.

Table 8-1: Study materials and relevant disaggregated industry sectors

Study Material	Aggregated Sector		Disaggregated Sector	
	NAICS	Sector	NAICS	Sector
Virgin steel	331110	Iron and steel mills and ferroalloy manufacturing	331111	Iron and steel mills
Primary aluminum	33131A	Alumina refining and primary aluminum production	331312	Primary aluminum production
Bricks & other clay products	32712A	Brick, tile, and other structural clay product manufacturing	327121	Brick and structural clay tile
Ceramic wall & floor tiles	32712A	Brick, tile, and other structural clay product manufacturing	327122	Ceramic wall and floor tile
Vitrified Sewer Pipes	32712A	Brick, tile, and other structural clay product manufacturing	327123	Vitrified clay sewer pipe and fittings
Gypsum	3274A0	Lime and gypsum product manufacturing	327420	Gypsum product manufacturing
Lime	3274A0	Lime and gypsum product manufacturing	327410	Lime manufacturing
Wood, lumber	321100	Sawmills and wood preservation	321113	Sawmills
Plywood & veneer, hardwood	32121A	Veneer and plywood manufacturing	321211	Hardwood veneer and plywood manufacturing
Plywood & veneer, softwood	32121A	Veneer and plywood manufacturing	321212	Softwood veneer and plywood manufacturing

8.1.1.1 Detailed Sectorial Output

The output of an industry sector is comprised of primary and secondary products. Because we used input-output tables after redefinition, the secondary products have been reallocated to the industry sectors in which they were primary. This was done through a process of redefinition. A detailed breakup of sectorial output was published by the USBEA as a part of its benchmark accounts. Table 8-2 illustrates an example of a detailed output of sector *veneer and plywood manufacturing* provided by the USBEA. It can be seen that each item that was produced as a part of the sector's total output was listed along with its share in the output. Using this data, the share of hardwood and softwood products can be extracted. Similar breakup of the total output was provided for most other sectors that also can be used to disaggregate the industry sectors.

Table 8-2: Detailed item output for veneer and plywood manufacturing

2002 Commodity Code	Commodity	Item Code	Item Description	Item Output
32121A	Veneer and plywood manufacturing	3212111	Hardwood veneer	1121.2
32121A	Veneer and plywood manufacturing	3212113	Hardwood plywood, except prefinished hardwood plywood	1049.9
32121A	Veneer and plywood manufacturing	3212115	Prefinished hardwood plywood made from purchased hardwood plywood	132.0
32121A	Veneer and plywood manufacturing	3212117	Hardwood plywood type products	476.0
32121A	Veneer and plywood manufacturing	321211AO	Hardwood veneer and plywood manufacturing, other miscellaneous receipts	9.4
32121A	Veneer and plywood manufacturing	321211CW	Hardwood veneer and plywood manufacturing, contract work	25.0
32121A	Veneer and plywood manufacturing	321211IC	Hardwood veneer and plywood manufacturing, inventory change	18.2
32121A	Veneer and plywood manufacturing	321211RSL	Hardwood veneer and plywood manufacturing, value of resales	-0.1
32121A	Veneer and plywood manufacturing	321211W	Hardwood veneer and plywood manufacturing, nsk*	272.1
32121A	Veneer and plywood manufacturing	3212121	Softwood veneer	867.2
32121A	Veneer and plywood manufacturing	321212AO	Softwood veneer and plywood manufacturing, other miscellaneous receipts	26.3
32121A	Veneer and plywood manufacturing	321212CW	Softwood veneer and plywood manufacturing, contract work	7.6
32121A	Veneer and plywood manufacturing	321212IC	Softwood veneer and plywood manufacturing, inventory change	12.7
32121A	Veneer and plywood manufacturing	321212RSL	Softwood veneer and plywood manufacturing, value of resales	-0.2
32121A	Veneer and plywood manufacturing	321212W	Softwood veneer and plywood manufacturing, nsk*	64.4
32121A	Veneer and plywood manufacturing	321212X	Softwood plywood products: rough, sanded, and specialties	3581.3

*nsk indicates *not specified by kind*

8.1.1.2 Detailed Sectorial Inputs

The monetary flows among various industry sectors included goods and services. Any raw material consumed by an industry was covered the under goods' flow. For instance, glue and adhesives consumed by sawmills was a flow of goods. To decompose the total inputs used by an industry sector, the proportion of both the goods and services in the total input was required. The USCB published a series entitled the Materials Summary as a part of its five-year Economic Census (USCB, 2006a). This summary provided few detailed input data under the category of *materials consumed by kind*. These data were specific to a subsector of the main aggregated sector. Under the 2002 Economic Census, the USCB published a data series entitled the *Industry Series* for each sector and subsector (USCB, 2002a). Under *Detailed Statistics by Industry*, the industry series report listed various expenses such as material consumed, fuel consumed, services used, etc. A set of disaggregation coefficients was developed for decomposing the total inputs of energy and nonenergy goods and services.

8.1.2 Applying Disaggregation to Economic Data

For calculating the embodied energy, a commodity-by-commodity square matrix of direct requirements was used. However, the disaggregated inputs were given by industry and therefore could not be inserted directly into the direct requirement matrix representing commodities. For the purpose of obtaining a disaggregated commodity-by-commodity square matrix, few adjustments were made to both the *use* and *make table*.

8.1.2.1 Use Table Modifications

The *use table* listed the consumption of the commodity of goods and services by industry sectors. The values in the row represented the commodity used by the industry at the top of the column. To disaggregate the industry column, a disaggregation coefficient for materials and services consumed was used. An existing sector was broken down into two columns. The first column vector depicted the disaggregated sector producing the study material. The second column contained the remaining inputs consumed in manufacturing all other products. The actual input data for the disaggregated sector were obtained from the economic census report and then inserted into the first column. As input data were not available for most of the sectors, a disaggregation coefficient (k) was calculated using the 2002 Economic Census data for materials and services consumed by the study material sector. If w denotes the share of study material sector $n+1$ in the total input of the aggregated sector n, then:

$$a_{in} = A_{i\,n+1} \times w + A_{in} \times (1 - w) \qquad \text{Equation 8-1}$$

Where **a** and **A** represent the original aggregated and disaggregated matrix, respectively.

$$A_{i\,n+1} = a_{i\,n} \times k \qquad \text{Equation 8-2}$$

$$A_{i\,n} = a_{i\,n} \times (1 - k) \qquad \text{Equation 8-3}$$

The above equations became a constraint for disaggregating an input-output industry sector. The column vector of the disaggregated sector contained all of its inputs drawn from other industry sectors.

The row entries in the *use table* contained the value of the row commodity used by the industry at the top of the column. As the purpose was to create a decomposed commodity-by-commodity square matrix of direct requirements, it was important to create a row commodity to represent the disaggregated industry sector *n+1*. In this study it was assumed that the use of the disaggregated commodity by the column industries can be depicted by the disaggregated commodity's share in the total output of the aggregated commodity.

8.1.2.2 Make Table Modifications

The row entries in the *make table* represented industries making various commodities listed in the columns. The row representing the aggregated industry sector *n* was divided into two rows. The first row defined the disaggregated industry and its make of column commodities. It was assumed that the share (*w*) of the disaggregated industry in the output of the aggregated industry would represent its proportion in making the column commodities. Therefore, the amount of a commodity produced by the aggregated sector was multiplied by *w* to compute the commodities made by the disaggregated sector *n+1*.The column vectors of the *make table* defined the amount of a commodity manufactured by each row industry. The sum of a column is always 1.0, as each cell in the column is a fraction of commodity produced by each row. It was considered that the disaggregated commodity was produced in the same proportion as the original aggregated commodity.

8.2 INSERTING HUMAN AND CAPITAL ENERGY

The calculated values of human and capital energy inputs were for each industry sector. However, we needed to apply these values to a square matrix representing commodities. Therefore, *make table* and *use table* adjustments were necessary to obtain a commodity-by-commodity direct requirement matrix with human and capital energy. A new commodity for each, the human and capital input category, was added to the *make table* and *use table*. In the *use table* there were two new rows with values of human and capital energy consumed by the industry at the top of the columns. In *make table*, there were two new columns representing the make of human and capital energy by industry sectors. As human and capital inputs were not a part of intermediate transactions, it was assumed that no industry made any of the two inputs. This meant that all values in the newly added columns of the *make table* would contain zero entries. The original *428 X 426 use table* matrix now became a *430 X 426* matrix and the *426 X 428 make table* matrix turned into a *426 X 430* matrix. If modified *use tables* and *make table*s are denoted by ***u*** and ***v***, respectively, then:

$$\boldsymbol{u} = \begin{bmatrix} a_{1\,1} & \cdots & a_{1\,n} \\ \vdots & \ddots & \vdots \\ a_{n\,1} & \cdots & a_{n\,n} \\ A_{n+1\,1} & \cdots & A_{n+1\,n} \\ A_{n+2\,1} & \cdots & A_{n+2\,n} \end{bmatrix} \quad \text{and} \quad \boldsymbol{v} = \begin{bmatrix} a_{1\,1} & \cdots & a_{1\,n} & A_{1\,n+1} & A_{1\,n+2} \\ \vdots & \ddots & \vdots & \vdots & \vdots \\ a_{1\,n} & \cdots & a_{n\,n} & A_{n\,n+1} & A_{n\,n+2} \end{bmatrix}$$

Where, the first *n x n* matrix was unchanged in both the *use table* and *make table*. Cells $A_{n+1\,1}$ and $A_{n+2\,1}$ depicted the use of human and capital energy commodities by the industry sector at the top of column 1. Cells of *make table* such as $A_{1\,n+1}$ to $A_{n\,n+1}$ and $A_{1\,n+2}$ to $A_{1\,n+2}$ contained zero values representing make of human and capital energy by the industry sectors. The process of inserting human and capital inputs was discussed with Penson (2012 and 2013) and Dudensing (2012 and 2013).

8.3 CALCULATING DIRECT ENERGY INTENSITIES

To calculate the direct energy intensities of industry sectors, a commodity-by-commodity direct requirement matrix was derived with process data of energy use. The collected process data of energy use were in physical units (MBtu). However, to replace the monetary data of the original *use table* by energy data, some adjustments were needed in the energy data. There were two approaches to insert process data. In the first approach, energy use data could be converted to monetary data using national average prices of different energy sources and then inserted into the *use table*. After multiplying the *use* and *make tables,* the energy data could be converted back to energy units using the same energy prices. In the second approach (based on Carter et al., 1981), the energy data could be included into the *use table* in energy units (e.g. MBtu) only. The row commodities representing energy providing sectors would have MBtu/$ units, whereas the energy providing industry sectors in the columns would have data in units $/$. Cells at the cross-section of energy providing commodities and corresponding industry sectors would also contain values in MBtu/$. In this approach, the calculated direct requirement coefficient for each industry sector would be in MBtu/$. If the following matrix represented a portion of the *use table* and if the middle row and middle column depict the energy commodity and energy providing industry, then as per the second approach:

$$Part\ of\ \boldsymbol{u} = \begin{bmatrix} A_{1\,1} & \cdots & A_{1\,j} & \cdots & A_{1\,n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ A_{i\,1} & \cdots & A_{i\,j} & \cdots & A_{i\,n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ A_{n\,1} & \cdots & A_{n\,j} & \cdots & A_{n\,n} \end{bmatrix} \qquad \begin{bmatrix} \frac{\$}{\$} & \cdots & \frac{\$}{\$} & \cdots & \frac{\$}{\$} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \frac{MBtu}{\$} & \cdots & \frac{MBtu}{\$} & \cdots & \frac{MBtu}{\$} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \frac{\$}{\$} & \cdots & \frac{\$}{\$} & \cdots & \frac{\$}{\$} \end{bmatrix}$$

As the *make table* provided the fraction of a commodity manufactured by various industries, no changes were made to the *make table*. In the second approach, as the energy data were in physical units (MBtu), not changing the *make table* meant that the proportions of energy commodities made by industry sectors is the same in both the monetary and energy units. It can be seen that both the approaches are actually similar. The only difference is that in the first approach, there is no assumption of commodity fractions in monetary or energy terms. In this research, we adopted the second approach.

The second matrix shows the various units after inserting process data as per approach two as discussed in the earlier paragraph. One major advantage of using process data in physical units was that no average energy prices were used to convert the monetary data into energy intensities. As energy prices may vary and may not be representative of the actual prices paid by the industries, they could seriously affect the embodied energy calculations (Crawford, 2004; Acquaye, 2010). By avoiding the use of average energy prices, the reliability of input-output-based energy analysis was further improved.

After modifying the *use table*, it was multiplied by the *make table* to derive a commodity-by-commodity square matrix of direct requirements. The direct requirement matrix provided the direct energy intensity of each commodity by five energy providing sectors:

- Oil and gas extraction
- Coal mining
- Electric power generation, transmission, and distribution
- Natural gas distribution
- Petroleum refineries

In addition, there were two other energy sources, namely human and capital energy. It can be seen that calculating and using separate energy intensity values for different energy providing sectors eliminates the error caused by using a single representative energy commodity and a fixed energy price that is a national average.

8.4 CALCULATING INDIRECT ENERGY INTENSITIES

There were two ways to calculate the indirect fraction of the total energy intensity of an industry sector. First, it could be calculated using Leontief's Inverse Matrix that represents the total requirements of the sectors of an economy. The direct requirement matrix was subtracted from an identity matrix and inverted to find Leontief's total requirement matrix. The difference of total and direct requirements would provide the indirect requirements. However, this approach was like a "black box." We had no idea how the total energy was calculated (Treloar, 1998). In other words, we could not determine how much energy is embodied in each stage upstream of the main product. The second approach utilized the Power Series

Approximation method, which could provide us with energy intensities by each upstream stage. If more detailed product quantities were available, then those quantities could replace the monetary flows in a Power Series Approximation method (Treloar, 1998; Crawford, 2004). For example, if quantities of major ingredients of a complex product such as concrete were known, any monetary flow from sectors producing ingredients to the sector of the complex product could be replaced with physical flows. Treloar (1998) and Crawford (2004) adopted a similar approach called embodied energy path extraction.

If **A** represented the direct requirement matrix, then the energy intensity by stage (Treloar, 1998):

$$E_{sn} = \sum_{i=1}^{N} A_{i\,n} \times E_{i,(s-1)} \qquad \text{Equation 8-4}$$

Where *s*, *n*, *i* indicated the number of stage, sector of study material, and input sector, respectively. The terms E_{sn}, A_{in}, and $E_{i,(s-1)}$ were energy intensity of study material at stage *s*, direct input from sector *i* to *n*, and energy intensity of sector *i* one stage downstream, respectively. It should be noted that energy intensity of sector *i* was a product of direct energy intensity and PEF. The energy intensity of sector *i*:

$$E_i = \sum_{e=1}^{E} A_{e\,i} \times PEF_e \qquad \text{Equation 8-5}$$

Where "*e*" represents the number of energy providing sectors. Unlike Treloar (1998) and Crawford (2004), we did not use energy prices, as we calculated energy intensities in energy units (MBtu/$). According to Acquaye (2010), in Treloar's (2004) and Crawford's (2004) work, energy prices were used multiple times increasing chances of error if energy products were underestimated or overestimated. Since we did not use energy prices at this stage, the chances of error were minimized. The process of indirect energy calculation was also discussed with Penson (2012 and 2013) and Dudensing (2012 and 2013).

In this research, we did not calculate a single energy intensity for sector *i* as shown in Equation 8-4. Instead, we calculated embodied energy intensity using Equation 8-5 for each fuel category including human and capital energy. There were two advantages in doing so. First, the relative fraction of various energy types in the total embodied energy was clear. Second, energy source wise embodied energy calculation was more appropriate if carbon emissions were to be determined using embodied energy values.

After calculating the direct energy intensity of industry sectors of the economy, the total energy intensities were calculated using the Power Series Approximation. The total energy intensities were calculated for oil and gas extraction, coal, natural gas, oil, electricity, human energy, and capital energy up to 12 stages in the upstream. The total embodied energy was the sum of total energy embodied in all 12 stages. According to Treloar (1998) and Miller and Blair (2009), up to the 12th stage most of the indirect inputs can be covered. In a test conducted in this research prior to developing the calculation model, we found that if calculated up to the 12th stage, more than 99.5% of the inputs were covered (see Appendix A1).

CHAPTER IX

RESULTS

9.1 EMBODIED ENERGY CALCULATION GUIDELINES

The literature clearly pointed out serious issues with the way embodied energy calculations have been planned, carried out, and their results were reported. The guidelines for calculating embodied energy can be tied to the four major issues with the current embodied energy research. These issues include lack of embodied energy definition, inconsistent system boundary model, poor data quality, and a lack of a standard calculation method. The following sections describe the embodied energy guidelines.

9.1.1 Embodied Energy: General Interpretation

The term "embodied energy" is interpreted as a net value of all types of primary energy consumed in various products (goods) and processes (services) used in manufacturing a building or its materials. The term "all types of primary energy" includes heat of combustion of all materials used as an energy source and as a feedstock. It also covers the energy embedded in human labor, plant facilities, and other capital expenditure. The use of an energy source as a raw material in the process of delivering goods and services is considered a feedstock use. The amount of energy wasted or lost during the process is also considered energy consumption. The final embodied energy value is a net consumption of primary energy use meaning it excludes any energy recovered by the reuse or recycling of resources. The term "primary energy" signifies the importance of tracking a delivered energy back to its point of extraction.

9.1.2 Embodied Energy: Definitions

A set of standard definitions of embodied energy terms is important to build a consensus on embodied energy interpretation. The following four terms are defined based on the literature opinion**:**

Embodied Energy of a Product

The net sum of all primary energy, including human and mechanical energy, consumed directly or indirectly in products (goods) and processes (services) used in manufacturing and delivering a final product for end use is termed the embodied energy.

Life Cycle Embodied Energy: Building

The net sum of embodied energy of all products (goods) and processes (services) consumed by a building in the life cycle stages of initial construction, occupancy and use, and demolition and material disposal is known as the life cycle embodied energy.

Life Cycle Operating Energy: Building

The net total primary energy, including direct and indirect components, used by a building in its operation over its service life is called the life cycle operating energy.

Life Cycle Energy: Building

The sum of a building's total life cycle embodied and operating energy is termed the life cycle energy.

9.1.3 System Boundary Definition

The system under study is defined using a boundary that starts from and returns to the biosphere. The goal is to define a boundary in a complete manner. An in-depth analysis of system boundary models proposed in the literature showed two distinct dimensions defining the length and width of a system under study (see Figure 9-1). The longitudinal dimension ("X" dimension) covers the upstream and downstream of a product such as a building (e.g. life cycle stages). The cross sectional dimension ("Y" dimension) defines the upstream and downstream of each stage covered by the longitudinal dimension. The cross sectional dimension "Y" is also applied to transition between the stages of the longitudinal dimension. The following guidelines apply:

- Defining a boundary in the "X" dimension means tracking each input from its point of extraction in the upstream of a building to its disposal or recovery in the distant downstream. The "X" dimension (length) stretches across the life cycle of a building starting with the material production stage, going through initial construction and use, and ending with the end-of-life phase. All transportation and transformation of resources are also included. The term "resources" includes energy and nonenergy raw materials, labor, and machines.
- Each life cycle stage of the "X" dimension consumes energy and nonenergy inputs in its upstream and causes emission, pollution, and waste generation in the downstream. The upstream of a life cycle stage covers all primary energy inputs, whereas the downstream deals with the primary energy used in remediation of emission, pollution, and waste generation. The term "all primary energy inputs" means total primary energy of all energy and nonenergy inputs. This dimension ("Y" dimension) defines the width of a system boundary.

In the case of a complex product such as a building, a system under investigation may include the building in its entirety or in parts. For instance, the scope of study may be limited to only the structure, envelope, or building services or may be extended to the site, surroundings or neighborhood. The differing levels of study scope indicate the "Z" dimension. For a basic material (e.g., cement, aggregate, glass etc.) including both the "X" and "Y" dimensions is recommended. In the case of a complex product (e.g., windows, equipment, buildings), it is recommended that all three dimensions (X, Y, and Z) are covered as shown in Figure 9-1. A complex product is a product that is made of multiple basic materials. For instance, a window assembly is fabricated using metal, glass, rubber, coatings, and gases filled between the glass layers. Another example of a complex product is a material such as concrete that is made of cement, additives, aggregate, sand, and water.

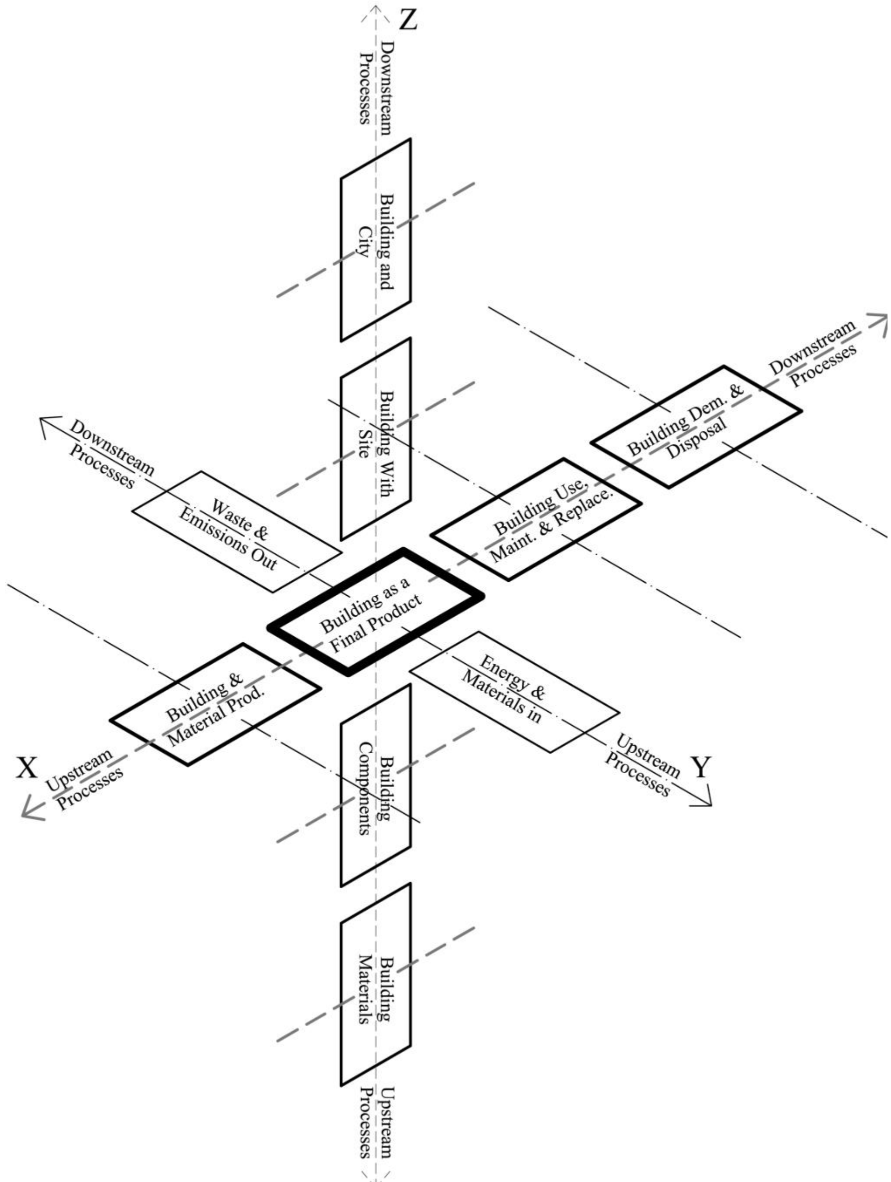


Figure 9-1: The three dimensions of a system boundary for a building

9.1.3.1 Explanation of the Three Dimensions

The process of defining a system boundary starts with the production of building materials stage (see block "A" in Figure 9-2), which is made of the main production process, upstream processes such as raw material extraction, treatment, and transportation, and the downstream processes such as finished product packaging, storage, and delivery. Block "A" analysis is repeated for each material (e.g., fuels, building materials, water, etc.) and product (building assemblies, equipment, machines, etc.) used in constructing a building.

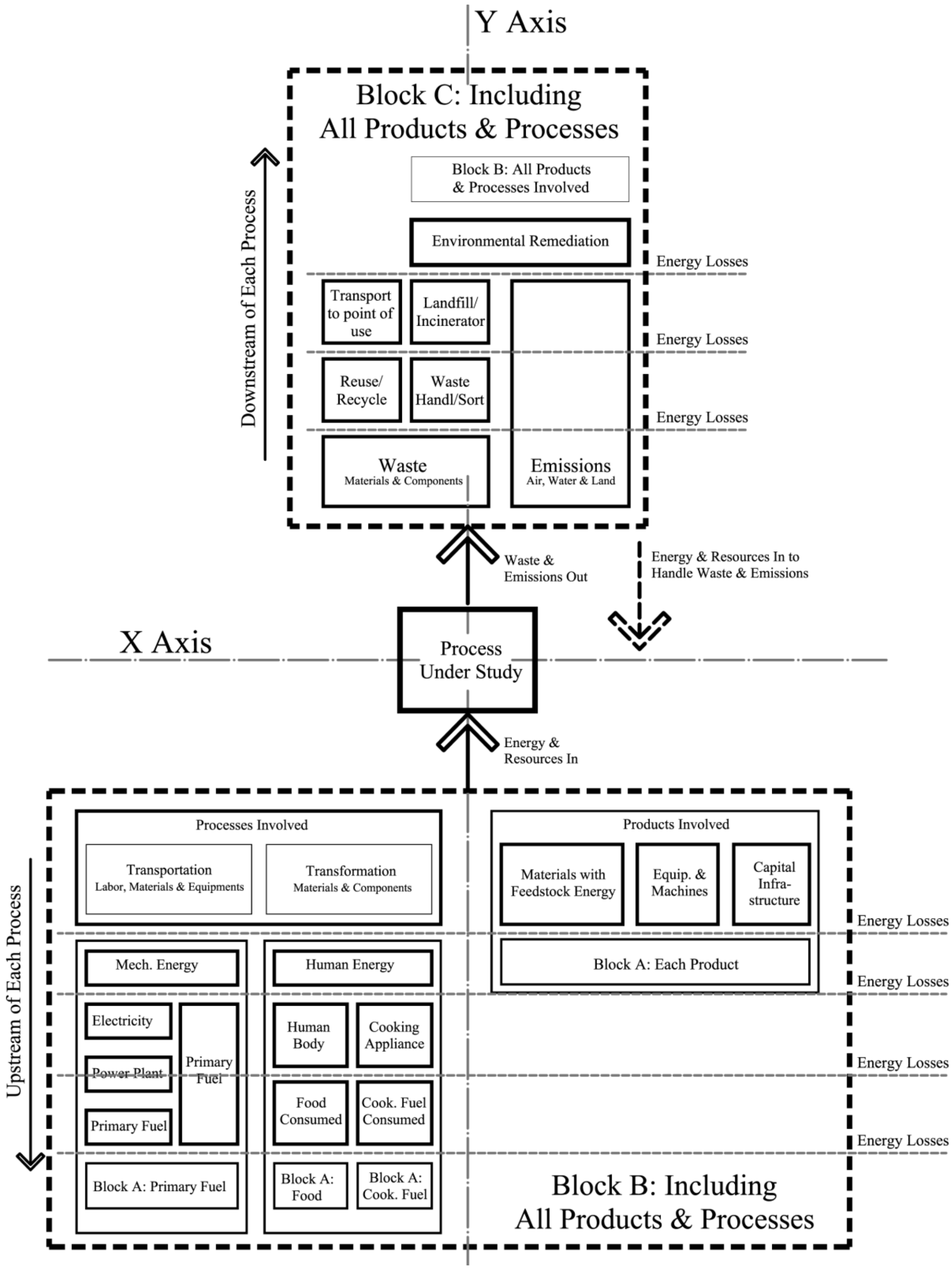


Figure 9-2: System in the Y dimension

Each block “A” analysis is divided into block “B” and “C” analysis defining the input and output side of “Y” dimension as shown in Figure 9-2. The input side (block “B”) determines the products and processes entering each life cycle stage including the transitional stages. The product category consists of raw materials (including feedstock energy), equipment and machines, and capital infrastructure (e.g., automobiles, software, temporary or permanent structures) that are fed into each life cycle stage. For each item involved in the product input category, the block “A” analysis is done.

The process category represents the transformation or transportation of resources such as material, labor, and equipment. Each input and output side incorporates mechanical as well as human energy use including losses due to acquisition (primary fuel extraction or electricity generation), storage, and supply (transmission and distribution of primary or electrical energy) of energy sources. The losses due to efficiency of equipment and the productivity of human labor are also accounted for. Block “A” analysis is repeated for each primary fuel used by machines and each food item consumed by labor. The output side (block “C”) covers the consumption of resources and energy in the remediation of the environmental consequences of resource use (input side). Similar to block “B,” each item in the product and process category is tied back to block “A” analysis. Hence, we can visualize that the system boundary starts with block “A” analysis, covers blocks “B” and “C,” and finally returns to block “A” analysis at a micro level. This seems an unending process with each block “A” analysis getting relatively insignificant (in terms of its relative impact on the product under study) than the earlier one.

Each life cycle stage of a building incorporates blocks “B” and “C” as shown in Figure 9-3, which illustrates a building’s system boundary comprehensively. As indicated in Figure 9-3, transition from one stage to another includes each activity of transportation, loading and unloading, temporary storage, etc. The block “B” and “C” calculations for all products (cranes, trucks, loaders, dumpers, etc.) and processes (transportation, loading, and unloading) involved in transitional stages are done. Two types of recycling or reuse of resources are considered: open or closed loop. Resources may also be recovered from combustion of products that contained feedstock energy (e.g. wood, plastic and other petrochemical products). The open loop recycling includes recycling and reuse between the life cycle stages or between the various industry sectors. The closed loop includes reuse or recycling within a life cycle stage or an industry sector.

9.1.4 Embodied Energy: Data Quality

The data utilized in the embodied energy calculation are of two types, the energy and nonenergy inputs. Two aspects of data used in embodied energy calculation are paramount. First, the data are complete with respect to the system boundary defined. Second, they are representative of the study with respect to the location and time.

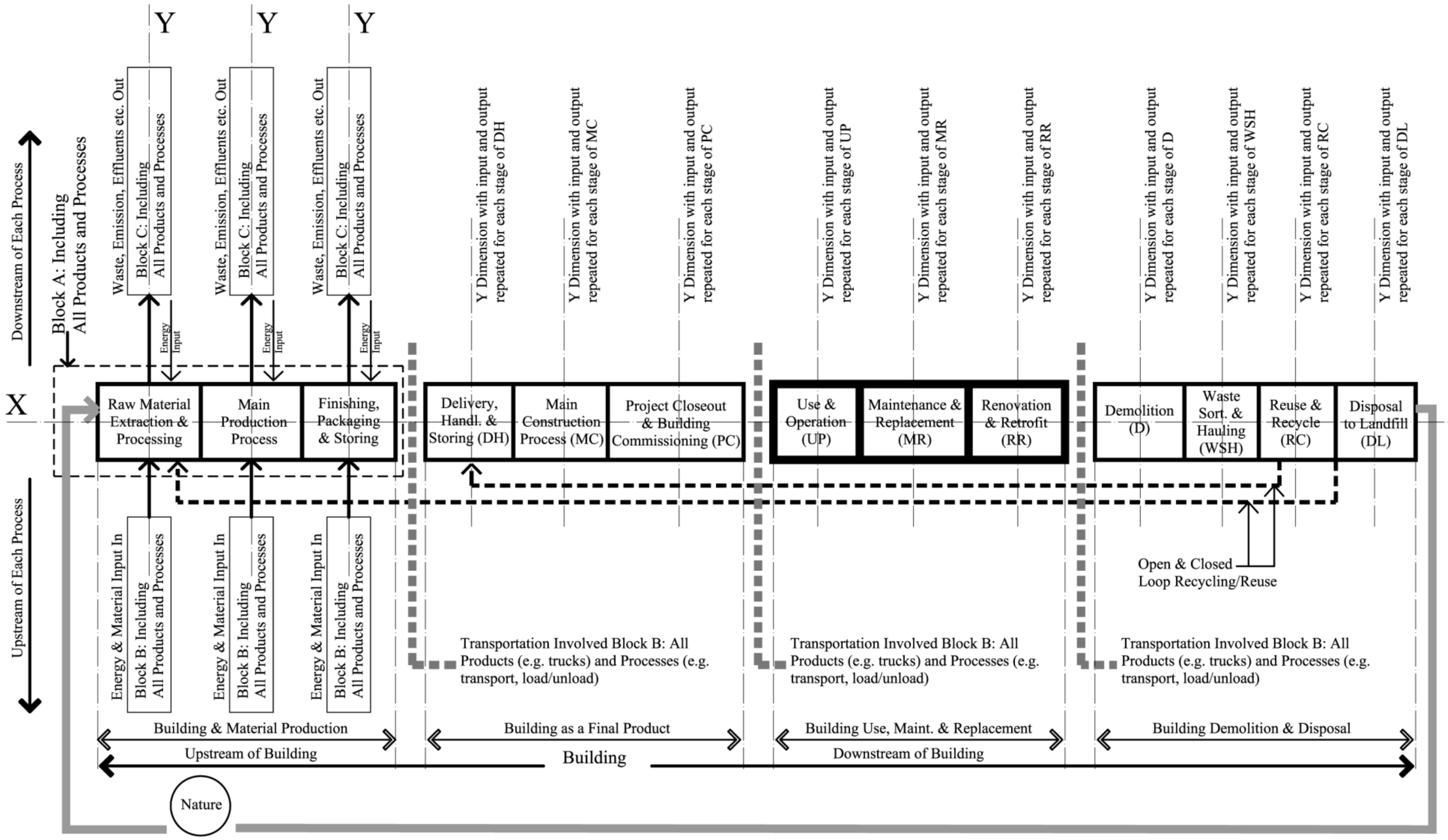


Figure 9-3: Complete system boundary for a building

9.1.4.1 Data Completeness

The completeness relates to the purpose the data serve in embodied energy analysis. For instance, if process-based energy intensities are used to replace the direct energy components of an input-output analysis, they should completely cover all relevant direct inputs. Before incorporating primary data in the calculation, it is important to apply a calculation method that does not result in incomplete values. If secondary data are used, it is important to verify their completeness. If the data is found to be incomplete, it is recommended that necessary adjustments are made to attain completeness.

9.1.4.2 Data Representativeness

The representativeness of data is measured with respect to geographic location, time, and technology. If primary data are calculated, their representativeness needs to be verified. For instance, data are from the same region and year as the study, and data represent the technology of manufacture and construction in terms of resource use. If for any reason old data are used, adjustments are required to convert them to the current time. If no adjustments can be made, a study for the old time can be performed. However, in such a case, all other data should also come from the same time period. When using data from a region other than the study, adjustments are needed based upon the socio-economic and technological aspects.

The technology of manufacture and construction differs with the location. In addition, economic systems and policies are also different within and across geographic boundaries. Sourcing data from a non-representative region can produce erroneous results. Even within the same geographic region, if two manufacturing units apply different technology, their energy intensities are not comparable, and hence, cannot be substituted for each other. The third aspect relates to the temporal representation of data. If old data are used, they may not demonstrate the time of the study accurately.

9.1.4.3 Secondary Data

Secondary data can be used if the information about how the data were originally derived is available. Using data from a source that lacked transparency can seriously hamper the reliability of the energy results. In addition to transparency, completeness and representativeness of secondary data are also needs to be verified.

9.1.5 Embodied Energy: Calculation Method

The most commonly used method for embodied energy calculation is the process-based approach. However, incompleteness due to the truncation of the system boundary is a major issue with this method. The input-output-based methods are regarded as complete but their results, in most cases, are not specific to the product under study. Looking at the system boundary model proposed in Section 9.1.3, an input-output analysis seems the only approach to account for all indirect inputs. The chances that the incompleteness of a process-based analysis would be improved to an extent that all indirect inputs are counted are rare. In the view of current research, it can be expected that the specificity of an input-output-based method would improve significantly over time.

An input-output-based hybrid method is appropriate to conduct the embodied energy calculation. The process data on energy inputs can be collected and inserted into the input-output model to improve its reliability. The following guidelines apply to an input-output-based hybrid approach:

- Avoiding the use of energy and product prices is recommended, as it would improve the reliability of the method. If possible, replacing direct requirement coefficients of energy use by process data can avoid relying on energy prices, which vary across industry sectors and geographic boundaries. In such a case, the direct energy requirement coefficients are calculated directly in energy units.
- Ensure that the inputs such as human energy and capital investment that are not covered in a conventional input-output model are quantified and added to the economic model.
- If disaggregated data on main inputs and outputs of commodities are available, the process of sector disaggregation is a recommended way to make the results of an input-output-based method more study specific.
- There are multiple chances of double counting due to the way economic input-output accounts are prepared. One approach used to avoid the double counting of energy is keeping all energy and nonenergy inputs to zero and multiplying energy intensities with Primary Energy Factors (PEFs) by fuel. There are sectors such as wholesale and retail trades, which buy energy goods and sell them for a profit. However, when their energy intensity is quantified based on how much they bought from the energy providing sectors, the results may be inaccurate because most of the energy purchased was not consumed but traded.
- When using PEFs, the assumption is that the PEFs take into account all indirect energy inputs consumed by an energy providing sector. Therefore, it is important to calculate PEF for each energy source in a complete manner by covering all direct and indirect inputs. An input-output-based hybrid approach is appropriate for calculating the PEFs.
- If all energy sources used in an economy are averaged into one energy source for the purpose of calculating the embodied energy, its relevance to environmental issues is lost. Embodied energy results by fuel type can be used to further quantify other environmental impacts such as carbon emission and pollution.
- Once the embodied energy intensities of industry sectors are calculated, product prices are used to convert the energy intensities to embodied energy values per unit of mass or volume. If suitable data are readily available, using the production quantity of a finished product and the total embodied energy of the sector manufacturing the product, embodied energy per unit of mass or

volume can be calculated without using the price of the product. Using product prices for converting energy intensities to energy units poses serious problems, as product prices also vary and may be underestimated or overestimated. For instance, iron and steel mills sector not only manufactures virgin steel but also produces a wide range of structural shapes each of which has quite different prices. One way to avoid this is collecting data on total production of the product in physical quantities. The calculated embodied energy values then can be multiplied by the monetary sectorial output to obtain total embodied energy of the entire industry sector. This value if divided by the total embodied energy would give embodied energy per unit of mass or volume.

9.1.6 Embodied Energy: Reporting

It is recommended that the reporting of the embodied energy process and results is done in a transparent manner so that the reader can make informed decisions about analyzing or applying the study with or without modifications. The following information must be supplied in order to attain a reasonable degree of transparency:

- System boundary: A boundary defining the extent of the study is graphically supplied and explained in the text in detail. Each input, major or minor, is reported if included or excluded from the system. Any recovery of resources is mentioned in the text. As mentioned in Section 8.1.3, a complete coverage of the system boundary is recommended. If the product under study is a complex product such as a building, a detailed account of its and its constituent materials' service life is given. Factors such as a waste factor and replacement factor, if used in the calculation, are listed clearly by each material and assembly. Any schedule of maintenance or renovation, if applied, needs to be explained while reporting the system boundary.
- Calculation method: The method applied for the calculation is explained step by step stating and explaining each variable. If any modification is done to an established method, it needs explanation so that a reader can evaluate the applicability of the modified method. All major assumptions regarding energy and nonenergy inputs and calculation process are listed. It is also recommended that the approach to evaluate the study results is explained clearly.
- Data sources: Any primary or secondary source referred in the study needs to be listed along with a way to approach them if needed. Three types of information are included in data source reporting: date, geographic location, and the details of the publishing organization or agency. If any modification is done to the sourced data to improve its representativeness, it needs detailed explanation.
- Study results: The embodied energy results are presented in primary energy units only. If secondary energy units are used, a factor to convert them into primary units is supplied and

explained. Embodied energy results are reported collectively and also by each fuel or energy source used in the region.

- Case study description: In the case of a research conducting case studies of materials or products, a detailed description of their physical, spatial, and environmental characteristics is recommended. For instance, if the study object is a building, information about its construction (at a minimum, structural frame, envelope, and interiors), design (representative floor plans and sections), and surroundings (site, climate, and socio-economic conditions) is mentioned briefly in the report.

9.2 EMBODIED ENERGY OF STUDY MATERIALS

This chapter provides the results of the embodied energy calculation performed for the study materials. The calculated values are presented as energy intensities per unit of monetary output and also as embodied energy per unit of mass. The results are also reported by each energy source so that the share of each in the total carbon emission can be analyzed at a later date. Reporting of results by each stage is also provided to demonstrate how energy intensities get smaller with each stage in the upstream. Here, upstream stages indicate the subcomponents of a material. For instance, the use of cement in the production of concrete is stage I input to concrete. Similarly the use of limestone in manufacturing cement is the stage II input to concrete production and so on. It is also important to analyze the share of direct and indirect components in the total embodied energy. For some materials, the direct energy could be significantly less than the indirect fraction of the total embodied energy. As the calculations were performed in steps indicating gradual improvements, the results are also presented by each step to observe the impact on embodied energy.

9.2.1 Embodied Energy of Study Materials

Table 9-1 provides the values of embodied energy calculated for each study material. The values are listed for each calculation approach. The first column lists embodied energy calculated using a basic input-output approach in which the total energy coefficients were calculated by dividing the total requirements with average energy prices. In the second approach, in order to avoid the use of average energy prices, process data of energy use were inserted into the input-output model. The human and capital energy were added in the next approach. Finally, some sectors were disaggregated to quantify the material specific embodied energy for materials such as wood, plywood, brick, clay tiles, vitrified clay pipes, gypsum building products, lime, steel, and primary aluminum. Materials such as wood lumbers are manufactured by a sector that is also engaged in wood preservation activities, and hence, embodied energy specific to wood lumber production should be calculated separately. The embodied energy of wood lumber changed slightly from 2.7 to 2.8 kBtu/lb after the sector disaggregation. However, in the case of hardwood plywood

(-30%), clay tiles (-25%), and gypsum (-28%), the embodied energy actually decreased considerably. This change in material's embodied energy was due to the different energy intensities of various products that were manufactured by the disaggregated sector. For instance, in the case of steel, due to a higher energy intensity of ferro-alloy sector, the energy intensity of primary steel decreased by 1%. Surprisingly the energy embodied in carpet per unit of its mass was the highest among the study materials. The calculated embodied energy of carpet supports the literature opinion (Winistorefer et al., 2005) that the carpet is the "largest energy consumer" among the commonly used building materials. Treloar et al. (2001a) also found that the embodied energy of carpet was the largest among the major building materials when calculated per unit of its area.

Table 9-1: Calculated values of embodied energy of study materials

	Final Embodied Energy (kBtu/lb)			
Study Material	IO-based Method	Hybrid Method	Hybrid with Human & Capital Method	After Disaggregation
Carpet (3/8" Thk.), Level Loop	235.3	228.2	242.1	242.1
Wood Lumber	2.2	2.4	2.7	2.8
Hardwood Plywood & Veneer	11.5	14.0	15.2	10.6
Softwood Plywood & Veneer	3.0	3.6	4.0	4.0
Paints & Coatings	29.0	22.8	24.1	24.1
Adhesives	56.2	21.6	23.0	23.0
Plastic Pipes & Fittings	42.2	46.9	48.7	48.7
Polystyrene Foam Insulation	104.8	104.7	110.1	110.1
Bricks	2.1	1.6	1.7	1.9
Clay Wall & Floor Tiles (1/4" Thk.)	19.0	14.4	15.2	11.3
Vitrified Clay Sewer Pipes	8.4	6.4	6.7	6.1
Flat Glass	10.6	10.3	10.6	10.6
Cement	1.9	3.1	3.2	3.2
Concrete	0.5	0.5	0.6	0.6
Gypsum, Bldg. Products	9.1	10.1	10.4	7.5
Lime	1.7	1.9	1.9	3.2
Stone	1.3	1.2	1.4	1.4
Mineral Wool Insulation	11.8	11.9	12.6	12.6
Virgin Steel	35.2	34.2	35.2	34.9
Primary Aluminum	29.2	79.3	80.2	82.0
Copper	18.8	24.7	25.8	25.8

It was evident that the embodied energy values calculated using the input-output-based approach were within 25% of the hybrid analysis values in most cases. However, in the case of adhesives, cement, and aluminum the difference was considerable (61 - 171%). A possible explanation for the less embodied energy of cement and aluminum could be the higher electricity consumption of the aluminum and cement sector, which is actually four times if converted to primary energy terms. As input-output analysis is based upon the monetary data, if electricity prices are underestimated, the calculated values of embodied energy would be much smaller. Similarly in the case of adhesives, a higher petroleum intensity of the input-output analysis caused the embodied energy to increase sharply. There could be several reasons for a larger embodied energy of chemical products such as adhesives. The chances of double counting and a large share of feedstock energy use are among them. Based on these results, it can be concluded that the results of an input-output-based analysis are quite different than the other hybrid methods. Although the increase in embodied energy due to the inclusion of human and capital inputs was within 10% for most materials, in the case of wood lumber and stone, it actually increased by 11 - 17%. The least change occurred in the case of aluminum, where embodied energy increased by just one percent as a result of human and capital energy inclusion.

9.2.2 Energy Intensities by Energy Source

Figure 9-4, Figure 9-5, and Figure 9-6 demonstrate the energy intensities in MBtu/$ output of the study material sector by energy source calculated using the three approaches. It can be seen that the fuel intensities were quite different in the input-output-based and input-output-based hybrid approaches. In the input-output-based approach, the electricity use was mostly within 0.005 MBtu/$ except for the aluminum production. However, in the hybrid approaches, it increased to a range of 0.007 - 0.08 MBtu/$. The most electricity-intensive sector was the primary aluminum production, which consumed 0.08 MBtu of energy per dollar of its output. Other sectors producing materials such as cement (0.026 MBtu/$), gypsum (0.012 MBtu/$), and lime (0.012 MBtu/$) also consumed considerable electricity. The cement manufacturing sector was the most coal-intensive sector. Other sectors producing steel, gypsum, and lime also consumed coal in relatively large quantities per dollar of their outputs. Interestingly, the aluminum and plastic industries were among the most petroleum-consuming industries.

The effect of sectorial disaggregation is clearly visible in Figure 9-6 . The seemingly flat energy use of gypsum, lime, and clay product manufacturing as seen in Figure 9-5 , disappeared in Figure 9-6. The significance of reporting energy use by energy source is that one can identify sectors that are critical to combating the increased levels of carbon emissions. Sectors producing aluminum, steel, and cement consume considerably higher quantities of electricity and coal energy, the key contributors to global carbon emissions.

Figure 9-7 shows the share of each fuel in the total energy used by sectors producing the study materials. Figure 9-7 only presents the results of the input-output-based hybrid analysis with human and capital inputs after disaggregation. It can be observed that nearly 25% of the total energy requirements of all sectors came from the electricity and coal supply. Materials such as aluminum, steel, and cement used extensively in building construction, came from manufacturing sectors that were the largest consumers of electricity and coal (>50% of the total energy use collectively). The fraction of human energy in the total embodied energy ranged from 0.7-9.3%, whereas it was within 1.2 - 5.2% for the capital energy. The calculated energy intensities per dollar of sectorial output by each energy source are listed in Table A1-16, Table A1-17, Table A1-18, and Table A1-19 in Appendix A1.

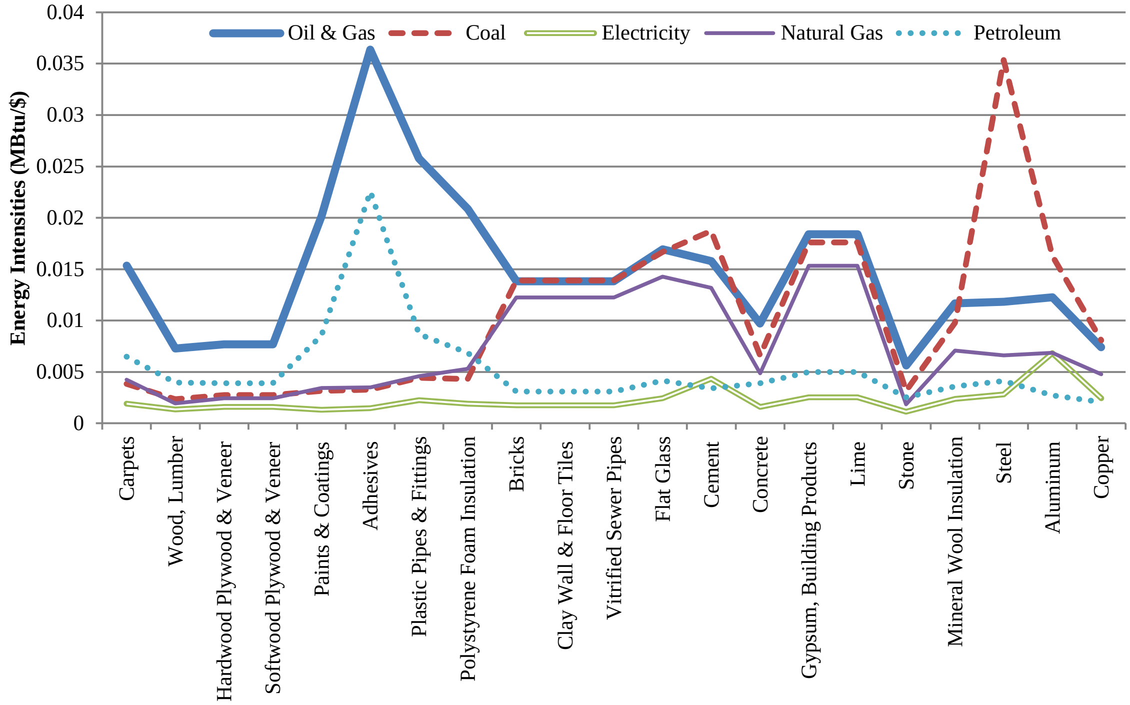


Figure 9-4: Energy intensities using input-output analysis

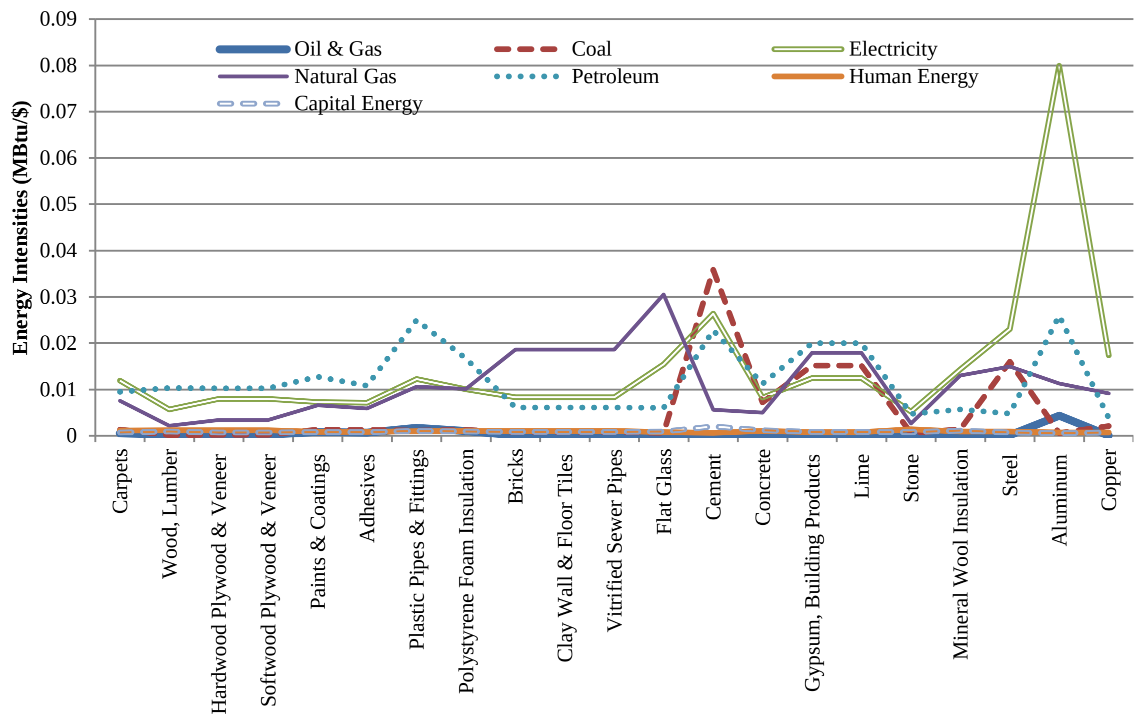


Figure 9-5: Energy intensities using input-output-based hybrid approach with human and capital inputs

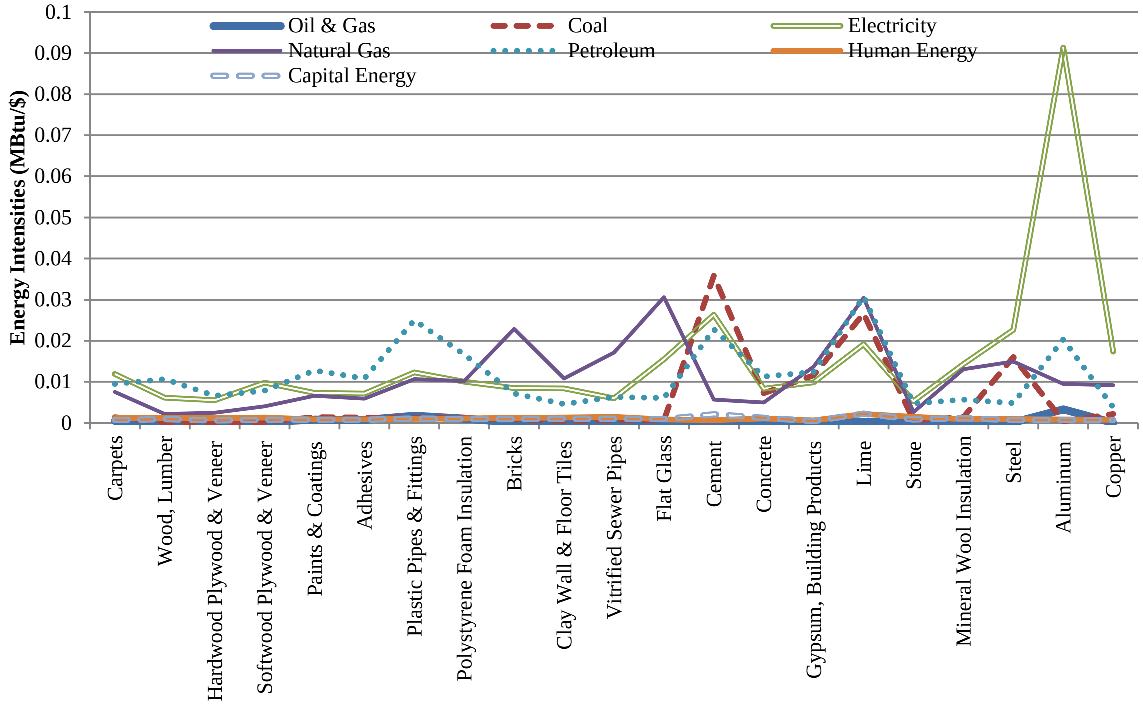


Figure 9-6: Energy intensities using input-output-based hybrid approach with sector disaggregation

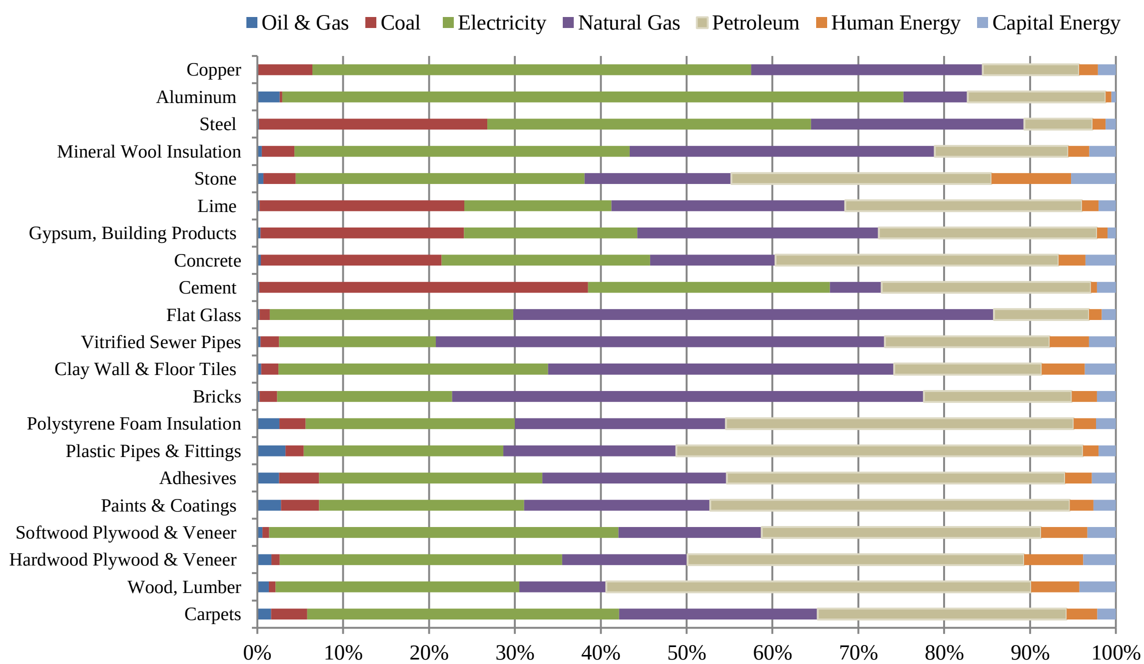


Figure 9-7: Relative share of energy sources in the total embodied energy intensities of study materials

Table 9-2: Final embodied energy values by energy source using hybrid approach after sector disaggregation

Study Material	Final Embodied Energy Breakup by Energy Source (kBtu/lb)							
	Oil & Gas	Coal	Electricity	Natural Gas	Petroleum	Human Energy	Capital Energy	Total Embodied Energy
Carpet (3/8" Thk), Level Loop	3.871	10.195	87.994	55.945	70.203	8.604	5.285	242.096
Wood Lumber	0.038	0.022	0.795	0.283	1.385	0.157	0.119	2.800
Hardwood Plywood & Veneer	0.175	0.102	3.477	1.548	4.143	0.730	0.401	10.577
Softwood Plywood & Veneer	0.024	0.030	1.609	0.660	1.286	0.214	0.131	3.953
Paints & Coatings	0.665	1.073	5.756	5.227	10.099	0.662	0.633	24.116
Adhesives	0.582	1.072	5.984	4.942	9.055	0.720	0.644	23.000
Plastic Pipes & Fittings	1.596	1.034	11.335	9.819	23.074	0.895	0.987	48.740
Polystyrene Foam Insulation	2.822	3.385	26.803	27.107	44.578	2.884	2.545	110.125
Bricks	0.005	0.039	0.391	1.055	0.331	0.057	0.042	1.920
Clay Wall & Floor Tiles (1/4" Thk)	0.052	0.226	3.563	4.571	1.949	0.569	0.413	11.343
Vitrified Clay Sewer Pipes	0.023	0.134	1.120	3.210	1.177	0.281	0.192	6.137
Flat Glass	0.029	0.125	3.012	5.943	1.178	0.157	0.175	10.619
Cement	0.007	1.235	0.908	0.195	0.786	0.023	0.071	3.225
Concrete	0.002	0.123	0.141	0.085	0.192	0.018	0.021	0.583
Gypsum, Bldg. Products	0.027	1.780	1.515	2.109	1.906	0.093	0.074	7.503
Lime	0.008	0.756	0.543	0.863	0.873	0.062	0.064	3.169
Stone	0.010	0.054	0.481	0.245	0.433	0.133	0.075	1.430
Mineral Wool Insulation	0.066	0.481	4.914	4.477	1.957	0.309	0.391	12.595
Virgin Steel	0.064	9.282	13.143	8.672	2.773	0.532	0.415	34.881
Primary Aluminum	2.151	0.243	59.275	6.143	13.162	0.546	0.431	81.952
Copper	0.034	1.622	13.167	6.946	2.896	0.565	0.539	25.769

Table 9-2 provides the final values of embodied energy per unit of study materials' mass calculated using the input-output-based hybrid approach after sector disaggregation including human and capital energy. The values of embodied energy are listed by energy source. The relative share of human and capital inputs was significant in the case of study materials such as stone (nearly 15% of the total energy).

9.2.3 Energy Intensities by Upstream Stages: Direct and Indirect Energy

The indirect energy component includes the energy embodied in materials and processes that are used to produce a product. For instance, for calculating the embodied energy of cement, the energy embodied in clinker needs to be determined (stage one in the upstream). To compute the embodied energy of clinker, the energy of limestone extraction and delivery is determined (stage two in the upstream). Hence, one can go up to infinite stage in the upstream to count all of the indirect energy. In the system boundary model proposed in Section 9.1.3, it was discussed that the indirect inputs, due to repetition of block "A" analysis, get smaller with each stage in the upstream. The same pattern can be seen in economic input-output-based hybrid analysis while calculating the total requirements using the Power Series Approximation approach. With each stage in the upstream, the indirect energy requirements become smaller. To verify and illustrate this assertion, the indirect energy intensities were also presented by upstream stages. Figure 9-8 shows the distribution of indirect energy intensities of sectors by each upstream stage producing the materials under study. The intensities shown were calculated using the hybrid approach with human and capital inputs. The energy intensities of most sectors became nearly zero after Stage 8. The first four stages covered more than 90 - 98% of the total indirect energy, whereas stage 12 consisted of only 0.002 - 0.02%. The pattern of stage wise decreasing energy intensities differed due to different direct energy coefficients. As seen in the Power Series Approximation equation, the indirect impacts are actually a function of the direct requirement coefficients. The pattern of indirect energy distribution clearly demonstrated the direct requirement coefficients as carriers of indirect impacts of a dollar increase in the output of a sector.

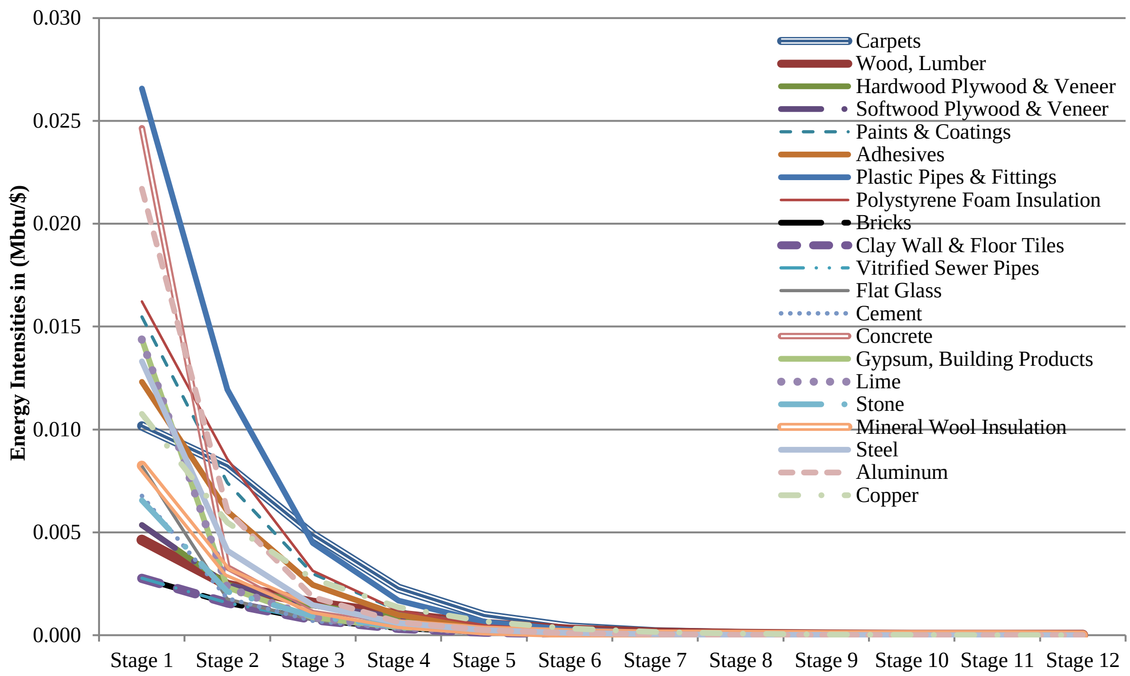


Figure 9-8: Stage wise energy intensity distribution

A careful look at the share of direct and indirect components in the total embodied energy revealed that in some cases the indirect component was actually larger than the direct component. Figure 9-9 illustrates the direct and indirect energy components of the total embodied energy calculated using the input-output-based hybrid approach with human and capital inputs. Materials such as concrete are expected to have a larger share of indirect energy (>87%) due to the use of cement, which according to this study had the third largest total energy intensity per dollar of its output (0.09 MBtu/$). Other materials such as paints, adhesives, plastics, and Styrofoam also had a significantly larger indirect energy component (72 - 92%) probably due to the use of petroleum as a feedstock material. Due to the larger share of indirect energy (>83%), the embodied energy of carpet was quite high. The calculated indirect energy intensities by each upstream stage are presented in Table A1-20, Table A1-21, and Table A1-22 in Appendix A1.

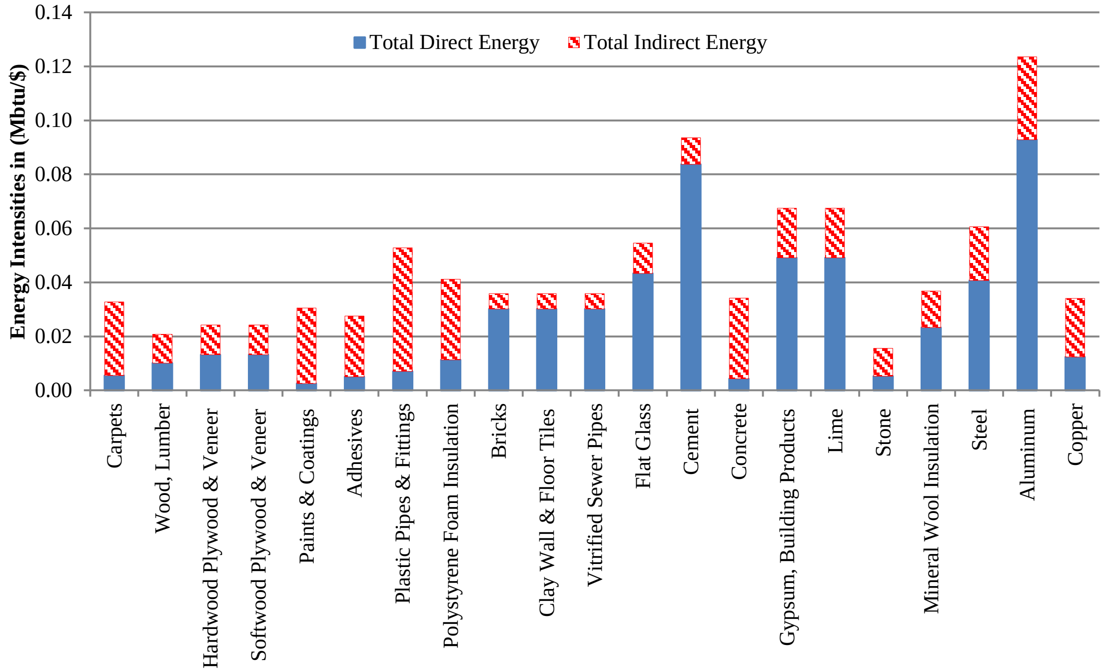


Figure 9-9: Direct and indirect energy in total embodied energy before sector disaggregation

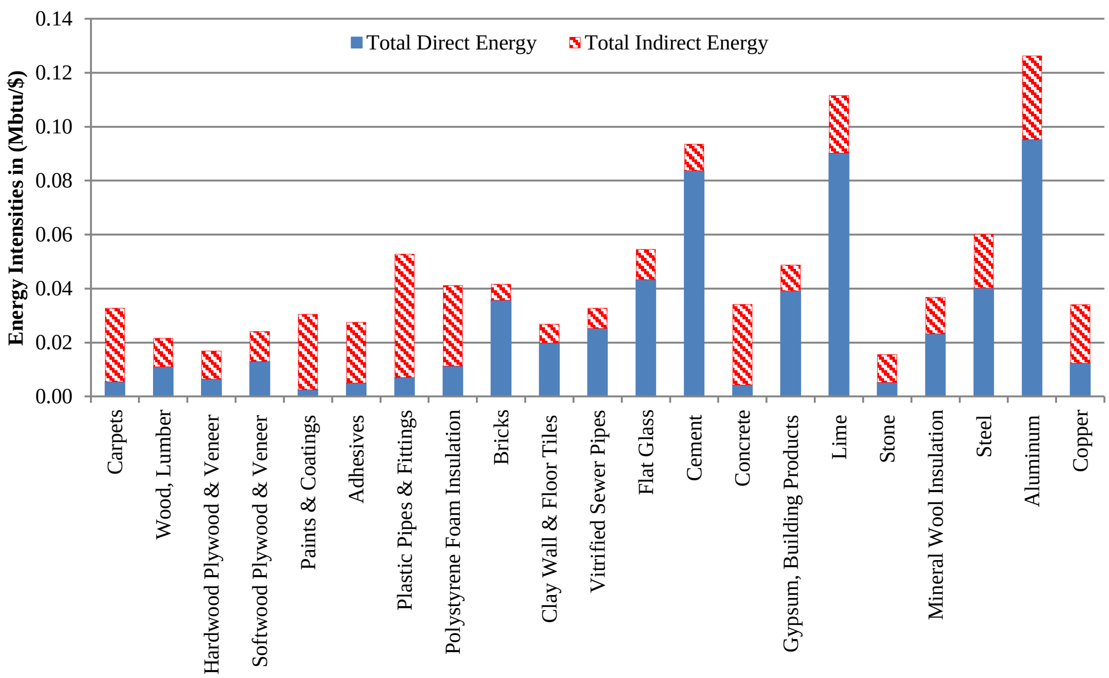


Figure 9-10: Direct and indirect energy in total embodied energy after sector disaggregation

Figure 9-10 shows the direct and indirect energy after disaggregating some of the industry sectors. Sectors producing lime and gypsum products, which initially shared the same energy intensity (0.067 MBtu/$), now had different ones after sector disaggregation. After sector disaggregation, the energy intensity of lime increased to 0.11 MBtu/$, whereas it decreased to 0.05 MBtu/$ for gypsum products. The highest indirect energy intensity (0.046 MBtu/$) was calculated for sectors producing plastic products. As mentioned earlier, the plastic industry consumes fuel not only as an energy source but also as a raw material resulting in higher indirect energy intensities. The sectors manufacturing clay products shared the lowest indirect embodied energy (0.007 MBtu/$) due to the use of relatively low energy intensive raw materials such as clay in their production. The higher embodied energy of carpet as discussed in section 9.2.1 was partly due to a larger indirect energy component (83% of the total energy) as seen in Figure 9-9 and Figure 9-10

9.3 HYPOTHESES TESTING

9.3.1 Energy and Cost Relationship

It was hypothesized that the energy embodied in a building material share a positive and strong correlation with its cost and price. Such types of hypotheses are one-tailed, as increasing one variable means a proportionate increase to the other.

9.3.1.1 Correlation of Embodied Energy and Material Cost

The scatter chart shown in Figure 9-11demonstrates the correlation of the cost of study materials with their embodied energy. The cost was calculated in physical units for materials for which the production quantities were available (using Equation 3-1). For the remaining materials without production quantities, their prices were used. Table 9-3 lists the cost and the calculated values of embodied energy of each study material. According to the scatter plot, the input-output-based results showed a very strong and positive correlation (r^2 = 0.96) with the cost of study materials. Since an input-output analysis is based on monetary transactions, a strong correlation with the cost was expected. When the correlation of cost was analyzed with the input-output-based hybrid analysis results, the correlation was positive and strong (r^2 = 0.77). A similar correlation (r^2 = 0.78) was found after including the human and capital energy fractions to the input-output-based hybrid model. This correlation remained strong and positive (r^2 = 0.78) even after the disaggregation of some of the industry sectors. For testing the hypotheses, a simple regression analysis was performed in Microsoft Excel 2010. Table 9-4 and Table 9-5 list the results of simple regression analysis for the results of the input-output-based and the hybrid approach.

Table 9-3: The cost and embodied energy of study materials

Study Materials		Embodied Energy (kBtu/lb)			
	Cost $/lb	IO-based Method	Hybrid Method	Hybrid with Human & Capital Method	After Disaggregation
Carpet (3/8" Thk), Level Loop	7.39	235.25	228.21	242.10	242.10
Wood Lumber	0.16	2.72	3.01	3.36	3.48
Hardwood Plywood & Veneer	0.68	12.54	15.17	16.51	11.50
Softwood Plywood & Veneer	0.13	2.44	2.95	3.22	3.20
Paints & Coatings	0.79	28.99	22.82	24.12	24.12
Adhesives	0.84	56.16	21.64	23.00	23.00
Plastic Pipes & Fittings	0.92	42.23	46.86	48.74	48.74
Polystyrene Foam Insulation	2.67	104.84	104.70	110.12	110.12
Bricks	0.05	2.11	1.60	1.69	1.96
Clay Wall & Floor Tiles (1/4" Thk)	0.48	21.73	16.46	17.40	12.98
Vitrified Clay Sewer Pipes	0.16	7.37	5.58	5.90	5.39
Flat Glass	0.20	11.09	10.77	11.11	11.11
Cement	0.04	2.04	3.35	3.45	3.45
Concrete	0.01	0.35	0.42	0.45	0.45
Gypsum, Bldg. Products	0.08	4.67	5.22	5.36	3.87
Lime	0.03	1.53	1.71	1.75	2.90
Stone	0.83	11.92	11.14	13.03	13.03
Mineral Wool Insulation	0.34	11.83	11.90	12.60	12.60
Virgin Steel	0.27	16.59	16.11	16.56	16.43
Primary Aluminum	1.42	63.65	172.93	174.82	178.71
Copper	0.88	21.68	28.51	29.79	29.79

Table 9-4: Regression analysis results for cost and input-output-based results

SUMMARY OUTPUT		Cost & Input-output-based Embodied Energy					
Regression Statistics							
Multiple R	0.986314						
R Square	0.972816						
Adjusted R Square	0.922816						
Standard Error	10.29948						
Observations	21						
ANOVA							
	df	*SS*	*MS*	*F*	*Significance F*		
Regression	1	75922.91	75922.91	715.719	1.52E-16		
Residual	20	2121.584	106.0792				
Total	21	78044.49					
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	33.31446	1.245264	26.75293	3.93E-17	30.71688	35.91204	30.71688

Two observations in the correlation plot shown in Figure 9-11 are important to discuss. First, since the embodied energy of a material such as aluminum was very high and its cost per unit of mass was low, it was way off the trend line. In addition, a material such as carpet with its high embodied energy could influence the trend line as shown in Figure 9-11. A further validation of this linear, positive, and strong correlation of cost and embodied energy is needed before making any judgment about using cost to predict the embodied energy of a material.

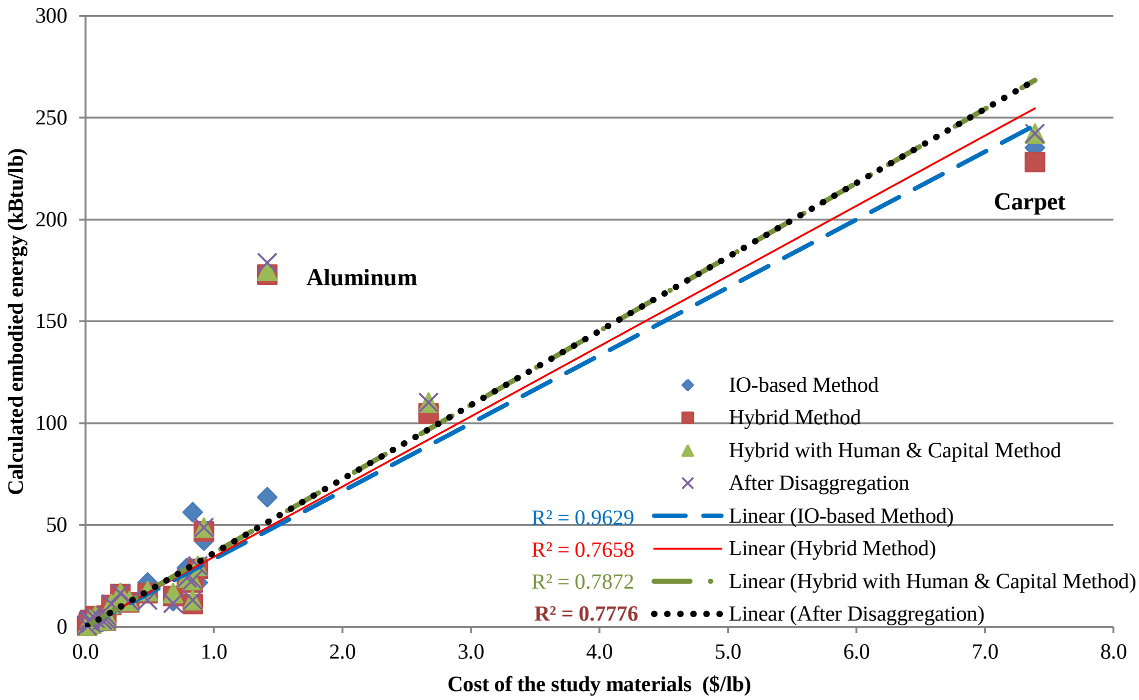


Figure 9-11: Correlation of cost with embodied energy results from the input-output-based and hybrid approaches

Table 9-5 Regression analysis results for cost and input-output-based hybrid analysis results

SUMMARY OUTPUT			Cost & Input-output-based Hybrid Embodied Energy				
Regression Statistics							
Multiple R	0.909106						
R Square	0.826474						
Adjusted R Square	0.776474						
Standard Error	29.18558						
Observations	21						
ANOVA							
	df	*SS*	*MS*	*F*	*Significance F*		
Regression	1	81139.41	81139.41	95.25662	7.77E-09		
Residual	20	17035.96	851.7981				
Total	21	98175.37					
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
Cost	34.43993	3.5287	9.75995	4.75E-09	27.07919	41.80067	27.07919

Two criteria were used for testing the hypotheses. First, the coefficient of determination was strong and positive as mentioned in Section 3.1.5.4. Second, the *p-value* for the cost of study materials was less than 0.05 for a 95% interval. This regression analysis assumed that the value of intercept (constant) is zero, as seen in the scatter plots (Langston, 2006). Looking at the values of r^2 and *p-value*, the null hypothesis can be rejected in favor of the alternative hypothesis. The same is found true for the embodied energy results obtained after adding the human and capital inputs and disaggregating the industry sectors. Based on the results, a strong and positive correlation was found between the cost and the embodied energy of study materials calculated using an input-output-based hybrid analysis. The regression analysis results can be seen in Table A1-8 and Table A1-9 in Appendix A1 for other hybrid approaches.

9.3.1.2 Correlation of Embodied Energy and Material Price

To test the second hypothesis, the correlation between the study materials' price and embodied energy was evaluated. Table 9-6 provides the materials' price and embodied energy data. The correlation of the price of study materials was checked with the energy results of all four approaches (one input-output-based and three input-output-based hybrid methods). The material prices were plotted on the x-axis, whereas the embodied energy values on the y-axis. The initial scatter plot, as shown in Figure 9-12, exhibited a very strong and positive correlation of the study materials' price and embodied energy. In the case of the results of input-output-based analysis, the value of r^2 was 0.97, which decreased to 0.92 when the hybrid analysis results were used. After adding the human and capital energy, the correlation remained very strong and positive (r^2= 0.93). The value of r^2 was 0.93 for embodied energy values calculated after disaggregating the industry sectors.

To test the second hypothesis, a simple regression analysis was performed using Microsoft Excel 2010. Again, the origin was assumed as zero and the values of r^2 and *p-value* were used to reject or accept the null hypothesis. The results of regression analysis are shown in Table 9-7 and Table 9-8 for the input-output-based and input-output-based hybrid embodied energy values. Similar to the cost and embodied energy correlation, the higher embodied energy of carpet tends to influence the trend line. However, in the case of material price and embodied energy correlation, the point representing aluminum came close to the trend line as seen in Figure 9-12. As mentioned earlier, a further validation of this correlation is required in the future.

The values of r^2 were found greater than 0.9 in both the cases indicating a very strong and positive correlation. In the case of input-output-based hybrid method, the *p-value* for material prices was less than 0.05 at 95% confidence interval. Hence, observing the value of r^2 and *p-value*, the null hypothesis can be rejected in favor of the alternative hypothesis. The results of regression analysis for other hybrid approaches can be seen in Table A1-10 and Table A1-11 in Appendix A1.

Table 9-6: The price and embodied energy of study materials

Study Materials	Price$/lb	Embodied Energy (kBtu/lb) IO-based Method	Hybrid Method	Hybrid with Human & Capital Method	After Disaggregation
Carpet (3/8" Thk), Level Loop	7.39	235.25	228.21	242.10	242.10
Wood Lumber	0.13	2.19	2.42	2.70	2.80
Hardwood Plywood & Veneer	0.63	11.54	13.95	15.19	10.58
Softwood Plywood & Veneer	0.16	3.01	3.64	3.97	3.95
Paints & Coatings	0.79	28.99	22.82	24.12	24.12
Adhesives	0.84	56.16	21.64	23.00	23.00
Plastic Pipes & Fittings	0.92	42.23	46.86	48.74	48.74
Polystyrene Foam Insulation	2.67	104.84	104.70	110.12	110.12
Bricks	0.05	2.07	1.57	1.66	1.92
Clay Wall & Floor Tiles (1/4" Thk)	0.42	18.99	14.38	15.20	11.34
Vitrified Clay Sewer Pipes	0.19	8.39	6.36	6.72	6.14
Flat Glass	0.19	10.60	10.29	10.62	10.62
Cement	0.03	1.91	3.13	3.23	3.23
Concrete	0.02	0.46	0.54	0.58	0.58
Gypsum, Bldg. Products	0.15	9.05	10.12	10.38	7.50
Lime	0.03	1.67	1.87	1.92	3.17
Stone	0.09	1.31	1.22	1.43	1.43
Mineral Wool Insulation	0.34	11.83	11.90	12.60	12.60
Virgin Steel	0.17	10.41	10.11	10.39	10.31
Primary Aluminum	0.65	29.19	79.30	80.17	81.95
Copper	0.76	18.76	24.67	25.77	25.77

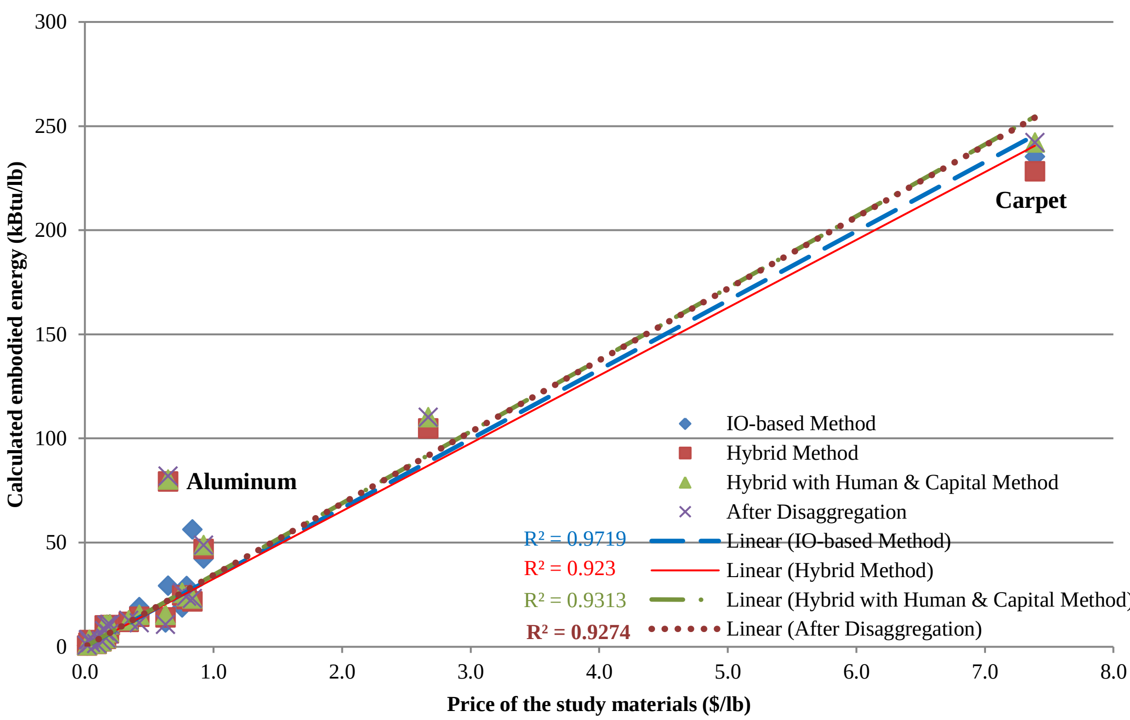


Figure 9-12: Correlation of price with embodied energy results from the input-output-based and hybrid approaches

Table 9-7: Regression analysis results for price and input-output-based results

SUMMARY OUTPUT		Price & Input-output-based Embodied Energy				
Regression Statistics						
Multiple R	0.989212					
R Square	0.978541					
Adjusted R Square	0.928541					
Standard Error	8.931565					
Observations	21					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	72754.63	72754.63	912.0224	1.6E-17	
Residual	20	1595.457	79.77286			
Total	21	74350.09				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	33.25343	1.101118	30.19971	3.68E-18	30.95654	35.55032

Table 9-8: Regression analysis results for price and input-output-based hybrid analysis results

SUMMARY OUTPUT		Price & Input-output-based Hybrid Embodied Energy					
Regression Statistics							
Multiple R	0.970574						
R Square	0.942013						
Adjusted R Square	0.892013						
Standard Error	14.65269						
Observations	21						
ANOVA							
	df	*SS*	*MS*	*F*	*Significance F*		
Regression	1	69757.66	69757.66	324.9057	2.09E-13		
Residual	20	4294.026	214.7013				
Total	21	74051.69					
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	32.56132	1.80644	18.02514	7.78E-14	28.79316	36.32949	28.79316

Because the price data were obtained from a range of sources, a correlation analysis was also done for material prices selected from the 2002 National Construction Estimator, 50th Edition (Ogershok, 2002). This was done to ensure that correlation is tested for material prices that were published by the construction cost guides. Since the study utilized the input-output data from the year 2002, the 2002 version of the cost guide was used. For a few materials, the prices could not be calculated in per unit of mass, and therefore, prices from Table 9-6 were used. Table A1-12 in Appendix A1 lists the prices obtained from the National Construction Estimator. Figure 9-13 shows a strong and positive correlation of material prices and embodied energy calculated using the four approaches. The correlation weakened slightly due to several reasons. The material prices given in the cost guide included waste factors and also the cost of additional materials such as glue, nails etc. Hence a different correlation could be expected. The results of the simple regression analysis are shown in Table 9-9 for the input-output-based hybrid method.

The values of r^2 and *p-value* in this case also supported the alternative hypothesis that the materials' prices were strongly and positively correlated to their embodied energy.

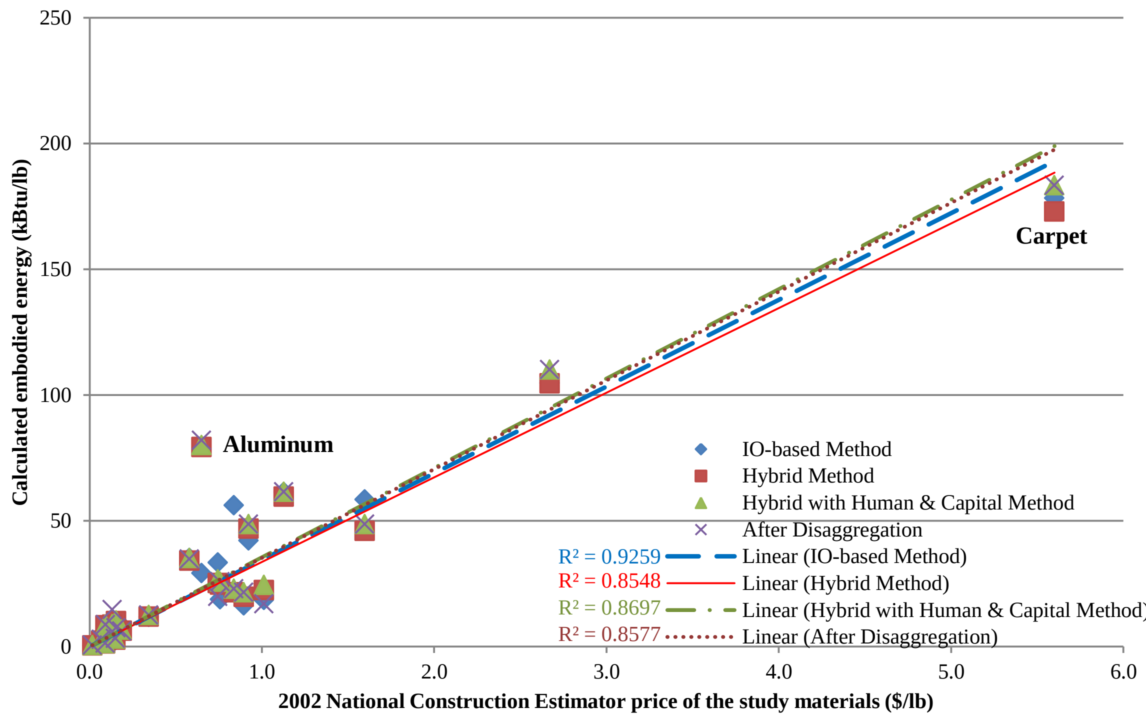


Figure 9-13: Correlation of construction cost guide price with the calculated embodied energy values

From the correlation and simple regression analysis of the study materials' cost and input-output-based hybrid embodied energy values, it can be concluded that the cost of the study materials was positively and strongly correlated to their embodied energy. This correlation was found very strong and positive in the case of material prices. When material prices were sourced from a construction cost guide, the correlation remained strong and positive. However, the correlation in the case of materials such as aluminum and carpet showed that a further validation is required by including more materials in the calculation. As seen in all three scatter plots, most of the study materials are gathered near the origin. Using the calculation method proposed by this study, more building materials can be added to further validate the correlation between a material's embodied energy and its price and cost

Table 9-9: Regression analysis results for the construction cost guide prices and input-output-based hybrid results

SUMMARY OUTPUT		2002 National Construction Estimator Price & Input-output-based Hybrid Embodied Energy						
Regression Statistics								
Multiple R	0.955835							
R Square	0.913621							
Adjusted R Square	0.863621							
Standard Error	15.9976							
Observations	21							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	54137.36	54137.36	211.5374	9.46E-12			
Residual	20	5118.467	255.9233					
Total	21	59255.82						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	33.64688	2.313402	14.54433	4.24E-12	28.82121	38.47255	28.82121	38.47255

9.4 EVALUATION OF RESULTS

9.4.1 Gap Analysis

The gap analysis was performed in order to evaluate the differences the calculated values have with other methods. As mentioned in the literature review, studies irrespective of what methods they adopted defined their system boundaries subjectively. This made their results incomparable across studies with different system boundaries. If the gap is analyzed for process-based embodied energy values with differing system boundaries, the analysis may not be comparable. In this research, we considered it appropriate to analyze the gap of process-based (direct energy) and input-output-based energy values with the values calculated using the hybrid analyses. Such analysis is more valuable because it provides a range of embodied energy value calculated using a relatively incomplete and a more complete method. In addition, we can measure how much incompleteness the process-based values might have due to a system boundary truncation. Table 9-10 shows the results of the gap analysis. The first three columns list the gap between the process-based energy values and the three hybrid approaches (calculated using Equation 3-2). In these columns, it was evident that the gaps in the embodied energy values of study materials ranged from 10% to 99% of the hybrid values, which was significant.

Table 9-10: Gap analysis results

Study Materials	Gap with Process-based Data (Direct Energy)			Gap with IO-based Data		
	IO-based Hybrid	With Human & Capital Inputs	Disaggregated Sectors	IO-based Hybrid	With Human & Capital Inputs	Disaggregated Sectors
Carpet (3/8" Thk), Level Loop	83.4%	89.5%	88.1%	-3.1%	3.0%	3.0%
Wood Lumber	49.5%	61.0%	56.1%	9.8%	21.2%	25.3%
Hardwood Plywood & Veneer	44.3%	53.1%	46.6%	17.3%	26.2%	-6.9%
Softwood Plywood & Veneer	44.3%	53.1%	49.9%	17.3%	26.2%	25.8%
Paints & Coatings	92.8%	98.5%	96.8%	-27.0%	-21.3%	-21.3%
Adhesives	82.7%	89.0%	86.8%	-159.6%	-153.3%	-153.3%
Plastic Pipes & Fittings	88.0%	92.0%	90.2%	9.9%	13.9%	13.9%
Polystyrene Foam Insulation	73.7%	78.9%	76.4%	-0.1%	5.0%	5.0%
Bricks	15.2%	20.9%	17.4%	-32.0%	-26.3%	-9.5%
Clay Wall & Floor Tiles (1/4" Thk)	15.2%	20.9%	20.3%	-32.0%	-26.3%	-53.2%
Vitrified Clay Sewer Pipes	15.2%	20.9%	22.2%	-32.0%	-26.3%	-35.5%
Glass	20.1%	23.3%	21.4%	-3.0%	0.2%	0.2%
Cement	10.0%	13.0%	10.8%	39.0%	42.0%	42.0%
Concrete	89.4%	96.5%	93.7%	16.3%	23.5%	23.5%
Gypsum, Bldg. Products	26.4%	29.0%	14.6%	10.5%	13.1%	-15.3%
Lime	26.4%	29.0%	32.5%	10.5%	13.1%	80.2%
Stone	70.4%	87.3%	77.7%	-7.0%	10.0%	10.0%
Mineral Wool Insulation	36.3%	42.2%	38.9%	0.5%	6.4%	6.4%
Virgin Steel	32.0%	34.8%	33.9%	-3.0%	-0.2%	-1.0%
Primary Aluminum	24.4%	25.5%	25.4%	63.2%	64.3%	66.5%
Copper	62.9%	67.4%	66.4%	23.9%	28.4%	28.4%

Table 9-11: Gap with process-based analysis up to two upstream stages

Study Materials	Process Analysis up to Stage 1			Process Analysis up to Stage 2		
	% Indirect Energy	% Total Energy	Incompleteness (kBtu/lb)	% Indirect Energy	% Total Energy	Incompleteness (kBtu/lb)
Carpet (3/8" Thk), Level Loop	62.6%	52.0%	125.85	32.3%	26.9%	65.04
Wood Lumber	56.1%	27.2%	0.76	33.4%	16.2%	0.45
Hardwood Plywood & Veneer	45.4%	27.9%	2.95	24.5%	15.0%	1.59
Softwood Plywood & Veneer	57.4%	26.4%	1.04	33.6%	15.4%	0.61
Paints & Coatings	44.6%	40.8%	9.85	18.0%	16.5%	3.98
Adhesives	45.1%	36.9%	8.48	18.3%	15.0%	3.44
Plastic Pipes & Fittings	42.0%	36.4%	17.76	15.9%	13.8%	6.73
Polystyrene Foam Insulation	45.8%	33.3%	36.68	17.2%	12.5%	13.80
Bricks	52.7%	7.5%	0.14	24.9%	3.5%	0.07
Clay Wall & Floor Tiles (1/4" Thk)	52.6%	13.5%	1.53	24.6%	6.3%	0.72
Vitrified Clay Sewer Pipes	51.4%	11.8%	0.72	24.5%	5.6%	0.34
Glass	27.4%	5.7%	0.60	11.9%	2.5%	0.26
Cement	31.2%	3.3%	0.11	12.9%	1.4%	0.04
Concrete	17.5%	15.3%	0.09	6.4%	5.6%	0.03
Gypsum, Bldg. Products	44.5%	8.8%	0.66	19.5%	3.9%	0.29
Lime	22.5%	4.3%	0.14	8.8%	1.7%	0.05
Stone	36.7%	24.4%	0.35	16.2%	10.7%	0.15
Mineral Wool Insulation	39.0%	14.3%	1.80	16.3%	6.0%	0.75
Virgin Steel	33.2%	3.3%	1.14	12.6%	1.2%	0.43
Primary Aluminum	29.1%	7.2%	5.86	9.9%	2.4%	1.99
Copper	50.3%	32.0%	8.24	24.9%	15.9%	4.09

According to the literature (e.g., Treloar, 1998; Crawford, 2004; Acquaye, 2010), the process-based analysis could go up to one stage in the upstream in the case of a building material. With this in mind, consider a case of the lowest gap (11%), which was for the hybrid values of cement production. If a process-based analysis is performed covering the indirect inputs up to stage 1, then according to the results of this study, nearly 69% of the indirect inputs would be accounted for. This leaves a gap or incompleteness of 31% in the total indirect impacts. If the highest gap (99% for paints and coating) is considered, this incompleteness could reach up to 45% of the total indirect impacts. Table 9-11 provides the incompleteness as a percentage of the study materials' indirect energy and the total embodied energy if a process-based analysis is carried out up to stage 1 and 2 in the upstream. According to Lenzen (2000) and Mattila et al. (2010), the process-based analyses could have up to 50% incompleteness in the embodied energy calculation due to system boundary truncation. The results of this study support their assertion.

Based on the results of this study, it can be asserted that a process-based analysis, even if performed up to stage 2, could have significant incompleteness. It is important to note that the values of incompleteness in embodied energy given in Table 9-11 are per mass of the study material. Looking at the quantities of these materials routinely used in the construction industry, the incompleteness could be large enough to cause serious errors in the calculation of the total embodied energy of a building.

The last three columns of Table 9-10 present the gap in the results of the three hybrid approaches and the input-output-based analysis (calculated using Equation 3-3). The gap ranged from -160% to 80% of the compared hybrid values. The input-output-based embodied energy values of chemical industries producing products such as paints and adhesives were quite higher than the hybrid values. One reason for this could be the variation of energy prices paid by the industry sectors. The chemical industries also consumed large amounts of petroleum products as an energy source and as a feedstock material. Looking at the chances of double counting highlighted by the literature (Treloar, 1998; Crawford, 2004), high energy intensity could be expected. The manufacturing sectors also purchased fuel to generate electricity on-site, which could be counted twice if the produced electricity and fuel use both were counted in the indirect energy calculation. In the case of most study materials, the hybrid analysis-based values were higher than the input-output-based results. This was expected due to two reasons. First, the calculated PEFs for various energy sources accounted for the direct energy of human and capital inputs and most of the indirect energy inputs. In addition, the indirect impacts of the imported energy source were included. Therefore, the calculated values of PEFs were comprehensive. Using these PEFs to convert delivered energy into primary energy could raise the total energy values. Second, the human and capital energy was counted for each industry sector that may also have contributed to the total energy intensity.

As a part of the gap analysis, the trend in calculated embodied energy values was examined for determining the range of embodied energy. Figure 9-14 shows the pattern of embodied energy values calculated using the three hybrid approaches for some of the study materials. It can be seen that some materials such as polystyrene foam insulation and copper showed a wider range of embodied energy. In the case of polystyrene foam insulation, the process-based lower value of 27.5 kBtu/lb reached 110 kBtu/lb as a result of hybrid analysis. For materials such as cement, gypsum, and glass, the embodied energy range was narrower. For instance, the process-based embodied energy of glass, which was 8.2 kBtu/lb, changed to 10.3 - 10.6 kBtu/lb if calculated using the hybrid methods. The pattern of embodied energy values was irregular in the case of materials such as paints, adhesives, and primary aluminum. Figure 9-15 illustrates the irregular pattern of embodied energy values calculated using various approaches. Table A1-14 in Appendix A1 lists the results of process, input-output and hybrid-based analyses.

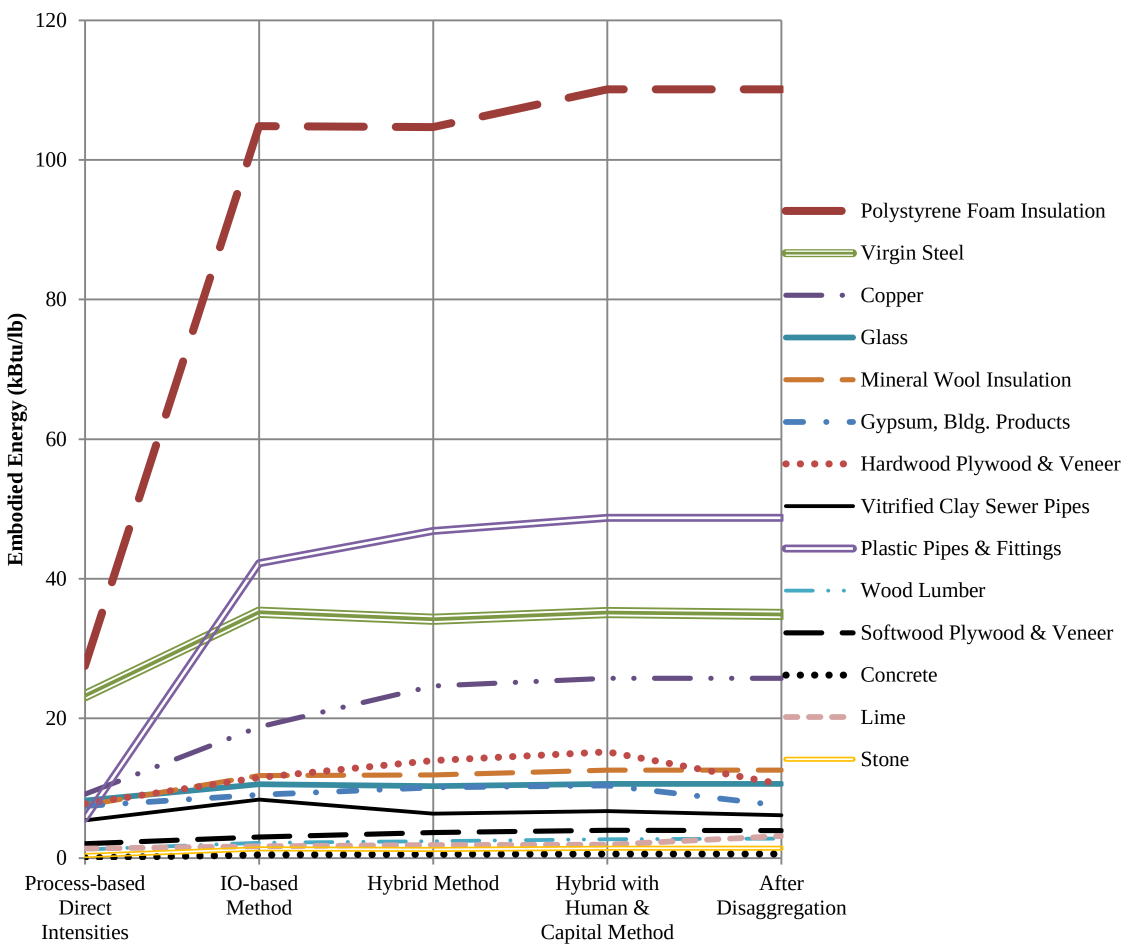


Figure 9-14: Pattern of embodied energy values calculated using different approaches

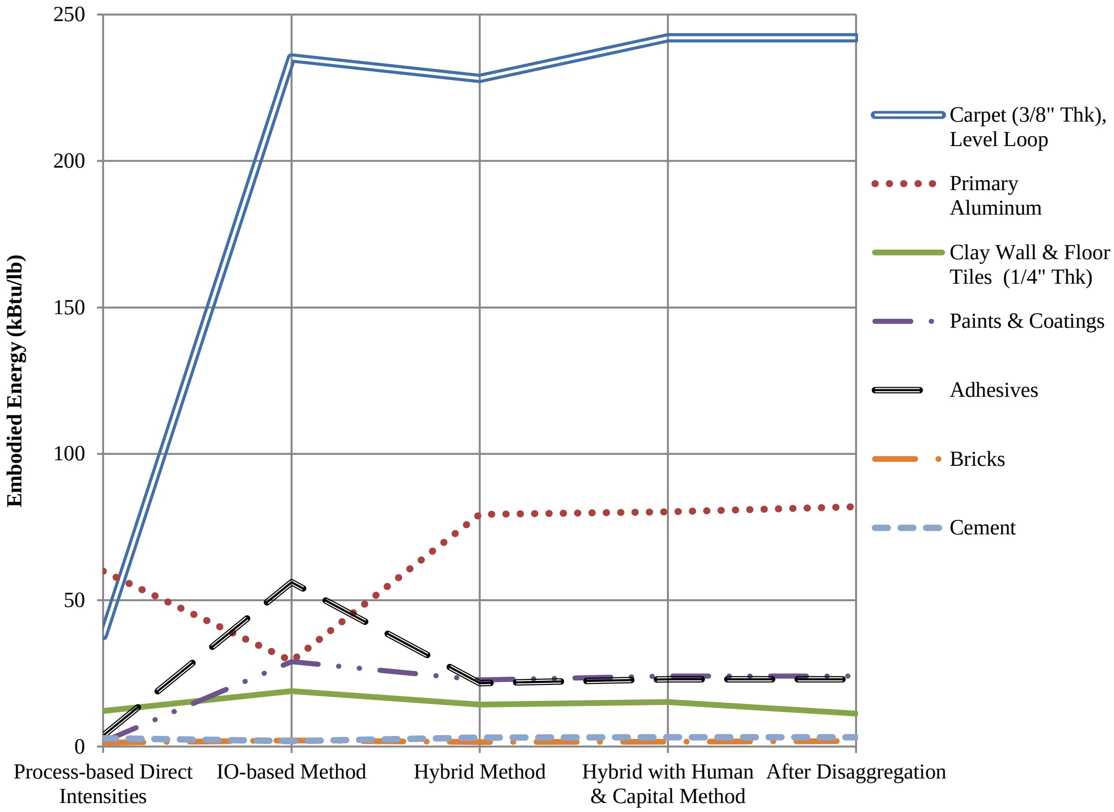


Figure 9-15: Irregular pattern of embodied energy values calculated using different approaches

9.4.2 Comparative Analysis

The comparative analysis evaluates the relationship of process energy data that replaced the comparable input-output-based values. Figure 9-16 shows a scatter plot showing the correlation of process-based energy use data with the replaced input-output-based values for all commodities produced in the United States' economy. The monetary direct requirement coefficients were converted to energy requirements by dividing them with fuel specific prices averaged over the industry sectors. These prices were calculated using the total output of the energy commodity in monetary and physical units. From Figure 9-16, it is clear that the correlation between the process energy values and the replaced input-output data was positive but weak (r^2=0.36). From the correlation analysis, it was concluded that the replaced values did not represent the actual energy use data. This meant that the input-output-based energy requirement coefficients may not represent the actual energy use. This also validated the argument (by Treloar, 1998; Crawford, 2004) that the input-output-based analysis should be augmented by inserting more process data to improve the specificity of its results.

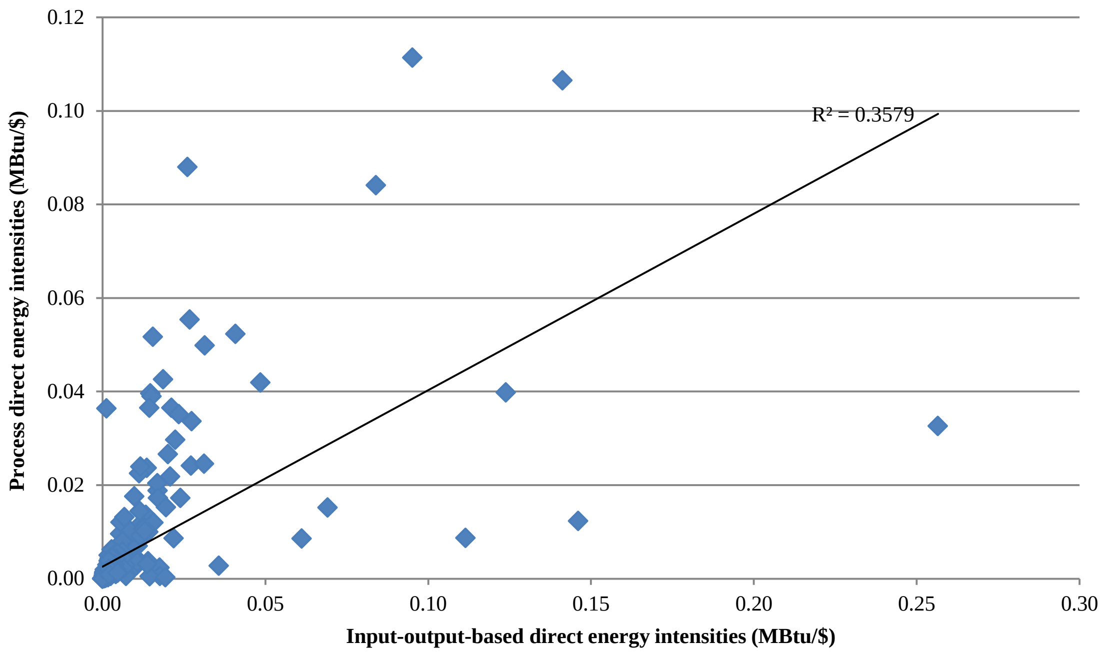


Figure 9-16: Correlation of process energy data and replaced input-output values

When process-based energy requirement coefficients were used to calculate the total energy requirements, the relationships of total energy values obtained from the input-output and hybrid analyses were also examined. Figure 9-17 demonstrates the correlation of input-output-based total energy coefficients with hybrid-based coefficients for the entire economy. The correlation (r^2=0.52) improved probably due to the fact that the variations of direct energy coefficients were lost in the aggregated total energy values. When human and capital energy inputs were added to the input-output-based hybrid model, the correlation weakened slightly (r^2=0.48). In the case of study materials such as concrete, brick, glass, stone, and mineral wool insulation, the input-output-based total embodied energy values were very close to the hybrid values (standard deviation of 0.1 - 0.4). However, when analyzed by energy source, the energy use values differed significantly (see Table 9-2). This indicated another problem with using input-output-based total energy intensities. The input-output-based total embodied energy values may not provide an accurate representation of the true environmental loadings of fuel use in the economy.

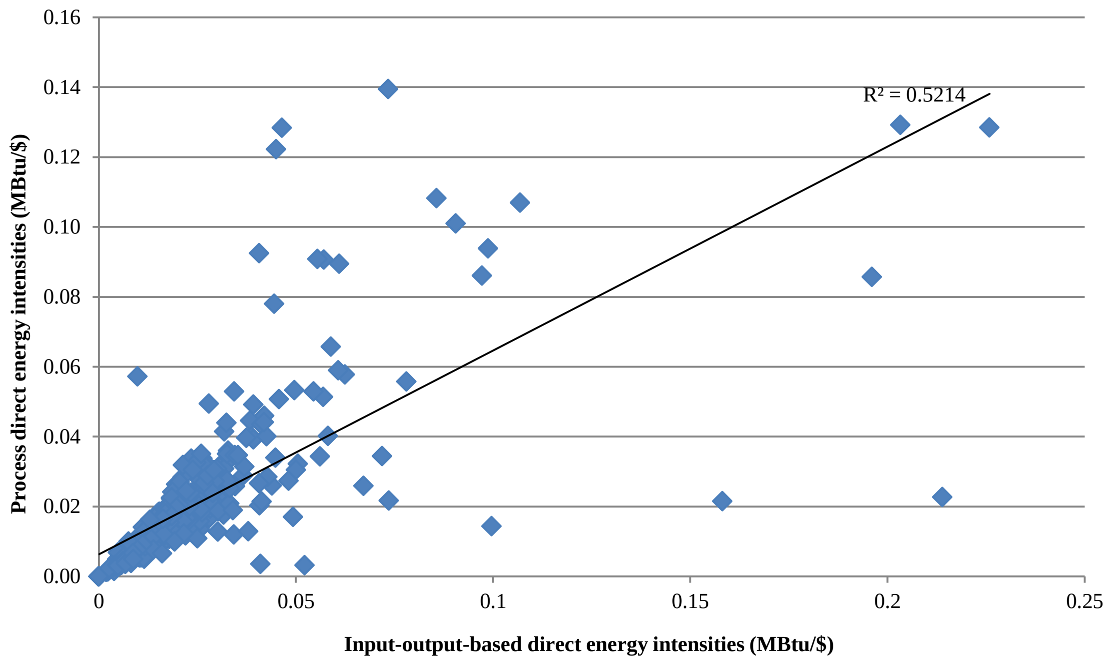


Figure 9-17: Correlation of input-output and hybrid analysis based total energy requirements

The values of total energy embodied in study materials were examined for their correlation with input-output results. Figure 9-18 shows a very strong and positive correlation (r^2=0.93-0.94) indicating that in totality, the input-output analysis may represent the trend of the total energy use. However, for quantification of embodied energy at a material or product level, an input-output analysis may not produce product specific results. The calculated values of embodied energy per unit of study materials' mass were also compared with the Inventory of Carbon and Energy (ICE) (Hammond and Jones, 2011) database originally developed by Geoffrey P. Hammond and Craig I. Jones at the University of Bath, United Kingdom. A set of the average values of embodied energy reported in the literature was also prepared for a comparison with the calculated hybrid values. The sourced average embodied energy values can be seen in Table A1-13 in Appendix A1. Figure 9-19 and Figure 9-20 demonstrate the correlation of the calculated values with the ICE and the average values from the literature, respectively. It was evident that the results of this study from the input-output-based hybrid analyses showed a positive and very strong correlation (r^2=0.9) with the ICE data. However, when the average values from the literature were compared, the correlation was found to be positive and strong (r^2=0.71 - 0.72). The embodied energy of carpet and polystyrene insulation differed in the referred literature. After removing the two outliers, the correlation became positive and very strong (r^2=0.95-0.96).

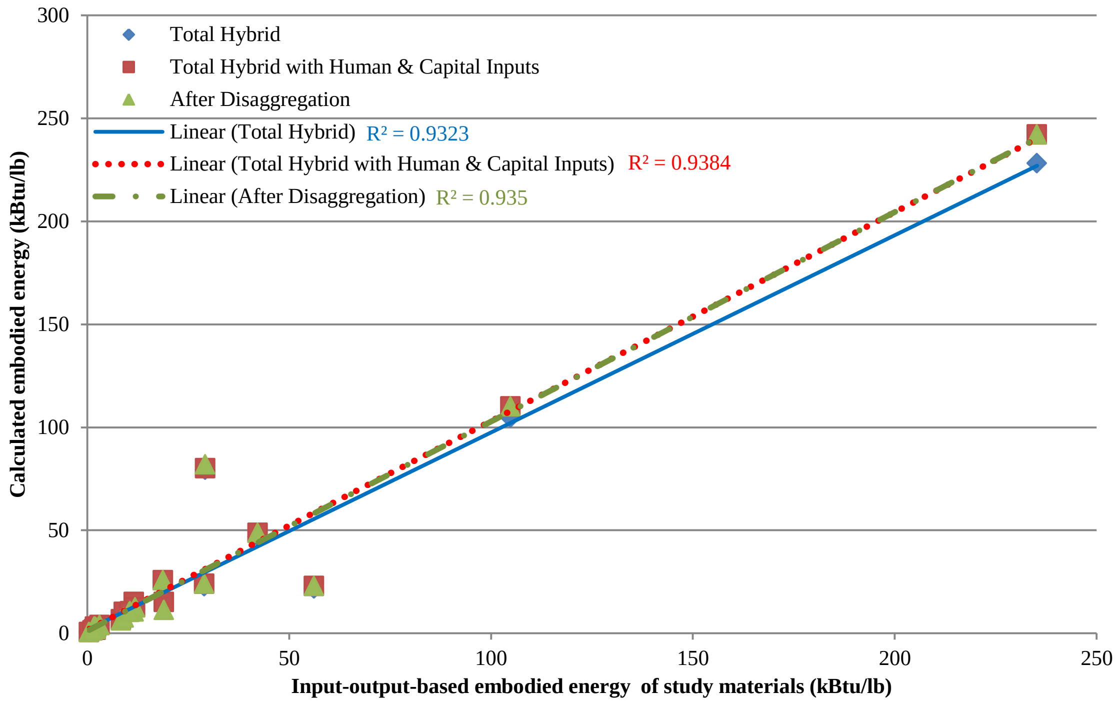


Figure 9-18: Correlation of final embodied energy values from input-output and hybrid analysis

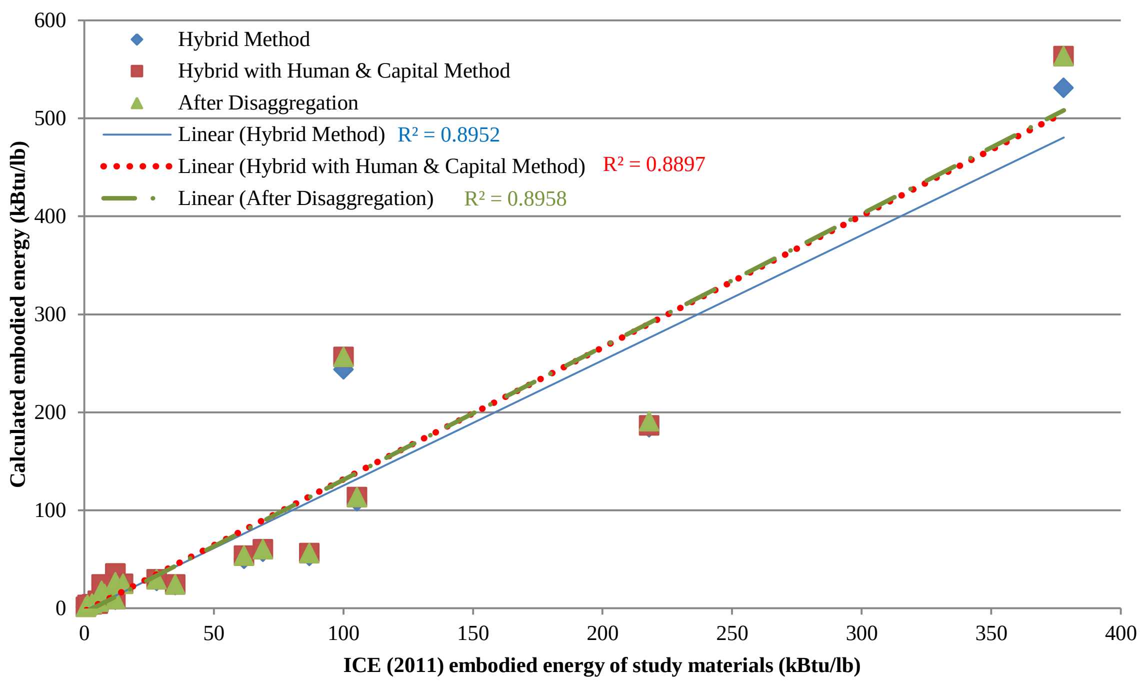


Figure 9-19: Correlation of calculated and Hammond and Jones (2011) embodied energy values

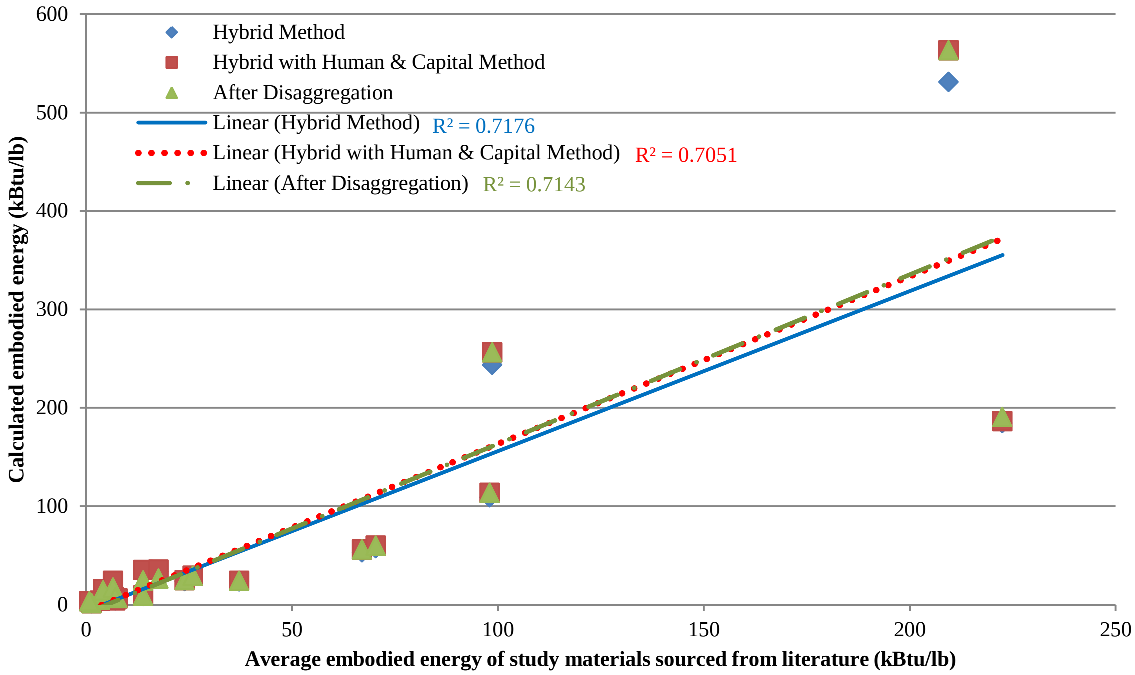


Figure 9-20: Correlation of calculated and average values of embodied energy sourced from literature

The comparative analysis indicated that the embodied energy values calculated using the three hybrid approaches in this study are positively and strongly correlated with the values published in literature. A positive and strong correlation meant a similar trend of embodied energy values. Therefore, in absolute embodied energy terms, the results of this study may differ considerably from the published values. The comparative analysis also revealed that the correlation between the total embodied energy values calculated in this study and the ones sourced from the literature was very strong and positive. However, it was concluded that the input-output-based values may not be representative of the actual environmental impacts of building materials.

CHAPTER X

DISCUSSION

10.1 GUIDELINES FOR EMBODIED ENERGY CALCULATION

The review of literature revealed a need for a set of guidelines for streamlining the embodied energy calculation process. The international standards such as ISO 14040 and ISO 14044 were developed originally for providing guidance to the process of Life Cycle Assessment (LCA). Some studies mentioned applying these standards to their research. However, literature (Suh et al., 2004; Weidema et al., 2008; Zamagni et al., 2008) supported that the ISO standards in their current form provide very little guidance to an embodied energy analysis or LCA. Some critics also said that some of the requirements mentioned in the ISO standards are open to interpretation; as a result, subjectivity has become a major issue with LCA. In this research, the four most important embodied energy parameters were streamlined. First, a definition of embodied energy was proposed based on the opinion of literature. Other related terms such as life cycle embodied energy, operating energy, and life cycle energy were also defined. The main purpose of defining these terms was to clarify and standardize their meaning. The second parameter relates to the system boundary model. A building is a large and complex product, and its design and construction is unique to each case. In defining a system to calculate the embodied energy of the building, various aspects need to be considered. If the energy use of the building is analyzed on the basis of just the initial embodied energy, the analysis may not be valid. For a comprehensive and genuine energy evaluation, it is important to perform the energy accounting of the whole life cycle of the building. In this study, various system boundary models were synthesized to propose one model that is complete.

The third parameter is embodied energy calculation method. Various methods have been proposed including process-based and input-output-based analyses. Each method has both advantages and disadvantages. As a result, various combinations of these methods were developed in order to reduce their disadvantages. However, there is still no consensus on which method to use for calculating the embodied energy. Looking at the system boundary model emphasized by the literature, an input-output-based hybrid analysis seems more appropriate. The biggest advantage of an input-output-based hybrid analysis is that it is complete. Although its results, in some cases, are regarded as less specific to the study, various approaches to address this issue were also proposed. Economic input-output models across the globe are becoming more disaggregated, and with the readily available energy data, a more robust input-output-based model could be developed in the future. Based on the results of this study, it would be fair to say that the chances of improving the specificity of an input-output-based method are greater than making a process-based analysis complete. To standardize the calculation of embodied energy, an input-output-based hybrid approach was proposed in this study.

The last parameter is about using energy and nonenergy data in the calculation. Two aspects of the used data are important: completeness and representativeness. If these aspects of the data are not clear, they should not be incorporated in the study. The guidelines for reporting results of the study were also proposed. One major issue with energy reporting is that the energy results are provided in either delivered or primary energy form without describing any conversion factors. Such results in different energy units cannot be compared, and hence, could not be applied.

10.2 EMBODIED ENERGY CALCULATION METHOD

10.2.1 Input-output Model

The latest input-output data published by the United States Bureau of Economic Analysis is available from 2002. The commodity-by-commodity matrix is highly disaggregated, and hence, provides a robust model in terms of specificity. Although assumptions of proportionality and homogeneity still exist, the process of redefinition helps reduce some of the impacts of these assumptions. The coefficient of direct requirements is the most influential parameter for calculating the total requirements. If an industry sector buys more to produce a unit dollar of its output, its indirect requirements also increase. This assertion assumes that the direct requirements govern the total requirements. While creating the model, it was observed that there may be serious issues with this assumption. For instance, there are sectors that do not consume everything they purchase, as they may be reselling the purchased materials. In monetary terms, this may be appropriate but for the energy use analysis, it may cause double counting. For sectors such as retail and wholesale trade, the total purchases from energy providing sectors are quite large. However, most of the energy may be purchased to be traded. Such aspects are not clear in the direct and total requirements.

10.2.2 Process Data of Direct Energy Use

The energy data provided for most manufacturing industries were in both the monetary and energy units, whereas for other sectors they were mostly in monetary units. However, some sector specific energy prices were also available to convert the energy use from monetary to energy units. One major issue with the energy data is that some of the data are either missing or are highly aggregated. However, input-output-based monetary flows can be used to disaggregate the total energy use. Some manufacturing sectors purchased fuel and used a fraction of it in on-site electricity production. According to MECS data, this electricity is either used by the sector completely, sold out to other sectors, or transferred to other industries within the sector. If no monetary transactions occurred, the flow of electricity may not be recorded in the input-output model. To avoid the double counting and completely account for each energy input it is important to consider only inputs that are primary energy. For instance, if all fuel purchases of an industry sector are counted, then any on-site generation of electricity can be ignored, as this energy is generated using the purchased fuel. Only the electricity purchased by the sector should be included in the calculation. Another important issue is of feedstock use of energy sources. Fossil fuels such as petroleum are extensively used as raw materials. In 2002, nearly 60%, 35%, and 10% of the total use of petroleum, coal, and natural gas was as raw materials, respectively. As these purchases are recorded in the input-output model, they are assumed as consumption and counted in the total energy intensity of a sector. However, the fraction of a fuel that is used as a raw material is actually not combusted. Hence, from a carbon emission standpoint, including feedstock energy may not be relevant. However, if carbon emission is counted in the life cycle terms, inclusion of feedstock energy makes sense because the stored fuel would release carbon whenever it would be burnt or disposed of to the landfills. In this study, we counted all energy and nonenergy use of fuels.

10.2.3 Primary Energy Factors (PEFs)

The values of PEFs were calculated using the input-output-based hybrid approach for each energy source. Using PEFs can avoid the counting of energy inputs multiple times. As mentioned earlier, if a PEF is applied to embodied energy calculation, it should be calculated rather than obtained from a secondary source. As all of the energy and nonenergy inputs were kept at zero in the input-output model, a PEF should account for all these inputs.

In this study, the PEFs for primary fuels such as coal, crude oil, and natural gas were calculated first and used later in deriving PEFs for delivered electricity, dry natural gas, and refined petroleum. One of the important aspects of PEF calculation was the treatment of energy imports. For instance, more than 60% of the United States' daily total supply of oil came from other countries in 2002. The imported energy was assumed to be extracted and processed domestically. This assumption was reasonable to account for all energy used in extracting and delivering the imported primary energy. In addition, the energy of human and capital inputs was also added to the total PEF calculation. The values of PEF were calculated using three approaches. Figure 10-1 shows the calculated PEFs by fuel using the three approaches. The first two approaches were process-based and input-output-based hybrid analyses in which input-output and process data were used to fill the gap in the energy impacts of energy sectors. The third approach was purely input-output-based and utilized the average energy prices. The results of the first two approaches seemed consistent, whereas they varied in the third approach. Major variations occurred in the case of delivered energy such as dry natural gas, refined petroleum, and electricity. This was due to the double counting of energy inputs inherent in an input-output model, as the delivered energy sectors received large quantities of primary fuel. Table 10-1 provides a comparison of the calculated values with those published in the literature. It can be seen that the values of PEF calculated in this study are higher than the reported values. The PEF calculation, in this research, accounted for all indirect energy impacts, human energy, capital energy, and energy of imports. Inclusion of these inputs caused the calculated values of PEF to differ from the published values. As indicated in the literature, the energy conversion efficiency is getting better with time due to improved technology. This means that the PEFs for years later than 2002 are expected to be smaller. In addition, the system boundary differences also caused variations in the reported values of PEFs.

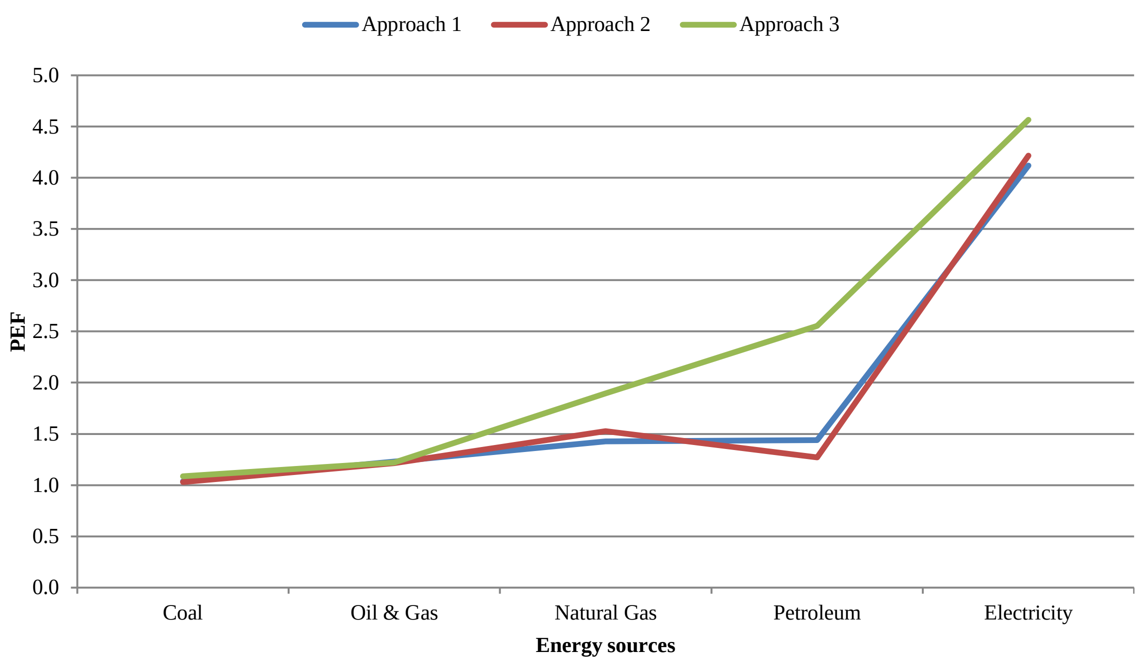


Figure 10-1: The calculated values of PEFs for various energy sources

Table 10-1: Calculated and published values of PEFs

United States Primary Energy Factors: Comparison with Published Values				
Sources	Electricity	Coal	Oil	Natural Gas
This Study (2002)	**4.12**	**1.04**	**1.44**	**1.43**
Energy Star, 2011	3.34	1.00	1.01	1.05
Ueno & Straube, 2010	3.37		1.16	1.09
Czachorski et al., 2009	3.13		1.13	1.09
Deru & Torcellini, 2007	3.32	1.06	1.18	1.09
DEQ, 2004	3.20	1.12	1.05	1.12
AGA, 2000	3.10		1.20	1.10

10.2.4 Modifications to Input-output Matrix

Although the United States' economic input-output accounts were highly disaggregated, three improvements were performed in the model. First, the process energy data were directly inserted in the *use table*. This avoided using the national average energy prices. However, in the case of the sectors such as service industries, energy data were available in monetary units. Instead of using energy prices, we allotted the total energy use to each sector using the share of each in the total energy purchases using the input-output data.

Second, human and capital energy inputs were also added to each industry. Although the energy of food was calculated in detail, the energy embodied in other expenses was estimated deriving a fixed percentage. For instance, nearly 27 - 30% of other expenses such as clothing and transportation were allotted to the employment. This area of research still needs a lot of work, as estimation based on a fixed percentage may not be representative. The capital investment accounts are not published in a timely manner. The energy embodied in capital goods can be calculated by gathering the data about the capital investments in buildings, automobiles, equipment, and software using a variety of sources. A detailed account of capital expenses was only available for a few sectors such as manufacturing. The argument given in the literature (e.g., Gao et al., 2001; Alcorn, 1997 cited by Crawford, 2004) that the energy embodied in human and capital goods may not be significant was not supported by the results of this study. In some sectors, producing items such as dimension stone, the embodied energy of human and capital inputs accounted for nearly 15% of the total embodied energy. This is significant especially in the case of countries such as India and China where the industry sectors are still more labor intensive. In this study, the lowest fraction of human and capital energy was 1.1% for primary aluminum, which was probably due to a much higher use of other energy sources.

Third, some of the industry sectors that produced more than one item were disaggregated to produce material-specific embodied energy results. Joshi (1998) discussed various models that can be introduced to modify the input-output tables for obtaining the desired results. The detailed input and output information was available from the USCB. However, this information was of little help, as most inputs were clumped together under the category of "not specified by kind" or "nsk." The change in total embodied energy due to disaggregation was within a range of 0.4% to 66%. Table 10-2 lists values of various embodied energy components before and after disaggregation. It can be seen that in some cases, the disaggregation may result in significant changes to the total energy intensities.

It was observable that the energy intensity was reduced only when the other products manufactured by the industry sectors were more energy intensive than the material under study. For instance, the intensity of virgin steel production reduced slightly due to a higher energy intensity of ferro-alloy products. The energy intensity per dollar of a material's output is governed by not only the material's share in the total energy use but also its share in the total output.

Table 10-2: Embodied energy components before and after disaggregation

Study Material	Direct Energy (kBtu/$)		Indirect Energy (kBtu/$)		Total Energy (kBtu/$)		% Change in Total Energy
	Before Disagg.	After Disagg.	Before Disagg.	After Disagg.	Before Disagg.	After Disagg.	
Wood, Lumber	10.2	11.1	10.6	10.5	20.8	21.6	-3.6%
Hardwood Plywood & Veneer	13.2	6.5	11.0	10.3	24.2	16.8	30.4%
Softwood Plywood & Veneer	13.2	13.0	11.0	11.1	24.2	24.1	0.4%
Bricks	30.2	35.7	5.7	5.9	35.9	41.6	-15.9%
Clay Wall & Floor Tiles	30.2	19.9	5.7	6.9	35.9	26.8	25.4%
Vitrified Sewer Pipes	30.2	25.2	5.7	7.5	35.9	32.8	8.7%
Gypsum, Building Products	49.1	39.1	18.3	9.6	67.4	48.8	27.7%
Lime	49.1	90.2	18.3	21.4	67.4	111.6	-65.5%
Steel	40.7	40.2	19.9	20.0	60.6	60.1	0.8%
Aluminum	92.8	95.2	30.7	31.1	123.5	126.3	-2.2%

10.2.5 Embodied Energy Results and Evaluation

The calculated values of embodied energy intensities were provided for each fuel by the upstream stages of the study material. Reporting of energy results by energy source has environmental significance, as these intensities can be used to determine the total carbon emission due to the manufacturing of study materials. However, issues such as the feedstock energy of study materials should be taken into account while estimating the emissions. The energy reporting by energy source also points out the critical materials, production of which involves more use of energy sources such as coal and electricity, which are among the largest contributors to the total carbon emission. It also shows the opportunities for improvements in the manufacturing process in order to reduce the consumption of carbon intensive fuels. The reporting of results by stage was done to highlight the importance of completeness that an input-output-based hybrid analysis provides. As mentioned in Section 9.4.1, even if a process-based analysis is conducted completely up to stage 1 in the upstream, a considerable fraction of the total indirect energy could be left behind. For a complex product such as a building, due to the enormity of indirect inputs, this incompleteness could be large enough to cause serious errors in the final embodied energy results.

The final results of embodied energy were listed per unit of mass of the materials under study. As energy prices and costs were used, some issues such as price variations could influence the quality of the end results. One option to avoid the use of product prices is to gather the total commodity output in physical units. If this data are readily available, it can then divide the total energy use of the commodity sector to quantify the embodied energy per unit of mass or volume using Equation 3-1. Unfortunately, data on actual quantities of production in physical units are not readily available for most of the materials. Availability of detailed monthly product prices can also help reduce the uncertainties associated with using the product prices for energy calculation.

The calculated values were found to be in accordance with the published values. Their strong and positive correlation demonstrated a similar pattern of energy intensities to the published results. Some values varied most probably due to the product price variations. For instance, the embodied energy of aluminum, when calculated using the aluminum price, was roughly 80.0 kBtu/lb. When the aluminum cost (calculated using Equation 3-1) was used, the total embodied energy was approximately 175 kBtu/lb. These results pointed out a serious problem with converting energy intensities per unit of dollar to per unit of mass. Solving this problem does not require more research at the embodied energy calculation level but a detailed and accurate reporting of production data in physical units. The energy intensities resulted from the hybrid approaches were complete and consistent in their results. The problem arises when these are converted to embodied energy per unit of mass. Another issue with using product prices relates to the aggregated sectorial output. For instance, in the case of steel manufacturing, both the raw steel and other structural shapes (rebar, I-section, round pipe, etc.) were manufactured. If the price of steel is used, it may underestimate the embodied energy of structural shapes. There may be an overestimation of embodied energy of raw steel if the price of structural shapes is used. A weighted average price can be calculated on the basis of proportion of each in the total output and used in the calculation but it may not be representative of their actual prices.

The input-output data on energy use did not represent the actual energy use as indicated by the comparative analysis. There could be several reasons for this as stated earlier in Section 9.2.1. The double counting of energy inputs and the complexity of energy transfer within the sectors are among them. If the total embodied energy calculated by input-output analysis and by input-output-based hybrid analysis are compared, they were positively and strongly correlated. Their absolute values per unit of mass may not be close, but the pattern of energy per unit of mass was quite similar. The hypotheses' tests revealed a positive and strong correlation between the price (and cost) and the embodied energy of the study materials. This finding is significant, especially looking at the studies that suggested a strong and positive correlation between the energy and the cost. However, the correlation of material cost and price with the embodied energy needs further validation in order to use the material cost and price as predictors of the embodied energy.

CHAPTER XI

CONCLUSIONS

The impact of a growing global population and a rising standard of living are exerting pressure on the globe's capacity to maintain a balanced natural capital. With more people migrating from rural to urban areas in the future, the situation of resource consumption would only get worse. The use of energy, mostly fossil fuels, for fuel and non-fuel purposes is getting bigger and bigger. The construction industry, particularly buildings that currently consume an extensive amount of energy can bring a significant change if the whole life cycle energy use of buildings is optimized. For this purpose, both the operating and embodied energy use over a building's life cycle should be reduced. However, the focus of energy research remained mostly on the optimization of operating energy. There were several reasons for this. The existing embodied energy data are either not available or available with issues of inconsistency, incompleteness, and non-representativeness. To add to the problems, no efforts have been made to define the term "embodied energy." Very little guidance is available to calculate embodied energy in a standard manner. There are no guidelines that can streamline the embodied energy calculation by consistently defining the system boundaries and by using quality data. The available methods for energy calculation have various advantages and disadvantages. Some remarkable efforts by Stein et al. (1981), Treloar (1998), and Crawford (2004), helped in developing a method that is complete and can provide more study-specific results. However, there were still areas of improvement in the proposed methods.

In this research, an input-output-based hybrid approach was developed to calculate the embodied energy of construction materials. A set of guidelines for standardizing the process of embodied energy analysis was also proposed. The current form of input-output-based hybrid analysis can be improved by inserting process energy data. A thorough understanding of input-output accounts and energy flows in the economy is vital to avoid issues such as double counting of inputs. It was found that the use of PEFs, originally proposed by Treloar (1998), can avoid the issue of double counting of energy sources. It was also concluded that the PEFs should be calculated in a complete manner ensuring that all direct and indirect inputs associated with an energy source extraction, processing, and delivery are included in the factors. In addition, human and capital energy inputs not only can be quantified but also can be incorporated into the economic model. Based on the results of this study, it was concluded that the energy embodied in these inputs could be significant (up to 15% of the total), and hence, should not be ignored. It was also found that the results of an input-output-based hybrid approach can be made more product-specific in the future. However, achieving the same degree of completeness in a process-based analysis seems impractical. For instance, it was demonstrated that if detailed information on sectorial inputs and outputs is available, the process of sector disaggregation can be used to improve the specificity of the embodied energy results. Currently, the availability of detailed information on inputs and outputs of industry sectors is limited. However, in the future, this information may be readily available.

Conventionally, prices of products are sourced to convert the energy intensities per dollar to energy use per mass or volume. As the prices could be underestimated or overestimated, the end results may have uncertainties. An approach to calculate the energy intensity per unit of mass was also proposed but it requires reliable data on the total production in physical units, which is only available for some industry sectors currently. A significant portion of the total fuel use was consumed as a raw material, which should be noted especially when using the embodied energy to quantify the resulting carbon emissions.

The relationship of embodied energy and cost of a product has been highlighted in the literature. Costanza (1980) had supported the positive correlation of cost and embodied energy. Recently, Ding (2004) and recently Langston (2006) found a strong and positive correlation between the capital cost and the total embodied energy of a building. However, when the analysis was performed at a component or product level the correlation weakened. In this research, it was hypothesized that there is a strong and positive correlation between the price (and cost) and embodied energy of a product. The input-output-based hybrid approach was modified to calculate the energy embodied in 21 commonly used building materials to test the hypotheses. Based on the results, it was concluded that the price and cost of a product shared a strong and positive correlation with its total embodied energy. Hence, the cost or a price of a product can be used for determining the total energy impacts of manufacturing and using a product. This finding is significant especially when looking at the three dimensions of a sustainable system: economics, environment, and society. In a life cycle term, monetary savings could mean proportional savings in the energy use. However, before prediction the embodied energy form the cost and price, a validation of positive correlation by incorporating more materials should be done. In addition, it should also be checked if the relationship is linear or nonlinear. A widely used information tool such as the Computer-Aided Design (CAD) or Building Information Model (BIM) can be used to estimate the total embodied energy of a construction project, if embodied energy can be predicted from the cost data. This not only can simplify the whole embodied energy calculation process but also help in its widespread application in the process of whole building energy accounting.

To summarize, three main improvements were done to the current form of the input-output-based hybrid analysis. First, the actual energy use data in energy units was inserted into the input-output model. Second, the energy embodied in human and capital inputs was quantified and added to the input-output model. Third, the process of sector disaggregation was demonstrated using the 2002 Benchmark Input-output data. In addition, in this research, the PEF for each energy source was calculated in a complete manner. Also, A method is proposed to convert the energy intensities per unit of monetary output into the embodied energy per unit of mass without using the volatile material and energy prices. Among the most significant values of this research was the demonstration that the energy embodied in a product can be calculated in a complete and standardized manner with results specific to the product under study. One of the biggest surprises of this study was the positive and strong correlation of a material's price and its embodied energy. The fact that the correlation became stronger after adding the human and capital inputs was also surprising. This fact also suggested that adding more and more missing inputs (e.g. human and capital inputs) to the input-output-model would make it more robust for the use of embodied energy analysis.

11.1 FUTURE RESEARCH

A further investigation into the correlation of cost and price with embodied energy is necessary. A correlation analysis by material types such as metal, minerals, and plastic products may also be useful in deriving an equation to predict embodied energy from cost and price data. This study can also be extended to include more construction materials in the research to test the correlation of material prices and costs with embodied energy. A series of equations then can be derived to develop a tool that can be used to calculate the energy embodied in a product using its cost or price. At this stage, a rigorous evaluation of results would be necessary. A case study of a wide range of construction materials can be performed to investigate whether the results of the tool are reliable.

Such tools can be integrated into a CAD or a BIM platform. Currently, there is no single tool that can perform the whole building energy accounting. For instance, if an embodied energy tool is used to select a low embodied energy material, it is still not known what effects this material may have on a building's operating energy. For doing that, one needs to use another tool that can simulate the operating energy performance. In the whole process one may end up switching back and forth between the embodied and operating energy tools. The whole process becomes not only tedious but also time and resource consuming. If a single information tool, such as BIM, can be augmented with capabilities to evaluate the embodied and operating energy performance, it could save a significant amount of time and resources.

Another venue for future research lies in the field of input-output analysis. A more robust approach can be developed to disaggregate the industry sectors so that more product-specific values of embodied energy can be calculated in a complete manner. If capital expenditure accounts are available in a timely manner, they can be inserted into the economic model to account for capital energy in the total embodied energy in a more reliable manner.

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APPENDIX A1

TABLES

Table A1-1: Life cycle energy of brick buildings

			Reported Service Life (Years) and Embodied Energy (MJ/m^2/year)				
Study	Building Type	Construction	Service Life	IEE	REE	OE	DE
Barnes & Rankin (1975)	Residential	Brick	25	92.27	20.80	449.07	
Kohler et al. (1997b)	Residential	Brick	100	90.00	140.00	1200.00	1.50
Newton et al. (2000)	Residential	Brick	80	62.33	53.75	121.67	
Treloar et al. (2001b)	Residential	Brick	30	390.67	125.00	840.00	
Randolph et al. (2006)	Residential	Brick	60	127.50	67.64	274.31	
Utama & Gheewala (2008)	Residential	Brick	40	25.25	20.00	273.75	
Utama & Gheewala (2009)	Residential	Brick	40	22.60	1.60	84.88	
Fay et al. (2000)	Residential	Brick	25	305.21	179.25	1005.33	
Treloar et al. (2000b)	Residential	Brick	30	390.67	125.00	840.00	
Shukla et al. (2009)	Residential	Brick	40	104.00	14.75	0.00	
Fay & Treloar (1998)	Commercial	Brick	25	298.96	179.25	1005.33	
Average Values				173.59	84.28		

Table A1-2: Life cycle energy of concrete buildings

			Reported Service Life (Years) and Embodied Energy (MJ/m^2/year)				
Study	Building Type	Construction	Service Life	IEE	REE	OE	DE
Fay et al. (2000b)	Residential	Concrete	100	169.60	120.00	90.00	
Lippke et al. (2004)	Residential	Concrete	75	26.40	7.33	305.33	0.47
Winistorfer et al. (2005)	Residential	Concrete	75	29.33	7.33	315.00	0.47
Newton et al. (2000)	Residential	Concrete	80	64.96	50.08	144.44	
DINCEL (2009)	Residential	Concrete	50	89.10	42.80	148.00	
Utama & Gheewala (2008)	Residential	Concrete	40	24.13	1.85	310.75	
Utama & Gheewala (2009)	Residential	Concrete	40	21.80	0.55	112.75	
Humphrey et al. (2004)	Residential	Concrete	50	147.66	201.80	305.69	1.39
Kernan (1996)	Commercial	Concrete	100	47.37	71.37	666.53	0.47
Suzuki & Oka (1998)	Commercial	Concrete	40	223.75	38.50	1210.00	12.25
Citherlet & Hand (2002)	Commercial	Concrete	80	76.25	130.00	512.50	10.00
Junnila et al. (2006)	Commercial	Concrete	50	125.40	70.70	1140.00	9.30
John et al. (2008)	Commercial	Concrete	60	56.30	6.75	533.17	5.25
Cole & Kernan (1996)	Commercial	Concrete	50	93.10	128.70	1351.50	
Jaques (1996)	Commercial	Concrete	50	89.00	44.20	360.00	
Eaton et al. (1998)	Commercial	Concrete	60	150.00	243.33	1158.33	
Treloar et al. (2001d)	Commercial	Concrete	40	434.50	143.50	401.50	
Junnila et al. (2006)	Commercial	Concrete	50	125.40	70.70	1140.00	9.30
Page (2006)	Commercial	Concrete	50	61.20	1.85	416.20	
Fernandez (2008)	Commercial	Concrete	60	72.58	11.17	301.67	
Shen (2010)	Commercial	Concrete	50	222.00	37.60	630.00	
Average Values				111.90	68.10		

Table A1-3: Life cycle energy of steel buildings

	Reported Service Life (Years) and Embodied Energy (MJ/m^2/year)						
Study	Building Type	Construction	Service Life	IEE	REE	OE	DE
Lippke et al. (2004)	Residential	Steel	75	44.80	5.33	541.60	0.53
John et al. (2008)	Commercial	Steel	60	72.58	8.63	543.17	2.70
Cole & Kernan (1996)	Commercial	Steel	50	99.90	131.60	1351.50	
Eaton et al. (1998)	Commercial	Steel	60	149.58	243.33	1159.58	
Pullen (2000c)	Commercial	Steel	60	201.67	141.67	1570.00	
Page (2006)	Commercial	Steel	50	46.60	3.15	416.20	
Fernandez (2008)	Commercial	Steel	60	103.33	13.67	308.33	
Average Values				102.64	78.20		

Table A1-4: Life cycle energy of wood buildings

	Reported Service Life (Years) and Embodied Energy (MJ/m^2/year)						
Study	Building Type	Construction	Service Life	IEE	REE	OE	DE
Adalberth, 1997b	Residential	Wood	50	67.44	26.87	501.60	
Barnes & Rankin, 1975	Residential	Wood	25	34.80	8.00	510.40	
Blanchard & Reppe, 1998	Residential	Wood	50	82.77	53.07	1219.37	
Lippke et al., 2004	Residential	Wood	75	41.67	6.33	423.47	
Winistorfer et al., 2005	Residential	Wood	75	40.00	6.20	423.33	
Leckner & Zmeureanu, 2011	Residential	Wood	40	89.00	30.50	470.00	
Jaques, 1996	Residential	Wood	50	73.80	115.00	300.00	
Johnstone et al., 2001	Residential	Wood	60	45.83	24.57	334.00	
Thormark, 2002	Residential	Wood	50	107.37	16.64	164.10	
Thormark, 2006	Residential	Wood	50	81.16	23.37	219.80	
Thormark, 2007	Residential	Wood	40	91.71	23.54	213.75	
John et al., 2008	Commercial	Wood	60	38.53	6.68	554.67	
Cole & Kernan, 1996	Commercial	Wood	50	88.00	126.40	1351.50	
Page, 2006	Commercial	Wood	50	40.50	3.15	428.00	
Fernandez, 2008	Commercial	Wood	60	53.75	12.08	313.33	
Average Values				65.09	32.16		

Table A1-5: Description of referred case studies and % of embodied energy in the total LCE

Study	% of EE	Study	% of EE	Study	% of EE
Malin, 1993	15.8	Itard, 2007	28.0	Pullen, 2000a	23.6
Malin, 1993	12.2	Citherlet & Defaux, 2007	18.6	Pullen, 2000a	31.9
Malin, 1993	26.3	Citherlet & Defaux, 2007	29.7	Pullen, 2000a	36.0
Malin, 1993	20.7	Citherlet & Defaux, 2007	51.5	Pullen, 2000a	29.6
Blanchard & Reppe, 1998	10.2	Citherlet & Defaux, 2007	14.8	Pullen, 2000a	36.8
Blanchard & Reppe, 1998	25.8	Citherlet & Defaux, 2007	20.8	Pullen, 2000a	25.3
Shaw et al., 1998	4.7	Citherlet & Defaux, 2007	42.0	Fay et al., 2000	100.0
Keoleian et al., 2001	9.6	Karlsson & Moshfegh, 2007	16.6	Fay et al., 2000	38.8
Keoleian et al., 2001	26.5	Karlsson & Moshfegh, 2007	38.5	Fay et al., 2000	30.9
Olgyay & Herdt, 2004	36.4	Thormark, 2007	36.5	Fay et al., 2000	27.6
Olgyay & Herdt, 2004	23.2	Thormark, 2007	33.7	Fay et al., 2000	25.2
Lippke et al., 2004	8.6	Thormark, 2007	37.0	Fay et al., 2000	100.0
Lippke et al., 2004	9.8	Sobotka & Rolak, 2009	1.6	Fay et al., 2000	42.6
Lippke et al., 2004	10.1	Bribian et al., 2009	18.1	Fay et al., 2000	33.9
Lippke et al., 2004	11.2	Blengini, 2009	7.1	Fay et al., 2000	30.2
Winistorfer et al., 2005	10.8	Anastaselos et al., 2009	1.8	Fay et al., 2000	27.5

Winistorfer et al., 2005	10.5	Anastaselos et al., 2009	2.0	Vale et al., 2000	31.6
Winistorfer et al., 2005	9.4	Gustavsson & Joelsson, 2010	25.7	Vale et al., 2000	37.4
Baouendi et al., 2005	6.3	Gustavsson & Joelsson, 2010	10.3	Vale et al., 2000	69.2
Baouendi et al., 2005	7.2	Gustavsson & Joelsson, 2010	8.7	Fay et al., 2000b	43.3
Norman et al., 2006	14.5	Gustavsson & Joelsson, 2010	16.8	Fay et al., 2000b	76.3
Norman et al., 2006	12.9	Gustavsson & Joelsson, 2010	28.8	Newton et al., 2000	73.8
Haines et al., 2007	9.2	Gustavsson et al., 2010	9.9	Newton et al., 2000	69.6
Haines et al., 2007	11.5	Dodoo et al., 2010	1.1	Newton et al., 2000	49.7
Haines et al., 2007	15.1	Dodoo et al., 2010	1.9	Newton et al., 2000	70.2
Kim, 2008	6.8	Dodoo et al., 2010	2.4	Newton et al., 2000	62.2
Kim, 2008	5.2	Dodoo et al., 2010	2.6	Newton et al., 2000	54.7
Leckner & Zmeureanu, 2011	20.4	Dodoo et al., 2010	3.4	Newton et al., 2000	71.5
Leckner & Zmeureanu, 2011	36.8	Dodoo et al., 2010	3.7	Newton et al., 2000	62.5
Chulsukon et al., 2002	30.9	Dodoo et al., 2010	1.3	Newton et al., 2000	42.2
Chulsukon et al., 2002	30.3	Dodoo et al., 2010	2.2	Newton et al., 2000	70.7
Humphrey et al., 2004	44.4	Dodoo et al., 2010	3.0	Newton et al., 2000	59.3
Humphrey et al., 2004	62.0	Dodoo et al., 2010	3.0	Newton et al., 2000	51.6
Jeyasingh & Sam, 2004	41.5	Dodoo et al., 2010	3.9	Newton et al., 2000	45.2
Huberman & Pearlmutter, 2004	4.6	Dodoo et al., 2010	4.4	Newton et al., 2000	37.0
Huberman & Pearlmutter, 2004	26.2	Blengini & Di Carlo, 2010	18.3	Newton et al., 2000	29.4
Huberman & Pearlmutter, 2004	14.8	Blengini & Di Carlo, 2010	54.0	Newton et al., 2000	35.0
Huberman & Pearlmutter, 2004	55.5	Aste et al., 2010	14.1	Newton et al., 2000	28.6
Pearlmutter et al., 2007	81.5	Aste et al., 2010	18.8	Newton et al., 2000	25.0
Pearlmutter et al., 2007	79.4	Aste et al., 2010	46.8	Treloar et al., 2000b	38.0
Pearlmutter et al., 2007	90.9	Buchanan & Honey, 1994	38.3	Johnstone et al., 2001	17.9
Pearlmutter et al., 2007	77.3	Buchanan & Honey, 1994	73.3	Troy et al., 2003	17.3
Huberman & Pearlmutter, 2008	66.6	Buchanan & Honey, 1994	84.2	Troy et al., 2003	13.3
Huberman & Pearlmutter, 2008	54.2	Pullen, 1996	19.1	Troy et al., 2003	18.9
Huberman & Pearlmutter, 2008	57.0	Pullen, 1996	32.7	Troy et al., 2003	18.1
Huberman & Pearlmutter, 2008	53.4	Pullen, 1996	37.2	Troy et al., 2003	16.7
Huberman & Pearlmutter, 2008	53.4	Pullen, 1996	32.3	Troy et al., 2003	74.1
Huberman & Pearlmutter, 2008	57.6	Pullen, 1996	29.4	Troy et al., 2003	16.9
Utama & Gheewala, 2008	14.2	Pullen, 1996	47.6	Troy et al., 2003	14.4
Utama & Gheewala, 2008	7.7	Pullen, 1996	87.4	Mithraratne & Vale, 2004	26.0
Utama & Gheewala, 2009	16.5	Pullen, 1996	40.7	Mithraratne & Vale, 2004	29.3
Utama & Gheewala, 2009	31.4	Pullen, 1996	31.1	Mithraratne & Vale, 2004	42.6
Chel & Tiwari, 2009	12.2	Pullen, 1996	27.0	Duell & Martin, 2005	66.7
Barnes & Rankin, 1975	10.7	Pullen, 1996	42.3	Duell & Martin, 2005	69.3
Barnes & Rankin, 1975	7.7	Pullen, 1996	46.7	Duell & Martin, 2005	71.2
Barnes & Rankin, 1975	29.0	Pullen, 1996	40.7	Duell & Martin, 2005	66.7
Barnes & Rankin, 1975	25.4	Pullen, 1996	33.3	Duell & Martin, 2005	69.3
Fossdal & Edwardson, 1995	4.9	Pullen, 1996	55.2	Duell & Martin, 2005	71.5
Fossdal & Edwardson, 1995	3.6	Jaques, 1996	6.2	Page, 2006	21.2
Feist, 1996	53.7	Jaques, 1996	38.6	Page, 2006	20.3
Feist, 1996	31.5	Fay & Treloar, 1998	100.0	Page, 2006	28.4
Feist, 1996	17.3	Fay & Treloar, 1998	38.4	Page, 2006	7.8
Kohler et al., 1997b	16.2	Fay & Treloar, 1998	30.6	Page, 2006	6.3
Adalberth, 1997b	17.1	Fay & Treloar, 1998	27.4	Page, 2006	8.6
Adalberth, 1997b	15.8	Fay & Treloar, 1998	25.1	Randolph et al., 2006	37.5
Adalberth, 1997b	15.6	Fay & Treloar, 1998	100.0	Randolph et al., 2006	35.9
Winther & Hestnes, 1999	28.3	Fay & Treloar, 1998	42.2	Randolph et al., 2006	38.2
Winther & Hestnes, 1999	11.3	Fay & Treloar, 1998	33.6	Randolph et al., 2006	34.4
Winther & Hestnes, 1999	7.7	Fay & Treloar, 1998	30.0	Randolph et al., 2006	44.9
Winther & Hestnes, 1999	5.1	Fay & Treloar, 1998	27.4	Randolph et al., 2006	49.7
Winther & Hestnes, 1999	8.8	Pullen, 2000a	22.4	Randolph et al., 2006	44.3
Thormark, 2002	49.6	Pullen, 2000a	29.1	Randolph et al., 2006	50.3
Thormark, 2002	39.8	Pullen, 2000a	16.7	Randolph et al., 2006	40.3
Thormark, 2002	38.4	Pullen, 2000a	21.3	Randolph et al., 2006	32.6
Citherlet & Hand, 2002	27.6	Pullen, 2000a	29.7	Randolph et al., 2006	50.5
Citherlet & Hand, 2002	31.9	Pullen, 2000a	31.9	Randolph et al., 2006	53.7
Almeida et al., 2005	29.9	Pullen, 2000a	24.3	Langston & Langston, 2007	20.5
Almeida et al., 2005	40.1	Pullen, 2000a	15.0	Langston & Langston, 2007	19.9
Almeida et al., 2005	41.5	Pullen, 2000a	31.3	Langston & Langston, 2007	21.4

Almeida et al., 2005	47.8	Pullen, 2000a	32.9	Langston & Langston, 2007	25.4
Thormark, 2006	39.8	Pullen, 2000a	25.2	Langston & Langston, 2007	20.4
Thormark, 2006	30.4	Pullen, 2000a	34.1	Langston & Langston, 2007	21.3
Thormark, 2006	28.7	Pullen, 2000a	25.5	Langston & Langston, 2007	15.7
Thormark, 2006	41.6	Pullen, 2000a	21.5	Perkins et al., 2009	32.9
Thormark, 2006	31.3	Pullen, 2000a	39.0	Perkins et al., 2009	38.2
Thormark, 2006	28.9	Pullen, 2000a	32.9	Perkins et al., 2009	44.5
Thormark, 2006	36.5	Pullen, 2000a	34.3	DINCEL, 2009	32.8
Thormark, 2006	25.1	Pullen, 2000a	26.7	DINCEL, 2009	56.4
Thormark, 2006	22.8	Pullen, 2000a	22.4		

Table A1-6: Comparing construction sub-sector classification by USBEA and USCB

2002 Economic Census Construction Subsectors	
2002 NAICS	Description
236115	New single-family housing construction (except operative builders)
236116	New multifamily housing construction (except operative builders)
236117	New housing operative builders
236118	Residential remodelers
236210	Industrial building construction
236220	Commercial and institutional building construction
237110	Water and sewer line and related structures construction
237120	Oil and gas pipeline and related structures construction
237130	Power and communication line and related structures construction
237210	Land subdivision
237310	Highway, street, and bridge construction
237990	Other heavy and civil engineering construction
238110	Poured concrete foundation and structure contractors
238120	Structural steel and precast concrete contractors
238130	Framing contractors
238140	Masonry contractors
238150	Glass and glazing contractors
238160	Roofing contractors
238170	Siding contractors
238190	Other foundation, structure, and building exterior contractors
238210	Electrical contractors and other wiring installation contractors
238220	Plumbing, heating, and air-conditioning contractors
238290	Other building equipment contractors
238310	Drywall and insulation contractors
238320	Painting and wall covering contractors
238330	Flooring contractors
238340	Tile and terrazzo contractors
238350	Finish carpentry contractors
238390	Other building finishing contractors
238910	Site preparation contractors
238990	All other specialty trade contractors
2002 Benchmark Input-Output Construction Subsectors	
230101	Nonresidential commercial and health care structures
230102	Nonresidential manufacturing structures
230103	Other nonresidential structures
230201	Residential permanent site single- and multi-family structures
230202	Other residential structures
230301	Nonresidential maintenance and repair
230302	Residential maintenance and repair

Table A1-7: Service sectors and major service activities

NAICS	Sector Description	Activities
51	Information	Creating, processing, and distributing or transmitting the information and cultural products and rendering related services. Products and services include print and electronic media such as newspapers, magazines, periodicals, books, directories, music, sound recording, movies, other videos, videography, software, broadcasting, internet publishing, telecommunication, internet services, data processing services, libraries, and other information services.
52	Finance and insurance	Financial transactions such as creating, liquidating, and modifying ownership status of financial assets. Included are establishments such as central and other banks, lending establishments (e.g., credit unions, mortgage & real estate loans, credit card companies), securities, commodity contract establishments, insurance companies, and other related industries.
53	Real Estate, and Rental and Leasing	Renting, leasing, and selling tangible and intangible assets for others (e.g., clients) and rendering related services. Included in this sector are establishments such as lesser, real estate agents, brokers, real estate appraisers, and rental and leasing agencies.
54	Professional, Scientific, and Technical Services	Providing professional, scientific, and technical services such as legal; accounting, bookkeeping, and payroll; architectural, engineering, and related; other specialized design services; computer design; management, scientific, and technical consulting; research and development; advertising and related services; and other similar services.
55	Management of Companies and Enterprises	Include establishments such as equity holders and those who oversee, manage, or administer a company or a portfolio of companies of a government or non-government organization.
56	Administrative and Support, and Waste Management and Remediation Services	Administering and supporting routine operations of various organizations (e.g., facilities, employment, business, travel, investigation, security, building support and management). Also included are establishments engaged in waste collection, sorting, treatment, and disposal and waste remediation services.
61	Educational Services	Providing education by instruction and training in a variety of disciplines. Included are schools, junior colleges, professional schools, community colleges, and universities.
62	Healthcare and Social Assistance	Establishments such as health practitioners, clinics, hospitals, nursing homes, medical & diagnostic laboratories, blood banks, ambulance services, child & youth services, elderly care services, community food services, and child daycare centers providing healthcare and social assistance.
71	Arts, Entertainment, and Recreation	Establishments producing, organizing, promoting, or participating in live events or exhibits. Also included are establishments operating and maintaining facilities to exhibit objects and sites of historical, cultural, or educational importance. Other leisure, recreational, cultural, or hobby-related organizations are also covered in this sector. Museums, historical sites, sports arena, theaters, performing art centers, racetracks, zoos, botanical gardens, theme parks, nature parks, casinos, golf courses, country clubs, skiing facilities, marinas, bowling centers, fitness centers, and similar establishments.
72	Accommodation and Food Services	Providing accommodation and or food and beverages for immediate consumption. Included are hotels, motels, bed-and-breakfast inns, RV parks, restaurants, cafeterias, bars & drinking places, caterers, and mobile eating joints.
81	Other Services (except Public Administration)	Providing services not covered under other service sectors. Services such as equipment and machinery repair and maintenance; religious activities promotion and administration; advocacy; grant-making; dry-cleaning and laundries, personal care; death care; pet care; dating, and other similar services.

Table A1-8: Regression analysis results for cost and input-output-based hybrid results with human and capital inputs

SUMMARY OUTPUT		Cost & IO-Based Hybrid with Human & Capital Inputs						
Regression Statistics								
Multiple R	0.917937							
R Square	0.842608							
Adjusted R Square	0.792608							
Standard Error	29.02843							
Observations	21							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	90223.58	90223.58	107.0713	3.03E-09			
Residual	20	16853	842.6498					
Total	21	107076.6						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	36.3167	3.509699	10.34752	1.78E-09	28.99559	43.6378	28.99559	43.6378

Table A1-9: Regression analysis results for cost and input-output-based hybrid results after sector disaggregation

SUMMARY OUTPUT		Cost & IO-Based Hybrid with Human & Capital Inputs After Disaggregation						
Regression Statistics								
Multiple R	0.913238							
R Square	0.834004							
Adjusted R Square	0.784004							
Standard Error	29.96184							
Observations	21							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	90206.28	90206.28	100.4847	5.06E-09			
Residual	20	17954.23	897.7117					
Total	21	108160.5						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	36.31322	3.622553	10.02421	3.04E-09	28.7567	43.86973	28.7567	43.86973

Table A1-10: Regression analysis results for price and input-output-based hybrid results with human and capital inputs

SUMMARY OUTPUT		Price & Input-output-based Hybrid with Human & Capital Inputs						
Regression Statistics								
Multiple R	0.973701							
R Square	0.948093							
Adjusted R Square	0.898093							
Standard Error	14.61958							
Observations	21							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	78076.82	78076.82	365.3022	7.25E-14			
Residual	20	4274.643	213.7321					
Total	21	82351.46						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	34.44825	1.802358	19.11288	2.56E-14	30.6886	38.2079	30.6886	38.2079

Table A1-11: Regression analysis results for price and input-output-based hybrid results after sector disaggregation

SUMMARY OUTPUT		Price & Input-output-based Hybrid with Human & Capital Inputs After Disaggregation						
Regression Statistics								
Multiple R	0.971943							
R Square	0.944673							
Adjusted R Square	0.894673							
Standard Error	15.09479							
Observations	21							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	77809.47	77809.47	341.4903	1.33E-13			
Residual	20	4557.053	227.8527					
Total	21	82366.53						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	34.38922	1.860943	18.47946	4.86E-14	30.50736	38.27108	30.50736	38.27108

Table A1-12: Material prices sourced from 2002 National Construction Estimator and embodied energy values

Study Material	Final Embodied Energy (kBtu/lb)				
	Price $/lb	IO-based Method	Hybrid Method	With Human & Capital Method	After Disaggregation
Base grade, 3/8" level loop, 20 oz	5.60	178.27	172.93	183.46	183.46
Softwood average price, 2 by 4	0.15	2.52	2.80	3.12	3.23
Birch Plywood, 1/4"	1.01	18.59	22.49	24.48	17.05
1/4 " Western plywood int. grade AB grade	0.89	16.43	19.87	21.63	21.56
House paint interior, acrylic enamel	1.60	58.49	46.05	48.66	48.66
Adhesive, general	0.84	56.16	21.64	23.00	23.00
Plastic pipe	0.92	42.23	46.86	48.74	48.74
Foam Insulation	2.67	104.84	104.70	110.12	110.12
Brick	0.07	3.06	2.32	2.45	2.84
Wall tile	0.75	33.39	25.29	26.74	19.95
Vitrified sewer pipe	0.19	8.39	6.36	6.72	6.14
Glass, 1/4" float	1.13	61.38	59.59	61.51	61.51
Cement, Portland, 94 lb	0.09	5.18	8.48	8.74	8.74
Concrete	0.02	0.42	0.50	0.54	0.54
Gypsum drywall 3/8" plain board	0.15	9.05	10.12	10.38	7.50
Lime (hydrated), 50lb sack	0.13	7.77	8.68	8.90	14.73
Stone	0.09	1.31	1.22	1.43	1.43
Mineral wool	0.34	11.83	11.90	12.60	12.60
Steel, rebar #2	0.58	35.21	34.20	35.15	34.88
Aluminum	0.65	29.19	79.30	80.17	81.95
Copper	0.76	18.76	24.67	25.77	25.77

Table A1-13: Embodied energy values sourced from Hammond and Jones (2011) and literature

Study Material	Final Embodied Energy (kBtu/lb)	
	Hammond and Jones, 2011	Literature Average
Carpet (3/8" Thk), Level Loop	378	209.5
Wood Lumber	5.55	7.6458333
Hardwood Plywood & Veneer	12	13.842857
Softwood Plywood & Veneer	12	13.842857
Paints & Coatings	86.91	67.054
Adhesives	61.67	0
Plastic Pipes & Fittings	105.3	98.03
Polystyrene Foam Insulation	100.09	98.63
Bricks	3	3.3888889
Clay Wall & Floor Tiles (1/4" Thk)	12	17.578333
Vitrified Clay Sewer Pipes	7.9	4.1402751
Flat Glass	15	23.928571
Cement	5.32	6.7654545
Concrete	0.75	1.3875
Gypsum, Bldg. Products	6.75	6.585
Lime	5.3	7.1066667
Stone	1.26	0.8075
Mineral Wool Insulation	28	25.916667
Virgin Steel	35.1	37.194118
Primary Aluminum	218	222.56667
Copper	69.02	70.3775

Table A1-14: Embodied energy values calculated using the five approaches

Study Material	Embodied Energy of Study Materials (kBtu/lb)				
	Process-based Direct Intensities	IO-based Method	Hybrid Method	Hybrid with Human & Capital Method	After Disaggregation
Carpet (3/8" Thk), Level Loop	37.9	235.3	228.2	242.1	242.1
Wood Lumber	1.2	2.2	2.4	2.7	2.8
Hardwood Plywood & Veneer	7.8	11.5	14.0	15.2	10.6
Softwood Plywood & Veneer	2.0	3.0	3.6	4.0	4.0
Paints & Coatings	1.6	29.0	22.8	24.1	24.1
Adhesives	3.7	56.2	21.6	23.0	23.0
Plastic Pipes & Fittings	5.6	42.2	46.9	48.7	48.7
Polystyrene Foam Insulation	27.5	104.8	104.7	110.1	110.1
Bricks	1.3	2.1	1.6	1.7	1.9
Clay Wall & Floor Tiles (1/4" Thk)	12.2	19.0	14.4	15.2	11.3
Vitrified Clay Sewer Pipes	5.4	8.4	6.4	6.7	6.1
Glass	8.2	10.6	10.3	10.6	10.6
Cement	2.8	1.9	3.1	3.2	3.2
Concrete	0.1	0.5	0.5	0.6	0.6
Gypsum, Bldg. Products	7.4	9.1	10.1	10.4	7.5
Lime	1.4	1.7	1.9	1.9	3.2
Stone	0.4	1.3	1.2	1.4	1.4
Mineral Wool Insulation	7.6	11.8	11.9	12.6	12.6
Virgin Steel	23.3	35.2	34.2	35.2	34.9
Primary Aluminum	60.0	29.2	79.3	80.2	82.0
Copper	9.1	18.8	24.7	25.8	25.8

Table A1-15: Weight/density of study materials

Study Material	Weight/Density
Carpets (lb/ft^2)	0.093
Wood (lb/ft^3)	38.5
Hardwood Plywood & Veneer (lb/ft^3)	37.4
Softwood Plywood & Veneer (lb/ft^3)	36.5
Paints & Coatings (gm/cm^3)	1.5
Polystyrene Foam Insulation (lb/ ft^3)	1.6
Concrete (lb/ft^3)	150
Gypsum, Bldg. Products, 3/8 inch (lb/ft^2)	1.56
Mineral Wool Insulation (lb/ft3)	2.0
Bricks, 3 5/8 inch (lb/no.)	4.53
Plastic Pipe 4" (267-110 psi) (lb/ft)	2.46
Glass (lb/ft2)	3.0

Table A1-16: Energy intensities using input-output-based analysis by energy source

NAICS	Study Material	Input-output-based Energy Intensities (MBtu/$)					
		Oil & Gas	Coal	Electricity	Natural Gas	Petroleum	Total Energy
314110	Carpets	0.015345856	0.003849343	0.001903391	0.00424457	0.00649083	0.031833989
321100	Wood, Lumber	0.007265618	0.002337288	0.001343232	0.001922913	0.00397017	0.016839221
321211	Hardwood Plywood & Veneer	0.007673649	0.002755383	0.0015896	0.002444314	0.00389527	0.018358213
321212	Softwood Plywood & Veneer	0.007673649	0.002755383	0.0015896	0.002444314	0.00389527	0.018358213
325510	Paints & Coatings	0.020179229	0.003156752	0.001323586	0.003417933	0.00853234	0.036609842
325520	Adhesives	0.036366486	0.003276948	0.001466163	0.00347961	0.02254213	0.067131334
326122	Plastic Pipes & Fittings	0.02578542	0.004440479	0.002244788	0.004600544	0.0086727	0.045743927
326140	Polystyrene Foam Insulation	0.020860745	0.004313477	0.001917279	0.00530993	0.00685004	0.039251472
32712A	Bricks	0.013816594	0.013901385	0.001742213	0.01226008	0.00309546	0.044815733
32712A	Clay Wall & Floor Tiles	0.013816594	0.013901385	0.001742213	0.01226008	0.00309546	0.044815733
32712A	Vitrified Sewer Pipes	0.013816594	0.013901385	0.001742213	0.01226008	0.00309546	0.044815733
327211	Flat Glass	0.016930626	0.016675191	0.002446676	0.014272347	0.00415665	0.05448149
327310	Cement	0.015778373	0.01873328	0.004340106	0.013191423	0.00338819	0.055431371
327320	Concrete	0.009722269	0.00657355	0.001592723	0.004876628	0.00390471	0.026669877
3274A0	Gypsum, Building Products	0.01841063	0.017590877	0.002529873	0.015330795	0.0049935	0.058855671
3274A1	Lime	0.01841063	0.017590877	0.002529873	0.015330795	0.0049935	0.058855671
327991	Stone	0.005635799	0.003148127	0.001119531	0.001852826	0.00251621	0.01427249
327993	Mineral Wool Insulation	0.011679903	0.009792543	0.002369314	0.007085096	0.00358591	0.034512765
331110	Steel	0.011835217	0.03537021	0.002797481	0.006594307	0.00411796	0.060715177
33131A	Aluminum	0.012267572	0.016308839	0.006815836	0.006862862	0.00271996	0.044975067
331411	Copper	0.007390519	0.008082278	0.002430598	0.004786428	0.00207645	0.024766271

Table A1-17: Energy intensities using input-output-based hybrid analysis by energy source

NAICS	Study Material	Input-output-based Hybrid Energy Intensities (MBtu/$)					
		Oil & Gas	Coal	Electricity	Natural Gas	Petroleum	Total Energy
314110	Carpets	0.000523766	0.001379514	0.011907255	0.00757035	0.00949984	0.03088072
321100	Wood, Lumber	0.000281068	0.000169407	0.005685562	0.002176061	0.01035303	0.018665124
321211	Hardwood Plywood & Veneer	0.000291114	0.000271736	0.007962986	0.003386458	0.01029243	0.022204728
321212	Softwood Plywood & Veneer	0.000291114	0.000271736	0.007962986	0.003386458	0.01029243	0.022204728
325510	Paints & Coatings	0.000840462	0.001355329	0.007270166	0.006601917	0.01275521	0.028823084
325520	Adhesives	0.000696037	0.001281845	0.007152518	0.005907463	0.01082305	0.025860912
326122	Plastic Pipes & Fittings	0.001728769	0.001120028	0.012276705	0.010635346	0.02499163	0.050752477
326140	Polystyrene Foam Insulation	0.001056556	0.001267267	0.010035077	0.010148759	0.01668984	0.039197494
32712A	Bricks	0.000112376	0.000766309	0.008324705	0.018628364	0.00610876	0.033940513
32712A	Clay Wall & Floor Tiles	0.000112376	0.000766309	0.008324705	0.018628364	0.00610876	0.033940513
32712A	Vitrified Sewer Pipes	0.000112376	0.000766309	0.008324705	0.018628364	0.00610876	0.033940513
327211	Flat Glass	0.000150829	0.00064161	0.015486734	0.030557117	0.00605834	0.052894631
327310	Cement	0.00020174	0.035829532	0.026344653	0.005643552	0.02280218	0.09082166
327320	Concrete	0.000141528	0.007191011	0.008292172	0.004990808	0.01126587	0.031881392
3274A0	Gypsum, Building Products	0.000203742	0.015169683	0.012477651	0.017913986	0.01999574	0.065760801
3274A1	Lime	0.000203742	0.015169683	0.012477651	0.017913986	0.01999574	0.065760801
327991	Stone	0.000112376	0.000586861	0.005248459	0.002669475	0.00472301	0.013340185
327993	Mineral Wool Insulation	0.000191827	0.0014035	0.014331884	0.013059308	0.00570756	0.034694082
331110	Steel	0.000110496	0.016020768	0.023071288	0.014969071	0.00479174	0.058963364
33131A	Aluminum	0.004370913	0.000593918	0.079907677	0.011324482	0.02599323	0.122190222
331411	Copper	4.55148E-05	0.002141199	0.017381736	0.009170104	0.0038231	0.032561656

Table A1-18: Energy intensities using input-output-based hybrid analysis with human and capital inputs by energy source

NAICS	Study Material	Input-output-based Hybrid Energy Intensities With Human and Capital Energy (MBtu/$)							
		Oil & Gas	Coal	Electricity	Natural Gas	Petroleum	Human Energy	Capital Energy	Total Energy
314110	Carpets	0.00052	0.00138	0.01191	0.00757	0.00950	0.00116	0.00072	0.03276
321100	Wood, Lumber	0.00028	0.00017	0.00569	0.00218	0.01035	0.00122	0.00092	0.02080
321211	Hardwood Plywood & Veneer	0.00029	0.00027	0.00796	0.00339	0.01029	0.00124	0.00073	0.02417
321212	Softwood Plywood & Veneer	0.00029	0.00027	0.00796	0.00339	0.01029	0.00124	0.00073	0.02417
325510	Paints & Coatings	0.00084	0.00136	0.00727	0.00660	0.01276	0.00084	0.00080	0.03046
325520	Adhesives	0.00070	0.00128	0.00715	0.00591	0.01082	0.00086	0.00077	0.02749
326122	Plastic Pipes & Fittings	0.00173	0.00112	0.01228	0.01064	0.02499	0.00097	0.00107	0.05279
326140	Polystyrene Foam Insulation	0.00106	0.00127	0.01004	0.01015	0.01669	0.00108	0.00095	0.04123
32712A	Bricks	0.00011	0.00077	0.00832	0.01863	0.00611	0.00106	0.00088	0.03589
32712A	Clay Wall & Floor Tiles	0.00011	0.00077	0.00832	0.01863	0.00611	0.00106	0.00088	0.03589
32712A	Vitrified Sewer Pipes	0.00011	0.00077	0.00832	0.01863	0.00611	0.00106	0.00088	0.03589
327211	Flat Glass	0.00015	0.00064	0.01549	0.03056	0.00606	0.00080	0.00090	0.05460
327310	Cement	0.00020	0.03583	0.02634	0.00564	0.02280	0.00067	0.00207	0.09356
327320	Concrete	0.00014	0.00719	0.00829	0.00499	0.01127	0.00107	0.00121	0.03416
3274A0	Gypsum, Building Products	0.00020	0.01517	0.01248	0.01791	0.02000	0.00082	0.00087	0.06744
3274A1	Lime	0.00020	0.01517	0.01248	0.01791	0.02000	0.00082	0.00087	0.06744
327991	Stone	0.00011	0.00059	0.00525	0.00267	0.00472	0.00145	0.00082	0.01560
327993	Mineral Wool Insulation	0.00019	0.00140	0.01433	0.01306	0.00571	0.00090	0.00114	0.03674
331110	Steel	0.00011	0.01602	0.02307	0.01497	0.00479	0.00092	0.00072	0.06061
33131A	Aluminum	0.00437	0.00059	0.07991	0.01132	0.02599	0.00072	0.00062	0.12353
331411	Copper	0.00005	0.00214	0.01738	0.00917	0.00382	0.00075	0.00071	0.03402

Table A1-19: Energy intensities using input-output-based hybrid analysis after sector disaggregation by energy source

NAICS	Study Material	Input-output-based Hybrid Energy Intensities After Sector Disaggregation(MBtu/$)							
		Oil & Gas	Coal	Electricity	Natural Gas	Petroleum	Human Energy	Capital Energy	Total Energy
314110	Carpets	0.00052	0.00138	0.01191	0.00757	0.00950	0.00116	0.00072	0.03276
321100	Wood, Lumber	0.00029	0.00017	0.00612	0.00218	0.01067	0.00121	0.00092	0.02156
321211	Hardwood Plywood & Veneer	0.00028	0.00016	0.00553	0.00246	0.00659	0.00116	0.00064	0.01683
321212	Softwood Plywood & Veneer	0.00015	0.00018	0.00980	0.00402	0.00783	0.00130	0.00080	0.02409
325510	Paints & Coatings	0.00084	0.00136	0.00727	0.00660	0.01276	0.00084	0.00080	0.03046
325520	Adhesives	0.00070	0.00128	0.00715	0.00591	0.01082	0.00086	0.00077	0.02749
326122	Plastic Pipes & Fittings	0.00173	0.00112	0.01228	0.01064	0.02499	0.00097	0.00107	0.05279
326140	Polystyrene Foam Insulation	0.00106	0.00127	0.01004	0.01015	0.01669	0.00108	0.00095	0.04123
32712A	Bricks	0.00012	0.00085	0.00847	0.02286	0.00716	0.00123	0.00092	0.04161
32712A	Clay Wall & Floor Tiles	0.00012	0.00053	0.00841	0.01079	0.00460	0.00134	0.00097	0.02678
32712A	Vitrified Sewer Pipes	0.00012	0.00071	0.00598	0.01714	0.00628	0.00150	0.00102	0.03276
327211	Flat Glass	0.00015	0.00064	0.01549	0.03056	0.00606	0.00080	0.00090	0.05460
327310	Cement	0.00020	0.03583	0.02634	0.00564	0.02280	0.00067	0.00207	0.09356
327320	Concrete	0.00014	0.00719	0.00829	0.00499	0.01127	0.00107	0.00121	0.03416
3274A0	Gypsum, Building Products	0.00018	0.01157	0.00985	0.01371	0.01239	0.00061	0.00048	0.04877
3274A1	Lime	0.00028	0.02663	0.01911	0.03041	0.03075	0.00219	0.00224	0.11160
327991	Stone	0.00011	0.00059	0.00525	0.00267	0.00472	0.00145	0.00082	0.01560
327993	Mineral Wool Insulation	0.00019	0.00140	0.01433	0.01306	0.00571	0.00090	0.00114	0.03674
331110	Steel	0.00011	0.01600	0.02266	0.01495	0.00478	0.00092	0.00071	0.06014
33131A	Aluminum	0.00331	0.00038	0.09133	0.00947	0.02028	0.00084	0.00066	0.12627
331411	Copper	0.00005	0.00214	0.01738	0.00917	0.00382	0.00075	0.00071	0.03402

Table A1-20: Energy intensities using input-output-based hybrid analysis by upstream stages

Study Material	Input-output-based Hybrid Energy Intensities by Upstream Stages (MBtu/$)													Total Energy
	0	1	2	3	4	5	6	7	8	9	10	11	12	
Carpets	5.1	9.6	7.8	4.6	2.2	0.90	0.37	0.15	0.06	0.027	0.012	0.005	0.0023	30.88
Wood, Lumber	9.4	4.1	2.0	1.3	0.9	0.48	0.24	0.11	0.05	0.022	0.010	0.004	0.0020	18.67
Hardwood Plywood & Veneer	12.4	4.9	2.1	1.3	0.8	0.42	0.21	0.10	0.04	0.019	0.009	0.004	0.0017	22.20
Softwood Plywood & Veneer	12.4	4.9	2.1	1.3	0.8	0.42	0.21	0.10	0.04	0.019	0.009	0.004	0.0017	22.20
Paints & Coatings	2.1	15.0	7.1	2.8	1.1	0.45	0.19	0.08	0.03	0.015	0.007	0.003	0.0013	28.82
Adhesives	4.5	11.8	5.7	2.3	0.9	0.37	0.15	0.07	0.03	0.012	0.005	0.002	0.0011	25.86
Plastic Pipes & Fittings	6.1	26.1	11.6	4.3	1.6	0.61	0.25	0.10	0.04	0.019	0.008	0.004	0.0016	50.75
Polystyrene Foam Insulation	10.3	15.7	8.3	3.0	1.1	0.45	0.18	0.08	0.03	0.015	0.006	0.003	0.0013	39.20
Bricks	28.8	2.5	1.4	0.7	0.3	0.14	0.06	0.03	0.01	0.006	0.002	0.001	0.0005	33.94
Clay Wall & Floor Tiles	28.8	2.5	1.4	0.7	0.3	0.14	0.06	0.03	0.01	0.006	0.002	0.001	0.0005	33.94
Vitrified Sewer Pipes	28.8	2.5	1.4	0.7	0.3	0.14	0.06	0.03	0.01	0.006	0.002	0.001	0.0005	33.94
Flat Glass	42.3	7.8	1.6	0.7	0.3	0.14	0.06	0.03	0.01	0.006	0.003	0.001	0.0005	52.89
Cement	81.7	6.3	1.6	0.6	0.3	0.13	0.06	0.03	0.01	0.005	0.002	0.001	0.0005	90.82
Concrete	3.4	23.8	3.0	1.0	0.4	0.19	0.08	0.04	0.02	0.008	0.003	0.002	0.0007	31.88
Gypsum, Building Products	48.4	13.9	2.1	0.8	0.3	0.17	0.08	0.04	0.02	0.007	0.003	0.001	0.0006	65.76
Lime	48.4	13.9	2.1	0.8	0.3	0.17	0.08	0.04	0.02	0.007	0.003	0.001	0.0006	65.76
Stone	4.0	6.0	1.9	0.8	0.4	0.17	0.08	0.03	0.02	0.007	0.003	0.001	0.0006	13.34
Mineral Wool Insulation	22.1	7.7	2.8	1.2	0.5	0.21	0.09	0.04	0.02	0.008	0.003	0.002	0.0007	34.69
Steel	40.1	12.8	3.8	1.3	0.5	0.23	0.10	0.04	0.02	0.009	0.004	0.002	0.0008	58.96
Aluminum	92.4	21.3	5.8	1.8	0.6	0.23	0.09	0.04	0.02	0.007	0.003	0.001	0.0007	122.19
Copper	12.1	10.3	5.2	2.6	1.3	0.62	0.30	0.14	0.07	0.032	0.015	0.007	0.0034	32.56

Table A1-21: Energy intensities using input-output-based hybrid analysis with human and capital inputs by upstream stages

Study Material	Input-output-based Hybrid Energy Intensities With Human and Capital Energy by Upstream Stages (MBtu/$)													Total Energy
	0	1	2	3	4	5	6	7	8	9	10	11	12	
Carpets	5.5	10.2	8.2	4.9	2.3	0.96	0.40	0.17	0.07	0.030	0.013	0.006	0.0025	32.76
Wood, Lumber	10.2	4.6	2.4	1.6	1.0	0.54	0.26	0.12	0.06	0.025	0.011	0.005	0.0022	20.80
Hardwood Plywood & Veneer	13.2	5.4	2.5	1.4	0.9	0.47	0.23	0.11	0.05	0.022	0.010	0.004	0.0019	24.17
Softwood Plywood & Veneer	13.2	5.4	2.5	1.4	0.9	0.47	0.23	0.11	0.05	0.022	0.010	0.004	0.0019	24.17
Paints & Coatings	2.5	15.5	7.4	3.0	1.2	0.49	0.20	0.09	0.04	0.016	0.007	0.003	0.0014	30.46
Adhesives	5.0	12.3	6.0	2.4	1.0	0.40	0.17	0.07	0.03	0.014	0.006	0.003	0.0012	27.49
Plastic Pipes & Fittings	7.0	26.6	11.9	4.5	1.7	0.66	0.27	0.11	0.05	0.021	0.009	0.004	0.0018	52.79
Polystyrene Foam Insulation	11.3	16.2	8.6	3.1	1.2	0.48	0.20	0.09	0.04	0.016	0.007	0.003	0.0014	41.23
Bricks	30.2	2.8	1.6	0.8	0.3	0.15	0.07	0.03	0.01	0.006	0.003	0.001	0.0005	35.89
Clay Wall & Floor Tiles	30.2	2.8	1.6	0.8	0.3	0.15	0.07	0.03	0.01	0.006	0.003	0.001	0.0005	35.89
Vitrified Sewer Pipes	30.2	2.8	1.6	0.8	0.3	0.15	0.07	0.03	0.01	0.006	0.003	0.001	0.0005	35.89
Flat Glass	43.3	8.2	1.8	0.7	0.3	0.15	0.07	0.03	0.01	0.006	0.003	0.001	0.0006	54.60
Cement	83.7	6.8	1.8	0.7	0.3	0.14	0.06	0.03	0.01	0.006	0.003	0.001	0.0005	93.56
Concrete	4.3	24.6	3.3	1.1	0.5	0.21	0.09	0.04	0.02	0.008	0.004	0.002	0.0007	34.16
Gypsum, Building Products	49.1	14.4	2.3	0.9	0.4	0.19	0.09	0.04	0.02	0.008	0.004	0.002	0.0007	67.44
Lime	49.1	14.4	2.3	0.9	0.4	0.19	0.09	0.04	0.02	0.008	0.004	0.002	0.0007	67.44
Stone	5.2	6.6	2.1	0.9	0.4	0.19	0.08	0.04	0.02	0.007	0.003	0.001	0.0007	15.60
Mineral Wool Insulation	23.2	8.2	3.1	1.3	0.5	0.23	0.10	0.04	0.02	0.009	0.004	0.002	0.0008	36.74
Steel	40.7	13.3	4.1	1.5	0.6	0.25	0.11	0.05	0.02	0.010	0.004	0.002	0.0009	60.61
Aluminum	92.8	21.7	6.1	1.9	0.6	0.25	0.10	0.04	0.02	0.008	0.004	0.002	0.0007	123.53
Copper	12.4	10.8	5.5	2.7	1.4	0.67	0.32	0.16	0.07	0.035	0.017	0.008	0.0037	34.02

Table A1-22: Energy intensities using input-output-based hybrid analysis after sector disaggregation by upstream stages

Study Material	Input-output-based Hybrid Energy Intensities After Sector Disaggregation by Upstream Stages (MBtu/$)													Total
	0	1	2	3	4	5	6	7	8	9	10	11	12	Energy
Carpets	5.5	10.2	8.2	4.9	2.3	0.96	0.40	0.17	0.07	0.030	0.013	0.006	0.0025	32.76
Wood, Lumber	11.1	4.6	2.4	1.5	1.0	0.52	0.25	0.12	0.05	0.024	0.011	0.005	0.0021	21.56
Hardwood Plywood & Veneer	6.5	5.6	2.2	1.2	0.7	0.37	0.18	0.09	0.04	0.018	0.008	0.004	0.0016	16.83
Softwood Plywood & Veneer	13.0	4.7	2.6	1.7	1.0	0.54	0.26	0.12	0.05	0.025	0.011	0.005	0.0022	24.09
Paints & Coatings	2.5	15.5	7.4	3.0	1.2	0.49	0.20	0.09	0.04	0.016	0.007	0.003	0.0014	30.46
Adhesives	5.0	12.3	6.0	2.4	1.0	0.40	0.17	0.07	0.03	0.014	0.006	0.003	0.0012	27.49
Plastic Pipes & Fittings	7.0	26.6	11.9	4.5	1.7	0.66	0.27	0.11	0.05	0.021	0.009	0.004	0.0018	52.79
Polystyrene Foam Insulation	11.3	16.2	8.6	3.1	1.2	0.48	0.20	0.09	0.04	0.016	0.007	0.003	0.0014	41.23
Bricks	35.7	2.8	1.6	0.8	0.4	0.17	0.08	0.03	0.01	0.007	0.003	0.001	0.0006	41.61
Clay Wall & Floor Tiles	19.9	3.3	1.9	0.9	0.4	0.19	0.09	0.04	0.02	0.008	0.003	0.002	0.0007	26.78
Vitrified Sewer Pipes	25.2	3.7	2.0	1.0	0.5	0.21	0.10	0.04	0.02	0.009	0.004	0.002	0.0008	32.76
Flat Glass	43.3	8.2	1.8	0.7	0.3	0.15	0.07	0.03	0.01	0.006	0.003	0.001	0.0006	54.60
Cement	83.7	6.8	1.8	0.7	0.3	0.14	0.06	0.03	0.01	0.006	0.003	0.001	0.0005	93.56
Concrete	4.3	24.6	3.3	1.1	0.5	0.21	0.09	0.04	0.02	0.008	0.004	0.002	0.0007	34.16
Gypsum, Building Products	39.1	5.3	2.4	1.1	0.5	0.20	0.09	0.04	0.02	0.008	0.003	0.002	0.0007	48.77
Lime	90.2	16.6	2.9	1.0	0.5	0.22	0.10	0.05	0.02	0.009	0.004	0.002	0.0009	111.60
Stone	5.2	6.6	2.1	0.9	0.4	0.19	0.08	0.04	0.02	0.007	0.003	0.001	0.0007	15.60
Mineral Wool Insulation	23.2	8.2	3.1	1.3	0.5	0.23	0.10	0.04	0.02	0.009	0.004	0.002	0.0008	36.74
Steel	40.2	13.3	4.1	1.5	0.6	0.25	0.11	0.05	0.02	0.010	0.004	0.002	0.0009	60.14
Aluminum	95.2	22.0	6.0	1.9	0.7	0.27	0.11	0.05	0.02	0.009	0.004	0.002	0.0009	126.27
Copper	12.4	10.8	5.5	2.7	1.4	0.67	0.32	0.16	0.07	0.035	0.017	0.008	0.0037	34.02

Table A1-23: Disaggregation coefficients for energy sources and services

NAICS Aggregated	Product/Subsector	NAICS Disaggregated	Fraction in Total Material Inputs	Fraction in Total Other Inputs (services & tax)	Fraction in Total Electricity Inputs	Fraction in Total Fuel Inputs
321100	Wood Preservation	321114	0.20	0.12	0.05	0.11
	Sawmills	321113	0.80	0.88	0.95	0.89
32121A	Hardwood Plywood & Veneer	321211	0.36	0.72	0.21	0.25
	Softwood Plywood & Veneer	321212	0.64	0.28	0.79	0.75
331110	Iron & Steel Mills	331111	0.98	0.97	0.95	0.98
	Ferroalloy	331112	0.02	0.03	0.05	0.02
3274A0	Lime	327410	0.18	0.25	0.35	0.36
	Gypsum Building Materials	327420	0.82	0.75	0.65	0.64
32712A	Brick & Structural Clay Tiles	327121	0.57	0.71	0.64	0.77
	Ceramic Floor & Wall Tiles	327122	0.36	0.29	0.31	0.17
	Other Structural Clay Products	327123	0.07	0.13	0.04	0.06
33131A	Primary Aluminum	331312	0.90	0.64	0.99	0.62
	Alumina Production	331311	0.10	0.36	0.01	0.38

Table A1-24: Disaggregation coefficients for services

NAICS Aggregated	Product/Subsector	NAICS Disaggregated	Repair and maintenance services of buildings and/or machinery	Communications services	Legal services	Accounting, auditing, and bookkeeping services	Advertising and promotional services
321100	Wood Preservation	321114	0.09	0.10	0.10	0.17	0.20
	Sawmills	321113	0.91	0.90	0.90	0.83	0.80
32121A	Hardwood Plywood & Veneer	321211	0.32	0.59	0.74	0.78	0.42
	Softwood Plywood & Veneer	321212	0.68	0.41	0.26	0.22	0.58
331110	Iron & Steel Mills	331111	0.98	0.98	0.98	0.98	0.98
	Ferroalloy	331112	0.02	0.02	0.02	0.02	0.02
3274A0	Lime	327410	0.25	0.34	0.26	0.26	0.06
	Gypsum Building Materials	327420	0.75	0.66	0.74	0.74	0.94
32712A	Brick & Structural Clay Tiles	327121	0.71	0.49	0.45	0.62	0.20
	Ceramic Floor & Wall Tiles	327122	0.21	0.37	0.36	0.26	0.61
	Other Structural Clay Products	327123	0.08	0.13	0.19	0.12	0.19
33131A	Primary Aluminum	331312	0.60	0.99	0.60	0.99	0.60
	Alumina Production	331311	0.40	0.01	0.40	0.01	0.40

Table A1-25: Disaggregation coefficients for services

NAICS Aggregated	Product/Subsector	NAICS Disaggregated	Expensed computer hardware and supplies and purchased computer services	Refuse removal (including hazardous waste) services	Management consulting and administrative services	Taxes and license fees	All other expenses
321100	Wood Preservation	321114	0.16	0.25	0.17	0.09	0.13
	Sawmills	321113	0.84	0.75	0.83	0.91	0.87
32121A	Hardwood Plywood & Veneer	321211	0.59	0.60	0.70	0.94	0.68
	Softwood Plywood & Veneer	321212	0.41	0.40	0.30	0.06	0.32
331110	Iron & Steel Mills	331111	0.99	0.98	0.99	0.98	0.98
	Ferroalloy	331112	0.01	0.02	0.01	0.02	0.02
3274A0	Lime	327410	0.10	0.11	0.58	0.40	0.22
	Gypsum Building Materials	327420	0.90	0.89	0.42	0.60	0.78
32712A	Brick & Structural Clay Tiles	327121	0.42	0.34	0.26	0.68	0.68
	Ceramic Floor & Wall Tiles	327122	0.39	0.59	0.63	0.24	0.18
	Other Structural Clay Products	327123	0.18	0.07	0.10	0.09	0.13
33131A	Primary Aluminum	331312	0.60	0.97	0.60	0.60	0.60
	Alumina Production	331311	0.40	0.03	0.40	0.40	0.40

Table A1-26: Embodied energy of building materials as reported in literature

Study	Construction	Region	Building Material Embodied Energy (GJ/m2)
Hammond & Jones, 2010	Mixed	Europe	6.6
Hammond & Jones, 2010	Mixed	Europe	6.3
Hammond & Jones, 2010	Mixed	Europe	4.9
Hammond & Jones, 2010	Mixed	Europe	5.6
Hammond & Jones, 2010	Mixed	Europe	8.2
Hammond & Jones, 2010	Mixed	Europe	5.5
Troy et al., 2003	Mixed	Oceania	7.85
Troy et al., 2003	Mixed	Oceania	6.8
Troy et al., 2003	Mixed	Oceania	8.5
Troy et al., 2003	Mixed	Oceania	7.4
Troy et al., 2003	Mixed	Oceania	6.21
Troy et al., 2003	Mixed	Oceania	9.3
Troy et al., 2003	Mixed	Oceania	6.3
Troy et al., 2003	Mixed	Oceania	6.2
Borjesson & Gustavsson, 2000	Concrete	Europe	1.73
Borjesson & Gustavsson, 2000	Concrete	Europe	2
Lenzen & Treloar, 2002	Concrete	Europe	2.4
Lenzen & Treloar, 2002	Concrete	Europe	3.65
Gustavsson et al., 2006	Concrete	Europe	2.5
Gustavsson et al., 2006	Concrete	Europe	2.73
Gustavsson & Joelsson, 2010	Concrete	Europe	2.792
Gartner & Smith, 1976	Concrete	Europe	4.5
Winistorfer et al., 2005	Concrete	North America	2.2
Kahhat et al., 2009	Concrete	North America	3.17
Kahhat et al., 2009	Concrete	North America	3.075
Kahhat et al., 2009	Concrete	North America	3.435
Shiu et al., 2009	Concrete	North America	3.23
Mithraratne & Vale, 2004	Concrete	Oceania	4.764
Duell & Martin, 2005	Concrete	Oceania	18.47
Duell & Martin, 2005	Concrete	Oceania	14.64
Vale et al., 2000	Concrete	Oceania	2.68
Debnath et al., 1995	Concrete	Asia	4.3
Debnath et al., 1995	Concrete	Asia	3.1
Chulsukon et al., 2002	Concrete	Asia	3.21
Reddy, 2004	Concrete	Asia	4.21
Gumaste, 2006	Concrete	Asia	3.7
Gumaste, 2006	Concrete	Asia	2.91
Gumaste, 2006	Concrete	Asia	3.61
Utama & Gheewala, 2008	Concrete	Asia	0.819
Utama & Gheewala, 2009	Concrete	Asia	0.862
Shaw et al., 1998	Steel	North America	0.57
Lippke et al., 2004	Steel	North America	3.36
Lucuik et al., 2006	Steel	North America	4.83
Kahhat et al., 2009	Steel	North America	2.995
O'Brien & Soebarto, 2000	Steel	Oceania	3.56
O'Brien & Soebarto, 2000	Steel	Oceania	1.91
Fossdal & Edwardson, 1995	Wood	Europe	1.97
Adalberth, 1997	Wood	Europe	3.384
Adalberth, 1997	Wood	Europe	3.274
Adalberth, 1997	Wood	Europe	2.74
Winther & Hestnes, 1999	Wood	Europe	1.62
Borjesson & Gustavsson, 2000	Wood	Europe	1.1
Lenzen & Treloar, 2002	Wood	Europe	2.05
Lenzen & Treloar, 2002	Wood	Europe	3.41
Gustavsson et al., 2006	Wood	Europe	1.96
Gustavsson et al., 2006	Wood	Europe	0
Gustavsson et al., 2006	Wood	Europe	2.47
Gustavsson et al., 2006	Wood	Europe	0
Gustavsson & Joelsson, 2010	Wood	Europe	2.33

Gustavsson & Joelsson, 2010	Wood	Europe	2.36
Gustavsson et al., 2010	Wood	Europe	3.22
Verbeeck & Hens, 2010	Wood	Europe	2
Verbeeck & Hens, 2010	Wood	Europe	2.52
Verbeeck & Hens, 2010	Wood	Europe	2.93
Verbeeck & Hens, 2010	Wood	Europe	3.83
Verbeeck & Hens, 2010	Wood	Europe	2.41
Verbeeck & Hens, 2010	Wood	Europe	2.78
Verbeeck & Hens, 2010	Wood	Europe	2.94
Verbeeck & Hens, 2010	Wood	Europe	4.17
Almeida et al., 2005	Wood	Europe	5.72
Almeida et al., 2005	Wood	Europe	5.72
Asif et al., 2007	Wood	Europe	1.62
Sobotka & Rolak, 2009	Wood	Europe	0.71
Malin, 1993	Wood	North America	2.72
Malin, 1993	Wood	North America	2.72
Malin, 1993	Wood	North America	2.93
Malin, 1993	Wood	North America	2.93
Blanchard & Reppe, 1998	Wood	North America	4.138658
Keoleian et al., 2001	Wood	North America	6.62
Winistorfer et al., 2005	Wood	North America	2.2
Winistorfer et al., 2005	Wood	North America	3.8
Baouendi et al., 2005	Wood	North America	1.3
Baouendi et al., 2005	Wood	North America	1.326
Norman et al., 2006	Wood	North America	5.47
Norman et al., 2006	Wood	North America	4.58
Kim, 2008	Wood	North America	4.63
Kim, 2008	Wood	North America	3.41
Kahhat et al., 2009	Wood	North America	2.905
Kahhat et al., 2009	Wood	North America	2.915
Leckner & Zmeureanu, 2011	Wood	North America	3.36
Edwards et al._1994	Wood	Oceania	3.91
Edwards et al._1994	Wood	Oceania	4.45
Vale et al., 2000	Wood	Oceania	2.42
Mithraratne & Vale, 2004	Wood	Oceania	4.425
Gartner & Smith, 1976	Brick	Europe	1.75
Gartner & Smith, 1976	Brick	Europe	1.52
Gartner & Smith, 1976	Brick	Europe	2.19
Sobotka & Rolak, 2009	Brick	Europe	0.73
Verbeeck & Hens, 2010	Brick	Europe	2
Verbeeck & Hens, 2010	Brick	Europe	2.52
Verbeeck & Hens, 2010	Brick	Europe	2.93
Verbeeck & Hens, 2010	Brick	Europe	3.83
Verbeeck & Hens, 2010	Brick	Europe	2.41
Verbeeck & Hens, 2010	Brick	Europe	2.78
Verbeeck & Hens, 2010	Brick	Europe	2.94
Verbeeck & Hens, 2010	Brick	Europe	4.17
Aste et al., 2010	Brick	Europe	4
Feist, 1996	Brick	Europe	4.22
Edwards et al., 1994	Brick	Oceania	5.62
Treloar et al., 2001	Brick	Oceania	11.72
Treloar et al., 2001e	Brick	Oceania	9.82
Treloar et al., 2001e	Brick	Oceania	10.42
Treloar et al., 2001e	Brick	Oceania	9.34
Randolph et al., 2006	Brick	Oceania	6.4
Randolph et al., 2006	Brick	Oceania	6.4
Randolph et al., 2006	Brick	Oceania	6.5
Randolph et al., 2006	Brick	Oceania	6.5
Randolph et al., 2006	Brick	Oceania	7.1
Randolph et al., 2006	Brick	Oceania	7
Randolph et al., 2006	Brick	Oceania	6.8
Randolph et al., 2006	Brick	Oceania	6.5
Randolph et al., 2006	Brick	Oceania	5.4

Randolph et al., 2006	Brick	Oceania	8.3
Randolph et al., 2006	Brick	Oceania	7.9
Randolph et al., 2006	Brick	Oceania	6.7
Debnath et al., 1995	Brick	Asia	5
Debnath et al., 1995	Brick	Asia	4.2
Debnath et al., 1995	Brick	Asia	4.1
Debnath et al., 1995	Brick	Asia	3.7
Chulsukon et al., 2002	Brick	Asia	3.21
Reddy, 2004	Brick	Asia	4.21
Reddy, 2004	Brick	Asia	2.92
Reddy, 2004	Brick	Asia	1.61
Jeyasingh & Sam, 2004	Brick	Asia	6.44
Gumaste, 2006	Brick	Asia	3.67
Utama & Gheewala, 2008	Brick	Asia	0.838
Utama & Gheewala, 2009	Brick	Asia	0.862
Utama & Gheewala, 2009	Brick	Asia	0.926
Huberman & Pearlmutter, 2004	Brick	Asia	0.77
Huberman & Pearlmutter, 2004	Brick	Asia	1.06
Huberman & Pearlmutter, 2004	Brick	Asia	3.52
Huberman & Pearlmutter, 2004	Brick	Asia	3.8

APPENDIX B1

FIGURES

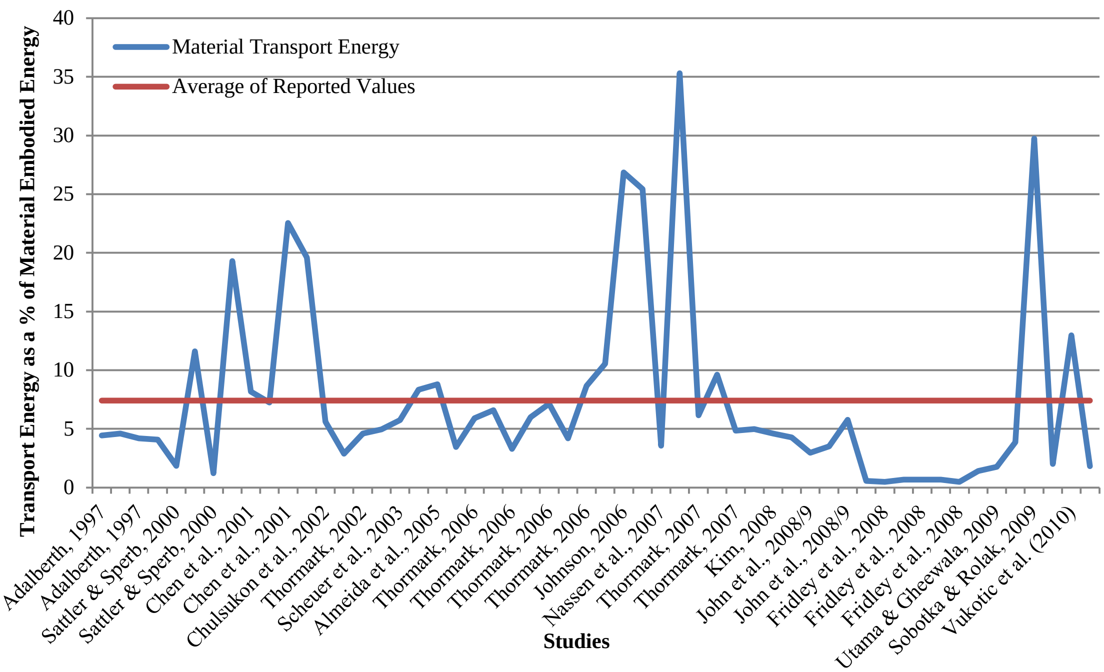

Figure B1-1: Transportation energy as% of total materials' embodied energy

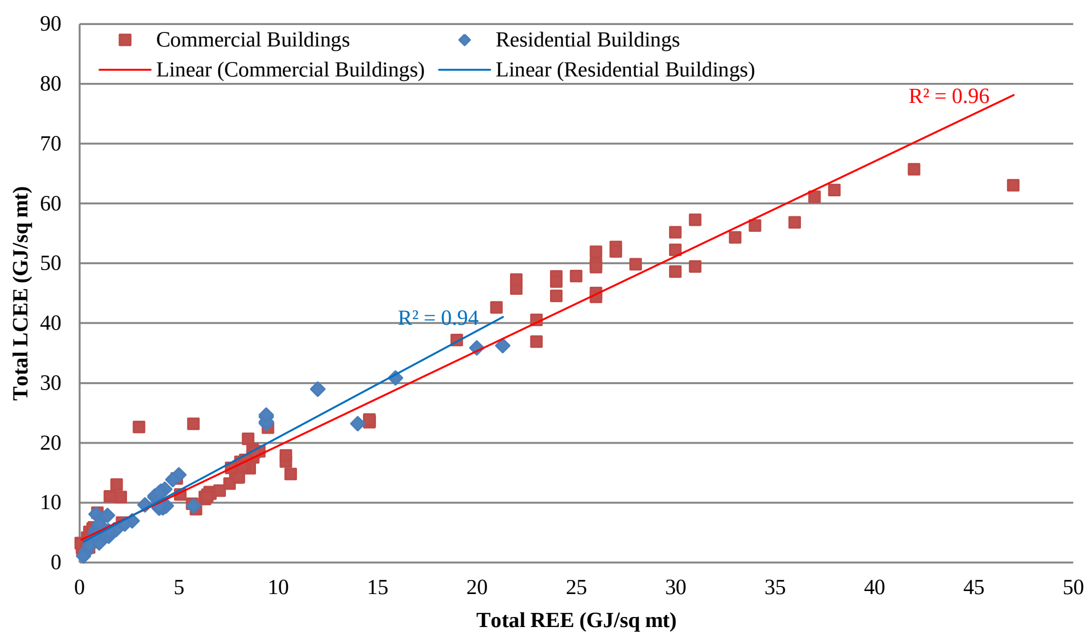

Figure B1-2: Correlation of LCEE with the total REE of residential and commercial buildings

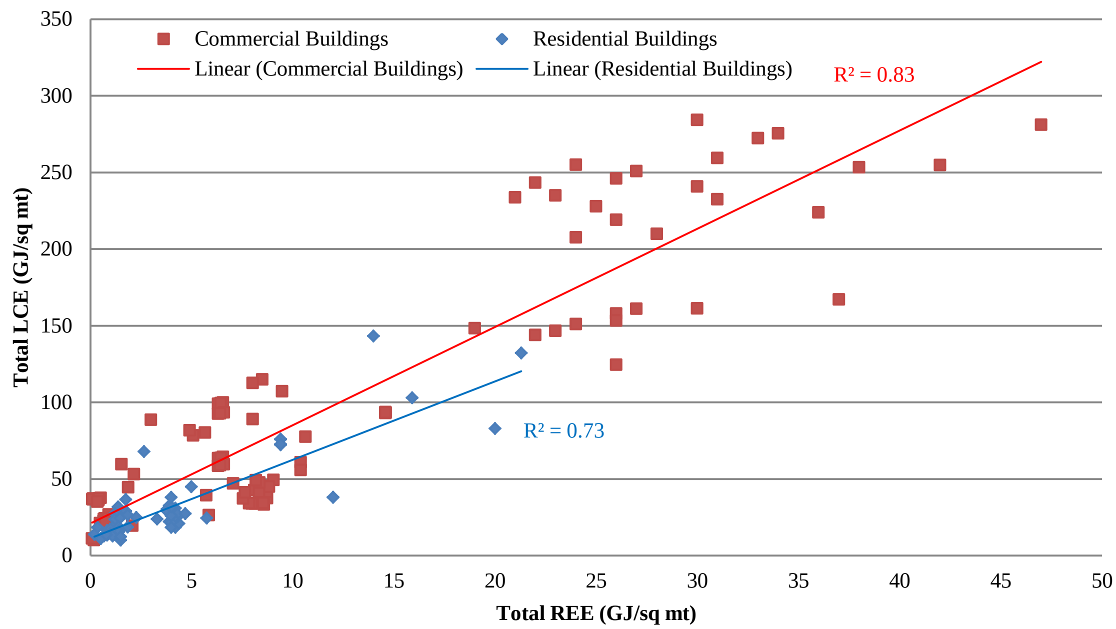

Figure B1-3: Correlation of LCE with the total REE of commercial buildings

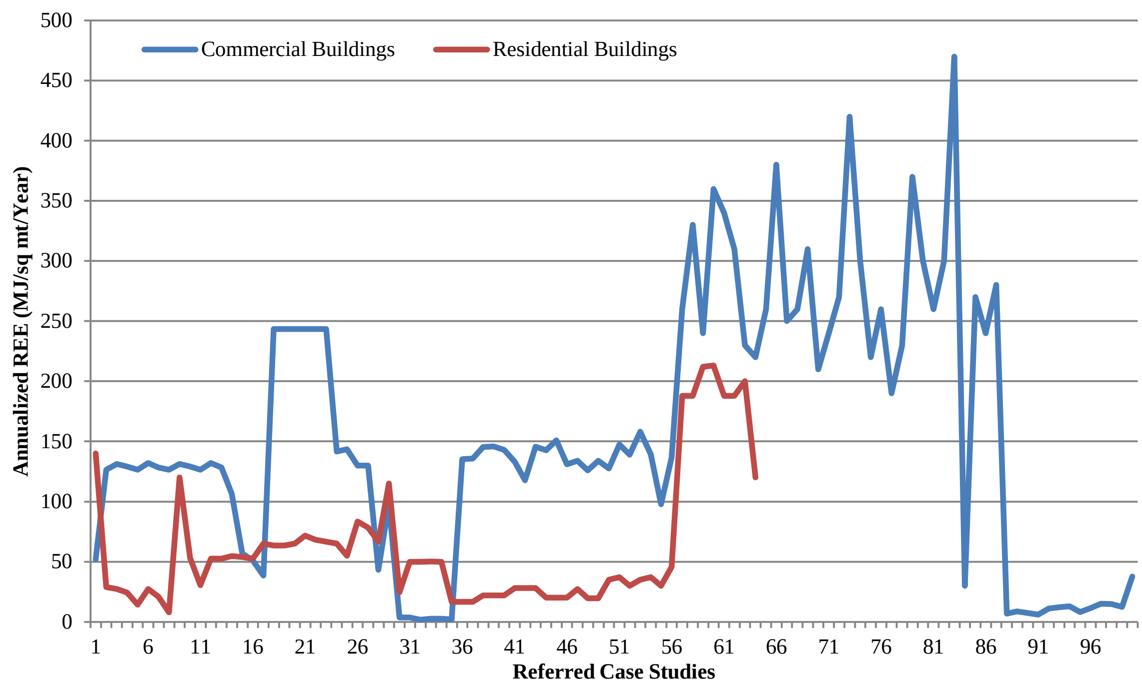

Figure B1-4: Annualized REE of the referred case studies

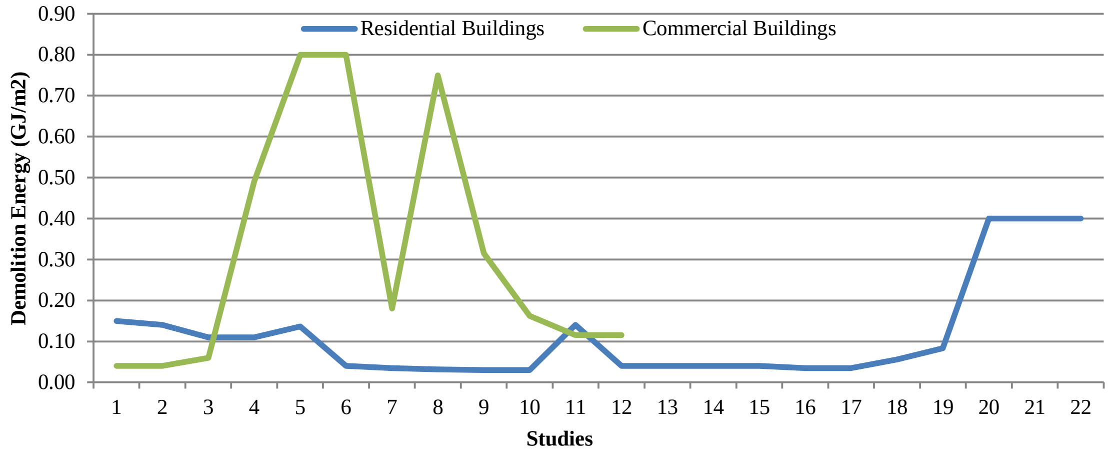

Figure B1-5: Demolition energy reported by the referred studies

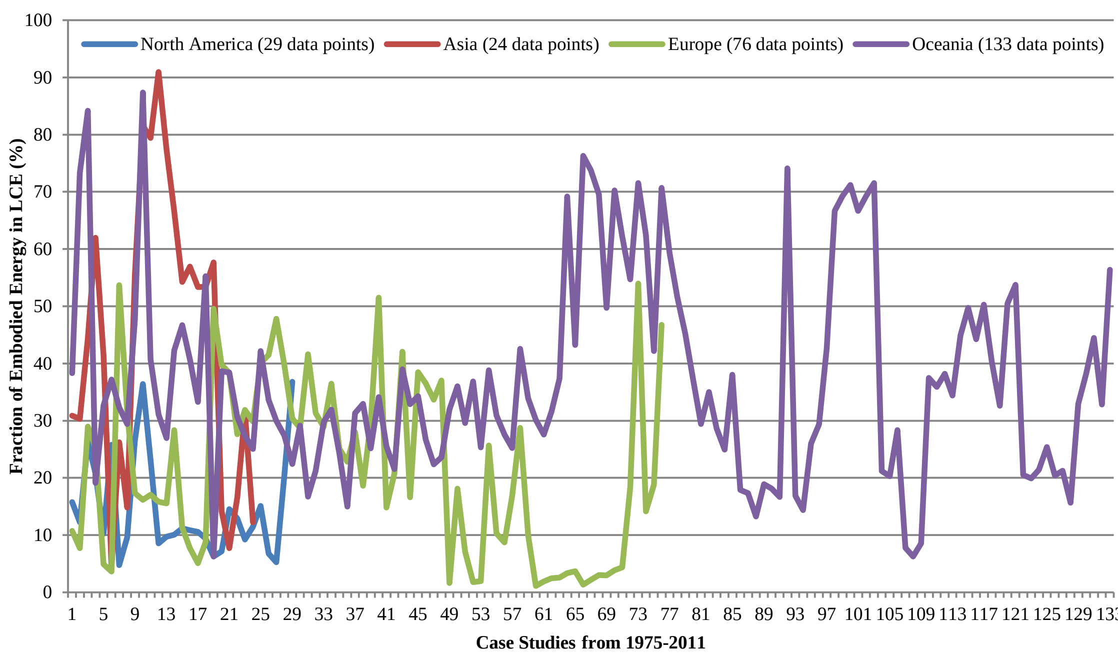

Figure B1-6: Embodied energy fraction in the total REE of referred residential buildings

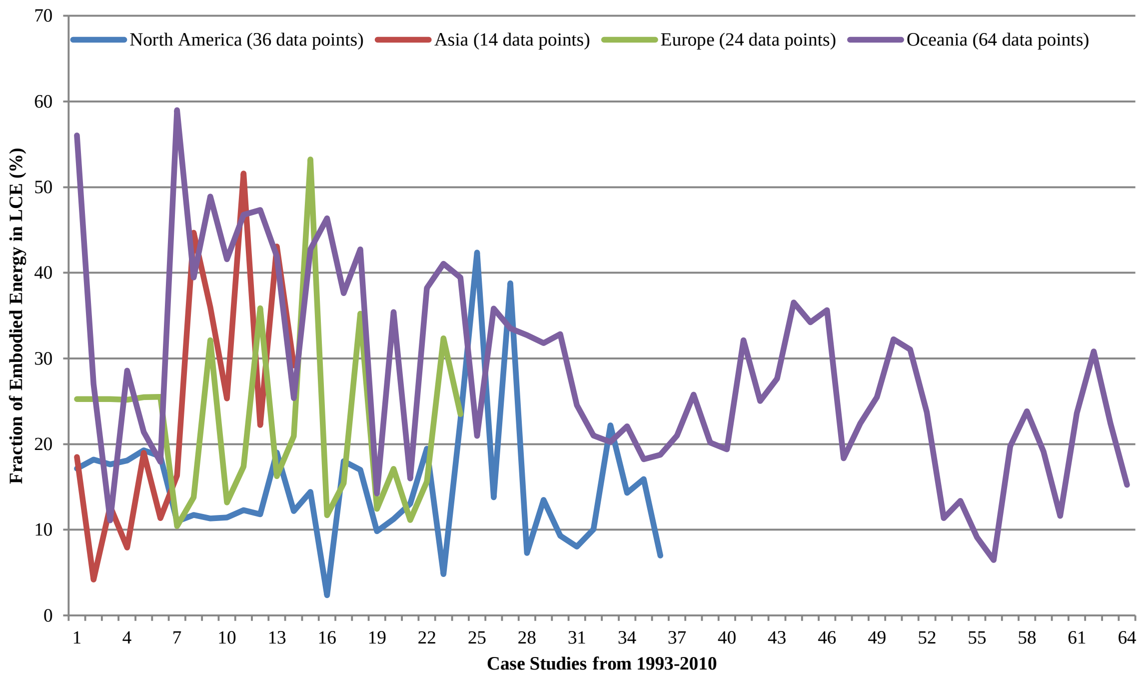

Figure B1-7: Embodied energy fraction in the total REE of referred commercial buildings

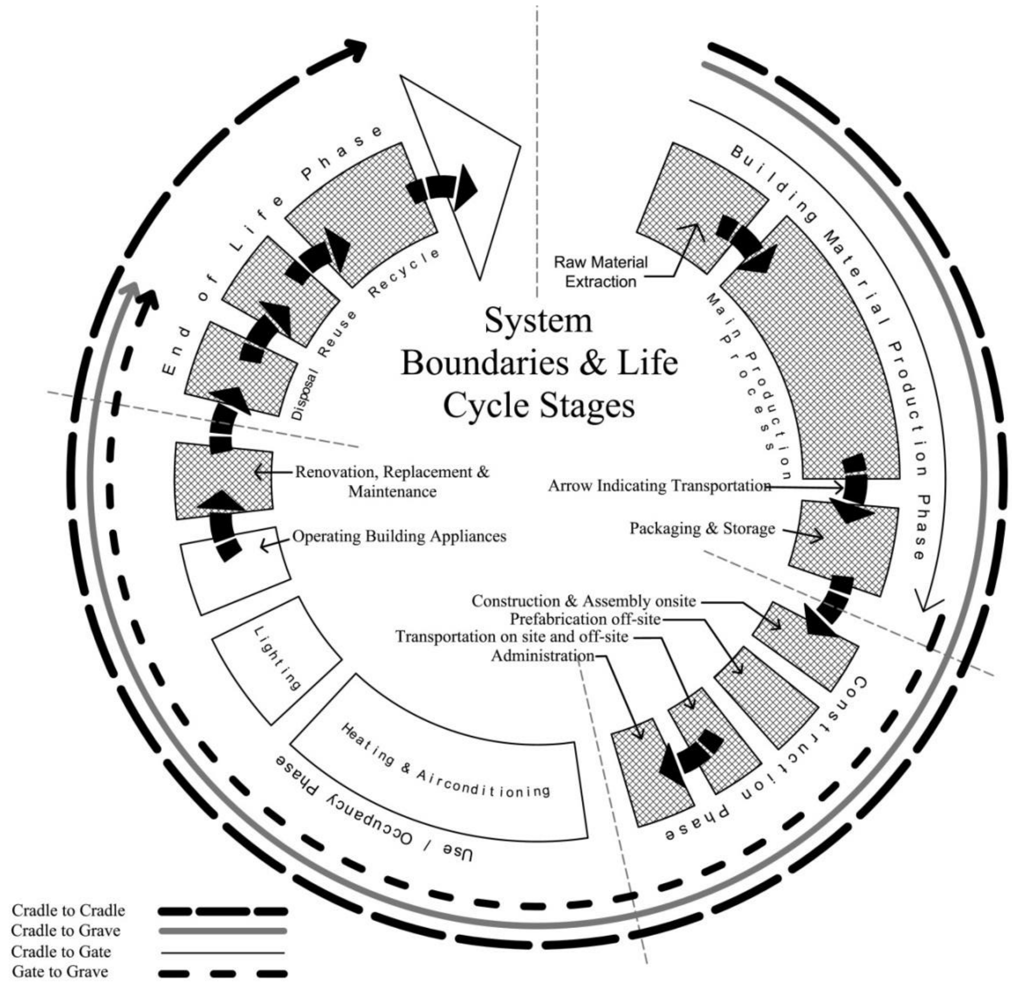

Figure B1-8: Various boundary definitions provided in the literature

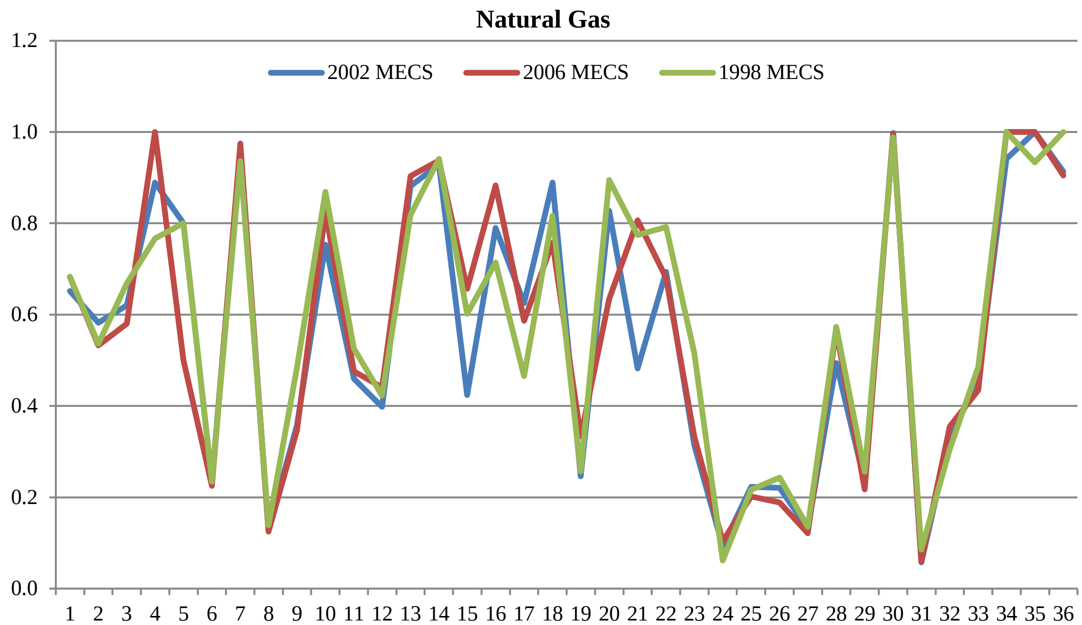

Figure B1-9: Ratio of natural gas use to total fuel use in selected manufacturing sectors

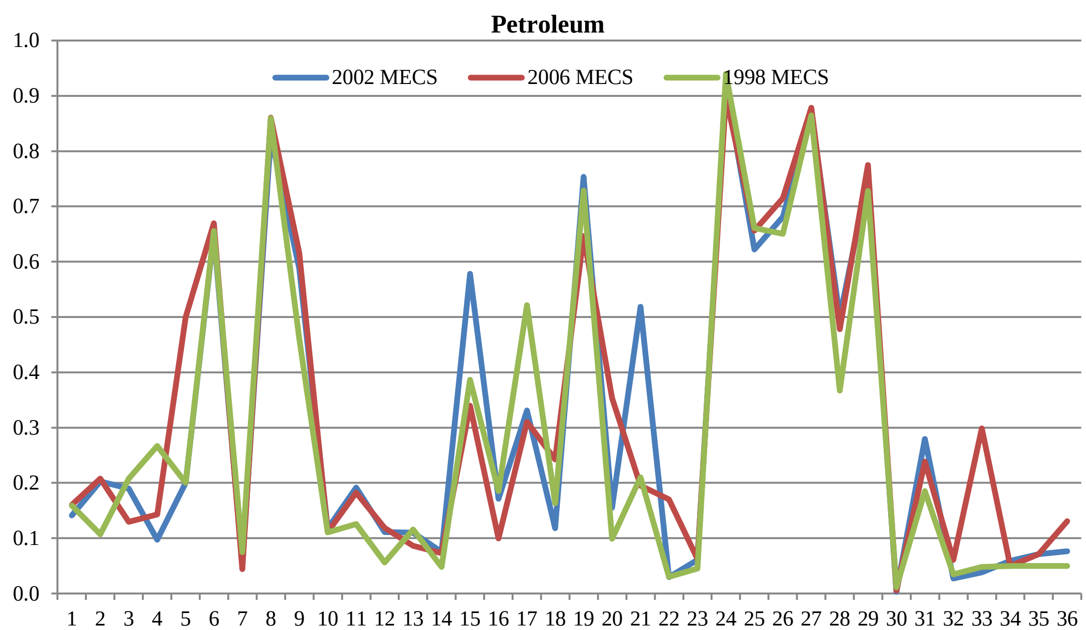

Figure B1-10: Ratio of petroleum use to total fuel use in selected manufacturing sectors

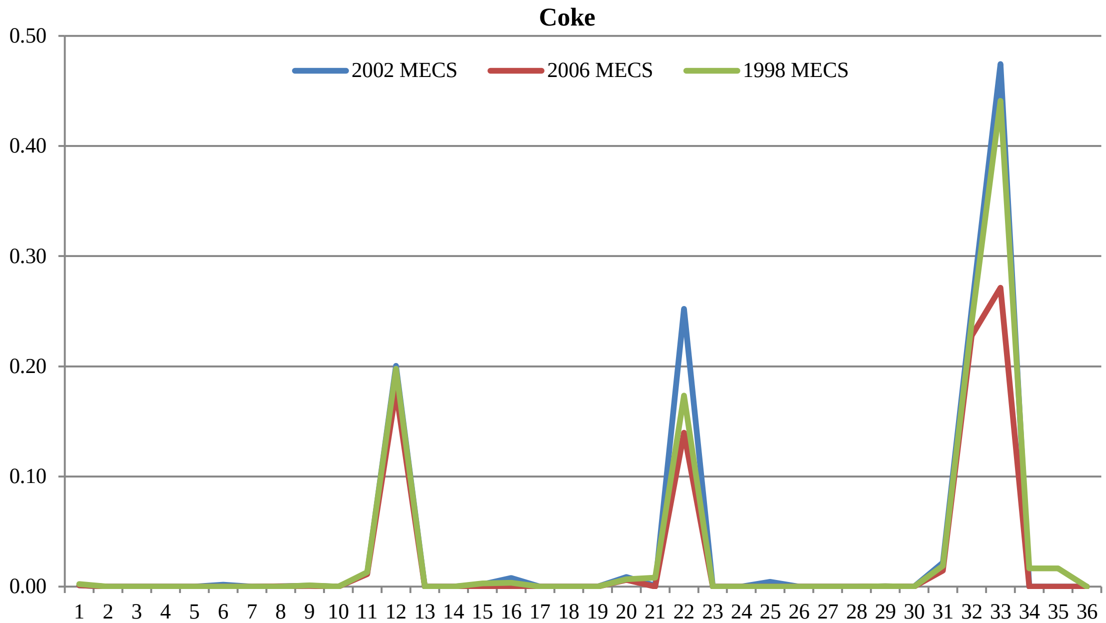

Figure B1-11: Ratio of coke use to total fuel use in selected manufacturing sectors

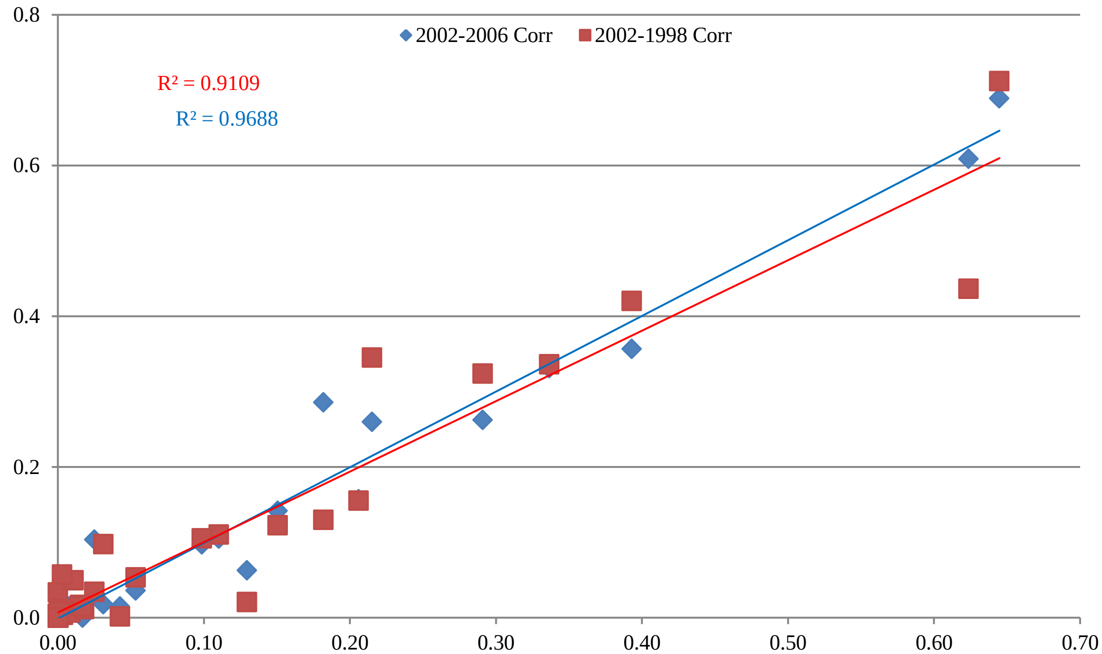

Figure B1-12: Correlation of coal fraction in total fuel use 1998, 2002, and 2006

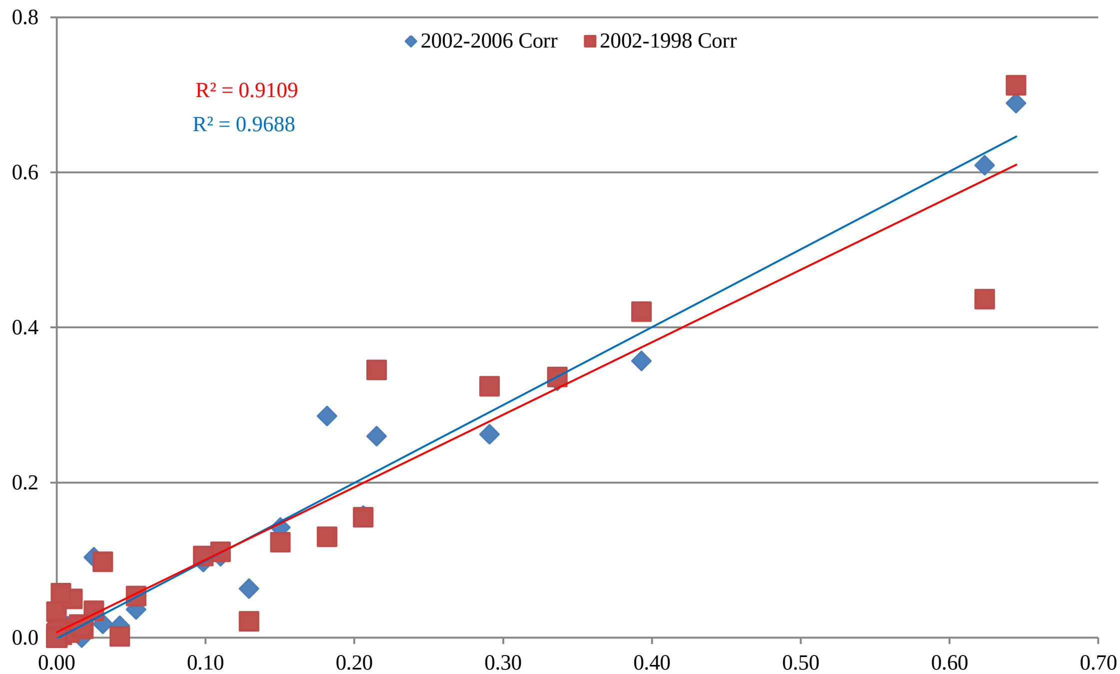

Figure B1-13: Correlation of natural gas fraction in total fuel use 1998, 2002, and 2006

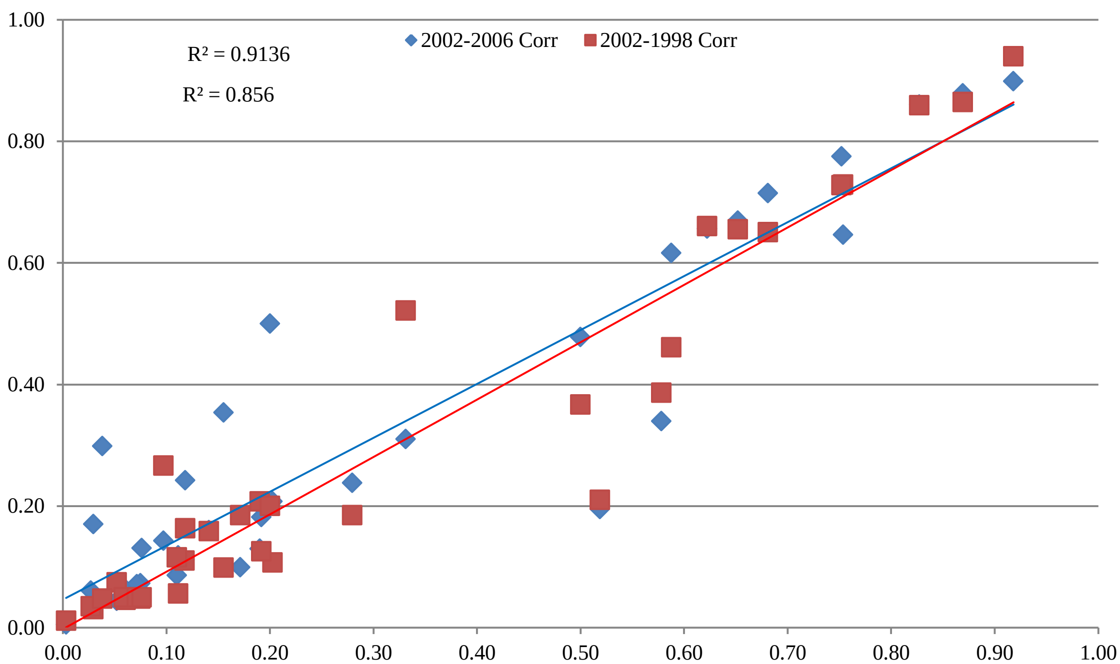

Figure B1-14: Correlation of petroleum fraction in total fuel use 1998, 2002, and 2006

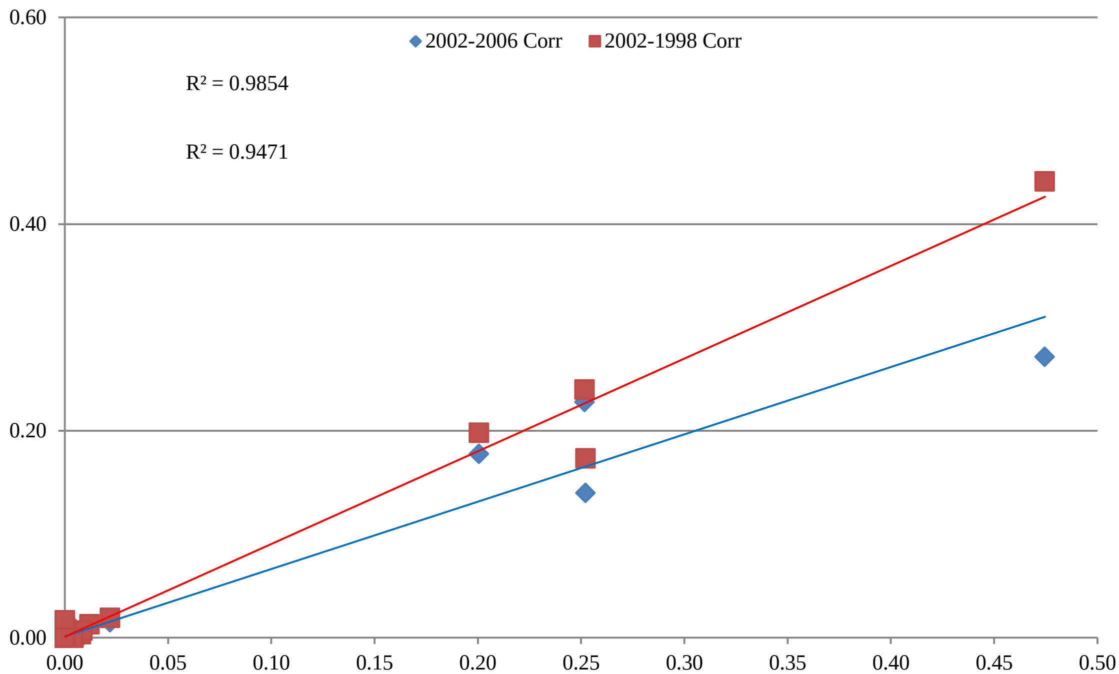

Figure B1-15: Correlation of coke fraction in total fuel use 1998, 2002, and 2006

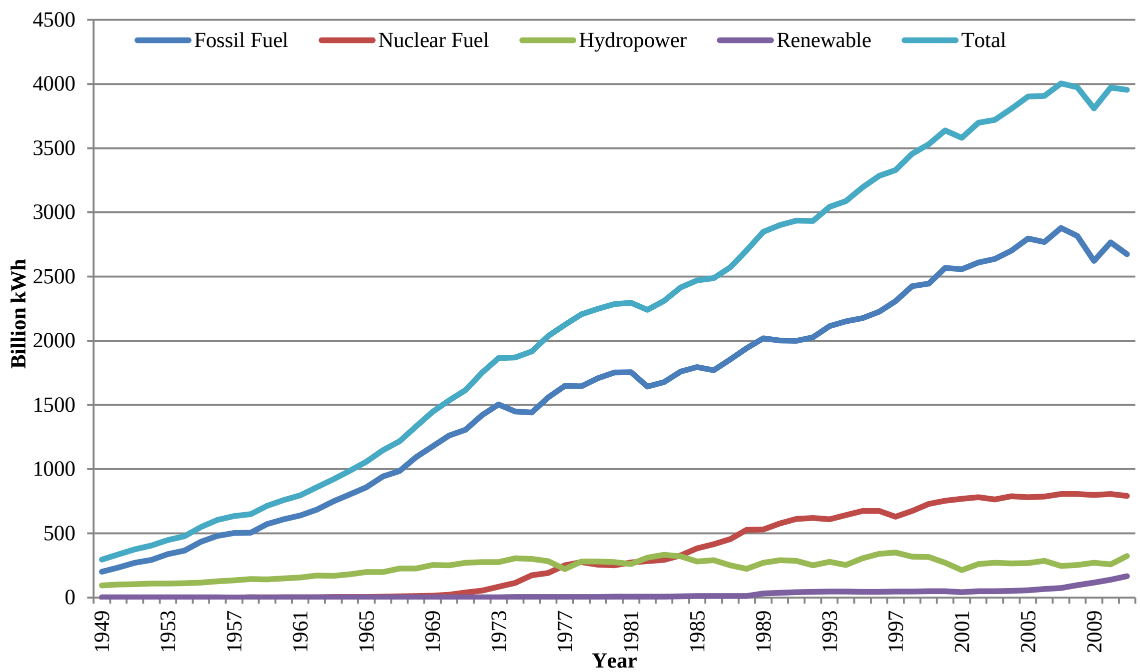

Figure B1-16: Electricity production in the United States by source from 1949-2011

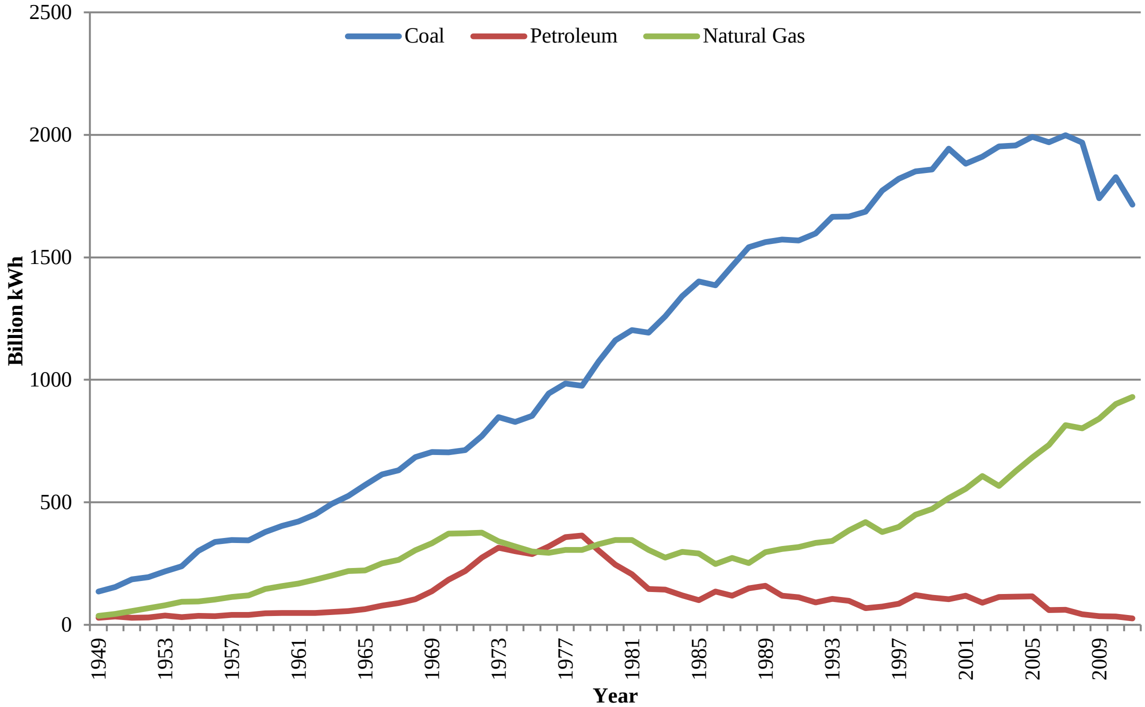

Figure B1-17: Dominance of coal in the fossil fuel use for the United States electricity production

APPENDIX C1

ARTICLES RESULTING FROM THE RESEARCH

Journal Papers

Dixit, M.K., Culp, C.H. Fernández-Solís, J.L. (2013). “System boundary for embodied energy in buildings: A conceptual model for definition.” *Renewable and Sustainable Energy Reviews*, 21, 153-164.

Dixit, M.K., Fernández-Solís, J.L., Lavy, S., and Culp, C.H. (2012). “Need for an embodied energy measurement protocol for buildings: A review paper.” *Renewable and Sustainable Energy Reviews*, 16 (6), 3730-3743.

Dixit, M.K., Culp, C.H., Lavy, S., and Fernández-Solís, J.L. (2012). “Recurrent Embodied Energy in Life Cycle of Built Facilities.” *Facilities*, accepted for publication.

Dixit, M.K., Fernández-Solís, J.L., Lavy, S., and Culp, C.H. (2010). “Identification of parameters for embodied energy measurement: A literature review.” *Energy and Buildings*, 42 (8), 1238-1247.

Conference Proceedings

Dixit, M.K., and Yan, W. (2012). “BIM-based BiPV prototype for the solar insolation calculation. In: ISG-ISARC Conference on Robotics and Automation in Construction,” Eindhoven, June 26-29, 2012.

Dixit, M.K., Culp, C.H., Lavy, S., and Fernández-Solís, J.L., (2012). “Recurrent embodied energy and its relationship with service life and life cycle energy: a review paper.” In: Joint CIB W070, W092 and TG72 International Conference, Cape Town, January 22-25, 2012.

Dixit, M.K., Fernández-Solís, J.L., Lavy, S., and Culp, C.H. (2010). “State of Standardization in Embodied Energy Computation: The need for a Protocol.” In: Proceedings of the CIB-W70 International Conference in Facilities Management: FM in the Experience Economy, Sao Paulo, September 13-15, 2010, pp. 571-583.

Dixit, M.K., Fernández-Solís, J.L., Lavy, S., and Culp, C.H. (2010). “Protocol for Embodied energy Measurement Parameters.” In: Proceedings of the TG66 - Special Track 18th CIB World Building Congress, Salford, UK, May 11-13, 2010, pp. 188-203.