ASSESSMENT OF BUILDING LIFECYLE CARBON EMISSIONS

BY

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Acknowledgements

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ABSTRACT

Even though the Carbon Capture & Sequestration Technologies (CC & ST) program at the Massachusetts Institute of Technology initiated carbon emission research in late 1990s (CSI, 2013), carbon emissions has only become a hot topic in the last decade since the Kyoto Protocol was adopted on December 11, 1997 in Kyoto, Japan. CC & ST is a protocol to United Nations Framework Convention on Climate Change (UNFCCC or FCCC) to overcome global climate change due to human activity. The protocol entered into force on February 16, 2005 and the entire Annex I countries ratified the protocol, with the exception of the United States. The U.S. already had a policy in place so that the country's carbon emissions were to be reduced by 7% from 1990 emission levels by 2012. Federal and state governments along with the private sector need to prepare for reductions in carbon emissions. The construction industry contributes over 40% of carbon emissions and generates significant amount of construction and demolition debris which is deposited into landfills. While some of the debris can be reused, recycled, and used as biomass fuel for energy. Building operations consume significant amounts of energy, but there are only a few comprehensive studies that estimate carbon emissions considering the whole building lifecycle. Many of these studies are conducted in independent carbon phases, which may miss emissions that an end-to-end review would capture. The purpose of this research is to develop methods to estimate and evaluate the carbon emissions and the environmental impact throughout a building lifecycle (from building construction to building demolition). This research integrates prior models and methods, in order to establish comprehensive models and

methods that would more accurately measure, track and quantify carbon- and environmental-related features, factors and variables. This research uses information and data that span four projects ranging from current green building designs, ways to determine the carbon emissions and carbon emission reduction of green features in green buildings, to the carbon residues of disposal materials. The first part of the research examines the operating carbon emissions of buildings. The operation data was gathered from Kansas Department of Transportation and the data is used in the analysis. The data is divided into building address, energy consumption per area, and carbon emissions per area. To complete the lifecycle study of buildings, a calorimeter is considered in the proposed framework to find the energy generated from the combustion of demolition waste.

The research establishes a comprehensive framework of carbon emission modeling that includes the modeling of energy use, water consumption, energy efficient technology, material production, transportation, and the end-of-life analysis of construction materials. The comprehensive framework of carbon emission modeling will establish the much needed framework that the industry needs to accurately and reliably estimate carbon emissions throughout a building lifecycle. The individual modeling methods used offer a methodology for carbon emissions estimation that can be applied to building parts and materials that are not covered by this research.

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CHAPTER 1: RESEARCH BACKGROUND AND MOTIVATION

Zhao, et al. (2012) stated that Corporate Social Responsibility (CSR) was an increasing valued factor of business success in the construction industry. Being an industry that generates large amounts of carbon emissions from the planning, design, construction, installation, maintenance, operation, decommissioning, and demolition stages of buildings, very few public agencies and construction companies understood what the meaning of CSR is and how to practice it within their scope of the project. Also, there is neither a universal agreement nor commonly accepted explanation of the definition of CSR (Zhao, Zhao, Davidson, & Zuo, 2012). The European Commission defined CSR as "the commercial activities and contacts with relevant stakeholders taking social and environmental factors into consideration on a voluntary basis" (European Commission, 2001; Zhao, Zhao, Davidson, & Zuo, 2012). Furthermore, Zhao, et al. (2012) also specified that CSR indicators, such as ISO9001:2000, ISO26000:2010, ISO14001:1996, OHSMS18001, and SA8000, were adopted by different countries and regions with differences in regional economic development and culture background; therefore, the evaluation conclusions drawn from them could not accurately reflect the CSR performance (Zhao, Zhao, Davidson, & Zuo, 2012). A framework of an indicator system for CSR performance was developed by Zhao, et al. (2012) but the indicator was focused on social and safety and did not provide detailed methodologies to measure the environmental CSR performance.

According to a study in the United Kingdom, 420 million tonnes of resources are used in the construction industry per year, and the wastage rate was 10% (Wu, 2008).

Buildings contributed about 50% of the UK's carbon emissions and construction contributed about another 7% (NBT, 2010). In China, water consumption was 30% higher than in the developed countries; steel consumption was 10 to 25 % higher, and cement usage was 80 kg more per cubic meter on average during construction per capita (Wu, 2008; Zhao, Zhao, Davidson, & Zuo, 2012). The European Union generated more than 450 million tonnes of construction and demolition waste every year. 16.6 million tonnes of waste were generated from construction activities in Australia in 2007, accounting for 38% of total waste (ABS, 2010; Zhao, Zhao, Davidson, & Zuo, 2012). The buildings in the U.S., China, and Australia generated over 40% of all carbon emitted (Zhao, Zhao, Davidson, & Zuo, 2012; ABS, 2010). The United States Greenhouse Gas Inventory 2011 data showed that building construction related activities, such as iron & steel production, cement production, and lime production, contributed the vast majority of carbon equivalent emissions, including carbon dioxide, nitrous oxide, and methane. Even though carbon emissions decreased in 2009 due to the economic recession, the construction related activities still contributed the majority of carbon emissions in the U.S. (USEPA, 2011c).

The construction industry in the United States generated 136 million tons of construction and demolition waste according to 1996 data (USEPA, 2002) of that, more than 5 million tons of organic hazardous waste requires thermal treatment every year. Construction waste and debris is a majority part of the urban waste stream. According to the California Department of Resources Recycling and Recovery Board's 2004 Statewide Waste Characterization Study, construction and demolition (C&D) materials made up approximately 22 % of California's waste disposal (CalRecycle, 2011). In a report by

Napier for the U.S. Army Corp of Engineers, construction waste was about 25% to 40 % of the solid waste stream in the United States and only 20% of construction and demolition waste was recycled (Napier, 2011). Also, other than debris from construction and demolition; natural disasters, such as wildfires, floods, earthquakes, hurricanes, tornadoes, and winter storms generate large amount of debris every year in the U.S. (USEPA, 2011a). The cement industry currently uses over one million tons of hazardous waste a year as an alternative fuel - replacing expensive and non-renewable fossil fuels such as coal (CKRC, 2004). However, using such fuel may have caused severe environmental impacts. Hazardous waste released dioxin, arsenic, and other toxic substance to the air during combustion (ATSDR, 2011; USEPA, 2011b). The Kyoto Protocol was put in place to reduce manmade greenhouse gas emissions and it was agreed upon by 150 countries in December 1997. With increased interest in international cooperation regarding the reduction of greenhouse gases via the Kyoto Protocol, the number of countries implementing regulations regarding incineration would increase (Parr, 2006). More regulations would be in place and existing emissions rules would be stricter. There was a need to determine the gas emissions and the environmental impact of varying construction and demolition waste, while also building lifecycle studies in order to satisfy the international regulations and prepare the U.S. to comply with such international protocols (Kessler, 2013).

The environmental impact of construction lacks sufficient attention (Fuertes, et al., 2013), environmental impact indicator systems for construction companies have not been established and adequate tools that cover the full-detailed performance indicators for construction companies do not exist (Zhao, Zhao, Davidson, & Zuo, 2012). Walker and

Johnston (1999) explored the existence of impact interactions and concluded that the environmental effects that could result from these interactions could be significant and their early identification may have contributed to sustainability improvement (Walker & Johnston, 1999). Fuertes, et al. (2013) pointed out that there was very little research on the identification of the impact causal factors and interactions in building construction, and they stated that the construction industry needs to improve the understanding of construction-related environmental impacts by identifying all the causal factors and associated immediate circumstances during construction processes (Fuertes, et al., 2013). Their research focused on the construction site during building construction, and they developed a construction-related Environmental Impact Causal Model based on 45 causal factors. Some of the factors considered were water consumption, electricity consumption, fuel consumption, and raw material consumption (Gangolells, et al., 2009; Brownea, O'Regan, & Molesc, 2012), and the model considered all the activities during construction processes, such as dumping of water resulting from the excavation of foundations and retaining walls, transport issues, and generation of greenhouse gas emissions due to construction machinery, and vehicle movements. They expected that the model would help the person responsible for environmental issues on the construction sites and other decision-makers, such as contractors, owners, and engineers to understand where and how impacts arose (Fuertes, et al., 2013).

According to Mann, Walther and Radcliffe (2005), sustainable design was the methodology of designing for the economy of resource, product lifecycle, and services for society to comply with the principles of sustainable development (Mann, Walther, & Radcliffe, 2005). The design principles were:

1. Managing, reducing, recycling and reusing of wastes;
2. Using environmentally preferable products and eliminate impacts on the environment;
3. Enhancing interaction between humans and the natural world;
4. Optimizing site potential;
5. Maximizing renewable energy use; and
6. Conserving materials, energy, and water.

In other words, sustainable designs should have considered the whole lifecycle of each product. In the construction industry, sustainability should have included the lifecycle of each raw material and how the materials may have impacted the environment locally and at their sources throughout the service life. During the operation of a building, users, and owners may have needed to consider the power and water consumption of a building and the amount of carbon footprint they contributed when they were occupying a building. The casual model by Fuertes, et al. (2013) could be adopted and extended from building construction to the full building lifecycle.

In Cradle-to-Cradle research by Liu (2009), she found that Cradle-to-Cradle and Cradle-to-Grave were integrated as the material and energy flows in both models could be tracked through the resource loop (Liu, 2009). Analysis of energy use could indicate ways for more effective energy use without impairing the economics of produce production (Guzmán & Alonso, 2008; Zafirioua, et al., 2012). In the pulp and paper industry, Chen, Chung, and Hong (2012) indicated that notable energy savings could be achieved in the pulp and paper industry through energy flow analysis. Their energy flow analysis identified areas of energy loss and they examined potential technology options for the capture of some of the energy that was currently lost in the processes (Chen, Hsu, & Hong, 2012).

In the construction industry, there was a lack of comprehensive research in carbon emissions. Arpad Horvath and his researchers had developed some of the most comprehensive research in carbon emission models for civil infrastructure, transportation, utility, and energy (UC Berkeley, 2013). Their works included carbon emissions of transportation fuel, water consumption, end-of-life impact of buildings, waste, and building energy consumption (Viera & Horvath, 2008; Strogen, Horvath, & McKone, 2012; Chester, Horvath, & Madanatc, 2010; Facanha & Horvath, 2007; Stokes & Horvath, 2009; Boughton & Horvath, 2004; Pacca & Horvath, 2002). Their research in carbon emissions from transportation found that the carbon emissions were wasted from poor management in the ethanol distribution processes, and carbon emissions from freight transportation of materials (including rail, air, and truck) (Facanha & Horvath, 2007; Strogen, Horvath, & McKone, 2012). Their research also extended to cover life-cycle energy and emission footprints of passenger transportation in the metropolitan regions. The focus included road construction, parking, and fuel consumption of vehicles (Chester, Horvath, & Madanatc, 2010). Their research on the energy and carbon emission effects of water supply successfully quantified the lifecycle carbon emission of water supply through the modeling of the impacts of water supply distribution, treatment, supply, maintenance, operation, construction, materials production. (Stokes & Horvath, 2009). Their team also conducted research to study the carbon emissions due to power supply and how green technology would mitigate carbon emissions in the future (Pacca &

Horvath, 2002). Further research was carried out to quantify the carbon emissions of a building's concrete frame at its end-of-life (Viera & Horvath, 2008).

While there was no shortage of research on carbon emission models, there was clearly a lack of carbon emission models that integrate all lifecycle phases of a building. Existing studies were not comprehensive enough to cover whole building lifecycle, from the design phases to end-of-life. While research had covered carbon emission modeling extensively, there were still several missing areas throughout the whole building lifecycle, such as:

- End-of-life of various construction materials like wood, metals, and plastic;
- The variability of operational energy due to different electronic devices and appliances;
- The overall carbon emission reduction by green technology;
- The effects of greenery on reducing carbon emissions; and
- Materials that are unique (such as building envelope).

There was a need to establish a standard carbon emission-modeling framework for each part of the building lifecycle in order to generate more accurate outputs. Such a method could be extended to all the phases, materials and parts for future research in building carbon emissions.

1.1 Structure of Dissertation

This research followed the structure as shown in Figure 1. Chapter 1 describes the research motivation and shows the structure of this research while Chapter 2 defines the research objectives. Chapter 3 is the literature review of this study that first located existing studies about carbon emissions and how these studies determined the methodologies, including the types of models, and types and sources of data. This section also discusses how the science of carbon dioxide emissions affect the climate and the existing protocols in the world to prevent its effect of climate change. In addition, this section discusses briefly the marketing and financial side of carbon emissions (carbon trading).

Later chapters cover different lifecycle phases of a building, ranging from raw materials, building construction, building operation, and the end-of-life of a building as shown in Figure 2. Building operation is covered by Chapters 5 and 6. Chapter 5 discusses the environmental impact and carbon emission of building operations due to utility and Chapter 6 discusses the environmental impact and carbon emissions due to building equipment. Chapters 5 and 6 conclud with the proposed carbon emissions and environmental impact models pertaining to building operation and equipment.

Chapter 7 focuses on the end-of-life analysis of selected building materials. This chapter covers how building materials are recycled and reused and discusses how building materials can be used as biofuel to generate electricity. Plans were made to conduct laboratory testing on construction materials using the IKA C200 calorimeter. However, due to the loss of the oxygen charging station, testing was not carried out as planned. As an alternative, this chapter discusses how the method would work and the method to estimate energy released from selected building materials during incineration in a calorimeter. Chapter 8 concludes the study with the overall findings and framework. Chapter 9 presents a model testing on webpages written by PHP coding with MySQL server.

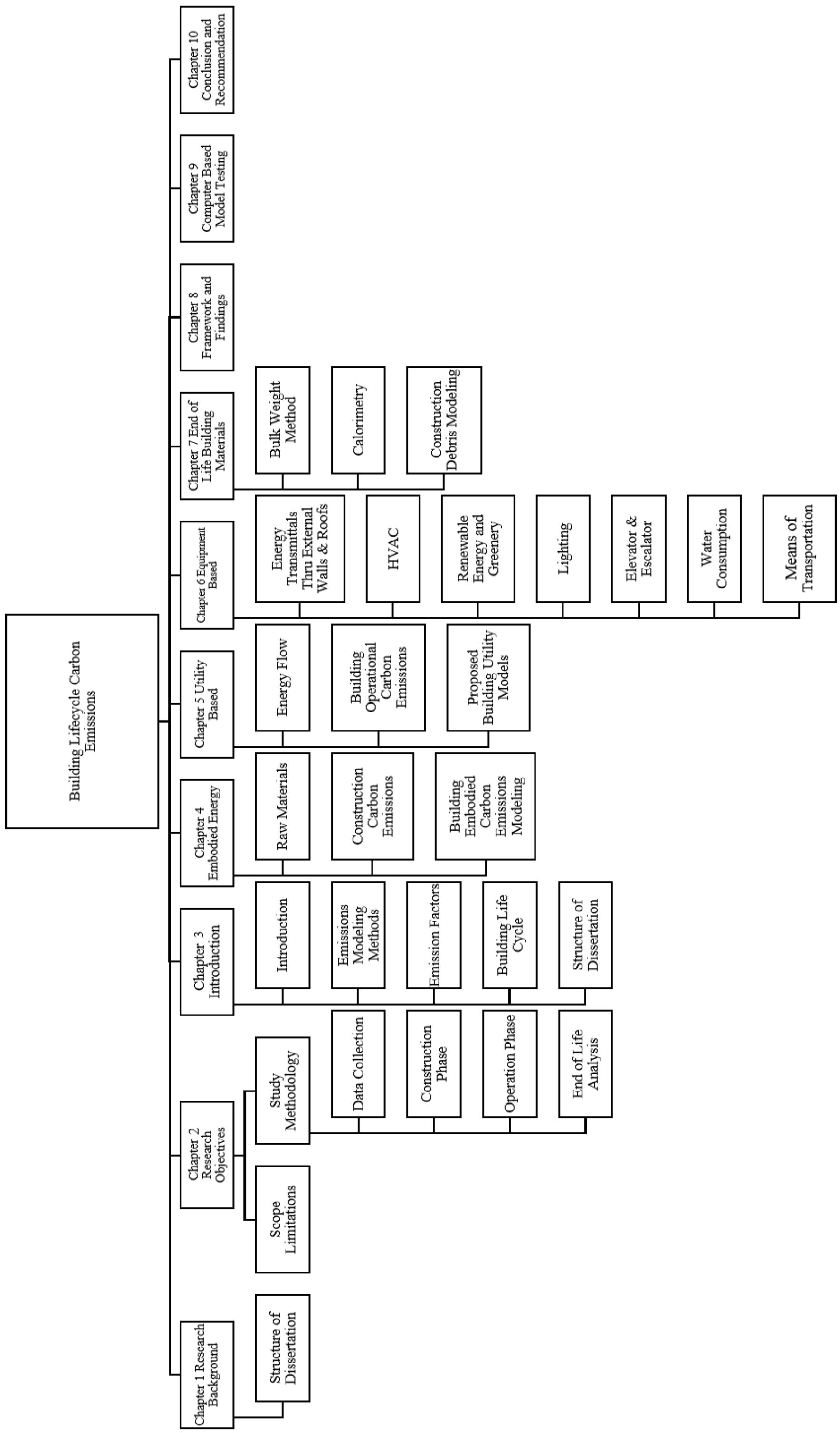


Figure 1 Structure of Dissertation

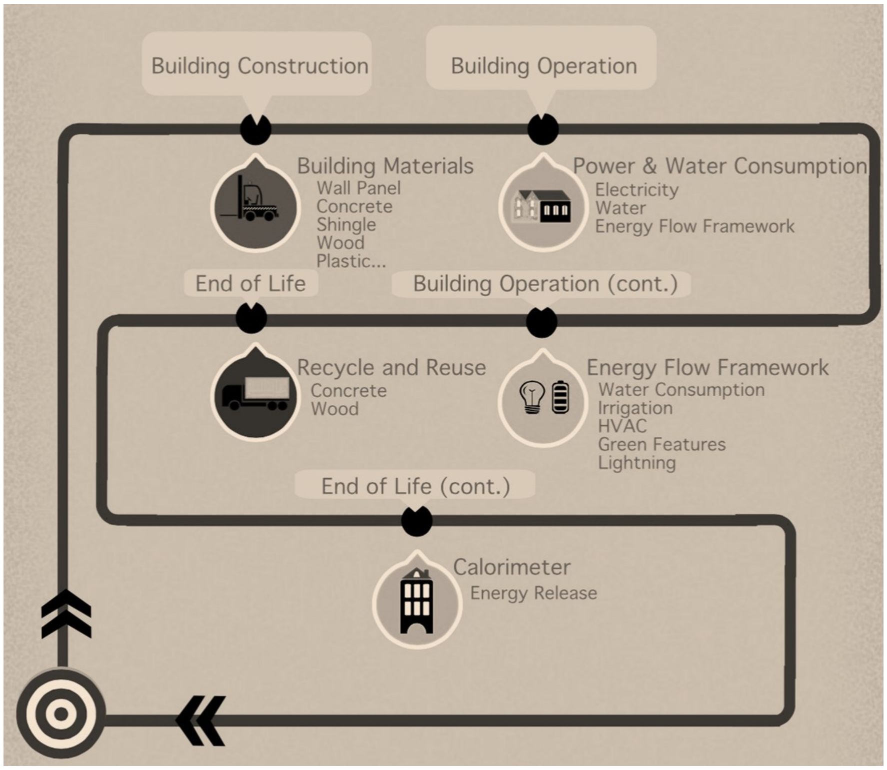


Figure 2 Building Lifecycle (Suzuki & Oka, 1998)

CHAPTER 2: RESEARCH OBJECTIVES

The purpose of this study is to understand and model the carbon emissions and environmental impact that relate to the construction industry. The objective of this study is to create a comprehensive frameworks to estimate the environmental impact and the carbon emissions throughout the whole building lifecycle. The framework can be extended and adjusted to other areas, processes, machinery, and devices that are not covered by this research.

The carbon emissions calculation methods will first be studied. There are three types of carbon emissions calculation models to be discussed in Chapter 3 (Oka, Suzuki, & Kounya, 1993; Green Design Institute, 2010). This study will determine their differences and how they include various carbon emission factors. In addition, the study will establish the approach on how these methods can be applied to model building lifecycle carbon emissions. This study will also review the sources of carbon emission factors generated from raw material production and transportation.

This research will also study how building lifecycle analysis is used to determine carbon emissions and environmental impact of each activity from building construction to building demolition. Since there are numerous activities involved during the construction, operation and demolition phases, only a few activities in each stage will be chosen to create the carbon emissions and the environmental impact estimation framework. Some power consuming activities, such as Heating, Ventilation, and Air Conditioning (HVAC), lift and escalator, and greenery, will be studied in detail to create a micro equipment-based framework. These frameworks and micro frameworks are modeled to be capable for adjustments and applied to other activities that are not covered in this study. The scope of study will include:

- Power consumption during construction
- Embodied energy of building materials
- Power consumption during operation of building
- Water consumption during operation of building
- Green features in buildings that generate carbon offset

The variables that are collected in this section include electricity consumption in kWh, water consumption in gallons, building embodied energy in Joules, and carbon offset in tons of CO_2. Operational and embodied energy, and water use are the most significant inputs contributing to carbon emissions from buildings.

This study will determine how construction debris can be reused and recycled at the end of the lifecycle of buildings. For materials that cannot be reused or recycled, this study will determine if it is possible for these materials to be used as biofuel to generate power and how much power that can be generated using construction debris. The materials that will be studied in this research are common construction debris, such as wood, concrete, and roof shingle.

The focus on the project is to develop the framework for carbon emissions modeling for the entire building lifecycle. While many individual frameworks covering different aspects of building lifecycle have been researched, none of the prior research has been completed to integrate these various frameworks into a single operational framework (as discussed before). The research will also test the use of part of the framework as the testing of the entire framework is too extensive for a dissertation.

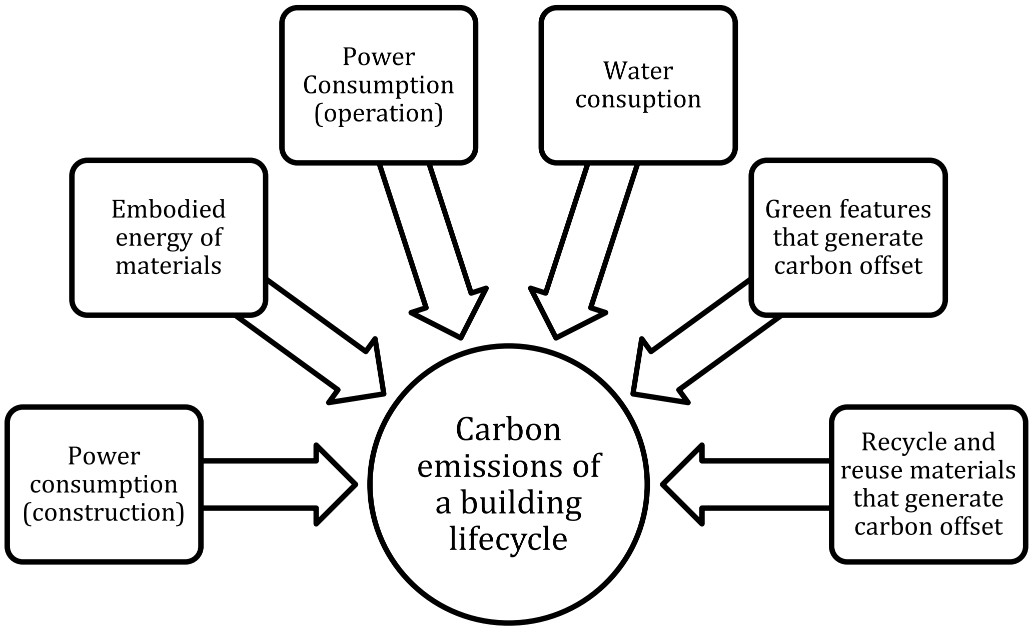


Figure 3 Summary of Research Objectives

2.1 Scope Limitations

This research will provide an insight to carbon emission factors generated throughout building lifecycle from the electricity, gasoline, water, concrete, and metals. The analysis will be explained in the methodology and the analysis chapters in this dissertation. The emissions factors used in this research came from Inventory of Carbon & Energy (ICE) by the University of Bath in Great Britain. If local factors are available, they will be used accordingly to improve accuracy. This data includes carbon emission factors for power generation in Kansas, reverse osmosis for water in Singapore, and power generation in Singapore. The carbon emissions factors of the production of raw construction materials are assumed to be the same as the data in Great Britain published in the ICE. Future studies are needed to include regional factors that create significant impacts on the models.

The operational building carbon emissions section contains two methods in this dissertation. Some building owners or operators do not have extensive record of power consuming equipment in their building. The estimation of operational carbon emissions of these buildings may need to rely on the utility records provided by utility companies and it is the utility-based analysis. In equipment-based analysis for power consumption, only HVAC, and green features, and greenery are chosen to be part of the research. Green features are included in the operational carbon emissions because green features like a green roof has a direct impact on the power consumption by heating and cooling systems. Other power consuming devices, such as computers, lighting, laboratory tools, TV or entertainment systems, should be included in future studies. Due to the complexity and the requirement of local electricity metering for each device, it is excluded from the scope of this study. In the utility-based section, only water and electricity are considered. The analysis will be explained in detail in the analysis chapters.

2.2 Overview of Study Methodology

2.2.1 Overview of Data Collection

During the construction of a building, the process involves a wide variety of construction materials and techniques (CalRecycle, 2011), and the process requires a wide variety of machinery. As a result, the estimates for fuel consumption and power use for tasks and equipment, for each construction project will vary widely (Peters & Manley, 2012). Peters and Manley found that it is difficult to estimate the fuel consumption and power consumption during building construction due to the wide variety of fuel and power sources, such as gasoline, diesel, and electricity, for tools and machinery. The authors also found that different companies and agencies used different terminology in their consumption estimation and there are no existing fuel consumption regulation standards or requirement in their study (Peters & Manley, 2012).

In the case study of this research, the construction of Measurement, Materials and Sustainable Environment Center (M2SEC) at the University of Kansas was examined. The M2SEC building contains labs and offices for faculty and staff and it is a good example to study as a model of a commercial building. Due to lack of records on the fuel and power consumption by the contractor, owner, and designer, the scope of this research does not consider the power and fuel consumption data.

The contractor and designer kept extensive records of all the materials used in the M2SEC. This research examines the materials used in excavation, structural, masonry, carpentry, roofing and flashing, doors and glazing, plaster and ceilings, flooring, equipment, fire protection and plumbing, HVAC, and electrical related materials. The data was used to find the embodied carbon emissions of the building.

Carbon emission calculation requires carbon emission factors in order to find the carbon emission equivalent of each construction item. The University of Bath Sustainable Energy Research Team collected most of the common materials and summarized into Inventory of Carbon & Energy (ICE). This research uses the carbon emission factors to convert the material data to carbon emissions.

For building operation, the Kansas Department of Transportation (KDOT) provided power consumption data from 900 buildings all over Kansas from 2007 to 2010. The carbon emission research with Singapore's Building and Construction Authority (BCA) would offer a framework of how to estimate power consumption of a building based on the equipment in a building using energy flow analysis. The focus in this framework included roof thermal resistance (R-value) or Envelope Thermal Transfer Value (ETTV), building façade, AC system, lighting, lift and escalator, green roof, renewable energy, water consumption, and irrigation.

For the end-of-life study in the building materials, calorimetry is used to find the energy released from construction materials during combustion. This research will determines a method to find the best building materials to be used as biomass fuel at the end of the building life.

2.2.2 Construction Phase

Data is collected from every phase in order to reflect the reality of a full building lifecycle. The data that is used for the earlier part of a building lifecycle is based on the M2SEC. M2SEC is located next to the Learned Hall of the School of Engineering at the University of Kansas (KU). The building square footage is about 47,000 square feet. It contains laboratory space for the School of Engineering and offices for the Transportation Research Institute (TRI) at KU. The data includes the materials used in the building and the energy use during construction as provided by JE Dunn, the general contractor of the building construction. This research uses the data to determine the environmental impact and embodied energy of the building. The data is compared to the United States Energy Information Administration (EIA) recommendation of similar educational facilities' energy use in the Building Energy Data Book (USEIA, 2008). This part of the research is the pilot framework of the carbon emissions estimation of building construction.

2.2.3 Building Operation Phase

The building operation section of lifecycle research is separated into two parts. The utility-based calculation for carbon emissions due to energy use was based on over 900

KDOT buildings. KDOT and its utility providers provided the electricity consumption data from 2007 to 2010. In addition to energy data, blueprints of KDOT buildings were used to determine the materials in the buildings to estimate the embodied energy and carbon emissions.

The second half of building operation research focused on energy consuming machines and building features during operations and studied how they affect energy use and their environmental impact. Existing research, calculations, and science in these machines and building features, including HVAC, roof, greenery, water consumption, elevator, escalator, lighting, recycle and reuse programs were used in this part of the research. The energy estimations and calculations in these areas come from basic science that was determined by existing research and machine manufacturers. The purpose of this was to establish a methodology to determine carbon emissions and environmental impact of each device in a building. Frameworks of the methodologies are the products of this research. These frameworks can be adjusted so that they can be applied to other machines or building features that were not studied in this research.

2.2.4 Building End-of-Life Analysis

Calorimetry is the science to measure the heat change of chemical reactions, and it covers direct and indirect calorimetry. Indirect calorimetry is the measurement of the production of carbon dioxide and nitrogen waste of a living organism while direct calorimetry is the measurement of heat generated by an oxidation reaction in a calorimeter (Laidler, 1995). Calorimeter is a device that measures the heat generated during an oxidation reaction. Bomb calorimeter is commonly used for solid and liquid fuel testing, waste and refuse disposal testing, food and metabolic studies, propellant and explosive testing, and fundamental thermodynamic studies (Parr, 2006). During a calorimetry test, a sample usually reacts with pure oxygen in a closed vessel (IKA, 2011a). Due to the high temperature combustion, calorimeter can simulate the combustion of fuel in a power plant or garbage incineration.

In this research, a bomb (or combustion) calorimeter were considered in the proposed material testing. The device contained a combustion vessel called a bomb, and a crucible was located inside this closed vessel. Material sample could be placed in the bomb and the bomb would be secured inside the water tank of a calorimeter. The device determined the changes in water temperature during the combustion test. Figure 4 showed the schematic drawing of the device.

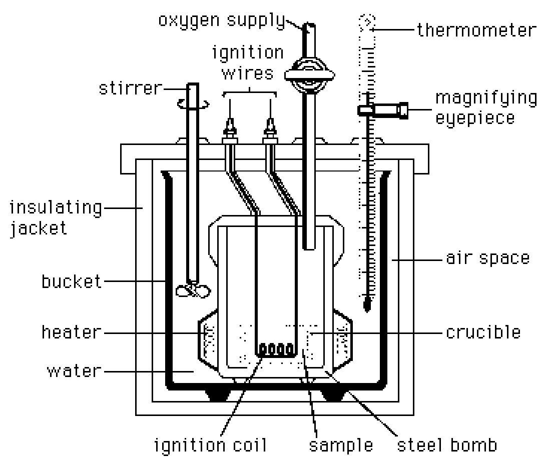


Figure 4 Bomb Calorimeter Diagram (Encyclopedia Britannica, 2011)

Even though other calorimeters, such as calvet-type calorimeters, constant-pressure (coffee cup) calorimeter, and differential scanning calorimeter, are available, bomb calorimeter is chosen because it is a closed system and adiabatic. The heat in the water tank does not transfer to the water around the bomb. The bomb is built with solid stainless steel with thick walls, and the heat will only transfer to the water in the testing device. In addition, bomb calorimeter complies with several ASTM standard test methods on the materials that are going to be tested. In addition the IKA C200 calorimeter considered for this research is automatic and the result can be display on a computer with the temperature changes by second throughout the approximate 17-minute testing.

Bomb calorimeter calculates the temperature change in the inner vessel and it also monitors the temperature of the water tank inside the device. The heat generated by a specimen is calculated using the formula below:

$$Ho = (C * DT - QExt1 - QExt2) / m \qquad \text{(IKA, 2011b)}$$

Where: m is Weight of fuel sample

C is heat capacity (C-value) of calorimeter system

DT is calculated temperature increase of water in inner vessel of measuring cell

QExt1 is correction value for the heat energy generated by the cotton thread as ignition aid

QExt2 is correction value for the heat energy from other burning aids

Equation 1 Heat Equation of Calorimeter

The correction value for the heat energy from burning aid QExt1, cotton thread in this case, is 50J, and the value is given by the manufacturer. The correction value for the heat energy from other burning aids is zero since no other burning aids will be used besides a cotton thread and a combustible crucible, manufactured by IKA.

Before any experiment starts, each bomb is required to calibrate with benzoic acid to determine the heat capacity of the calorimeter system. The formula below is used to determine the C-value.

$$C = (Ho * m + QExt1 + QExt2) / DT \qquad \text{(IKA, 2011b)}$$

Where: m is the heat capacity of calibration benzoic acid

DT is calculated temperature increase of water in inner vessel of measuring cell

QExt1 is correction value for the heat energy generated by the cotton thread as ignition aid, a default value of 50 J.

QExt2 is Correction value for the heat energy from other burning aids. The default value is 0.

Equation 2 Calibrating Equation for Calorimeter

The energy data of the end-of-life analysis is collected by using calorimetry. The purpose of this part of the research was to propose a method to find the energy release when construction materials were being cinerated. When building materials could not be reused and recycled, they were often shipped to power plants to be burned as biomass fuel for electricity generation. Calorimetry testing simulated this process and this research determined which common construction materials were best to be used as biofuel. Energy released from the biofuels in kilojoules could be collected in the proposed method.

CHAPTER 3: INTRODUCTION

The Greenhouse effect is the effect that greenhouse gases absorb infrared radiation reflected from the Earth and heat is trapped in the atmosphere. The phenomenon is caused by greenhouse gases such as carbon dioxide, nitrous oxide, and methane. According to a study by the National Oceanic & Atmospheric Administration (NOAA) in Mauna Loa, the concentration of carbon dioxide increased about 65ppm between 1960 and 2010 (NOAA, 2011). To lower the greenhouse gases in the atmosphere, countries signed the Kyoto Protocol, an international treaty that went into effect in 2005, limiting the carbon emissions of participating countries. The intention is to reduce the overall emissions by 5.2% from the 1990 level by the end of 2012. The Intergovernmental Panel on Climate Change (IPCC) provides standard guidelines and methodology to calculate greenhouse gases generated by the industries in different countries (IPCC, 2007; IPCC, 2013).

3.1 Carbon Emissions Policy

The Kyoto protocol emphasizes accounting for carbon emissions. This accounting for carbon emissions has led Annex I countries come up with ways to mitigate their emissions. Carbon taxation and trading (or cap and trade) is the most effective solution for reducing carbon emissions. Most of the Annex I countries (developed countries) have "cap and trade" policies in place, and carbon emissions are being traded in stock markets. Even though the United States has not ratified the treaty, over 1000 U.S. cities have adopted the protocol (IPCC, 2007). North America's only carbon trading system-Chicago Climate Exchange (CCX)-traded voluntary greenhouse gas reduction and offsets, but it ceased trading in November 2010 due to the lack of cap-and-trade legislation (Gronewold, 2011). Emission trading is only active in Europe and California as Over-The-Counter (OTC) forward and options through the Intercontinental Exchange (NYSE: ICE). Currently, ICE offers futures and futures options contracts in Europe. The quotation is calculated in Euro (€) and Euro cent (c) per metric tonne and the price was around € 6.450 to € 6.600 from November to December 2012. The minimum order is 1 lot, which is equivalent to 1000 Certified Emission Reduction units (CER) (ICE, 2011). In Australia, they will start to tax the most 500 polluting companies in the country in 2013. The carbon tax will be a fixed price at AUS$23 per metric tonne, they will have switch to a carbon trading scheme in 2015 (Pearlman, 2011). Worldwide, government resistance hinders carbon taxation and trading.

The emissions trading policies in participating countries primarily limit carbon emissions from manufacturing industries since they are the direct emission parties. However, the construction industry generates a large amount of carbon from the planning, design, construction, installation, maintenance, operation, decommissioning, and demolition stages of buildings. Very few public agencies and construction companies are monitoring their energy consumption and carbon emissions. According to a study in the United Kingdom, buildings contribute about 50% of the UK's carbon emissions and construction contributes about another 7% (NBT, 2010). Buildings in the U.S. generate over 40% of all carbon emitted in the country.

The first IPCC Guidelines for National GHG Inventories was published in 1995, and the Third Conference of the Parties (COP3) reaffirmed that it should be "the methodologies for estimating anthropogenic emissions by sources and removals by sinks of greenhouse gases" in the calculation of legally-binding targets during the first commitment period in Kyoto in 1997. Therefore, review of literature was conducted on the IPCC 2006 guidelines for National Greenhouse Gas Inventories in order to find how greenhouse gas emissions are calculated according to this international protocol (IPCC, 2007).

Although there are many carbon emission calculators online from different organization, they offer very little information on the concepts and basis of the resources of data or calculations. This research will examine the methodology of the carbon emission factors for fuels, and construction materials. Literature review indicates that the sources of carbon emission factors come from two types of models including Input-Output (I/O) Model, and Process Model. These models can also be combined (so called Hybrid models). They are defined by the sources of carbon factors. I/O Model data comes mainly from economic statistics whereas Process Model data comes from the process of contributing activities. Previous studies provided that carbon emission calculations depend on the boundary. If the carbon emissions are within the boundary of direct process, these emissions are considered as direct. On the other hand, the emissions outside the boundary would be considered indirect.

Green building certifications from various organizations usually provide manuals for their point rating systems. Leadership in Energy and Environmental Design (LEED) by United States Green Building Council offers Building Design + Construction (BD+C);

Building & Construction Authority in Singapore offer GreenMark guidelines; Building Research Establishment (BRE) offers BRE Environmental Assessment Method (BREEAM). These study manuals provide all the criteria included in the certification process. Extensive study is carried out in these manuals and areas that contribute carbon emissions. Carbon emission contributing activities would be listed on a spreadsheet, and related carbon emission factors are determined from previous studies.

Future research will convert the model to a carbon emissions calculator. The calculations can be implemented with Building Information Modeling (BIM) software in order to have accurate carbon emissions results for green buildings and shorten the calculation time.

3.2 Greenhouse Gases (GHGs): Types, Carbon Equivalence, and Carbon Accounting

GHGs include gases like carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), water vapor and some Volatile Organic Compounds (VOCs). GHGs absorb more heat energy than other gases (such as oxygen and hydrogen). As the amount of GHGs increase in the atmosphere, more solar heat is trapped in the gas and it increases the atmospheric temperature. If GHGs are not removed from the atmosphere and the GHG concentrations continue to increase, the atmospheric temperature will continue to rise. Temperature rise in the atmosphere may lead to the changes in climate (WRI, 2010b).

The solution to climate change is to remove GHGs from the atmosphere by sequestrating, and reducing GHG production. According to the Intergovernmental Panel on Climate Change (IPCC), other non-carbon dioxide GHGs have to be reported as carbon dioxide CO_2-equivalent (IPCC, 2010), by converting non-carbon GHGs into equivalent carbon . The following table shows the global distribution of carbon emissions from different sections and activities, and the types of GHGs generated by the industries:

Industry/Sector	End Uses/Activity	Gases
Transportation 13.5%	Road 9.9%	Carbon Dioxide 77%
	Air 1.6%	
	Rail, Ship, & Other Transport 2.3%	
Electricity& Heat 24.6%	Residential Buildings 9.9%	
	Commercial Buildings 5.4%	
	Unallocated Fuel Combustion 3.5%	
	Iron & Steel 3.2%	
	Aluminum/Non-Ferrous Metals 1.4%	
Other Fuel Combustion 9.0%	Machinery 1.0%	
Industry 10.4%	Pulp, Paper, & Printing 1.0%	
Fugitive Emissions 3.9%	Food & Tobacco 1.0%	
	Chemicals 4.8%	
	Cement 3.8%	
	Other Industry 5.0%	
	T&D Losses 1.9%	
	Coal/Mining 1.4%	
	Oil/Gas Extraction, Refining & Processing 6.3%	
Industrial Processes 3.4%	Deforestation18.3%	
Land Use Change 18.2%	Afforestation -1.5%	
	Reforestation -0.5%	
	Harvest/Management 2.5%	
	Other -0.6%	
Agricultural 13.5%	Agricultural Energy Use 1.4%	
	Agricultural Soils 6.0%	HFC, PFC, SF6 1%
	Livestock & Manure 5.1%	Methane 14%
	Rice Cultivation 1.5%	
Waste 3.6%	Landfills 2.0%	Nitrous Oxide 8%
	Wastewater, Other Waste 1.6%	

Table 1 World GHG Emissions Table (WRI, 2010b)

IPCC carbon emissions calculation, based on an agreement between the participants of the Kyoto Protocol, only include carbon dioxide, methane, nitrous oxide, hydroflurocarbons, perfluorocarbons, and sulfur hexafluoride (Carbon Trust, 2009). The total carbon emissions generated by activities in different industries can be measured by converting the GHG emissions to aggregated values of CO_2-equivalent and such values also equate to the Global Warming Potentials (GWP) (Baldo, Marino, Montani, & Ryding, 2009). GWP is used as a weighing factor that enables the comparison between the global warming effect of a GHG and a reference gas (i.e. CO_2). The 100-year GWP of CO_2, CH_4, N_20, and other VOCs are listed in Table 2.

Common name	**Chemical formula**	**Other names**	**GWP, 100 year time horizon**
Butane	C_4H_{10}	NA	0
Carbon dioxide	CO_2	NA	1
Dimethylether	CH_3OCH_3	NA	1
Ethane	C_2H_6	NA	0.4
Ethylene	C_2H_4	NA	0.8
HCFC-123	$CHCl_2CF_3$	Dichlorotrifluoroethane	76
HCFC-124	$CHClFCF_3$	Chlorotetrafluoroethane	599
HFC-125	CHF_2CF_3	Pentafluoroethane	3,450
HFC-134a	CH_2FCF_3	1,1,1,2-Tetrafluoroethane	1,410
Nitrous oxide	N_2O	NA	296
Propane	C_3H_8	NA	0.3
Propylene	C_3H_6	NA	0.9

Table 2 Table of GHGs and Their Global Warming Potentials

The GWP value of 23 for methane highlights that 1 ton of methane has an equivalent warming effect of 23 tons of carbon dioxide, while 1 ton of nitrous oxide generates an equivalent warming effect of 296 tons of carbon dioxide, over a period of 100 years.

CO_2 emission accounting commonly uses weight such as pound (lb) (English unit) and kilogram (kg) (International Standard unit) to determine the quantity of emission: The weight of CO_2 per energy consumption in energy units, Joule (J), kilowatthour (kWh), or British thermal unit (Btu), is used as the energy factor. These terminologies and factors are widely adopted by various agencies.

3.3 Carbon Emission Modeling

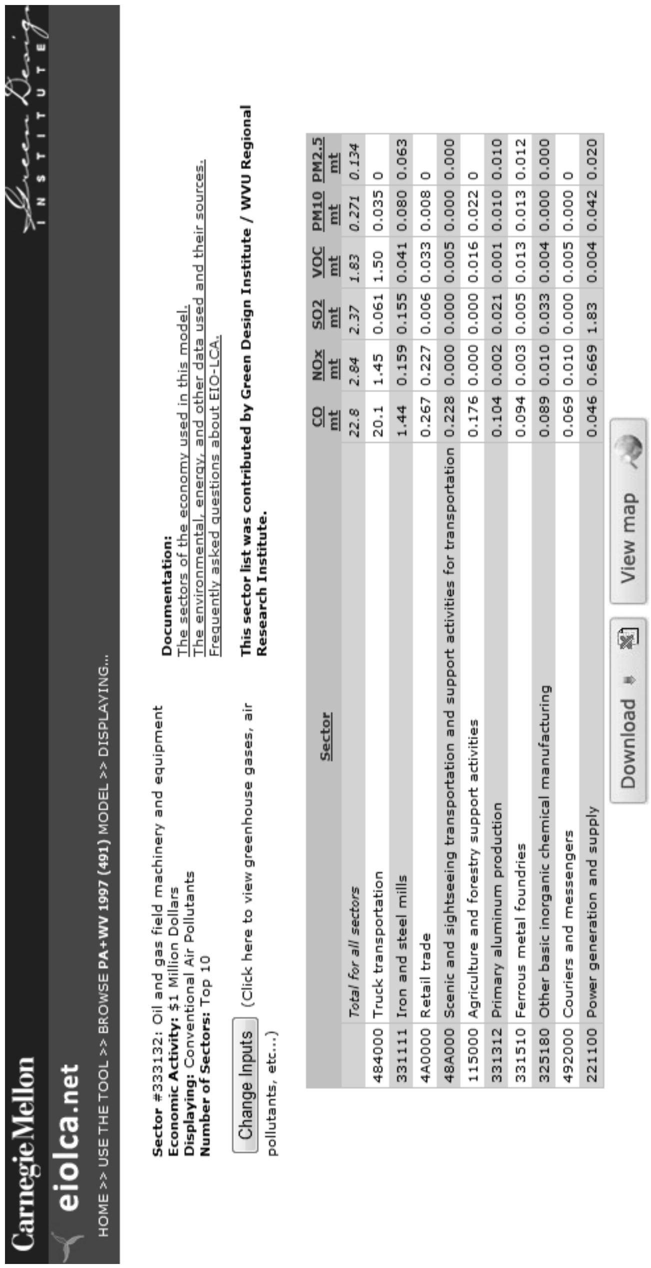
3.3.1 Input-Output Economic Model (Top-Down)

The Input-Output Economic Model mainly accounts for the annual economic activity of a country as a lump sum "revenue" such as Gross Domestic Product (GDP) data, or tax in different industry sectors. The percentages of each activity and sector are determined based on the amount of revenue generated by them. Applying the percentages to the lump-sum country's emissions, carbon footprint of each activity is determined. This method was first adopted in Japan by Oka and Michiya in 1993. In the Japanese method, the total amount of domestic, imported, and exported products produced by construction activities, such as steel and concrete, is published by the Research Committee of International Trade and Industry each year using the I/O Table of Japan (Oka, Suzuki, & Kounya, 1993).

The I/O Model was also adopted in Canada. The Canadian's models are very similar to the Japanese; however, the cost is switched to a market-based policy instrument, called the carbon permit system (Dissou, 2005). The revenue generated by carbon permit is calculated and then converted into carbon equivalent.

In the United States, Economic Input-Output Lifecycle Assessment (EIO-LCA) method developed by the Green Design Institute (GDI) at the Carnegie Mellon University (CMU) also uses a similar input-output method to measure carbon emissions. They adopt the Japanese economic model, but they localize it for Pennsylvania and West Virginia.

They compose different models for the 1992, 1997, and 2002 using the United States Department of Commerce’s Data. The CMU analysis result is displayed either in an excel file or on a webpage with specific industry sector and activity input. A sample result is shown below:



	Sector	CO mt	NOx mt	SO2 mt	VOC mt	PM10 mt	PM2.5 mt
	Total for all sectors	*22.8*	*2.84*	*2.37*	*1.83*	*0.271*	*0.134*
484000	Truck transportation	20.1	1.45	0.061	1.50	0.035	0
331111	Iron and steel mills	1.44	0.159	0.155	0.041	0.080	0.063
4A0000	Retail trade	0.267	0.227	0.006	0.033	0.008	0
48A000	Scenic and sightseeing transportation and support activities for transportation	0.228	0.000	0.000	0.005	0.000	0.000
115000	Agriculture and forestry support activities	0.176	0.000	0.000	0.016	0.022	0
331312	Primary aluminum production	0.104	0.002	0.021	0.001	0.010	0.010
331510	Ferrous metal foundries	0.094	0.003	0.005	0.013	0.013	0.012
325180	Other basic inorganic chemical manufacturing	0.089	0.010	0.033	0.004	0.000	0.000
492000	Couriers and messengers	0.069	0.010	0.000	0.005	0.000	0
221100	Power generation and supply	0.046	0.669	1.83	0.004	0.042	0.020

Figure 5 Sample Screen Interface from EIO-LCA (Green Design Institute, 2010)

There are advantages for the Input-Output Model. The most important advantage is the easy access of macroeconomic data since most countries have a statistics department to keep track of data such as power and water consumption in different industries. The calculations are fairly simple and they only require the combination of different weighting percentages in order to distribute the carbons according to the energy intensity of different production sectors. However, the disadvantage is that macroeconomic data requires a large number of assumptions as the data cannot be broken down further. The assumptions have to be made to address different types of equipment and fuel used, and production processes by different sectors. Power lost and other unexpected factors are likely ignored in the I/O models while the Process Models will count these factors in every step of the calculations (Chong & Hemreck, 2010). The assumptions could make the models less accurate.

3.3.2 Process Model (Bottom-Up)

The Process Model calculates carbon emissions based on the flow of energy use patterns at the manufacturing and production level. The energy consumption includes building construction, operation and maintenance, material production and extraction, and material transportation. This model is more precise compared to the I/O Model and it can be most effectively used to estimate the carbon emission of green building standards. According to IPCC guidelines on greenhouse gas emission calculation, greenhouse gas emissions can only be counted when the subject activities happen in that particular country (IPCC, 2007). In this modeling method, therefore, countries or regions that import most of their construction materials from neighboring countries, such as Singapore, Hong Kong, and the U.S. may have less carbon emissions on construction materials compared to materials exporting countries such as China. Similarly, within corporations, the raw material carbon emissions of products may not be counted in the supply chain emission accounting. In addition, the process model requires a clear boundary of the processes that will be counted in the calculation, and the boundary will define the direct and indirect carbon emissions that will be discussed later in the text. Moreover, the process of modeling each component is rather complicated since the carbon boundaries need to be established in order for this method to be feasible. Setting the boundary always creates controversies, and there is currently no standard to determine acceptable boundaries. Moreover, boundaries often fail to address the differences within countries, corporations and regions due to regulations (IPCC, 2007).

3.3.3 Hybrid Model

The Hybrid Model is a combination of the Economic Input-Output Model and the Process Model. In this modeling method, fuel consumption and its carbon emission factors are commonly estimated by the Economic Input-Output Model, while carbon emission factors from other criteria such as materials and water are estimated by the Process Model. Carbon emission factors depend on the level of accuracy needed, the types of information available, and the situations for modeling, The Hybrid Model is a very flexible method that often overcomes the disadvantages of either model, but the final model may suffer from the combination of errors of the other models. It contains both the disadvantages of the other two models, such as volume of assumptions, and boundary justification problems.

3.3.4 Direct and Indirect Carbon Emissions

The I/O Model, the Process Model, and the Hybrid Model require justification of what activities should be counted in the model. The justification is based on the boundary of direct and indirect carbon emissions. Direct carbon emissions refer to the emissions that are directly emitted from a process, while indirect emissions refer to emissions that are generated by supplementary processes that support the main process (Viera & Horvath, 2008). For example, energy consumed by a cooling system that is used to cool a retail store is a form of direct carbon emission to the store, however, this energy is an indirect carbon consumed by a consumer who buy something from the store. The definition of carbon emission depends on the established boundary of a product, material or individual. Figure 6 shows a simplified manufacturing process of plasterboard that highlights the classification method for carbon emissions. Carbon emissions within the boundary are “direct emissions”, while those outside the boundary are “indirect emissions”. The diagram also shows that at the end-of-life of the plasterboard, it will either go to landfills or be recycled or reused. For construction material, when it is reused or recycled, the process will be called cradle-to-cradle. On the other hand, when the material is shipped to landfills, the process will be called cradle-to-grave. Carbon emissions accounting will address both direct and indirect carbon emissions of cradle-to-cradle and cradle-to grave process because it will affect the decision on material use in the building (Viera & Horvath, 2008). In other words, the embodied energy of each construction material should be considered in the carbon emissions calculation.

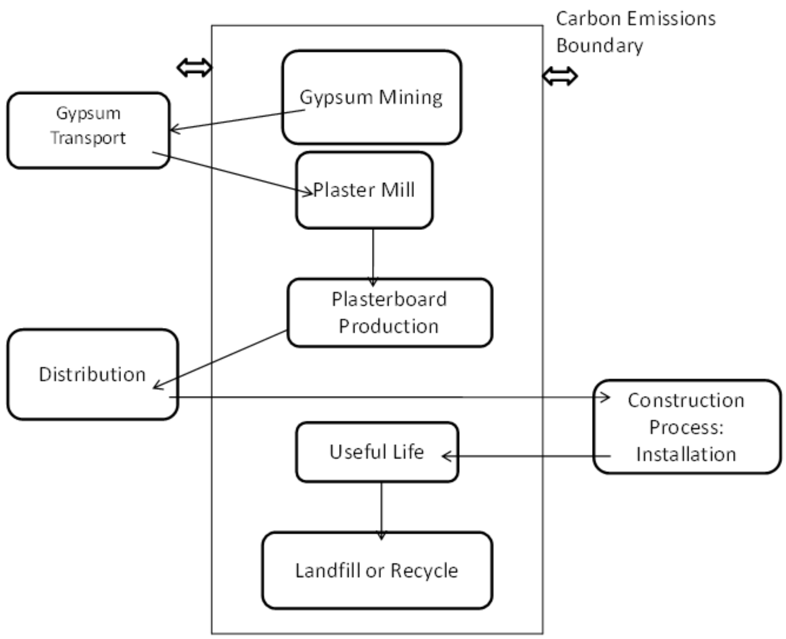


Figure 6 Direct and Indirect Carbon Emissions of Plasterboard (adapted from Lafarge Plasterboard, 2010)

3.4 Carbon Emissions for Raw Materials

The carbon emission factors used in this research came from multiple sources, such as Singapore Public Utility Board (PUB), United States Environmental Protection Agency (EPA), United States Energy Information Administration (EIA), and Inventory of Carbon and Energy at the University of Bath. The data from Singapore PUB was provided from their representatives and the research team had never been able to verify the methodology of the calculations. On the other hand, the data came from EPA came from the total carbon emissions of each region in the United States. Kansas was located on Region SPNO according to the eGRID report 2012 and the number was similar to the electricity carbon emission factor that was provided by the Singapore PUB. The emission factor from EPA was 0.8487 kg per kWh; the emission factor from Singapore was 0.5360 kg CO_2 per kWh; the emission factor from EIA was 0.8527 kgCO_2 per kWh for Kansas. The number that came from the United States EPA was higher due to the fact that coal was used to generate power in Kansas (Mufson, 2007). The research showed that data representing the same country was different due to the difference in methodology between agencies. The carbon emission factor that came from EPA was lower because it was normalized with Missouri and Missouri had Callaway nuclear power plant.

3.5 Inventory of Carbon and Energy (ICE)

This research used a large amount of data from the Inventory of Carbon and Energy at the University of Bath and the inventory was the most commonly used for carbon emissions estimation (Ekundayo, Perera, Udeaja, & Zhou, 2012). The inventory provided most of the embodied carbon emissions of the construction materials, such as glass, insulation, paper, paint, copper, clay, concrete, bricks…etc. All the materials have sources of embodied carbon emission breakdown, such as electricity, natural gas, and oil…etc., as shown on Table 3. The composers of the inventory provide the sources of their data in the reference section and the data shows that that they have been collecting data all over the world. The data may only be used as a reference to get a rough picture of how much carbon emissions each activity contributes in the construction industry. Thus, to estimate a more precise number, localized data should be used in the carbon emission calculation as discussed earlier on the electricity carbon emission factors. However, there is no current localized database for the U.S.

Embodied Energy & Embodied Carbon Split		
Energy source	**% of Embodied Energy from energy source**	**% of embodied carbon from source**
Coal	3.4%	5.1%
LPG	0.0%	0.0%
Oil	0.8%	0.9%
Natural gas	8.8%	7.5%
Electricity	87.0%	86.5%
Other	0.0%	0.0%
Total	100.0%	100.0%

Table 3 Sample Embodied Energy & Embodied Carbon Split: Brass (Hammond & Jones, 2011)

3.6 Localized Data and the Difficulties of Obtaining Data

Greenhouse Gas Protocol 2012 pointed out that many cities in the U.S. conducted a GHG inventory and set reduction targets, but there was no consistent guidance for conducting a city-level inventory. They also saw that there was a lack of common approach to determine carbon emission factors and it prevented comparison between cities (GPC, 2012).

As mentioned before, this research showed that different government agencies came up with different carbon emission factors because of their survey methodology. For power generation, the variances in power generation methods make a significant difference in carbon emissions. In addition, some cases like the Singapore PUB did not provide their methodology how they obtained their carbon emission factors for water and

NEWater (water that goes through reverse osmosis). The research team could not obtain the processes that were counted for the calculation and it took months for them to come up with the number that may not have been accurate. A common approach should have been established in order to have a fair comparison between cities, and between different construction materials. In the case of the construction materials carbon emissions, the data from ICE did not indicate whether or not transportation emissions were included in the calculation. According to a study by EPA, transportation accounted for 28% of the total greenhouse gas emissions in the U.S. The amount was too significant to be ignored (USEPA, 2013a).

3.7 Building Strategy in Carbon Emissions and Environmental Impact Reduction

3.7.1 Needs for Carbon Emissions Reduction and Carbon Trading

The American Clean Energy Act, President Obama's Energy and Environmental Security proposal, and the Kerry-Lieberman proposal contain many provisions for renewable electricity, carbon emission, energy efficiency, and cap and trade. Under the new bill and proposals, the state governments across the country are required to report, account for, and propose solutions to reduce its carbon emissions.

The American Clean Energy and Security Act institutes the future environmental and energy standards for the United States of America. It establishes the standards for renewable electricity, carbon emissions, energy efficiency, and cap and trade. Also, it sets the direction of investments in energy technology, alternative energy, workers' transition, and smart cars and grids. These standards and investments address several critical environmental and energy issues in the United States, such as climate change, and energy security, diversity, and technology.

One of the components of the bill is the cap and trade legislation. This will require private companies and public agencies to self-report and reduce greenhouse gases, toxic particles, sulfur dioxides, and nitrogen oxide emissions, along with sell or buy greenhouse gas credits from the market. Private companies that exceed their carbon emissions limits will have to buy carbon credits from the market, while those who have excess emissions will be able to sell the credits back to the market. Even though only private companies may be taxed or required to purchase credits for their carbon emissions, the U.S. Environmental Protection Agency (EPA) will require public agencies to report and reduce their carbon emission levels and the EPA set a target reduction each year for the public and private agencies.

Carbon emissions from large size corporation are generated from: (1) the energy use to run and operate the corporation's assets (like buildings, vehicles, equipment etc.); (2) the energy and materials used to produce or develop assets and products for the corporation; (3) the materials used to operate, maintain and repair the assets and products; and (4) the materials used by assets and/or its occupants. There are two ways to identify energy use and carbon emission: Direct and Embodied. Energy used and carbon emissions generated by the construction, operation, maintenance, repairing and running of the assets, and to produce and develop assets and products for the corporation is identified as direct energy use and carbon emissions. Embodied energy and carbon is defined as the sum of energy inputs and carbon emissions (fuels/power, materials, human resources etc.) that was used in the work to make any product, from the point of extraction and refining materials, bringing it to market, and disposal / re-purposing of it. A corporation consuming a product and not responsible to produce it is consuming embodied energy and carbon. A corporation has more control over its direct energy and carbon and able to implement plans to reduce them. On the other hand, a corporation has lesser control over its embodied energy and carbon and could only influence its embodied energy and carbon emissions with their procurement decisions.

Researchers find that energy and carbon footprint of buildings are effective methods to monitor buildings energy use efficiency and the overall energy efficiency of the whole industry and economy. Energy can be converted into carbon dioxide equivalents and the total may then be compared between similar buildings and the whole industry (USGBC, 2008).

The construction industry and the operation and maintenance of buildings consume over 40% of all energy consumed in the United States and generated over 35% of all carbon emissions. The transportation sector followed closely consuming 20% of energy and generating over 27% of all carbon emissions. Carbon dioxide is a form of Greenhouse Gas (GHG) that traps heat from the environment. Too much GHG in the environment will cause the atmosphere to heat up due to the dissipation of heat that is trapped in the GHG. This will lead to changes in the world's climate. Reducing GHG is thus important as it will alleviate the impact on the environment. In addition, growing demand for energy has pushed prices of fuels to new highs and threatens global economies and national security. Energy conservation has become more important than in the past as national security has overshadowed the need for just money savings.

Carbon and energy calculation is an important process of determining the energy use and carbon footprint of buildings and vehicles. Various studies suggest that the total energy consumption of buildings has increased year over year even though the energy use per square foot has actually decreased. This suggests that energy use has gone beyond the control of building occupants. Lighting and space cooling are the largest consumers of electricity while space heating consumes the majority of natural gas in the U.S. (Davis, 1998).

3.7.2 Green Building Criteria with Carbon Emissions

Different countries develop their own green building certifications. For example, the United States Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) is the green building standards adopted by the U.S., Canada, Mexico, and Italy. Building Research Establishment Environment Assessment Methods (BREEAM), and GreenMark are the standard in the UK and Singapore, respectively (BCA, 2010; USGBC, 2009; BREEAM, 2012).

These certifications rate buildings based on compliance with specified standards in energy and water efficiency, protection of greenfield, indoor environmental quality, and choice of materials(Guggemos & and Horvath, 2006). Newly constructed non-residential or residential buildings and existing buildings need to comply with a certain level in each criterion in order to be certified. Majority of the recommended green features in certification manuals saved large amount of energy. According to a study in the Cascadia Region, USA on eleven buildings, all eleven buildings performed better than their baseline, and six of the buildings performed better than their design energy use. Nine buildings performed better than the average commercial building stock (Newsham, Mancini, & Birt, 2009). However, these systems do not provide means to quantify the actual environmental impacts, and thus are unable to directly target the reduction of environmental impacts (like carbon emissions).

Carbon modeling and carbon emission boundary justification deliver carbon factors for each material or fuel during the construction and the operation of buildings. Still, carbon factors need to associate with the general information of buildings in order to calculate the carbon emissions or savings. General information is the specification and the information of the users of buildings including number of occupants, number of visitors, type of water faucets, number of lavatories, number of electric appliances, number of computers, and type of materials of the structure...etc. In Green Building certification such as Leadership in Energy & Environmental Design (LEED), GreenMark, and BRE Environmental Assessment Method (BREEAM), this information is used to calculate the points in order for a building to achieve certain level of certification. For example, material use may affect the quality carbon emissions. In Singapore, GreenMark addresses Concrete Usage Index (CUI) (BCA, 2010) due to the large numbers of high-rise buildings in Singapore while other certifications focus on green features, such as water saving faucets, greenery features in the building, and using energy saving appliances.

Using energy efficient appliances will reduce energy consumption in buildings. According to Appraisal of Policy Instruments for Reducing Buildings' CO_2 Emissions, Energy Star appliances can save significant amount of energy in buildings (ürge-Vorsatz, Harvey, Mirasgedis, & Levine, 2007). The U.S. Energy Star Program is expected to save 833 Mt CO_2 equivalent by 2010 according to ürge-Vorsatz, Koeppel, & Mirasgedis 2007 (ürge-Vorsatz, Koeppel, & Mirasgedis, 2007).

3.7.3 Building Operation and Construction Energy

Buildings (residential or non-residential) consume a significant amount of energy in the form of electricity, gas, or other types of fossil fuel during operation. A study indicated that energy use in buildings was responsible for 7.85 Giga ton of carbon dioxide emissions in 2002, which was 33% of the global total energy-related emissions in that year (ürge-Vorsatz, Harvey, Mirasgedis, & Levine, 2007). Electricity consumption in buildings for heating and cooling, water heating, office equipment, lighting, ventilation, refrigeration, and cooking will be included in the calculations. The energy consumption breakdown in Canada and the US is shown in Table 4. Energy consumption during building operation is recommended to follow American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 90.1 standards. The guidelines offer suggestions on building envelope, heating and cooling methods, service water heating, lighting, equipment and energy cost methods, and it contains energy consumption calculations, and ways to lower power consumptions and carbon emissions.

In addition, a significant amount of energy is needed to construct a building. A study in Japan showed that between 6.5 and 13 GJ/m^2 (an average of 8.95 GJ/m^2) is needed to construct every 1 m^2 of floor area (Suzuki & Oka, 1998). The significance of such emission renders it necessary to include the energy use (thus carbon emissions) during construction such as gas consumption on machines, transportation, materials, and power consumption during installation process.

Country	Space Heating (%)	Space Cooling (%)	Water Heating (%)	Refrigerators/Freezers	Lighting (%)	Cooking (%)	Major Appliances	Other Appliances	Clothes Dryers (%)	TVs (%)	Furnace Fans (%)	Miscellaneous (%)
USA	35	8	14	9	6	3	/	/	3	4	2	18
EU	57	/	25	/	11	7	/	/	/	/	/	/
Canada	60	1	21	/	5	/	8	5	/	/	/	/

Table 4 Breakdown of Residential Building Energy Use in the U.S., the EU, and Canada (Data from Mitigating CO_2 Emissions from Energy Use in the World's Buildings by urge-Vorsatz, Harvey et al. 2007)

Country	Space Heating (%)	Space Cooling (%)	Water Heating (%)	Office Equipment (%)	Lighting (%)	Cooking (%)	Ventilation (%)	Refrigeration (%)	Miscellaneous
USA	13	7	6	9	25	/	4	4	32
EU	52	5	9	/	14	5	/	/	16
Canada	54	6	7	20	13	/	/	/	/

Table 5 Breakdown of Commercial Building Energy Use in the U.S., the EU, and Canada (Data from Mitigating CO_2 Emissions from Energy Use in the World's Building by urge-Vorsatz, Harvey et al. 2007)

As shown on Table 4 and 5, energy use and carbon emissions from buildings come from several sources like space heating, water heating, refrigeration, and lighting. The tables also highlight that the numbers vary significantly between different building types; therefore, it shows that building characteristics are important variables to determine the amount and types of energy use in a building.

Oil, coal and natural gas are the three most common fuel sources to power buildings, even though an increasing number of buildings are beginning to use renewable energy. These sources of fuel emit carbon and thus should be counted towards the buildings' lifecycle energy and carbon footprints.

3.7.4 Water Consumption

Water consumption is also included in all the Green Building certification criteria and it contributes to carbon emissions. Water supply is one of the most significant indirect contributors to energy use and carbon emissions. Domestic water contributes almost as much carbon footprint as construction materials according to U. S. Green Building Council (USGBC, 2009). Energy is needed to sanitize and filter water in order to make it potable in a water treatment plant. Depending on the quality at the source, the energy use to treat water can be different. For example, water from lakes, rivers, and reservoirs uses relatively less energy than water treated through a desalination plant (sea water or reclaimed water). In addition, transportation of water from the source to the treatment plant and to its end users require a significant amount of energy due to water pumps used in the water distribution system.

Some countries such as Singapore reclaimed wastewater through reverse osmosis. Wastewater and rainwater that are treated using the reverse osmosis process consumes a lot more energy and thus it generates a larger carbon footprint. The sanitation process for tap water requires water pumps, mixer motors, which consume electricity, and gasoline. From a study in the United Kingdom, the carbon emissions factor for water is 0.276 kg

CO_2 per m^3 of water (DEFRA, 2009). In Singapore, the carbon emissions for potable water are 0.0005 $kgCO_2e$ per liter and the carbon emissions for water that goes through reverse osmosis are 0.0008 $kgCO_2e$ per liter. As such, water consumption needs to be considered for carbon emission calculation models for green buildings.

Table 6 highlights the carbon footprint contribution of water and water for landscape. Figure 7 summarizes the scheme for water and wastewater treatment carbon emission calculation for buildings. Water use, including distribution, supply and treatment, contributes 1.2% of the total carbon emissions in the United States. Figure 7 shows that other than water treatment for potable water, transportation of water and wastewater treatment should also be considered since these processes contribute carbon emissions and energy consumption too.

Categories	**Percentage (%)**
Building Systems	35.0
Transportation	2.0
Landscape	0.2
Domestic Water	1.0
Materials	63.0
Solid Waste	0.8
Total	100.0

Table 6 U.S. Carbon Footprint Breakdown (USEPA, 2013a)

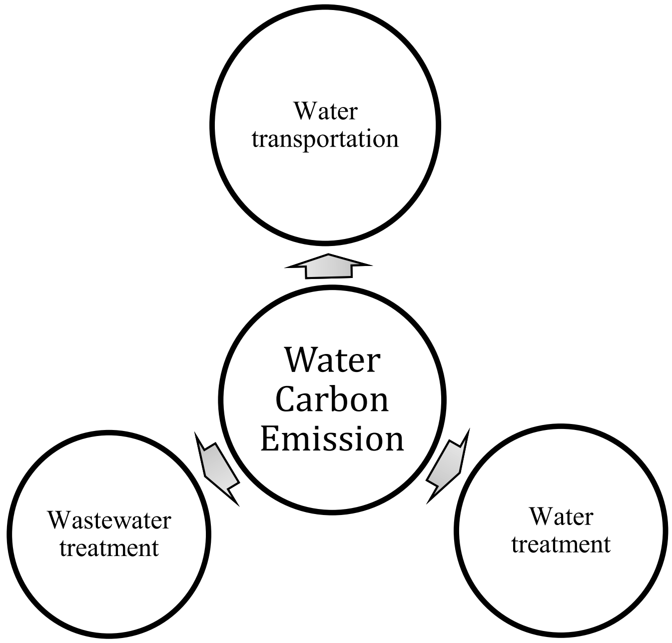


Figure 7 Summary of Water Carbon Calculation

3.7.5 Energy Saving

Indirect energy saving criteria is included in Green Building measurement such as transportation of materials. In LEED Material and Resources Credit 5, it encourages builders to use regional materials for their buildings. It can lower the gas consumption on transportation. In addition, other indirect factors may affect the energy efficiency of buildings. According to a study in Jordan, residential buildings in costal locations can save close to 50% on energy while residential buildings in the highland can save more than 90% energy on heating and cooling with better ventilation and insulation (Radhi, 2009). A pilot project in Stockholm had a heat exchange system installed in the ventilation system of a subway station and it generated 15-30% per year of heating of a 13-story building 100 yards away by the body heat of 250,000 commuters in the subway station per day (Kelly, 2010). The study also showed that the more people occupying a building, the more energy is needed for cooling and air ventilation (Kelly, 2010).

Therefore, characteristics (i.e. its use, types of occupants, purposes, density etc.) can determine the level of carbon emissions of each building. The characteristics have to be considered in carbon emission calculation during the certification for each green building rating criteria.

3.8 Building Materials Lifecycle

Construction materials are the backbone of the infrastructure of the modern society. For example, cement, which is one of the most commonly used materials in buildings, accounts for about 70-80% of the energy use in non-metallic minerals production, and it accounts for almost one-quarter of the total direct CO_2 emissions in the construction industry (International Energy Agency, 2010).

The study of the service life of construction materials is a continuing need since the industry adopts new materials and new composite materials. Even though prediction of service is essential, service life prediction is still unreliable due to the unpredicted natural events. In addition, life prediction is lack of the knowledge of service conditions, defects and flaws in materials, degradation mechanisms, and the kinetics of degradation. The life prediction of non-composite materials, such as concrete, metal, and coatings are well-documented and common predictions similar to steel corrosion. Concrete failure can be accurately simulated by computer. However, composite materials, such as fiber-reinforced concrete, plywood, and fiberglass, are not yet studied and it is hard to predict the service life due to the complexity of the combination of properties (Frohnsdorff, 1996).

A study by Willmott Dixon in the UK shows that construction material embodied energy in a normal house is about 10% of the total over its life. The number seems small; however, the construction material embodied energy is about 30 to 40 % of the total over its life for a low energy house (Willmott Dixon Re-Thinking Limited, 2010). In other words, construction material embodied energy can be significant for houses that use green features or green certified. Embodied energy analysis, Lifecycle Analysis (LCA), and transportation energy analysis on all the construction materials may be considered for carbon emission calculations during green building certification because they contribute significant of carbon emissions (Chong & Hemreck, 2010). The scheme of lifecycle analysis should include the processes from raw material extraction to recycle and reuse of the materials if LCA is adopted. Table 7 shows the common construction materials and their life duration.

Part/equipment		Life (years)
Roof	Bituminous membrane waterproofing	25
	Polyvinyl membrane waterproofing	15
	Protecting tile	30
	Exterior gloss paint	20
Outer wall		20
Floor finishing		20
Substation	Circuit breaker	20
	Disconnecting switch	20
Vinyl tile flooring	Transformer	20
	Capacitor	15
Battery	Lead storage battery	15
	Alkaline battery	15
	Battery charger	20
Electric cable	RN, BN	20
	CV 6.613.3 kV	20
	CV 600 V	20
	VV 600 V	20
	Bus duct	1.5
Lighting system	Fluorescent lamp	15
	Incandescent lamp	1.5
	Mercury lamp	20
Other electric systems	Amplifier/speaker	20
	Electric clock	20
	Interphone	20
Sanitary pump	Drain pump	10
	Drain pump (submerged)	25
	Water supply pump	30
	Fire pump	20
	Motor	20
Pipes	Hot dip galvanized steel pipe (supply)	20
	Hot dip galvanized steel pipe (drain)	20
	Valve	8
Hot water supply equipment	Storage type water heater (gas fired)	7
	Instantaneous water heater (gas fired)	20
Chiller	Centrifugal refrigerating machine	20
	Centrifugal refrigerating machine	20
	Accessories	20
	Absorption type chiller	20
Chilling unit		
Cooling tower	Fan	15
	Motor	15
	Casing	15

Table 7 Table of Lifecycle for Common Construction Materials (Oka, Suzuki, & Kounya, 1993)

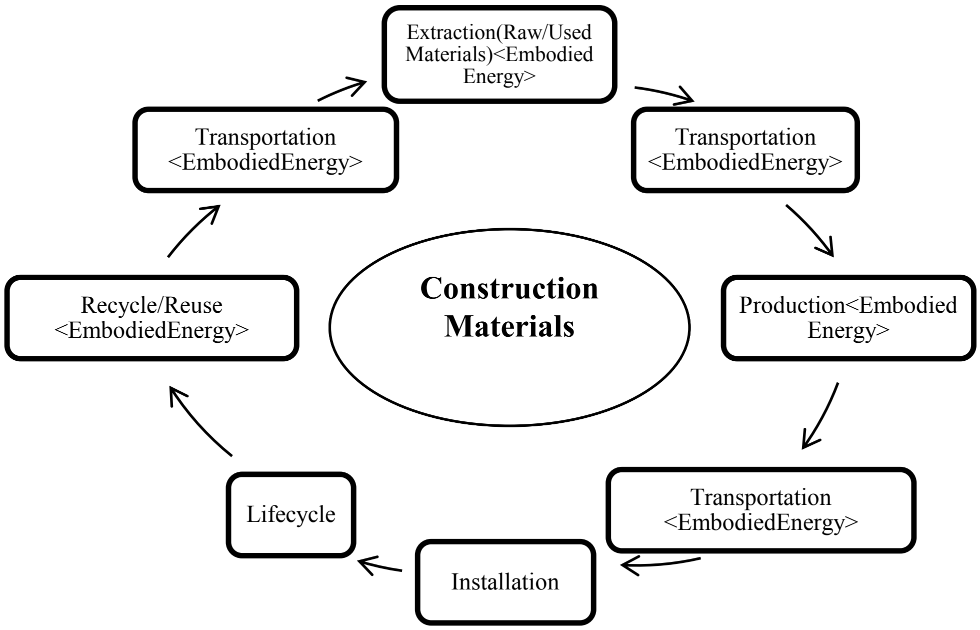


Figure 8 Construction Materials Lifecycle

3.9 Construction and Demolition Debris

The construction industry in the United States generated 136 million tons of construction and demolition waste according to 1996 data (USEPA, 2002) and more than 5 million tons of organic hazardous waste requires thermal treatment every year. Construction waste and debris are significant elements of the urban waste stream. According to the California Department of Resources Recycling and Recovery Board's 2004 Statewide Waste Characterization Study, construction and demolition (C&D) materials make up approximately 22% of California's waste disposal (CalRecycle, 2011). In a report by Napier for the U.S. Army Corp of Engineers, construction waste is about 25% to 40% of the solid waste stream in the United States and only 20% of construction and demolition waste is recycled (Napier, 2011). Also, other than debris from construction and demolition, natural disasters, such as wildfires, floods, earthquakes, hurricanes, tornadoes, and winter storms, generate large amounts of additional debris in the U.S. every year (USEPA, 2011a).

The cement industry currently uses over one million tons of hazardous waste a year as an alternative fuel - replacing expensive and non-renewable fossil fuels such as coal (CKRC, 2004). However, using such fuel cost may cause severe environmental impact. Hazardous waste releases dioxin, arsenic, and other toxic substance to the air during combustion (ATSDR, 2011; USEPA, 2011b). Construction waste and debris include absorbent materials, aerosol cans, asbestos, empty containers, paint, shop towels, treated woods…etc. (Washington State Department of Ecology, 2011). According to a study by the Massachusetts Department of Environmental Protection, wood, gypsum, and asphalt shingles are found primarily in building debris (DSM Environmental Services, Inc., 2008). Clean wood, and landscape materials that are not painted with lead-based paint, treated with arsenic-based preservative, or contaminated with hazardous materials are usually sold for boiler fuel (Napier, 2011). Construction and Demolition Debris (CDD), however, is usually shipped from the construction sites as mixed CDD. Mechanical processing is usually used to positively pick suitable materials like wood from conveyor belts for recycling or making biomass fuel. In Maine, for example, they use negative pick operations to remove non-recyclable or toxic materials from conveyor belts in order to have suitable materials for biomass fuel (Maine Department of Environmental Protection, 2007).

In mechanical processing, non-combustibles, plastics, treated wood, fines, asbestos arsenic, lead, pressure treated wood, and polychlorinated biphenyls (PCBs) are removed to fulfill the fuel quality standards (Maine Department of Environmental

Protection, 2007). Poly vinyl chlorides (PVCs), a type of plastics, releases hydrogen chloride when it is subjected to a 100 degree Celsius or higher environment (Huggett & Levin, 1987), and PVCs also release polychlorinated dibenzodioxins (or dioxins) during combustion (Beychok, 1987). Treated wood contains chemical preservatives, such as chromated copper arsenate (CCA), borate preservatives, and bifenthrin spray preservatives, releases arsenic during combustion (USEPA, 2011b) and arsenic may cause changes of human skin color, corn and small warts for low level exposure. Exposure to high levels of arsenic can cause death (ATSDR, 2011). Treated wood can only be used as fuel for cement kiln (DSM Environmental Services, Inc., 2008). Therefore, mixed CDD requires to be processed in order to lower the risk of toxin release to the environment when it is used as biomass fuel for power generation.

In mixed CDD, wood debris is about 25% of mixed CDD (CalRecycle, 2011) due to the fact that wood products made up a large portion of all industrial raw materials manufactured in the U.S., about 47% according to a 1987 study (APA, 1999). Figure 9 shows the breakdown of different types of wood from C&D waste in the U.S. Two commonly used types of plywood are softwood plywood, and hardwood plywood. Softwood plywood is made by cedar, Douglas fir or spruce, pine, and fir (collectively known as spruce-pine-fir or SPF) or redwood and is typically used for construction and industrial purposes. It is used to make floors, walls and roofs in house construction, wind bracing panels, and fencing. On the other hand, hardwood plywood is made by birch tree and it has high strength and high impact capacity. It is usually used to make panels in concrete formwork systems, floors, container floors; floors subjected to heavy wear in various buildings and factories, and scaffolding materials (APA, 2011). After construction or demolition, the wood debris is shipped with other debris and it may be used as biomass fuel if it is not contaminated. The use of wood debris as biomass fuel will be studied to determine the energy efficiency, and environmental impact in this research.

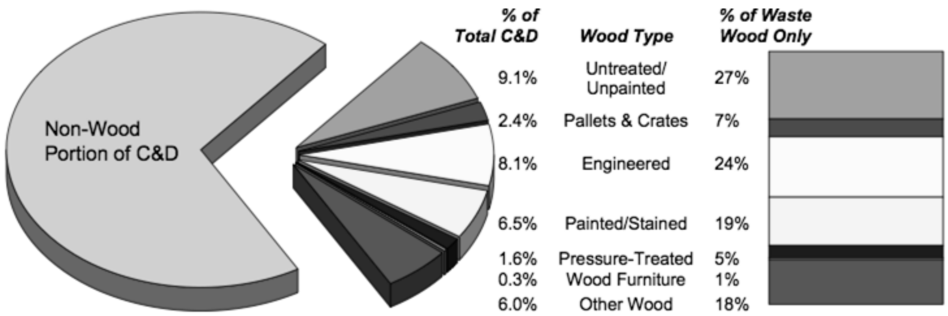


Figure 9 Average of C&D Waste Characterized Study Results (by Weight) (DSM Environmental Services, Inc., 2008)

CHAPTER 4: DATA ANALYSIS (EMBODIED ENERGY)

Building lifecycle includes five stages as shown in Figure 10 and the arrows below the stages are the corresponding methods used to calculate the environmental impact at different lifecycle stages. This research was to find methods to determine the environmental impact in different stages in the building lifecycle. In some models, such as the embodied carbon emissions model, building data was limited and may not have been available to this research. Alternative methods were used and other modeling methods were proposed for future research or projects that faced similar incidence. The following sections start from material extraction and manufacturing and this research shows how the carbon emissions factors were collected.

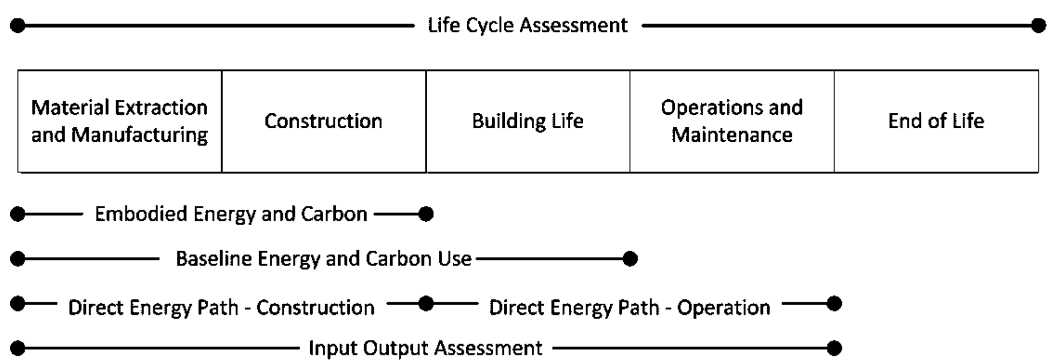


Figure 10 Lifecycle Breakdown and Analysis Methods

4.1 Raw Materials

The models, such as direct, indirect, hybrid, input-output, and process models, mentioned above are used to determine carbon emissions factors. Research institutes and government agencies are providing these factors for the public to find the total carbon emissions of their activities. Government agencies like United States Environmental

Protection Agency (USEPA), Department for Environment Food and Rural Affairs (DEFRA) in the United Kingdom provide electricity carbon emissions

However, not many agencies provide the carbon factors that the construction industry may use. To calculate carbon emissions for a building or create a carbon emission calculator for buildings, one should use data from different agencies and their methodology to determine such factors are not in line with each other. The result; using factors from different agencies may not be as accurate.

4.2 Building Construction Carbon Emissions

During the construction of a building, the carbon emissions are due to the manufacturing process of construction materials, the fuel consumption for machines and vehicles, and power supply for electric tools. The carbon emissions at this stage of the building lifecycle are the embodied carbon emissions of a building because the carbon emissions come from the raw materials, construction process, and installation (Cannon Design, 2012). Figure 11 shows the stage of embodied carbon emissions in a building lifecycle.

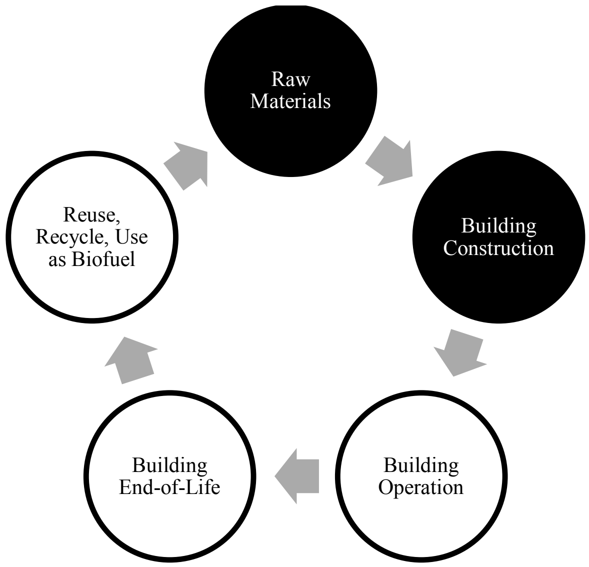


Figure 11 Embodied Carbon Emissions in a Building Lifecycle

4.2.1 Building and Construction Material Embodied Energy of the Material Measurement, Materials and Sustainable Environment Center

The Measurement, Materials and Sustainable Environment Center (M2SEC) was used as one of the case studies and pilot carbon emission estimation framework in this research for building materials. M2SEC was chosen in this study because the construction process and transactions are well documented due to the requirement for American Recovery and Reinvest Act. The general contractor for M2SEC was JE Dunn Construction and they provided all the transactions between sub-contractors, contractors, and engineers during construction. All the materials used in the building, excluding furniture and interior finishings, are included in these transactions and the scope of this research. The documents provide the size, quantity, and substance of the building materials. The data was organized on a spreadsheet. A sample table for excavation is shown on Table 8

Description	Unit	Quantity
Drilled Piers, 40' Long	m^3	995
Haul Pier Spoils	m^3	995
Grade Beam & Ftg Excavate	m^3	567
Crushed Rock @ SOG, 18" Thick	m^3	784
Granular Backfill	m^3	2031
Perimeter Foundation Drains	m	256

Table 8 Sample Data Collection from M2SEC with Only Quantity

The excavation, for example, includes piers, rocks, backfill, drain and the quantity is shown on Table 8. Using the average density of each material, the weights can be determined as shown on Table 9.

Description	Quantity	Unit	Density (kg/m^3)	Weight (kg)
Drilled Piers, 40' Long	995	m^3	2300	2288500
Haul Pier Spoils	995	m^3	2300	2288500
Grade Beam & Ftg Excavate	567	m^3	2300	1304100
Crushed Rock @ SOG, 18" Thick	784	m^3	1225	960165
Granular Backfill	2031	m^3	1225	2487366
Perimeter Foundation Drains	256	M	2300	259

Table 9 Sample Data Collection from M2SEC with Quantity, Density, and Weight

There is no existing localized collection of carbon emission factors of these materials in the United States. Therefore, this research used the carbon emissions factors provided by the Inventory of Energy and Carbon & Energy from the University of Bath and they are selected accordingly based on ICE Version 2.0 as shown on Table 10.

Description	**Quantity**	**Unit**	**Density (kg/m^3)**	**Weight (kg)**	**Carbon Factor ($kgCO_2e/kg$ of material)**
Drilled Piers, 40' Long	995	m^3	2300	2288500	0.107
Haul Pier Spoils	995	m^3	2300	2288500	0.107
Grade Beam & Ftg Excavate	567	m^3	2300	1304100	0.107
Crushed Rock @ SOG, 18" Thick	784	m^3	1225	960165	0.010
Granular Backfill	2031	m^3	1225	2487366	0.010
Perimeter Foundation Drains	256	m	2300	259	3.230

Table 10 Sample Data Collection from M2SEC with Quantity, Density, Weight, and Carbon Factor

Since ICE 2.0 provides all the carbon emissions in kg CO_2e per kg of the material, Equation 3 was used to calculate carbon emissions for a particular part of the building as shown on Table 11. For this example, all the carbon emissions are added to get the total carbon emissions for excavation.

Carbon Emissions = Weight of Material x Carbon Emission Factor

Equation 3 Carbon Emission Equation

Description	Quantity	Unit	Weight (kg)	Carbon Factor (kgCO$_2$e/kg)	Carbon Emissions (kg CO$_2$e)
Drilled Piers, 40' Long	995	m^3	2288500	0.107	244870
Haul Pier Spoils	995	m^3	2288500	0.107	244870
Grade Beam & Ftg Excavate	567	m^3	1304100	0.107	139539
Crushed Rock @ SOG, 18" Thick	784	m^3	960165	0.01	9602
Granular Backfill	2031	m^3	2487366	0.01	24874
Perimeter Foundation Drains	256	m	259	3.23	837
				Total	664590

Table 11 Sample Data Collection from M2SEC with Quantity, Density Weight, Carbon Factor, and Total Carbon Emissions

The calculations were repeated for the other parts of the building including:

- Excavation
- Structural
- Masonry
- Carpentry
- Roofing and Flashing
- Doors and Glazing
- Plaster and Ceilings
- Flooring
- Equipment
- Fire Protection and Plumbing
- HVAC
- Electrical

The summary tables are shown in Appendix A. Some of the materials or parts could not be found in the ICE version 2.0 and carbon emission factors are calculated based on the weight of different materials of a part. The calculation is shown in Equation 4.

$$Adjusted\ Carbon\ Emission\ Factor$$
$$= \sum_{i=1}^{n} (\%\ of\ Material\ i\ by\ Weight)(ICE\ Carbon\ Factor\ of\ Material\ i)$$

Equation 4 Adjusted Carbon Emission Factor

The embodied carbon emissions result of the M2SEC shows that all the structural works, including piers, beams, walls, and columns, contribute the most embodied carbon emissions in the M2SEC and it was about 33.59% of the total embodied carbon emissions. The second resource of embodied carbon emissions in the building is the excavation works of the building and the piers leave the most carbon footprint in this category, which is 244757.57 kg CO_2e. The high embodied carbon emissions from structural works is expected because the manufacturing process for concrete, aggregates, and sand consumed a lot of energy on grinding, explosion during mining, and transportation from mines (Wright, 2011; Hammond & Jones, 2011; Hammond & Jones, 2008). Therefore, the higher the carbon factors, the higher the embodied carbon emissions. In addition, concrete is the most common material of the building and floors, beams, columns, and walls are all made out of concrete. The other major sources of embodied carbon emissions come from roofing and flashing, and doors and glazing. The higher contribution is due to the high-energy consuming manufacturing process of the glass used in the curtain walls, windows, and door The other products that require high-energy consuming manufacturing process are the metal finishing, and the polycarbonate products used on the roofing. Table 12 shows the total embodied carbon emissions for M2SEC and the percentages of each category of the building. Figure 12 shows the breakdown of each category.

Category	**Carbon Emissions (kg CO_2e)**	**Percentage (%)**
Excavation	664590	24.82
Structural	899201	33.59
Masonry	74177	2.77
Carpentry	16965	0.63
Roofing and Flashing	279123	10.43
Doors and Glazing	162415	6.07
Plaster and Ceilings	300450	11.22
Flooring	11842	0.44
Equipment	72994	2.73
Fire Protection and Plumbing	7529	0.28
HVAC	57981	2.17
Electrical	129783	4.85
Total	2677050	100.00
in metric tons	2677	

Table 12 M2SEC Total Embodied Carbon Emissions Breakdown

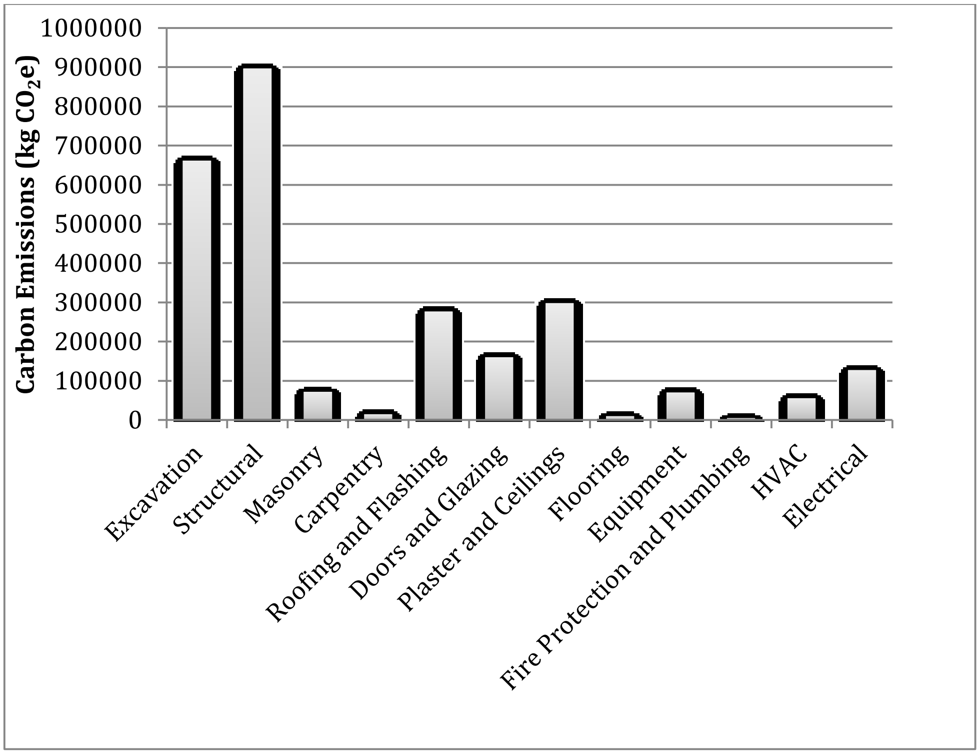


Figure 12 M2SEC Carbon Emissions Distribution

M2SEC study shows that if the materials in a building were well documented, the embodied carbon emissions of a building could easily be determined. The study also indicates that contractors, engineers/architects, and owners do not usually summarize the material and transaction data. They keep electronic copies of email, written communications, purchase orders, and invoices. It is difficult to determine the embodied carbon emissions of a building unless the professionals involved in the project reorganize the data. It is time consuming and some transactions may be lost.

To improve this, contractors, engineers/architects, and owners should develop a database before a building construction project begins. This would allow tracking of all the construction material data, including quantity, size, weight, and the element.

This study initially tried to determine the transportation emission of all the materials. However, no record was kept about the origin of the products and the fuel use of the construction machines. The addresses of all the businesses involved in the construction were the only records that existed. However, the locations of them may not have reflected where the materials came from.

In order to further study in this, a fuel usage record should be kept by contractors, and the engineers/architects and suppliers should keep a record of the origins of materials and save the data in the database.

4.2.2 Building and Construction Material Embodied Energy of Kansas Department of Transportation

Unlike M2SEC that was discussed earlier, KDOT had over 900 buildings across the state of Kansas. Majority of the buildings were old and no detailed data was available to the research team. KDOT representatives did not keep a database of all the materials used and installed in their buildings and they could only offer blueprints of their buildings. KDOT's buildings were first sorted into the by building size, locations, and building use.

Data was sorted according to the size, and the usage of the buildings. Data for these categories were collected from the KDOT blueprints. While most KDOT blueprints were available to the research team, the older ones were no longer reliable as many of the older buildings had been renovated or modified and information and new blueprints were not available to the research team. As a result, the research team visited illustrative buildings and called the occupants to verify the changes made to the older buildings. The research team visited a number of KDOT campuses to obtain an impression for the agency, its buildings, and their operations. Four additional trips were made to further clarify any discrepancies and confirm any updates.

Phone interviews with KDOT personnel were conducted on the buildings where plans were not available to verify the design of those buildings. In addition, Google

Maps® and street view were also used to determine the design and the materials of those buildings. As most KDOT buildings were very similar in design and materials, the research team made reliable assumptions on the design and materials as well.

Building blueprints showed the dimensions and types of materials of the buildings. Engineering judgments or phone call verifications were made to verify information that could not be seen clearly on the drawings. For example, materials used and the sizes of them were estimated using the older or damaged blueprints. Using the knowledge and the images from four site visits, the unknown materials were identifiable. The research team found many similarly designed buildings and thus made reliable assumptions based on several buildings that they visited. Phone call verifications allowed the research team to confirm their results.

Assumptions had to be made on most of the data and analysis. Only reasonable and verified assumptions were used in the models and analyses. As many KDOT blueprints and records were either missing or out of date, the following table of assumptions was used to reduce the impacts due to missing and out of date information.

Material	Thickness/ depth	Weight per Area (kg./m^2)	Other Notes
Plaster	1.5875 cm thick	13.48	
Glass	0.3175 cm thick	8.19	single pane
Glass	5.3975 cm thick	16.38	double pane with ⅛" to ¼" air gap
Gravel	10.16 cm deep	170.88	
Common Red Brick	Standard	195.30	4" x 2 2/3" x 8"
Cast Iron	0.635 cm thick	45.77	
Rolled Steel	0.9525 cm thick	75.53	
Wood doors	5.08 cm thick	13.43	solid doors
Sandstone	20.32 cm thick	472.13	value used
Sandstone	30.48 cm deep	707.95	not standard assumption
Concrete Wall	15.24 cm thick	361.30	not standard assumption
Concrete Wall	20.32 thick	481.90	value used
Concrete Wall	30.48 cm deep	722.60	not standard assumption
Fiberglass		4.88	Assumption
Shingles		4.88	Assume soft wood
Siding		4.88	Assume heavy duty plastic siding

Table 13 Material Assumptions (Legacy Formwork, 2011)

Data gathered from KDOT building blueprints were adjusted to reduce the amount of errors from some of the incomplete blueprints. Highway rest stops were excluded from the study due to time and resource constraints. Even though the rest stops were constructed by KDOT, they did not have direct control and jurisdiction over many of them (such as those inter-state highways). These rest stops were also unstaffed and thus data cannot be verified.

The Inventory of Carbon and Energy (ICE) by the University of Bath provided the carbon emission factors for the materials used in all the KDOT buildings. A summary table is shown on Table 14. Using the average sizes of materials and average ceiling heights that were shown on Table 13, average carbon emissions per area for different materials were obtained. For example, the average weight per area of reinforced concrete was 481.90 kg/m^2 and the carbon emission factor for reinforced concrete 0.1 kg CO_2 per kg according to ICE. The carbon emissions for reinforced concrete is:

Carbon emissions per Area for Reinforced Concrete = (Carbon Emission Factor) X (Weight per Area)

= (0.1) (481.90)

= 48.19 kgCO_2 per m^2

In general, the carbon emission per area for all the materials is:

$$CEA = (CF)(\text{WFA})\ (\text{UC})$$

Where CEA is Carbon Emission per Area

CF is Carbon Emission Factor from ICE

WFA is Weight per Area

UC is Unit Conversion (if necessary)

Equation 5 Equation of Carbon Emission per Area

The calculation was repeated for all the materials and the carbon emissions per area are shown on Table 15.

Material	Carbon Emission Factor ($kg\ CO_2$/kg of material)
Reinforced Concrete	0.100
Concrete	0.100
Concrete Block	0.100
Brick	0.230
Corr. Iron	1.910
Metal	1.820
Fiberglass	1.540
Gravel	0.073
Shingles	0.710
Lap Siding	2.730
Glass	0.860
Glass Skylight	0.860
Glass (Insulated)	0.860
Door	0.710
Door Reinforced Wood	0.710
Garage Door	1.910
Door with insulated Glass	0.860
Metal Door	1.910
Gravel	0.073
Stone	0.087

Table 14 Summary of Carbon Emission Factor Used in KDOT Building Embodied Carbon Emissions

Materials	Carbon Emission per Area (kg CO_2/m^2)
Reinforced Concrete	48.19
Concrete	48.19
Concrete Block	48.19
Brick	44.92
Corr. Iron	87.66
Metal	137.47
Fiberglass	7.52
Gravel	12.47
Shingles	3.47
Lap Siding	13.33
Reinforced Concrete	48.19
Concrete	48.19
Concrete Block	48.19
Brick	44.92
Corr. Iron	87.66
Metal	137.47
Fiberglass	7.52
Gravel	12.47
Shingles	3.47
Lap Siding	13.33

Table 15 Building Material Carbon Emissions per Area

The KDOT buildings are categorized into numbers of building types as shown in Appendix B. Using the blueprints provided by KDOT, the square footage of each material was determined and was saved on a spreadsheet. By using the carbon emissions per area shown on Table 15, carbon emissions for each building types were calculated as shown in Appendix C. Appendix D showed the result of the embodied carbon emissions of all KDOT buildings and the total embodied carbon emissions from KDOT buildings was 23319806 kgCO_2e.

The Kansas Department of Transportation (KDOT) has over 900 buildings throughout the state of Kansas and they consisted office buildings, garages for vehicles and construction equipment, wash bays, and laboratories…etc. As mentioned earlier, KDOT did not have a database to record all the construction materials that were used and installed in their buildings. Blueprints were the only records they have for their building. The materials were predicted using the blueprints and the embodied carbon emissions of the agency were estimated based on the area occupied by the materials. Assumptions were made according to the legacy formwork weights of construction materials and concrete.

The result showed that concrete, reinforced concrete, fiberglass, corrugated iron, garage door, and metal contributed the most embodied carbon emissions in KDOT's buildings as shown in Table 16. The garage doors were made out of steel. Therefore, the most embodied carbon emissions came from metal, concrete, and fiberglass. The main processes for iron and steel production included metallurgical coke production, sinter production, pellet production, iron ore processing, iron making, steelmaking, steel casting and very often combustion of blast furnace and coke oven gases for other purposes. The metal was required to be heated at very high temperature for forming, and treatment and they are very energy consuming. Thus, the production of metal lead to emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) from fuel, and the production processes (IPCC, 2006).

Material	Area of Material (m^2)	Carbon Emissions ($kgCO_2$)	Percentage of Material (%)	Percentage of CO_2 (%)
Concrete	8255	397800	2.09	1.70
Concrete Block	46220	2227331	11.68	9.60
Stone	2065	84831	0.52	0.40
Fiberglass	104365	784722	26.36	3.40
Glass	5072	35717	1.28	0.20
Insulated Glass	1062	14961	0.27	0.10
Glass Skylight	880	6194	0.22	0.00
Reinforce Concrete	34182	1647233	8.64	7.10
Brick	2263	26297	0.57	0.10
Gravel	5153	64286	1.30	0.30
Corrugated Iron	97536	8550041	24.64	36.70
Wood Door	4524	43128	1.14	0.20
Garage Door	22262	2981093	5.62	12.80
Standard Door	4361	43800	1.10	0.20
Shingles	39	134	0.01	0.00
Metal	57608	6412238	14.55	27.50
Total	395846	23319806	100.00	100.00

Table 16 Construction Materials and Carbon Emissions Distribution of KDOT Buildings

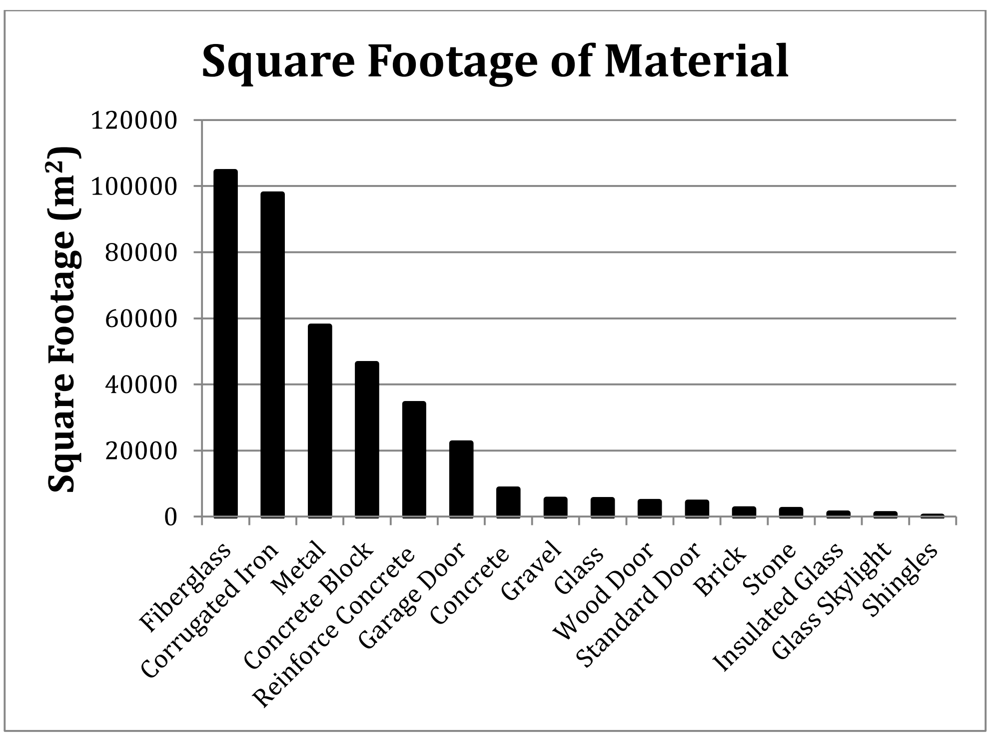


Figure 13 Square Footage of Materials in KDOT's Building

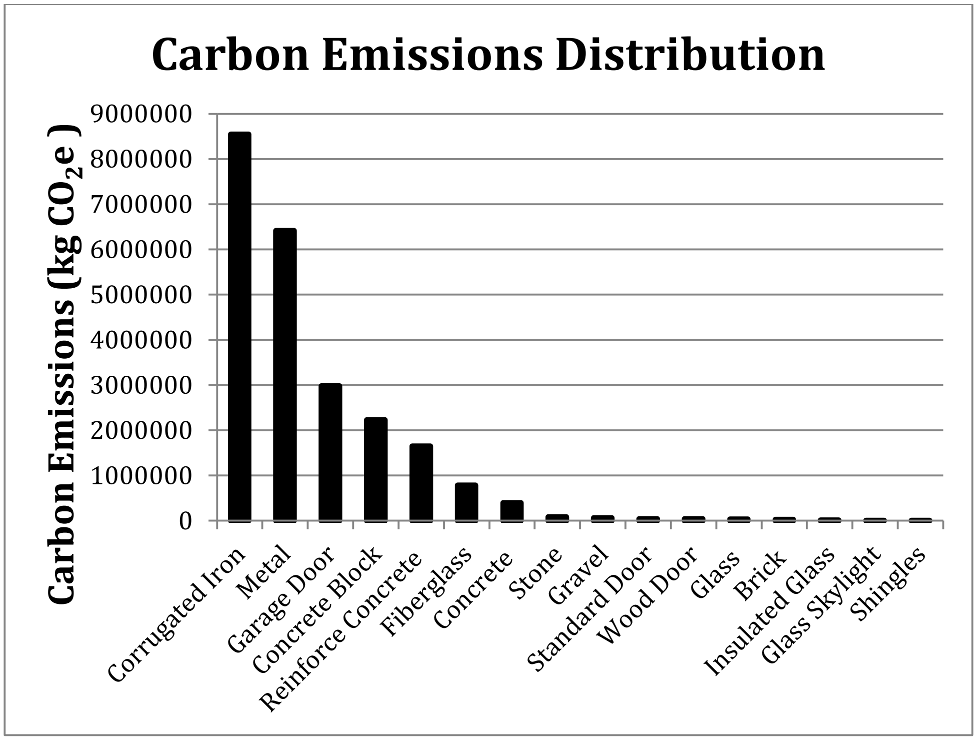


Figure 14 Embodied Carbon Emissions Distribution of KDOT Buildings

Unlike utility consumption, there was no benchmark or average value that buildings could follow like the values from United States Energy Information Administration for utility consumption. Hence, the accuracy for embodied carbon emissions was unknown and it was difficult to judge whether or not a building had too much embodied carbon emissions. Another unknown for embodied carbon emissions was the transportation carbon emissions during the construction process. As indicated, the parties in the construction industry did not keep a record of fuel consumption and distance travelled of the construction materials. For green buildings that obtained points for using regional materials in MRc5 requirement, the transportation carbon emissions of the materials could be lower because the contractors are required to use a simple 500-mile radius from the site for both extraction and manufacturing distance (USGBC, 2009).

4.2.3 Construction Equipment and Installation

Construction equipment consumed 11% of the U.S. energy consumption according to a study by the Department of Energy in 1981 (Stein, Buckley, Green, & Stein, 1981). Another study in the Netherlands showed that the largest fuel consumption and carbon emissions on a construction site is due to cars (van Gorkum, 2010). On a construction site, the energy sources could be categorized into two main categories: fossil fuel, and electricity for construction and interior installation. However, very little was known about the construction equipment activity (Kable, 2006) and there was no protocol to monitor construction site fuel consumption and electricity use (BREEAM, 2012).

M2SEC was used to determine a methodology to estimate the fuel consumption and electricity use during construction. However, the transactions between owner, engineers/architects, contractors and subcontractors did not show any fuel cost of their equipment. Even though extensive documentation was expected due to the requirements of the American Recovery and Reinvestment Act of 2009, the fuel cost was absorbed into the total work expenses by the contractors and subcontractors and it was not recorded.

The research team contacted the Business Operations Service Center at the University of Kansas for electricity use during construction and interior material installation of M2SEC. The representative could not provide the data, as they did not keep records until a building was occupied.

In order to determine the construction and installation energy consumption, the contractors and subcontractors should have a record of fuel consumption of all the heavy machines and vehicles. At the same time, the owner should have had a record of electricity consumption during the whole construction period. If, in the future, the construction industry kept track of the fuel consumption of machines and vehicles on the construction site, it would improve the accuracy of the environmental impact of buildings during construction. Similar methods could be applied to highway and road construction projects to determine their environmental impact.

Other than the energy that is used for the manufacturing process of materials, embodied energy calculation also includes the energy of the fuel used to power the harvesting or mining equipment, the processing equipment, and the transportation devices that move raw material to a processing facility (Kim & Rigdon, 1998). With globalization, transportation is accounting for a big part of the total amount of energy spent for implementing, operating and maintaining the international range and scope of human activities and it is growing radically. In developed countries, transportation accounts for between 20% and 25% of the total energy being consumed (Rodrigue & Comtois, 2013).

M2SEC at the University of Kansas was chosen for this part of the research to determine ways to quantify the transportation energy and carbon emissions of materials. The owner, contractor, and subcontractor were contacted and they provided only transactions and purchase orders of all the construction materials used to build M2SEC. No separated record from the suppliers that documented the distance travelled and fuel consumption of the materials were archived.

However, the purchase orders showed the address of the suppliers. Using the address of suppliers, the distance travelled by the materials could be determined, assuming the materials came from the location of their provider facilities. These addresses were inserted in a MySQL database and Google Map API was used to determine the fastest and closest routes to the construction site after pinpointing the longitudes and latitudes of the suppliers. Although the result may not have been completely accurate, it was still the most efficient approach and it was more reliable than existing method. The provider facilities of the suppliers may not have been located from the provided addresses and a lot of businesses had located their warehouses somewhere else. They shipped their materials direct from their warehouses to construction site. In addition, this method did not take truck drivers' behavior, and personal driving habits into account. The materials may have been transported to multiple locations.

4.3 Building Embodied Carbon Emissions Modeling

The result from the building embodied carbon emissions estimation of M2SEC and KDOT proves that building embodied carbon emissions can be roughly modeled. Two different methods provide an outlook how embodied carbon emissions can be modeled and what should be accounted for in the calculation. The KDOT case, on the other hand, shows that estimation can be done using the blueprints from the owner of the buildings with some assumptions. Therefore, older buildings that do not have sufficient records of their construction materials can use the method similar to the one that is used on the KDOT case study. Buildings that have good documentation of construction materials can use the method that is used in the M2SEC case study. For embodied carbon emissions that are contributed by transportation of materials, the construction industry should change the way they account for the transactions between engineers/architects, contractors, and suppliers. Contractors and engineers/architects, in the future, should require suppliers to provide the origins of the construction materials, including the country, and locations of warehouses. As such, the distance travelled by the construction materials can be calculated and the fuel consumption will be estimated. At the end, the carbon emissions due to transportation can be estimated. At the same time, the contractors and subcontractors should keep a record of total fuel consumption of the construction equipment and engineers/architects should require them to submit that at the end of their contracts. The summary of the modeling methods for building embodied carbon emissions is shown in Figure 15.

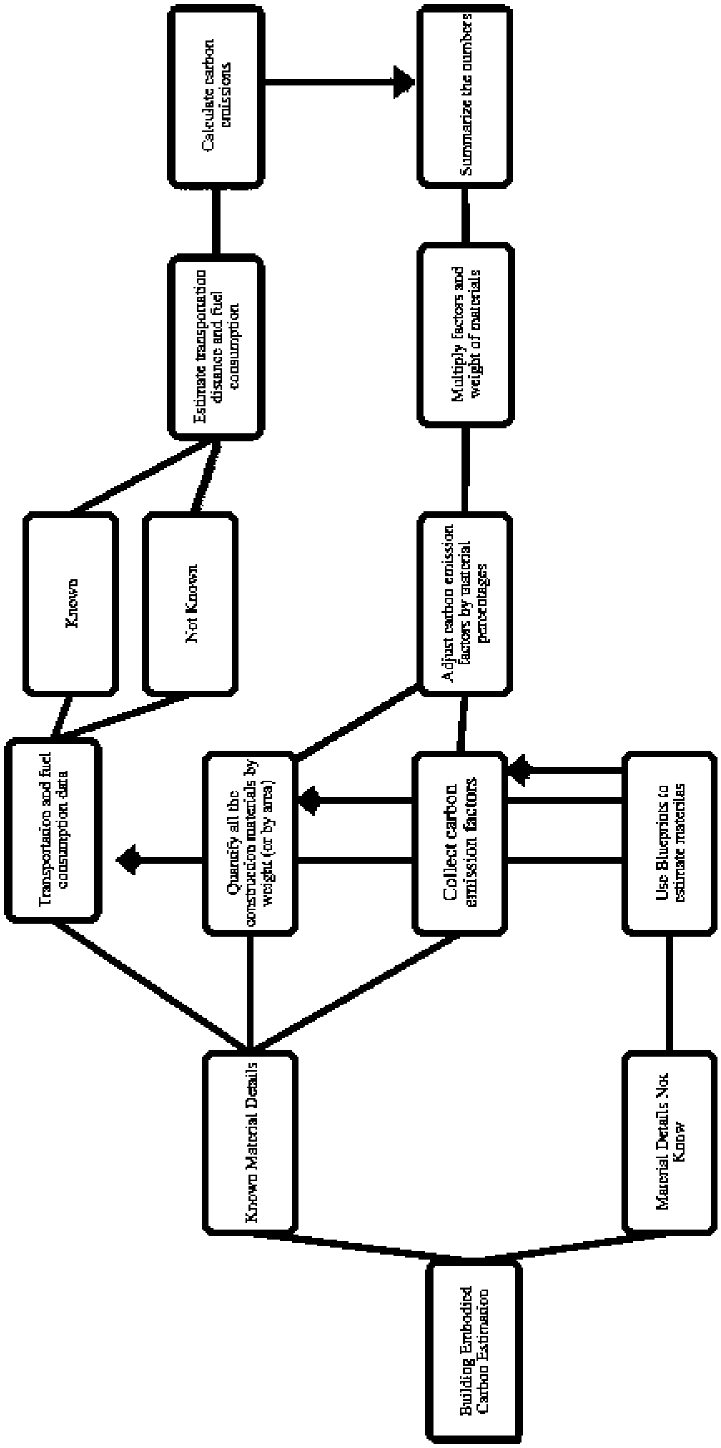


Figure 15 Summary of Building Embodied Carbon Emissions Modeling

CHAPTER 5: DATA ANALYSIS (UTILITY-BASED BUILDING OPERATION)

The carbon emissions generated during building operation come from the utilities used by the occupants. It includes electricity, natural gas, water, steam, and sewer. The building operation is in the middle of the building lifecycle as shown in Figure 16. Chapter 5 and 6 will discuss the carbon emissions during building operation.

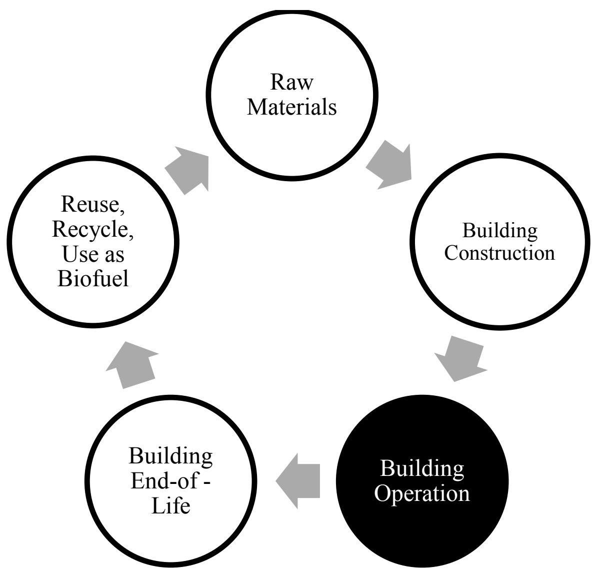


Figure 16 Building Operation in the Building Lifecycle

5.1 Energy Flow

In energy flow analysis, Chen, Hsu, and Hong suggested that five steps including energy supply, central energy generation/utilities, energy distribution, energy conversions, and process energy use (Chen, Hsu, & Hong, 2012). Similar steps proposed by Hong, et al. are:

- Step 1: Energy supply—Summation of fuel consumption, purchased electricity, steam, biomass, and black liquor or byproduct fuels.

- Step 2: Central energy generation/utilities—including the energy supply which is mentioned in Step 1. In addition, power generation means the energy produced onsite by fuel, biomass and renewable energy, which actually enters the plant.
- Step 3: Energy distribution—the energy distributed to the process energy systems is represented. Energy distribution is obtained by subtracting boiler and electricity generation losses in pipes, valves, traps, and electrical transmission lines from the central energy generation/utilities.
- Step 4: Energy conversion—the available energy that can be used by process equipment is called energy conversion, which is calculated by subtracting transmission losses and facilities energy from the energy distribution systems.
- Step 5: Process energy use—the energy use is estimated by subtracting energy losses due to equipment inefficiency from energy conversion systems to process energy use systems. (Hong, et al., 2011)

Guzmán's and Alonso's measured the energy flows and gas emissions of three asparagus production systems. In their energy flow analysis, they traced all the fertizers and chemicals, fuels for equipments, and electricity used in three farms and they converted the amount of fertilizer, fuel, and electricity used to emboidied energy in mega Joules . Using similar manner, they calculated the gas emissions using gas emissions in CO_2 equivalent (Guzmán & Alonso, 2008). This method was adopted to estimate the operational carbon emissions of a building. A building electronic device, like an asparagus production system, could be broken down into different parts. For example, a Heating, Ventilation, and Air Conditioning (HVAC) system can be broken down into ventilation, refrigerant, chiller, cooling tower, and furnace. Carbon emissions due to power consumption or water use could be estimated in each part of the system. This method can be applied to other devices in a building that would be discussed later in the chapter.

5.2 Building Operational Carbon Emissions

The United States Energy Information Administration (EIA) is a government agency that collects and analyzes energy data in the U.S. and promotes sound policy making in energy, environment, and economy. The agency publishes the Commercial Buildings Energy Consumption Survey (CBECS) every 4 years since 1992 and CBECS contains the total energy consumption in different forms, such as natural gas, gasoline, and electricity, in different sectors and economic activities (USEIA, 2011). The agency also provides average energy consumption for different types of buildings, such as education, food service, sales, and office. The data is published in a per square foot manner so that the public can use the data as a benchmark for different type of buildings. They assumed education, and office buildings are occupied only during office hours and the power usage is at minimum during weekends and holidays. The utility study at Eaton Hall at the University of Kansas and the utility study at the Kansas Department of Transportation would use the EIA benchmark to compare the energy consumption of the agency and the average national values for the agency’s 924 buildings. Table 17 shows an example of EIA energy consumption per square foot.

Principal Building Activity	RSEs for Total Electricity Expenditures				RSEs for Electricity Expenditures							
					per kWh				per Square foot			
	Northeast	Midwest	South	West	Northeast	Midwest	South	West	Northwest	Midwest	South	West
Education	20.5	14.5	13.7	10.9	7.2	4.1	3.3	10.6	10.4	10.5	6.7	9.1
Food Sales	17.7	32.9	28.3	41.3	16.5	9.1	6.3	9.8	13.0	19.8	10.3	43.5
Food Service	22.9	21.6	20.7	37.2	7.9	6.1	5.5	11.9	19.3	18.6	13.3	20.1
Health Care	13.0	16.8	12.1	18.0	11.3	5.3	6.2	6.3	14.3	7.6	11.6	6.0
…...Inpatient	17.9	11.1	15.8	19.5	11.2	4.2	7.8	8.9	15.6	7.8	9.7	7.6
…...Outpatient	27.8	26.8	16.9	22.3	9.1	7.0	6.6	9.9	21.2	16.7	24.5	11.5
Lodging	27.0	15.6	20.5	40.3	8.4	4.6	4.8	9.3	62.1	6.9	9.0	32.4
Retail (Other than Mall)	20.2	24.7	24.4	32.3	7.5	7.1	4.7	19.1	13.0	13.8	17.5	18.6
Office	16.6	37.4	14.9	17.8	7.8	3.4	2.7	7.4	9.6	7.5	5.0	7.9
Public Assembly	29.5	11.9	20.9	56.8	12.8	3.8	5.4	18.8	77.6	13.8	15.2	53.0

Table 17 Example of Energy Consumption Benchmark from EIA (USEIA, 2008)

5.2.1 Single Building Analysis (Eaton Hall)

Some state agencies, such as the University of Kansas, have a dedicated department that collects and organizes the operational energy consumption, and other utility data. Many states require their agencies to keep a database of all the utility data for future planning and for utility regulation and law (IURC, 2013; CPUC, 2007).

In this research, data was collected from the Business Operations Service Center through the Building Complex Manager of the School of Engineering at the University of Kansas. The data included electricity, gas, water, sewer, and steam from 2004 to 2012 as shown on Table 18. Discussed in the previous section, the United States Energy Information Administration (EIA) provided average values for electricity, gas, water, and steam consumption in the U.S. for buildings with different usages. Since Eaton Hall contained classrooms, computer laboratories, and offices, the average education building data from EIA was used to compare with Eaton Hall. Due to the fact that EIA did not provide data on sewer, the EIA comparison for sewer was skipped.

5.2.1.1 Eaton Hall Utility Result

EIA average values for education buildings were 118.40 kWh per square meter for electricity, 11.25 cubic meter per square meter for gas, 84.35 cubic meter per day for water, and 123051164 Joules per square foot for steam. The square footage at Eaton Hall was 7,872 square meters. The EIA average values were calculated as shown on Table 18. Using the carbon emission factors on Table 19, carbon emissions from each utility were determined as shown on Table 20.

Year	Power consumption (kWh)	Natural gas consumption (m^3)	Water consumption (m^3)	Sewer consumption (m^3)	Steam consumption (m^3)
2004	2,107,750	175,564	5031	1142	5,038,759,251
2005	2,132,220	42,475	5127	1050	477,983,7207
2006	2,065,800	283,168	4315	1001	2,705,811,068
2007	2,335,270	201,049	5068	1049	1,442,619,751
2008	2,267,080	65,129	4908	1229	3,817,207,444
2009	2,250,720	62,297	6159	1481	4,799,142,798
2010	2,321,100	87,782	8867	1228	4,296,061,809
2011	2,109,760	67,960	4570	1366	1,672,015,597
2012	2,140,336	76,455	7851	1434	1,477,066,982
Average	2,192,226	117,987	5766	1220	3,336,502,434
EIA Average Value	932,085	88,632	6,297	N/A	3,864,654,528

Table 18 Eaton Hall Utility from 2004 to 2012

Carbon Emissions Source	Carbon Emission Factor	Unit	Source
Electricity	0.8527	$kgCO_2/kWh$	EIA
Natural gas	2.422	$kgCO_2/m^3$	DEFRA
Steam	0.0002152	$kgCO_2/m^3$	DEFRA
Sewer	0.75	$kgCO_2/m^3$	Singapore PUB
Water	0.3441	$kgCO_2/m^3$	DEFRA

Table 19 Carbon Emission Factors Used For Eaton Hall Case Study

Year	Power Carbon Emissions ($kgCO_2e$)	Natural Gas Carbon Emissions ($kgCO_2e$)	Water Carbon Emissions ($kgCO_2e$)	Sewer Carbon Emissions ($kgCO_2e$)	Steam Carbon Emissions ($kgCO_2e$)	Total Carbon Emissions ($kgCO_2e$)
2004	1,797,278	425,216	1,731	857	1,084,601	4,165,455
2005	1,818,144	10,2875	1,764	787	1,028,868	3,739,044
2006	1,761,508	685,833	1,485	751	582,430	3,781,926
2007	1,991,285	486,941	1,744	786	310,526	3,576,945
2008	1,933,139	157,742	1,689	922	821,660	3,835,814
2009	1,919,189	150,883	2,119	1,111	1,033,023	4,216,025
2010	1,979,202	212,608	3,051	921	924,734	4,040,298
2011	1,798,992	164,600	1,572	1,025	359,904	3,349,875
2012	1,825,065	185,175	2,702	1,076	317,941	3,406,565
Average	1,869,311	285,764	1,984	915	718,188	3,790,216
EIA Average Value	794,789	214,666	2167	N/A	831873	N/A

Table 20 Utility Carbon Emission Summary of Eaton Hall from 2004 to 2012

Eaton Hall at the University of Kansas has 3 floors, and 7,872-square-meters of space and it was opened to student 24 hours a day, 7 days per week. It has classrooms, instructional and computer labs, an atrium and computing commons, faculty and graduate teaching assistant offices, and a multimedia lecture hall, which seats 250 (KU, 2011). The Business Operations Service Center at KU provided all the utility data from 2004 to 2012. The data included electricity, gas, water, sewer, and steam. The average American consumption on power, gas, water, and steam were compared to the average national values for educational buildings calculated by the United States Energy Information Administration (EIA). Sewer was not compared because EIA does not conduct survey on the average sewer release of buildings in the U.S. The carbon emissions from all the utilities were calculated and compared to the national value calculated by the average educational buildings per square foot.

Table 21 shows the summary of utilities, their carbon emissions, and the EIA average values for each utility, excluding sewer. The result shown on Figure 17 indicates that Eaton Hall consumed more than twice the amount of electricity per year during the study period and Eaton Hall consumed over 2,000,000 kWh per year during this period. The value was very high because it is open 24 hours per day, 7 days per week and lights are always on without regard for the presence of students and faculty. On the other hand, the EIA values assumed that buildings were only operating during office hours and power consumption went down to the minimum during holidays and weekends throughout the year. This may have been the reason why the power consumption at Eaton Hall was so high compared to the national average value. In addition, the values from EIA assumed that educational buildings contain classrooms and faculty offices only, while Eaton Hall had a few computer labs with hundreds of computers.

Power ($kgCO_2e$)	Natural Gas (m^3)	Natural Gas ($kgCO_2e$)	Water (m^3)	Water ($kgCO_2e$)	Sewer (m^3)	Sewer ($kgCO_2e$)	Steam (m^3)	Steam ($kgCO_2e$)	Total ($kgCO_2e$)
1797278.43	175564.16	425216.396	5031.36256	1731.29186	1142	857	5038759251	1084601.33	4165455.41
1818143.99	42475.2	102874.934	5127.23564	1764.28178	1050	787	4779837207	1028867.93	3739043.58
1761507.66	283168	685832.896	4314.53461	1484.63136	1001	751	2705811068	582430.344	3781925.9
1991284.73	201049.28	486941.356	5068.28166	1743.99572	1049	786	1442619751	310526.307	3576945.41
1933139.12	65128.64	157741.566	4907.81813	1688.78022	1229	922	3817207444	821660.267	3835813.63
1919188.94	62296.96	150883.237	6158.95671	2119.297	1481	1111	4799142798	1033023.49	4216024.89
1979201.97	87782.08	212608.198	8867.09959	3051.16897	1228	921	4296061809	924734.467	4040298.18
1798992.35	67960.32	164599.895	4569.64853	1572.41606	1366	1025	1672015597	359904.145	3349875.16
1825064.51	76455.36	185174.882	7851.01983	2701.53592	1434	1076	1477066982	317941.131	3406564.89
1869311.3	117986.667	285763.707	5766.21747	1984.15543	1220	915	3336502434	718187.712	3790216.34
794788.88	88631.584	214665.696	6297	2166.7977	N/A	N/A	3864654528	831873.331	N/A

Table 21 Summary of Eaton Hall Utility Usage from 2004 to 2012

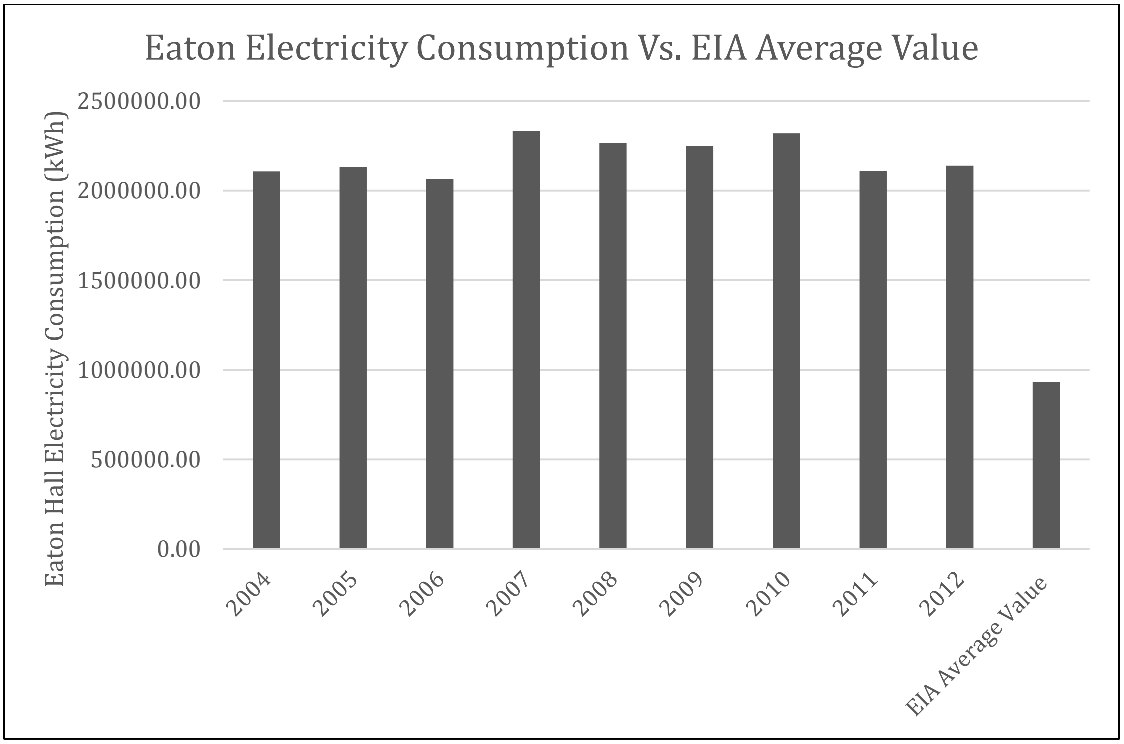


Figure 17 Eaton Hall Electricity Consumption 2004-2012 vs. EIA Average Value

The result on natural gas consumption showed that Eaton Hall consumed about national average in gas consumption except 2004, 2006, and 2007 as shown in Figure 18. The weather during the winters of these years was cooler than normal and several large winter weather events happened during these winters in Lawrence, KS (NOAA, 2007; NOAA, 2009; NOAA, 2008). The steam consumption was higher than EIA average value as shown in Figure 19 and it did not follow the weather pattern during the study period. Figure 20 indicated that the water consumption at Eaton Hall was about average when the data was compared to EIA average value.

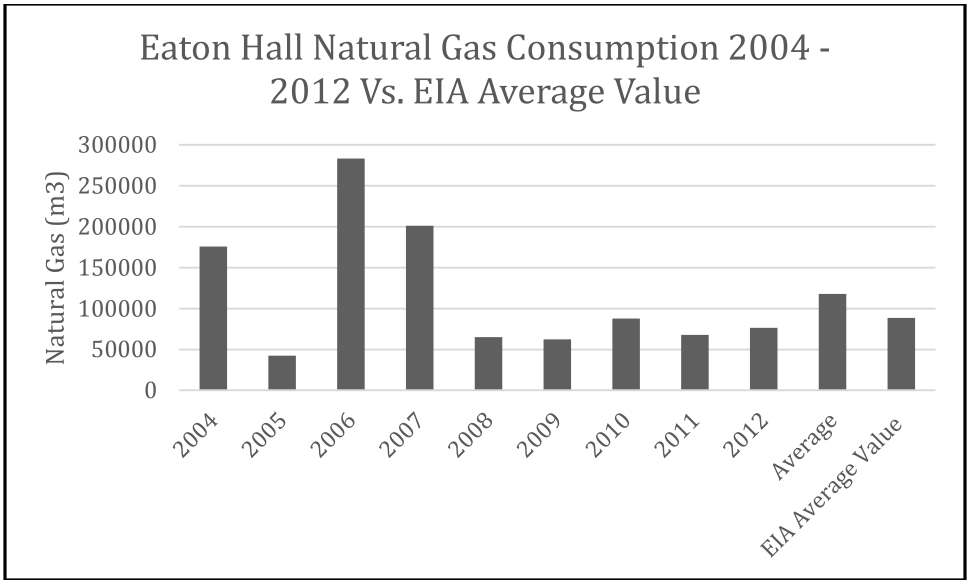


Figure 18 Eaton Hall Natural Gas Consumption 2004-2012 vs. EIA Average Value

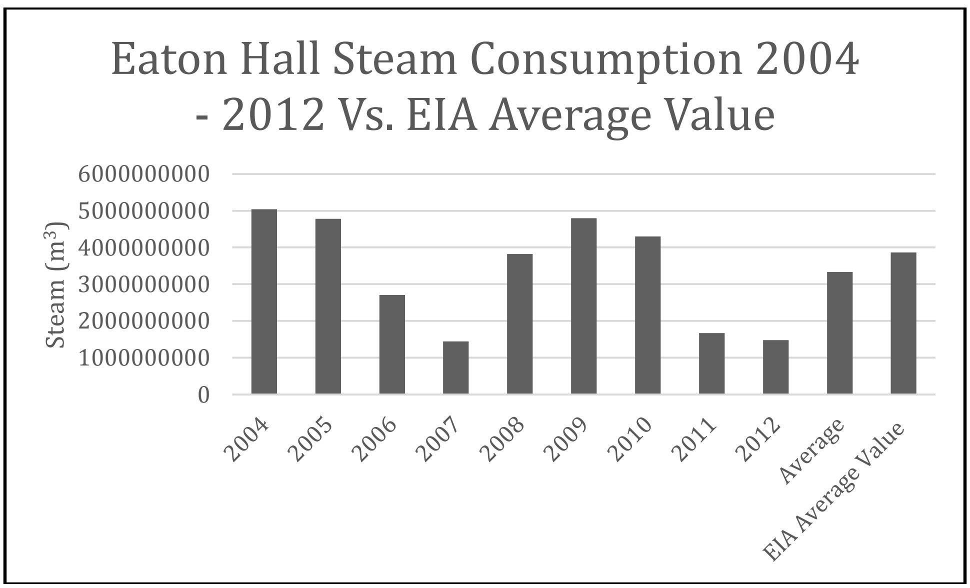


Figure 19 Eaton Hall Steam Consumption 2004-2012 vs. EIA Average Value

The result of the Eaton Hall study indicated that if all the utility data is available of a building, real time carbon emissions modeling could be made and building users, and owners could check their carbon footprints due to the operation of their buildings.

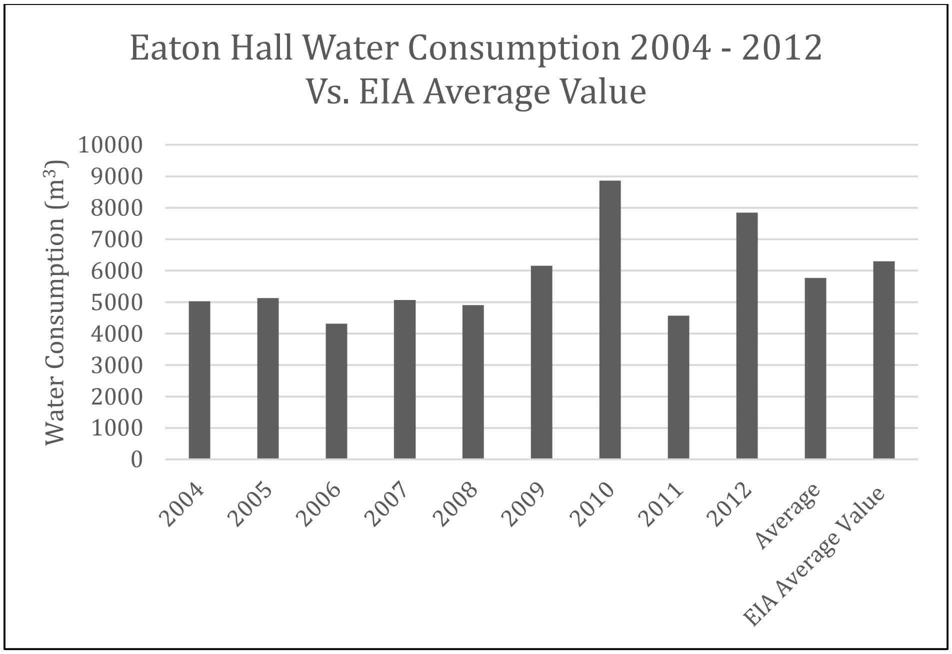


Figure 20 Eaton Hall Water Consumption 2004-2012 vs. EIA Average Value

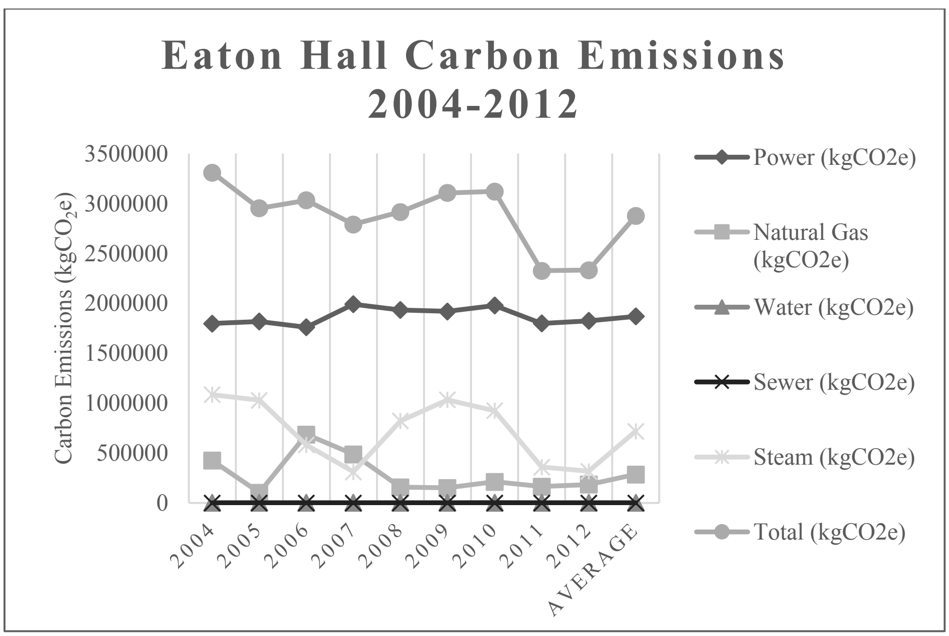


Figure 21 Eaton Hall Carbon Emissions 2004 to 2012

5.2.2 Multiple Buildings Analysis (KDOT)

Unlike Eaton Hall, KDOT had over 900 buildings and they have different types and usages. Not all the data was given to the research team. Also, unlike KU, KDOT did not have an individual department or a person to collect the data. Therefore, the data analysis was conducted in a different manner so that the building could be compared to the average values provided by EIA. Buildings were first categorized according to the actual use of the building rather than the intended or planned use. Building usage separated buildings based on their energy usage and space conditioning requirements. For example, office spaces required energy mainly to conditioned spaces for the occupants while workshops spent most of their energy on running equipment. KDOT representatives were interviewed to see if the building plans portray accurate building usage.

Even though some KDOT buildings were designed to deliver conditioned air for up to several occupants, these buildings were not frequently occupied during their operating hours. Most of the occupants spent their time on the roads. Phone calls were made with those who actually occupied the buildings to determine if the above was accurate. Full-time and part-time occupants were also separated in the analysis in order to determine how many actual occupants are occupying the buildings full time. Full-time occupants contribute to greater energy use in those buildings than part time occupants.

State policies and agency practices are also collected to understand how they impact energy consumption of various buildings. Space heating and cooling is the single greatest energy consumer. For this reason it is important to determine if occupants alter their interior temperatures based on the exterior temperatures. While a shop worker might be expected to wear gloves during winter and expect heat during the summer, an office workers' tolerance towards fluctuations in temperature tend to be lower than a shop worker. Cultural differences may also impact expectations and requirements.

Policies, practices, and employees' behaviors may vary from district to district. Some regions employ a "lights-out" policy that enforces that lights be turned off when no one is in a room. Some offices turn off lights on hot summer days in order to save energy, and some area offices may utilize windows rather than the thermostat to control indoor temperature.

Data gathered from KDOT building blueprints and from the utility companies were adjusted to reduce the amount of errors from some of the incomplete blueprints and unclear utility bills. Three trips were made to verify the locations of some of the meters. Highway rest stops were excluded from the study due to time and resource constraints. Even though the rest stops are constructed by KDOT, they did not have direct control and jurisdiction over many of them (such as those inter-state highways). These rest stops were also unstaffed and thus data cannot be verified.

The first task within the energy analysis was obtaining the utility data. The utility information for all accounts within the agency must have been amassed from each of the supplying utility companies. Large buildings and campuses occasionally were contained under a single account number or, in other cases, were broken into several accounts. Each account could consist of multiple meters. When contacting providers, the year, locations, value quantities, and meter detail were obtained from the providers

In the case of KDOT, a span from 2007 to 2010 was desired. Due to availability, most accounts contained roughly three and a half years of data since KDOT no longer had access to data before the spring of 2007 of many accounts.

Each account number was assigned to its corresponding address. Some addresses, such as those attached to large campuses, contained multiple account numbers with multiple meter numbers per account, so if possible, it was important to obtain as much meter data as the utility provider had available. An alternative was to summarize the meter values to create a total value per account number.

Utility data and analysis were grouped into building types. Building types described the uses and sizes of the buildings. As the utility companies installed one meter for each campus rather than for each building, the utility data were grouped by campuses first and then grouped by buildings (whenever possible). The building types were described in Appendix B. The table also highlighted some energy use averages for different building types based on the Department of Energy's Energy Information Agency's averages for the building types. With the buildings in the set categories, each building type was given an ideal version of the type based upon the majority of the buildings. These ideal buildings were used to get a uniform set of variables that would work for the building type. These variables included items such as building material, government/non-government owned, geographic location, number of workers, hours of operation, type of lights used, hours lit, etc. This ideal building was used to make the EIA benchmark that would be used for the analysis of the building type by kWh per m^2 per year. It was then compared to the meter data supplied for each building, showing if the building was performing above or below the national average for that type of building.

5.2.2.1 KDOT Utility Result

The analysis of direct energy use (utility) is divided into KDOT districts and is shown in the following table. District 1 consumes the highest amount of electricity, and this result is expected since District 1 covers the major metropolitan areas of Kansas such as Greater Kansas City, Topeka, Lawrence, and Manhattan. In addition, its energy intensity is also the highest.

Area	Total Annual Use kWh (2008)	Total Annual Use kWh (2009)	Total Area (m^2)
District 1	8,241,006	8,177,974	63784
District 2	1,131,044	1,225,434	34710
District 4	545,350	517,483	38532
District 5	6,043,107	6,144,828	41792
Total	15,960,507	16,065,719	178818

Table 22 Total Electricity Consumption in Relation to Square Footage

The Energy Information Administration (EIA) average per District is shown in Table 23. Table 25 exhibits the top 10 power consuming locations in various KDOT districts. Most of these buildings are located in Topeka, KS. The electricity use of the main campus consumed the most power and its average per kWh per square foot is higher than similar buildings across the United States. On the other hand, most of the other top 10 energy intensive KDOT locations have lower average per kWh per square foot than similar buildings across the United States. Districts 1, 4 and 5 total annual electricity use is higher than the baseline of the EIA CBECS. On the other hand, the overall total annual use in 2009 is lower than the EIA average.

Area	Total Annual Use kWh (2008)	Total Annual Use kWh (2009)	Total EIA Average kWh
District 1	8,241,006	8,177,974	7,825,825
District 2	1,131,044	1,225,434	4,154,812
District 4	545,350	517,483	3,709,672
District 5	6,043,107	6,144,828	5,518,733
Total	15,960,507	16,065,719	21,209,042

Table 23 Total Power Use Compared to EIA Average Value

Most of the top 10 locations have power consumption lower than EIA average. The total CO_2 produced by the power generation is shown in Table 24. The carbon factor used in the conversion is 1.871 pound per kWh (USEPA, 2007). Since District 1 has the highest power consumption, it has the highest carbon emissions on utilities in KDOT. The total KDOT utility carbon production in 2009 is 15,028 tons. The top 10 carbon producing buildings are the same as the top 10 power consuming buildings. Table 25 shows that 2300 Van Buren, Topeka (the main office of KDOT) contribute 17.8% of the carbon production of KDOT. The other locations are around or less than 5% of the total carbon production.

Area	Total Annual Use kWh (2009)	Total Annual CO_2 Production (2009) (Tons)
District 1	8,177,974	7,650
District 2	1,225,434	1,146
District 4	517,483	484
District 5	6,144,828	5,748
Total	16,065,719	15,028

Table 24 Total Amount CO_2 Emissions from Utilities by District

Rank	Location	Electricity Use kWh (2009)	Percent
1	2300 Van Buren, Topeka	2,858,580	17.80%
2	101 Gage, Topeka	826,783	5.15%
3	3200 45th, Wichita	631,937	3.93%
4	121 21st, Topeka	363,240	2.26%
5	500 Hendricks, Hutchinson	281,599	1.75%
6	650 K7 HWY, Bonner Springs	273,880	1.70%
7	1041 3rd, Salina	234,480	1.46%
8	1112 3rd, Salina	179,080	1.11%
9	1812 4th, Pittsburg	102,875	0.64%
10	1220 4th, Hutchinson	102,160	0.64%

Table 25 Top 10 Buildings in Carbon Emissions

The utility data from KDOT showed how energy use may have been varying more drastically than what they normally assumed. For example, a furnace was broken in an office basement one winter and their employees had to work without heating in the building for several weeks. Computers, lights, electronics, and laboratory equipment were left running throughout the day and into the night. The resulting heat was enough to maintain building temperature despite the outside wintery conditions. Many employees complimented the comfort level of the 'new method' over the previous furnace that produced uneven and spotty heating. The energy use during that period actually came down significantly. As there were massive amount of street lights and highways in the state, they were excluded from the research but will probably be included in future project.

5.3 Proposed Building Utility Models

The result of the findings in this research was presented on a website and the input page, and result pages were shown in Appendix E and F. The KDOT study and Eaton Hall study provided a new vision that utility data and its related carbon emissions could be modeled and organized on a website so that building users, and building owners could determine their carbon emissions due to their activities in the building. In the case of KDOT, it did not have a specific department that organizes the utility data.

In the proposed model for utility, data is collected from the utility providers and the data is organized and summarize by year and location. Then, the utility data is converted to carbon emissions by carbon emissions factors. The data is displayed as graphs and on a table so that building owners and operators know their operational carbon emissions of their buildings. A summary modeling method is shown in Figure 22.

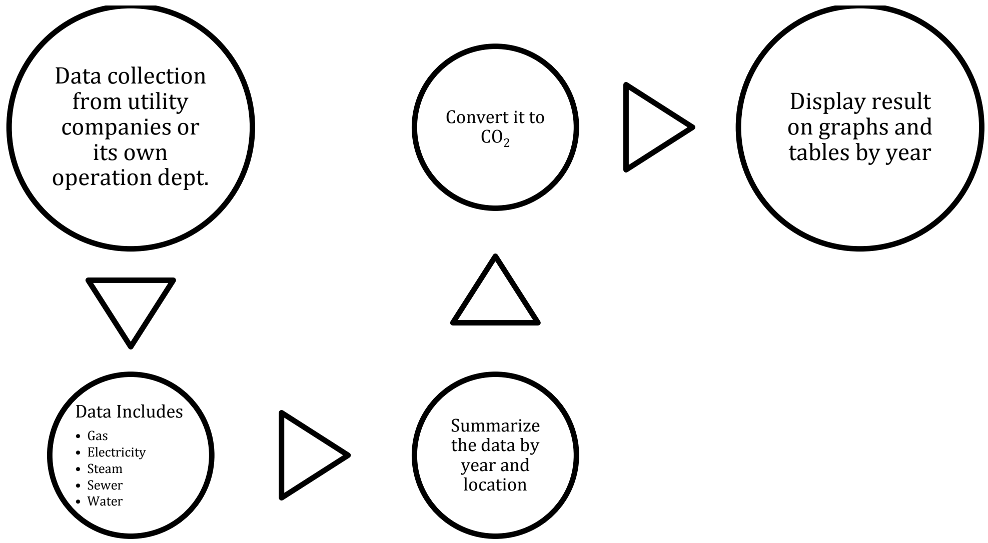


Figure 22 Building Utility And Carbon Emissions Model

An unforeseen problem occurred with the KDOT campus accounts. Due to utility provider's grouping of meters, it was impossible to separate security lights (highway lights, road lights, and campus yard lights) from building utility draw. After speaking with the utilities companies it was found that in many cases, coverage for these lights is on a set-fee basis rather than a wattage-usage basis. Further confusion was added when individual meters represented multiple small buildings.

Because of the discrepancies, buildings were grouped into campuses. KDOT proved to be the perfect candidate for this method since its campuses were repeated throughout the state in roughly the same form. For example, a standard sub area campus generally contained a chemical dome, a wash bay, a salt bunker, a sub area office, and a storage/equipment building. By being able to group accounts and meters into campuses, meter allocation problems were avoided.

CHAPTER 6: DATA ANALYSIS (EQUIPMENT-BASED BUILDING OPERATION)

There are wide variety of energy consuming devices and equipment in a building. By using the energy flow analysis mentioned in Chapter 3.3.1, energy consumption of each device can be obtained using related energy fundamental equations of each device.

This part of the research did not take equipment efficiency into account. Due to the wide variety of devices and equipment, only a few types of equipment and building areas were chosen in the study. The study could be extended to other energy consuming devices in the future. The study included the equipment and areas below:

- Building Envelope
- HVAC (including Chiller, Cooling Tower, and Ventilation only)
- Means of Transportation
- Lighting
- Elevator & Escalator
- Water Consumption
- Renewable Energy and Greenery

6.1 Energy Transmittals through External Wall: ETTV and U values

Green Building certification such as energy saving features from wall, façade, and roof materials are tackled in all the Green Building certifications. According to a study in Jordan, residential buildings in costal locations can save close to 50% on energy while residential buildings in the highland can save more than 90% energy on heating and cooling with better ventilation and insulation (Radhi, 2009). A pilot project in Stockholm had a heat exchange system installed in the ventilation system of a subway station and it generated 15-30% per year of the energy consumption used for the heating of a 13-story building 100-yards away by the body heat of 250,000 commuters in the subway station per day (Kelly, 2010). The more people occupying a building, the more energy is needed for cooling and air ventilation.

Materials used for building envelope including the walls, and the glass windows are important to the energy consumption related to heating, ventilation and cooling systems in a building. Envelope Thermal Transfer Value (ETTV), normally expressed in W/m^2, is a concept developed in Singapore to measure building cooling energy. U values of a building envelope not only represent the thermal conductivity of a building envelope material, they also represent the temperature difference between indoor and outdoor. The unit of U-values is $W/(m^2\ K)$. ETTV measures the thermal conductivity of building envelope materials. ETTV of a building material inversely correlated with its insulation and characteristic. Thus, lower ETTV value means that less energy is needed to cool down indoor space in a building during the summer. As such, ETTV and U values can be used to estimate the amount of energy needed for the immediate interior space of building (and thus the equivalent carbon) and energy saving from differentiating ETTV and U values. Carbon emissions can be calculated according to the savings from external wall and glass choices.

The ETTV is determined by the window and wall ratio, thermal transmittance of an opaque wall, thermal transmittance of fenestration, equivalent temperature difference, temperature difference, solar factor, correction factor for solar heat gain through fenestration, and shading coefficients of fenestration. The relationship between these variables is shown below:

$$\text{ETTV (in W/m}^2) = T_{Deq} \times (1\text{-WWR}) \times U_w + \Delta\ T(\text{WWR})U_f + \text{SF}(\text{CF} \times \text{WWR} \times \text{SC})$$

WWR: window/wall ratio

WWR = 0, U-value brickwall = 2.62 W/m^2 K

WWR < 0.5, U-value = 4.25 W/m^2 K

Uw: thermal transmittance of opaque wall (W/m^2 K)

Uf: thermal transmittance of fenestration (W/m^2 K)

Tdeq: equivalent temperature difference

ΔT: temperature difference

SF: solar factor

CF: correction factor for solar heat gain through fenestration

SC: shading coefficients of fenestration

Equation 6 Equation for ETTV

The solar factor is related to latitude where a building is located according to a study by Sam CM Hui and Chu (See Figure 23). In their study, they determined that solar factor increases with increasing latitude. In other words, locations at higher latitude will have higher heat gain from solar energy. The ETTV at higher latitude will be higher than the one at lower latitude (Hui & Chu, 2009). For example, in Singapore, the latitude is 1°22', and the solar factor will be 363 Watt per square meter.

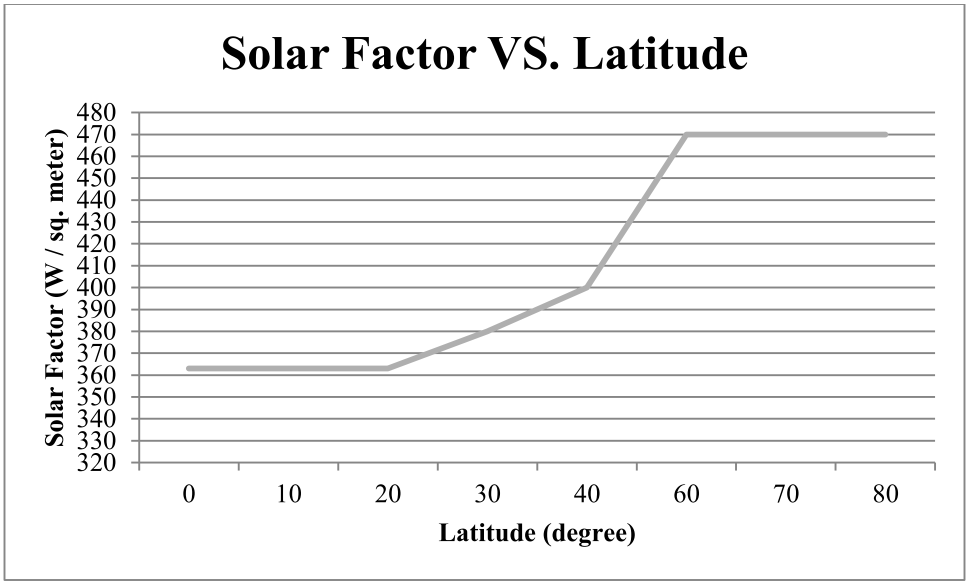


Figure 23 Solar Factor vs. Latitude (Hui & Chu, 2009)

Once the ETTV is found for a building, the carbon emissions savings from choosing better building envelope material can be calculated by multiplying the area of the wall, by the carbon emission factor for electricity, and by the amount of time that heating, ventilation, air-conditioning and cooling (HVAC) system is operating. The ETTV is multiplied by the electricity carbon emission factor because the materials of the wall, as previously mentioned, transfer the heat gain from the outside. Walls with lower ETTVs have less heat gain and they save the cooling load of the HVAC system. In other words, the materials used in the walls lower the energy consumption. Therefore, the ETTV is multiplied by the electricity carbon emission factor in order to calculate the carbon emissions lowered by changing the choice of wall materials.

6.2 HVAC

The Heating, Ventilating, and Air Conditioning (HVAC) system is a system that improves indoor environmental comfort by circulating the air and adjusting the indoor temperature according to user's preference. HVAC systems are often installed in commercial buildings and most of the residential housing the United States. In the rest of the world, and some parts of the U.S., window air-conditioners are used instead of universal HVAC units in residential buildings. In Singapore, most of the residential buildings use window units, while commercial buildings use HVAC systems.

The HVAC system includes a central heating system, ventilating systems, cooling tower, and air-conditioning system. The heating system usually has a boiler, furnace or heat pump. It is used to heat the air or the fluid, and the piping of the rest of the HVAC system distributes the heat by convection. The ventilating system is used to remove excess indoor humidity, odors, and contaminants and exhaust them outdoor by mechanical or force ventilation using a built-in fan. The system also introduces air from the outside to the inside of a building. The ventilating system can be replaced by a natural ventilation system that does not contain a fan. Opening windows or trickle vents replaces the fan of a ventilating system. Warm air rises and flows through the open windows and trickle vents, and natural air will be introduced through the windows and trickle vents. It is a good option and it uses less energy but it can only be used in low humidity and cool regions. Air conditioning systems, on the other hand, is the system which removes heat in the HVAC system. Heat is removed through the process of radiation, convection, and cooling through a process called the refrigeration cycle. The conduction mediums used in the industry are water, air, or refrigerants. The air-conditioning system also contains a dehumidifier to remove the humidity of the indoor air by evaporation.

The case study of this research was trying to estimate the air-conditioning power consumption of the HVAC system and the research assumed that the window unit had similar power consumption to the HVAC system.

6.2.1 Chiller

In a HVAC system, the chiller is used to remove the heat from the indoor air. Chiller Tonnage (TR) is a quantity that measures the amount of thermal energy removed from a room. One chiller tonnage is equivalent to 3024 kCal per hour, and 859.9 kCal is equal to 1 kW hour of electric energy. In order to determine TR, the mass flow rate of coolant, the specific type of coolant, and the temperature difference of coolant are needed in the calculation (See Equation 7). Since calories can be converted to electricity consumption by a conversion factor, carbon emissions can be calculated if the carbon emission factor of electricity is applied in the calculation.

$$\text{Chiller Tonnage (TR)} = \frac{QC_P(T_i - T_o)}{3024}$$

Where

Q is mass flow rate of coolant in kg/hr

Cp is coolant specific heat in kCal /kg °C

Ti is inlet, temperature of coolant to evaporator (chiller) in °C

To is outlet temperature of coolant from evaporator (chiller) in °C.

Equation 7 Chiller Tonnage

Chiller tonnage is the thermal energy removed from the interior per hour. In the chiller tonnage carbon emissions modeling, the efficiency of the chiller is assumed to be 100%. In other words, the electricity is well consumed by the chiller and all the power is used to remove the heat from a building. The carbon emissions of chiller can be estimated by multiplying the chiller tonnage by the carbon emission factor of electricity using the appropriate units (1kWh equals 3.6 mega joules).

6.2.2 Cooling Tower

The cooling tower is connected to the chiller in a HVAC system. The water running in a cooling tower removes heat from the chiller. Water is used as a coolant because it has high specific heat capacity and water can more efficiently remove heat from the chiller than air near the wet-bulb temperature.

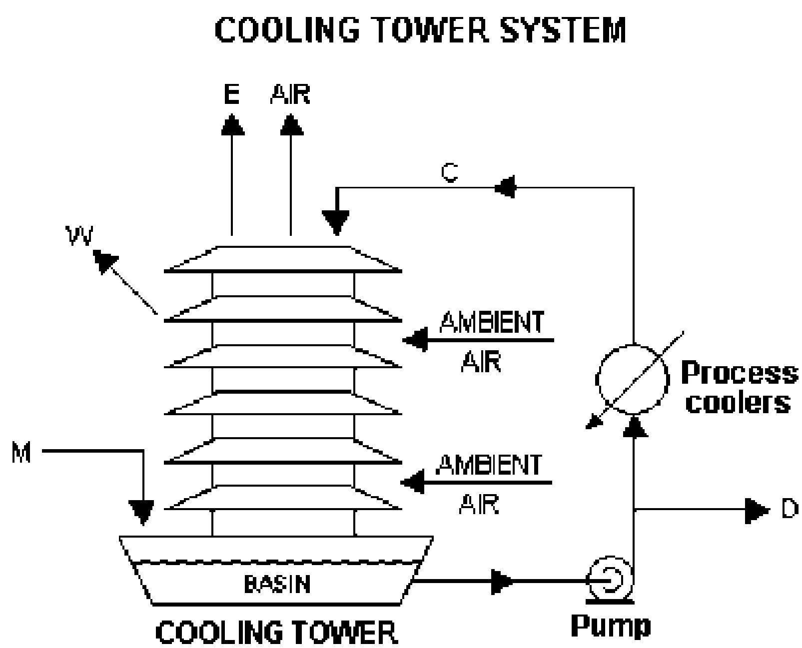


Figure 24 Schematic Diagram of Cooling Tower

The cooling tower consumes water. Therefore, the carbon emission calculation focuses on the water use and evaporation. The energy of the pump is disregarded in this case. The total water flow of a cooling tower is called Make-up (M) water, which is the summation of Circulating water (C), Draw-off water (D), Evaporated water (E), and Windage loss of water (W). The water flow measurement is in gallon per min. In order to calculate the annual water consumption of a building, the Make-up water in gallon per min should be multiplied by the operating minutes per year of a building. The carbon emissions of cooling tower will be the multiple of Make-up water and water carbon emission factor.

M=C+E+D+W

Where M is Make-up water in gal/min

C is Circulating water in gal/min

D is Draw-off water in gal/min

E is Evaporated water in gal/min

W is Windage loss of water in gal/min

Equation 8 Windage Loss Equation of Cooling Tower

The windage loss of a cooling tower measures the water evaporated when the warm water on top of the tower trickles downward over the fill material inside the tower, and the warm water contacts the rising ambient air by natural or forced draft using large fans in the tower. The loss depends on the type of draft and the total water loss due to windage is calculated by taking a percentage off from the circulating water inside a cooling tower. The carbon emissions of cooling tower can be calculated by multiplying the Make-up water by the carbon emission factor of water, and by the operating time of cooling tower. Also, if the energy consumption of the water pump is considered, the carbon emissions due to the water pump can be estimated by multiplying the energy consumption of the cooling tower water pump by the carbon emission factor of electricity.

Windage Loss	Type of draft
0.3 to 1.0 % of C	natural draft cooling tower
0.1 to 0.3 % of C	induced draft cooling tower
about 0.01 % of C	cooling tower with windage drift eliminators

Table 26 Windage Losses vs. Draft

6.2.3 Ventilation

Ventilation is the subcategory system of the HVAC system, and it is used to circulate the air in a building. Currently, there are three kinds of ventilation systems: Mechanical, Natural, and Hybrid. The mechanical ventilation system uses an air handler unit (AHU) to circulate the air. The AHU is usually made out of metal with a filter, and it is installed on the rooftop of a building. The unit has a fan, and it forces the fresh air inside through the air filter. Then, it exhales the indoor air with odor, humidity and contaminants outside a building (ASHRAE, 2005).

The energy consumption can be estimated by the design ventilation quantity, and operating hours. The average flow rate is between 900 to 1300 m^3/ (hr floor) (ECCJ, 2010). The equation is listed below:

$$E = Q \times T \times 3.676 \times 10^{-4}$$

Where

E: Assumed primary energy consumption for ventilation (unit: kWh)

Q: Design ventilation quantity (unit: m^3/hour)

T: Annual operation time (unit: hour)

Equation 9 Ventilation Energy Consumption

In Green Mark, the Green Building Certification in Singapore, Air-Conditioned System Efficiency (in kW/ton) is considered as factor for energy efficiency (BCA, 2010;

USGBC, 2009). Air-Conditioning System Efficiency is a factor that measures the power needed to generate a certain amount of cooling load. The lower the Air-Conditioned System Efficiency number, better the energy efficiency is. In other organizations around the world, such as Energy Star, energy efficiency is represented as Energy Efficiency Ratio (EER) (USDOE, 2007). Energy Efficiency Ratio (EER) is a measure of the efficiently of a cooling system during operating outdoor temperature at 95°F. Higher the EER, more efficient the system is (USDOE, 2007). The conversion between Air-Conditioned System Efficiency and EER is listed below:

$$EER=12/(Air – Conditioned\ System\ Efficiency)$$

Equation 10 Air-Conditioned System Efficiency

6.2.4 Refrigerant

Other than the ventilation and cooling tower, refrigerant is another part of the HVAC system that contributes carbon emissions. According to UK Department for Environment, Food and Rural Affairs, each type of refrigerant has a different Global Warming Potential (GWP). This is a relative scale enabling comparison to be drawn between the six Kyoto Protocol greenhouse gases (GHG). Each GHG is given a number based on its effect on the atmosphere relative to CO_2 (which has a GWP of 1). The GWP is expressed in kg of CO_2 equivalent, or $kgCO_2e$. For example, refrigerant R410a has a GWP of $1725kgCO_2e$. The GWP figures for each GHG are taken from "Guidelines to DEFRA/DECC's GHG Conversion Factors for Company Reporting" published by DEFRA in 2010. The table below shows different refrigerants have different carbon emissions factor.

Refrigerant	$GWP(kgCO_2e)$	ODP(kgCFC-11e)
HCFC-22 (R22)	1810	0.050000
HCFC123	76	0.020000
HCFC124	470	0.020000
HFC134A	1300	0.000015
R404A	3260	0.000010
R407B	2285	0.000010
R410A	1725	0.000020

Table 27 Refrigerant Global Warming Potentials & Ozone Depletion Potentials

6.3 Renewable Energy and Greenery

Buildings that use renewable energy, such as solar and wind power can “offset” the carbon emissions from equivalent amount of energy that energy sources generate. The offset varies on the sources of non-renewable energy that the renewable energy replaces. The total savings will be based on the carbon emitted by the non-renewable energy normally used in buildings (Carbon Retirement, 2013).

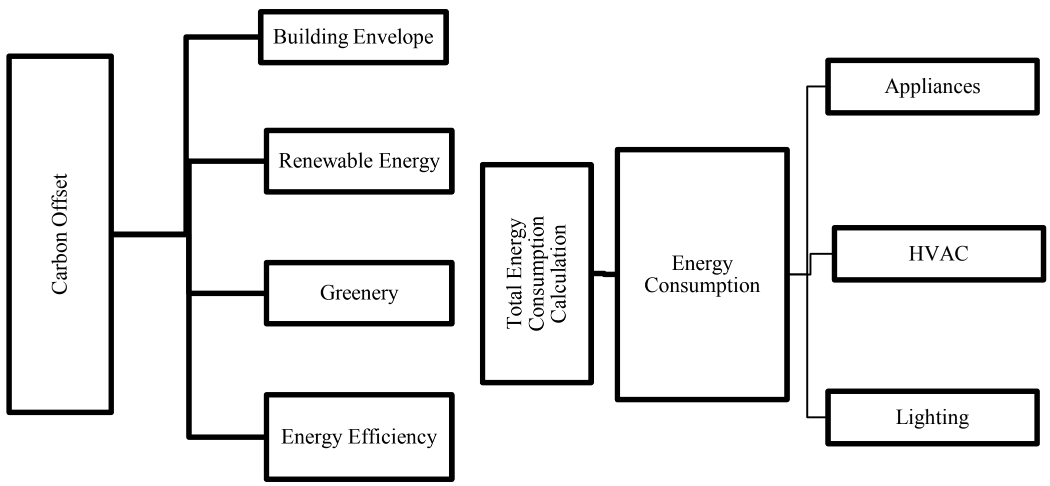


Figure 25 Summary of Energy Consumption and Savings

Increasing the amount of greenery, such as green roofs, green walls and fields, near or on site can lead to energy saving in buildings with the help of the evapotranspiration of plants depending on the height and orientation of buildings (USEPA, 2010). It increases R-values, and the benefit may vary by roofs depending on the building hotspot. Shading provided by green roofs and trees reduces surface temperature on the roof and pavement, and thus reduces cooling load in buildings during summer. In winter, the moisture in soil moderates the temperature of buildings with green roofs. In addition, plants absorb carbon dioxide for photosynthesis. Greenery, therefore, is a key criteria in most green building standards (USGBC, 2009; BCA, 2010), and carbon emissions saving can be estimated according to the energy use mitigation of this feature.

Water that evaporates from leaves will absorb thermal energy during the transition between liquid and gaseous state. According to U.S. EPA, maximum surface temperature reduction due to the shading from trees is ranging from 20 to 45ºF (11-25º C) for walls and roofs. In the winter, this insulating effect, on the other hand, causes less heat loss from the inside of the building roof, which reduces heating needs (USEPA, 2010).

A study by the EPA of Chicago City Hall, a 20,300 square foot building where a green roof was added, found the green roof saved 9,270 kWh per year on cooling and 740 million Btu per year on heating. The EPA carried out a similar study on the green roofs in Toronto, ON, and Santa Barbara, CA. A building in Toronto, ON with 32,000 square feet of green roof saves 6% on energy cost for cooling and 10% on energy cost for heating per year, while a building in Santa Barbara, CA with 32,000 square feet of green roof saves 10% on energy cost on cooling and 10% on energy cost for heating per year This study also shows that the cooling energy savings would be greater in lower latitudes (USEPA, 2010).

To determine the energy saving on cooling in Singapore, the research team extrapolated the data to the equator, and the other locations for further calculation (See Table 28 & Table 29). Singapore is at 1.36 degrees north of the equator, and the cooling saving is determined to be 24.36 % of the total cooling energy consumption if green roof is installed on top of a building. When the users of the carbon emission calculator indicate that their buildings have green roof, the cooling energy consumption is discounted according to the cooling saving percentage extrapolated from the study by USEPA.

Locations	**Latitude (degree)**	**Cooling saving (%)**
Toronto	43.67	6
Santa Barbara, CA	34.45	10
Equator	0	24.95

Table 28 Latitude and Cooling Saving in Different Locations (USEPA, 2010)

Locations	**Latitude (degree)**	**Cooling saving (%)**	**Cooling saving (kWh /(m^2 of greenery - year)**
Chicago	41.9	6.77	4.95
Singapore	1.36	24.36	17.65
Hong Kong	22.3	15.27	11.09
Kansas City	39.12	7.97	5.81
Lawrence	38.97	8.04	5.81

Table 29 Extrapolated Cooling Saving Results

Another green roof study showed that the plant absorbs 375 grams of CO_2 per square meter per 2 years, assuming that the weather will be very similar for the 2-year study (Gili, 2009).

In Chapter 5, the modeling methodologies of the major energy consuming, and carbon emissions contributing parts of the building was presented and it was discussed in details individually. In this chapter, they are grouped accordingly in order to create overall models for buildings. For example, the R-value or ETTV, and greenery are related to the energy saving of the HVAC system and the proposed models for air conditioning includes R-value, HVAC systems, and greenery.

6.4 Proposed Carbon Emissions Modeling for HVAC, R-Value, Greenery, Location

Earlier figures shows that the World GHG emissions on electricity and Heating is about 24.4% (WRI, 2010b) and Table 4 that energy use in HVAC system is about 43 to 61% in residential buildings, and 20 to 57% in commercial buildings in Canada, the United States, and European Union (ürge-Vorsatz, Harvey, Mirasgedis, & Levine, 2007). As mentioned, a study in the United Kingdom determines that water contains significant of carbon footprint, and the carbon emissions factor for water is 0.276 kg CO_2 per m^3 of water (DEFRA, 2009). In western countries, buildings are commonly made by concrete. Therefore, the proposed models for energy use and carbon emissions will consider these three major sources.

In the proposed model for HVAC system, the energy consumption determination will be broken down into different parts of the system, such as ventilation, cooling tower, and chiller. The Energy use in each component is determined in equipment-based manner. In current green building certification, energy saving features like façade, green roofs, and greenery will lower the energy consumption on heating and cooling. The ETTV, and RTTV values of a building are determined and they can be used to estimate the heat gain from solar radiation. Greenery near the building can have temperature-moderating effect to a building due to evapotranspiration. The proposed model is shown in Figure 26.

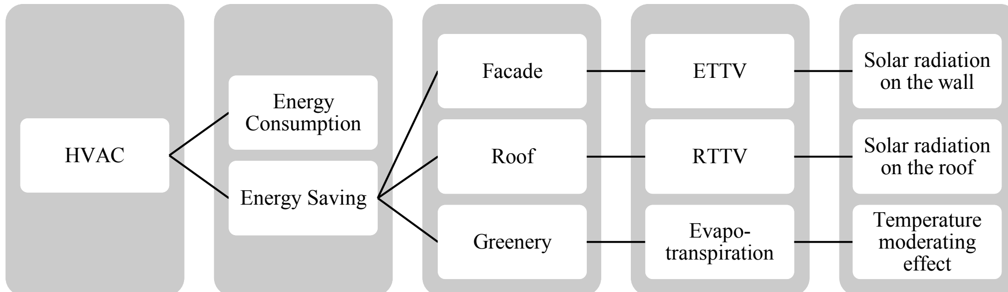


Figure 26 Proposed HVAC Energy and Carbon Emissions Model

6.5 Lighting

Lights consume significant amount of energy in a building. According to a study in 2011 by the United States Energy Information Administration (EIA), about 461 billion kilowatt-hours (kWh) of electricity were used for lighting by the residential and commercial sectors. This is equal to about 17% of the total electricity consumed by both of these sectors and about 12% of total U.S. electricity consumption (EIA, 2013). Estimating energy consumption in a building due to lighting only is difficult because a building usually does not put a meter for every single light and the large quantity of lights make it impractical. In order to generally estimate the energy consumption, the lighting power densities from the 90.1 standard by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) can be used. According to ASHRAE 90.1, office power consumption per square foot is 1.1 Watt per square meter as shown on Table 30 and the carbon emissions can by calculated by multiplying the carbon emission factor of electricity.

Common Space Types	LPD (W/m^2)	Building-Specific Types	LPD (W/m^2)
Office-Enclosed	11.84	Gymnasium/Exercise Center	
Office-Open Plan	11.84	…Playing Area	15.07
Conference/Meeting/Multipurpose	13.99	…Exercise Area	9.69
Classroom/Lecture/Training	15.07	Courthouse/Police Station/Penitentiary	
…For Penitentiary	13.99	...Courtroom	20.45
Lobby	13.99	…Confinement Cells	9.69
…For Hotel	11.84	…Judges' Chambers	13.99
...For Performing Arts Theater	35.52	Fire Stations	
...For Motion Picture Theater	11.84	…Engine Room	8.61
Audience/Seating Area	9.69	…Sleeping Quarters	3.23
...For Gymnasium	4.31	Post Office-Sorting Area	12.92
…For Exercise Center	3.23	Convention Center-Exhibit Space	13.99
…For Convention Center	7.53	Library	
…For Penitentiary	7.53	…Card File and Cataloging	11.84
…For Religious Buildings	18.30	….Stacks	18.30
…For Sports Arena	4.31	…Reading Area	12.92
…For Performing Arts Theater	27.99	Hospital	
…For Motion Picture Theater	12.92	…Emergency	29.06
…For Transportation	5.38	…Recovery	8.61

Table 30 ASHRAE 90.1 Lighting Power Densities (ASHRAE, 2013)

6.6 Elevator & Escalator

Elevators contribute a large percentage of building energy consumption. According to Al-Sharif, elevators consume 5 to 10% of a typical building's total energy costs, and the drive system and rated speed of an elevator affect the energy efficiency. The same study also shows that the hydraulic system is the least efficient and the VVVF system is the most efficient (Al-Sharif, 1996).

The estimation of power consumption of the elevator is very straight forward that requires the motor rating, number of starts per day, and the trip time factor (Al-Sharif, 1996). The architect or engineering company of a building should have this information. The equation used for energy consumption is listed below:

$E = (R \times ST \times TP)/3600$

Where E is daily energy consumed in kWh/day

R is motor rating in kW

ST is number of starts per day

TP is Trip Time Factor

Equation 11 Elevator Electricity Consumption

The energy consumption calculated by the equation above is determined on daily basis. However, the calculation of the carbon calculator is based on annual carbon emissions. The R will be multiplied by the number of operating days and hours in order to get the same time unit.

The motor rating is usually provided by the elevator manufacturer in the specification, and the trip time factor depends of the type of gear an elevator uses (See Table 31). By using the equation above, the power consumption of the elevator can be determined and it can be converted to carbon emissions by multiplying the local carbon emission factor of electricity.

Type of Lift Drive	**Trip Time Factor**
Hydraulic coefficient	6.0
Geared AC 2-speed coefficient	10.5
Geared ACVV (high mass) coefficient	8.5
Geared ACVV (low mass) coefficient	6.5
Gearless (MG) coefficient	5.0

Table 31 Trip Time Factors of Different Types of Lift Drive (Barney, 2004)

The power consumption of the escalator is estimated using results from the power consumption factors of a study at the Honolulu International Airport. The study looked at 15 horsepower escalators with three-phrase motor controllers with a twenty-foot rise per descent incline. The escalators chosen were subject to various loading conditions based upon the number of passengers traveling at a given time. The controllers were installed and ran for six days (140 hours) being controlled and ran for six days in bypass. Escalator in controlled means the escalator speed is controlled according to traffic and time of the day, while bypass means the escalator ran all the time regardless of the traffic. The results were collected in 15-minute intervals (Power Efficiency Corporation, 1999).

The calculation is based on the assumption outlines of the Honolulu International Airport. The average power consumption of escalators for the upward motion is 2.574 kW per (operating hours-year), and the power consumption for downward motion is 2.623kW per (operating hours-year) (Power Efficiency Corporation, 1999). The power of the lighting on the side of an escalator is ignored in this study. The power consumption is converted to carbon emissions using the local electricity carbon emission factor.

6.7 Proposed Carbon Emissions Modeling For Electronic Devices and Appliances

There are many electronic devices and electric appliances in a building. Other machines like elevators, and escalators are also consuming electricity in a building and their energy sources came from the same power source and so as the HVAC system. Due to the complexity, only lighting, elevator, and escalator (other than HVAC) are considered and the same method can be applied to other devices and appliances. As mentioned in the earlier chapter, some generalization on energy consumption estimation is needed because energy consumption is not known for all of the devices in a building. Sometimes, there is no fundamental equation to estimate the energy consumption. Lighting, for example, is needed to be generalized as 1.1 Watt per square foot per time of operation using existing studies. The proposed model for electronic appliances is shown in Figure 27.

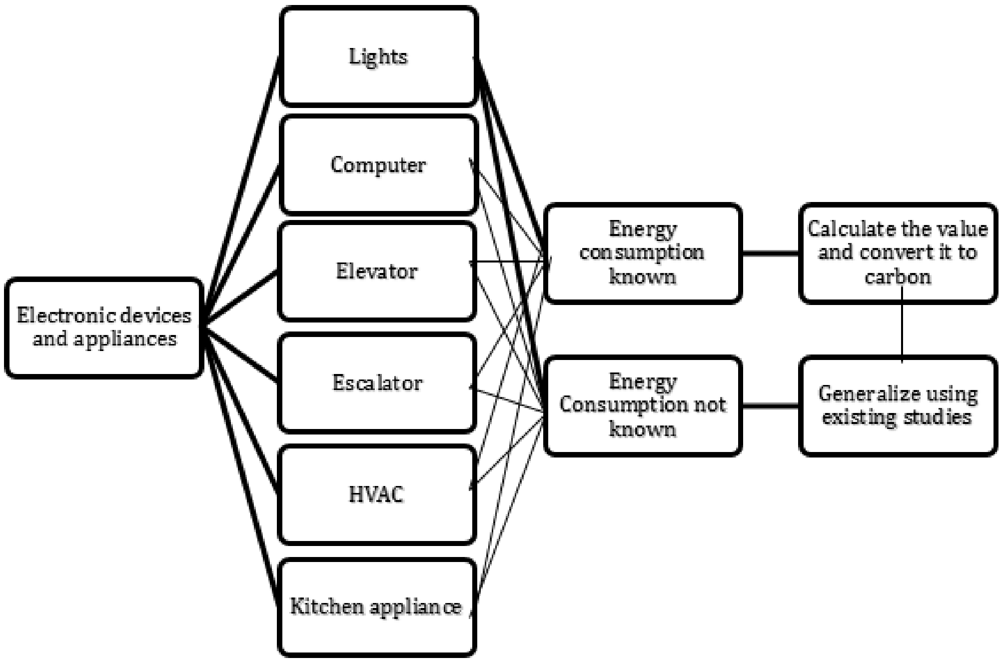


Figure 27 Proposed Carbon Emissions Model for Electronic Devices and Appliances

6.7.1 Example of Carbon Emissions Model for Electronic Devices and Appliances

Eaton Hall was chosen in the carbon emissions model testing for the carbon emissions from different electronic devices and appliances. Some electronic devices were excluded due to their non-existence in the building. The gross area of Eaton Hall was 7872 square meters and the exterior walls were facing north, east, south, west, and northwest. Using the ETTV equation mentioned in the earlier section of the chapter and with the help of Google Earth, the thermal transfer value of each side of the building was calculated as shown in the table below with the assumption of the outdoor and indoor temperature difference of 15 degree Celsius throughout the year.

Wall	Area (m^2)	Window Area (m^2)	WWR	CF	ETTV (W/m^2)	Carbon Emissions ($kgCO_2e$ per hour)
North	314	52.00	0.1657	1.00	96.89	25.92
East	1018	129.50	0.1273	1.29	95.06	82.48
South	1232	52.00	0.0422	1.43	56.23	59.08
West	768	68.00	0.0886	1.46	81.70	53.47
North West	216	72.00	0.3333	1.18	181.39	33.41

Table 32 ETTV Values Summary of Eaton Hall

The ETTV values varied from 56.23 to 181.30 W/m^2 and the numbers indicated that the heat transferred from the outdoor to the indoor of the building during the summer and the heat transferred from the indoor to the outdoor of the building during the winter. Assume there is no heat loss in this process, the air-conditioning was required to regulate the interior temperature throughout the year and the carbon emissions per hour of HVAC operation was shown on Table 32.

The chiller in Eaton Hall was assumed to be an average commercial chiller (IPCC, 2005) and it ran on average 236.21 kg per minute using R410A refrigerant. The chiller tonnage was calculated to be 6377.67 kilojoules per minute, which required 106.30 kW per hour of electricity. The carbon emissions would be 90.64 $kgCO_2e$ per hour of operation. The GWP of R410A refrigerant was 1725 $kgCO_2e$ per kg of refrigerant. According to IPCC, 0.25 kg per kW was the average refrigerant charge in the U.S. (IPCC, 2005) Therefore, the carbon emissions from the refrigerant was 431.25 $kgCO_2e$ per kW of electricity spent on the HVAC system.

The ventilation system in Eaton Hall required to serve 7872 square meters of space. Assuming the ceiling height was 3 meter high. The total volume of space is 23,616 cubic meters. The average exchange rate for the education building is about 4 (Bearg, 1993). Using the ventilation equation, the power consumption for ventilation would be:

E (kW per hour) = Q x T

= (4 x 23616) x3.676 x 10^{-4}

= 34.72 kW per hour

Therefore, the carbon emissions from the ventilation system would be 29.61 kgCO_2e per hour of operation.

The lighting fixtures in Eaton Hall were a combination of can lights and florescent lights. According to ASHRAE 90.1 standards, the energy consumption on lighting was 15.07 Watt per square meter. The energy consumption for lighting at Eaton Hall was 118.63 kW per hour of operation. Thus, the carbon emissions for lighting was 101.15 kgCO_2e per hour of operation.

The elevator used in Eaton Hall was Kone gearless Eco elevator with 52.23kW motor rating and number of uses per hour was about 20. Therefore, the energy consumption was:

E (kWh per hour) = (R x ST x TP)/3600

= (52.23 x 20 x 5)/3600

= 1.45 kWh per hour

The carbon emission of elevator at Eaton Hall was 1.24 kgCO_2e per hour of building operation.

6.8 Water Consumption

There is a lot of research and online calculators that are available for the public to estimate the water consumption from users and irrigation. Consumer Council for Water offers a calculator for residential buildings or houses (Consumer Council for Water, 2013) and Southwest Florida Water Management District offers water consumption estimation for domestic water use (SWFWMD, 2013). However, there is only one unified water consumption estimation for residential buildings, retail stores, schools, irrigation, and other commercial buildings and it is provided by United States Green Building Council (USGBC) in the LEED BD+C Reference Guide (USGBC, 2009). This study will borrow its method and the estimation will be explained below.

The USGBC reference guide provides a method of water consumption estimation and the method requires detailed information on the users of a building. For instance, to estimate a commercial building, the number of full time employees (FTE) and visitors are required and the users' genders are also need for the calculation due to the biological differences and requirements in water consumption. The USGBC provides number of uses per day for each type of user and each fixture type on a table as shown on Table 33. On the BD+C Reference Guide, the USGBC also includes a table that provides the flow rate of different types of flush and fixtures as shown on Table 35 and Table 35.

Fixture Type	FTE	Student /Visitor	Retail Customer	Resident
	Uses/Day			
Water Closet				
---Female	3	0.5	0.2	5
---Male	1	0.1	0.1	5
Urinal				
---Female	0	0	0	n/a
---Male	2	0.4	0.1	n/a
Lavatory Faucet				
---duration 15 sec; 12 sec with auto control	3	0.5	0.2	5
---residential, duration 60sec	0.1			
Shower				
---duration 300 sec	0.1	0	0	1
---residential, duration 480 sec				
Kitchen Sink				
---duration 15 sec	1	0	0	n/a
---residential, duration 60 sec	n/a	n/a	n/a	4

Table 33 Users and Fixture Types in a Building (USGBC, 2009)

Flush Fixture	Flow Rate (m^3/flush)
Conventional water closet	0.0061
High-efficiency toilet (HET), single-flush gravity	0.0048
HET, single-flush pressure assist	0.0038
HET, dual flush (full-flush)	0.0061
HET, dual flush (low-flush)	0.0042
HET, foam flush	0.0002
Nonwater toilet	0.0000
Conventional urinal	0.0038
High-efficiency urinal (HEU)	0.0019
Nonwater urinal	0.0000

Table 34 Flow Fixture in A Building (USGBC, 2009)

Flow Fixture	Flow rate (m^3/minute)
Conventional private lavatory	0.0083
Conventional public lavatory	0.0019 or <=0.0009
Conventional kitchen sink	0.0083
Low-flow kitchen sink	0.0068
Conventional shower	0.0095
Low-flow shower	0.0068

Table 35 Flow Fixture in A Building (USGBC, 2009)

To estimate the water consumption of a building per year, one can use the equation below:

$$Water\ Consumption\ per\ year = 365 \times \sum_{t=0}^{n} \sum_{i=0}^{n} O_i U F_t$$

Where O_i = Different Type of Users

U = Number of Uses Per day

F_t = Different Types of Flush and Flow Fixture

Equation 12 Water Consumption Equation for a Building

The USGBC also offers a method that can estimate water used on irrigation. This method is borrowed from Irrigation Association (IA, 2005; Awady, Vis, & Mitra, 2003) and the USGBC provides a table to identify the vegetation types and their Species Factor, Density Factor, and Microclimate Factor as shown on Table 36. Using the factors, one can determine the landscape coefficient one plant on site. Using the reference evapotranspiration, the landscape evapotranspiration can be found and the total water applied for each plant per day can be calculated using irrigation efficiency and controller coefficient. If the processes are repeated for each plant around a building, the total water applied (TWA) per day can be determined. Some buildings are reusing water or using rainwater for irrigation, the amount of water from these two water-saving systems can be deducted from the TWA. The total potable water applied (TPWA) per year can be calculated by multiplying the number of days per year as shown in Equation 13.

The total water use of a building can be obtained by adding the water consumption from water fixtures and irrigation together. To find the carbon emissions due to water consumption, the carbon emissions factor of water can be used. The carbon emission factor is 344100 kg CO_{2e} per m^3.

Vegetation Type	Species Factor (Ks)			Density Factor (Kd)			Microclimate Factor (Kmc)		
	Low	Average	High	Low	Average	High	Low	Average	High
Trees	0.2	0.5	0.9	0.5	1	1.3	0.5	1	1.4
Shrubs	0.2	0.5	0.7	0.5	1	1.1	0.5	1	1.3
Groundcover	0.2	0.5	0.7	0.5	1	1.1	0.5	1	1.2
Mixed Trees, shrubs, groundcover	0.2	0.5	0.9	0.6	1.1	1.3	0.5	1	1.4
Turf grass	0.6	0.7	0.8	0.6	1	1	0.8	1	1.2

Table 36 Table of Species, Density, and Microclimate Factors for Different Vegetation Types

$$K_L = K_s K_d K_{mc}$$

$$ET_L = ET_o K_L$$

$$Total\ Water\ Applied = \sum_{i=0}^{n} A_i \times \frac{ET_{L\,i}}{IE} \times CE \times 0.000645080699 \frac{m^3}{m^3 \cdot m}$$

Total Potable Water Applied TPWA (m^3) per year = 365 x (TWA – Reuse Water)

Where K_s is Species Factor

K_d is Density Factor

K_{mc} is Microclimate Factor

K_L is Landscape Coefficient

ET_L is Landscape Evapotranspiration

ET_o is Reference Evapotranspiration

A is Area Covered a Type of Plant

IE is Irrigation Efficiency

CE is Controller Coefficient

Equation 13 Equation for Water Consumption on Irrigation

6.9 Proposed Carbon Emissions Modeling for Water Consumption and Irrigation

Water consumption in a building is divided in two parts: water consumption by occupants, and irrigation. The water use by occupants is directly related to the water carbon footprint of a building and the carbon emissions of water come from water treatment plants, water pump, and other water treatment equipment. Some countries, such as Singapore, handle their water using reverse osmosis in the filtration process. The process requires more energy and the carbon emission factor is higher. The other water consumption consideration in a building is the irrigation for greenery. Water use for greenery depends on the species of the plants and the type of sprinklers used around a building. The proposed model is shown in Figure 28.

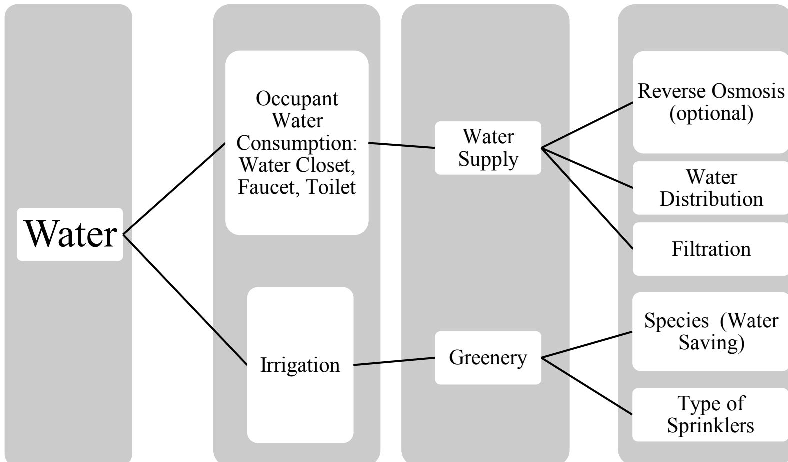


Figure 28 Proposed Water Consumption Energy and Carbon Emissions Model

6.9.1 Example of Carbon Emissions Model for Water Consumption

The School of Engineering had 2927 students and two main buildings on campus. There were about 70 faculty and staff also in Eaton Hall. The number of students that stayed in Eaton Hall was 1464 students. The male to female ratio was assumed to be 50/50. Using the methods by USGBC BD+C Reference Guide, the water consumption from water closet, urinal, and lavatory fixture were 2.66, 1.11, and 0.35 m^3 per day. The total water consumption per day was estimated to be 4.12 m^3 per day and the carbon emission per day of water use was 1.42 $kgCO_2e$.

The greenery around Eaton Hall were turf grass and trees only. The turf grass covered area was 362.5 m^2 and the tree covered area was 250.6 m^2. Using the equation from USGBC BD+C reference guide with the assumptions of irrigation efficiency of 0.8 and controller coefficient of 0.3, the total water applied to grass, and tree were 0.0620, and 0.0306 m^3 per day. The total carbon emissions was 0.0319 $kgCO_2e$ per day.

6.10 Means of Transportation

Transportation processes of construction materials, energy and water consume a significant amount of energy. The distances of which materials are shipped from their original sources to be installed on-site correlates to the amount of energy needed to transport them.

The green building certification process in the U.S., means of transportation is one of the factors that green buildings can get extra credits for. For example, bike racks and changing room installation and convenient access to public transportation could earn up to 7 points. LEED in the U.S. also awards points to buildings that use regional materials for the sake of lowering fuel consumption on transportation. Table 37 shows the significant differences on carbon emission between automobiles and public transportation.

Transportation	Emission	Units
Car	0.5812	$kgCO_{2e}/L$
Bus	0.4337	$kgCO_{2e}$/km/person
Rail	0.2200	$kgCO_{2e}$/km/person
MC	0.2206	$kgCO_{2e}$/km/person
Work at home/Walk/Bike	0.0000	$kgCO_{2e}$/km/person

Table 37 Means of Transport Carbon Emission Factors (Mäkivierikko 2009)

6.11 Proposed Carbon Emissions Modeling for the Means of Transportation

During building operation, the only carbon emissions contributing factor that is related to transportation is the means of transportation of building owners, and users. As mentioned in the earlier chapter, it is part of the green building certification of a building in the United States Leadership in Energy & Environmental Design (LEED) certification. If bike racks and changing rooms are installed for bikers in the building, and a building has convenient access to public transportation, it can earn up to 7 points in the certification. According to research, these features can reduce carbon emissions. For example, on average, a car contributes 5812 $kgCO_2e$ per m^3 whereas bus contributes 0.4337 $kgCO_2e$ per kilometers per person only.

To model the carbon emissions that are related to the users' means of transportation, the number of users of each mean in a building is needed. The proposed model is shown in Figure 29.

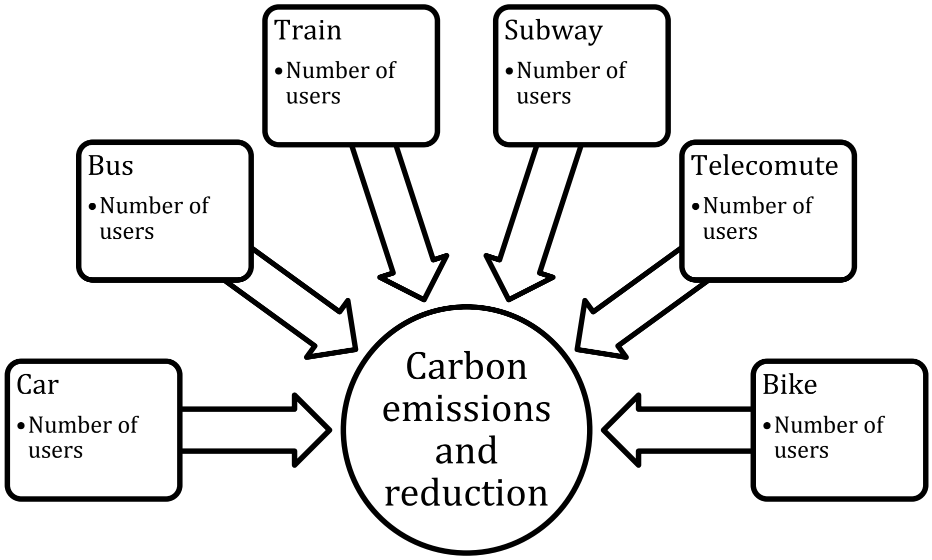


Figure 29 Proposed Carbon Emissions Model for the Means of Transportation

6.11.1 Example of the Mean of Transportation Model

The Eaton Hall was chosen to be the example of the mean of transportation number model. There were 1464 people staying full time in Eaton Hall. Most of the students and staff live within 4 miles (6.44 km) from school. Assuming 70% of the people drive to school and 20% of the people take the bus to school. The rest of the people walk or bike to school. Also, assuming the mileage of their vehicle is 16 miles per gallon (6.80 km per liter, the carbon emissions from the students' and faculties' vehicles was 1941.09 kgCO_2e per day and the carbon emissions from the buses was 1635.60 kgCO_2e per day.

CHAPTER 7: END-OF-LIFE OF BUILDING MATERIALS

Construction materials require high-energy during production. To determine the environmental impact of these materials, embodied energy calculation should be considered, and cradle-to-cradle strategy should be used to get accurate numbers. Cradle-to-Cradle model by McDonough and Braungart indicated that technical nutrients are strictly limited to non-toxic, non-harmful synthetic materials that have no negative effects on the natural environment, and they can be used in continuous cycles as the same product without losing their integrity or quality (McDonough & Braungart, 2002).

In earlier chapters, this research discussed the carbon emissions during the manufacturing process of materials. In this chapter, the end-of-life of the building materials would be examined and the stage of the building is at the end of the building lifecycle as shown in Figure 30 and two methods were used for end-of-life analysis.

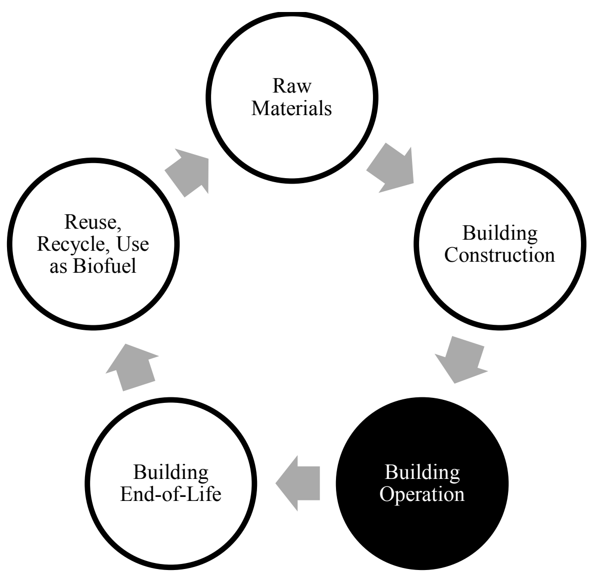


Figure 30 End-of-Life of the Building Materials in the Building Lifecycle

7.1 Bulk Weight Method

Solid waste calculation covers transportation to landfill, landfill emissions, and energy consumption on recycle and reuse treatment. During construction phase of buildings, contractors always try to recycle and reuse solid waste such as scaffolds, unused concrete, and tiles for green building certification credits. If materials cannot be reused or recycled, they will be transported to landfills as solid waste. These solid waste management methods are usually summarized as a lump-sum carbon factor based on the weight of solid waste for easy calculation. Solid waste emission factor of 0.7 $kgCO_2e/kg$ solid waste is recommended by a carbon calculator in the U.S. (Mäkivierikko, 2009). The disposal calculation model is shown in Figure 31. In order to determine the carbon emissions from disposal of construction materials, contractor and sub-contractor are required to keep a record of the weight of recycled and reused materials and the carbon emissions are estimated using the solid waste emission factor mentioned earlier. However, the method may not reflect the actual carbon emissions of C&D debris.

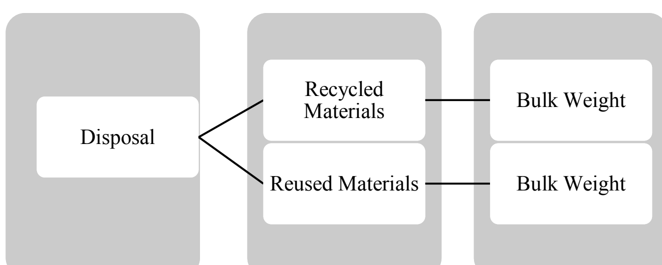


Figure 31 Disposals Calculation Model

7.2 Calorimetry

Most of the C&D debris ended up in landfills and being used as biomass fuel. The purpose of this research initially was to determine the best type of debris to be used as biomass fuel form C&D sites. Due to the loss of the oxygen charging station, testing was not carried out as planned. As a result, a method to determine energy release from the construction biomass fuel was proposed based on the IKA C200 calorimeter.

Bomb Calorimeter IKA C 200 was supposed to be used to determine the heat released from the proposed materials during combustion in this research and the calorimeter included other devices, such as decomposition vessel, combustible crucible, venting station, oxygen station as shown in Figure 32 to Figure 36. Wood debris (with varying moisture content), used shingles, used gypsum boards, and other C&D debris could be tested in the first phase of the experiment to determine the best types of construction debris to be used as biomass fuels based on the energy generated during combustion. The proposed experiment could be run according to ASTM D1102-04 for wood ash and ASTM E870-82 for wood debris, ASTM E711 for other construction materials, and ASTM D5865-10a calibration process for system calibration. For wood debris, the moisture content could be determined by ASTM D4442-07 method (ASTM, 1982; ASTM, 1984; ASTM, 2007; ASTM, 1987; ASTM, 2010a; ASTM, 2007; ASTM, 2005; ASTM, 2010c; ASTM, 2006; ASTM, 2011a).

The samples were supposed to be weighed before testing by a laboratory balance with accuracy up to 0.00001 gram. The result would be displayed on a computer or the LCD on the calorimeter in various energy units (kJ, Btu, Calories). The energy release factors would be calculated as energy release per weight unit of sample and each sample should have been tested at least 5 times to get an average data point.

Figure 32 IKA C200 Bomb Calorimeter

Figure 33 IKA C 5010 Decomposition Vessel

Figure 34 IKA C 5030 Venting Station with Gas Wash Bottle

Figure 35 IKA C 14 Combustible Crucible

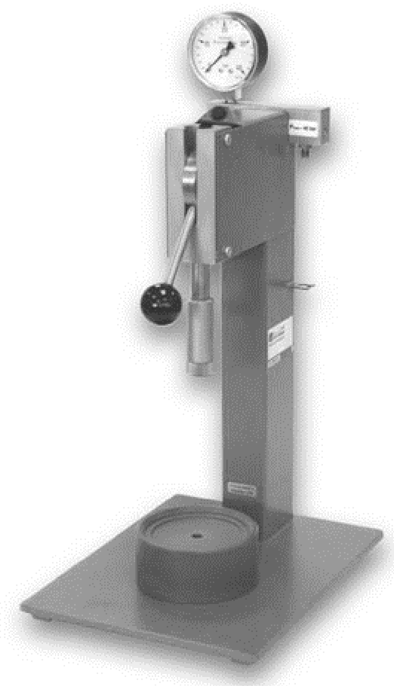


Figure 36 IKA C 248 Oxygen Station

The expected result showed that the heat generated by the construction materials as biomass fuel are Xc, Xw, and Xf. The Xc, Xw, and Xf could be converted into kWh electricity per kg of the material when construction debris was used as biomass fuel for power generation.

Material	Average Heat Generated (kg per kCal)	Average Heat Generated (kg per Joules)	Average energy Generated (kg per kWh)
Concrete	Xc	Xc/4184	Xc/[(4184)(2.78E-7]
Wood	Xw	Xw /4184	Xw/[(4184)(2.78E-7]
Fiberglass	Xf	Xf/4184	Xf/[(4184)(2.78E-7]

Table 38 Result of the Calorimetry

7.3 Proposed Models for Construction Debris

The proposed total embodied energy is the addition of energy consumption in raw material extraction, transportation, production, and reuse and recycling process as shown in Equation 3. Considering the materials like metal used in a building, the extraction energy includes the energy spent on extracting iron ore from rocks; the transportation energy includes the energy consumption on trucks to and from mine, factory, construction site, and recycle facilities. The production energy is the energy consumed in melting and metal treatment in a factory. The installation energy is the energy consumed during the installation process of metals, including power consumption on power tools. The recycling and reusing energy is the energy consumption in the melting, and retreatment during the recycling and reuse process. The Recycle/Reuse Ere in the embodied equation also represents the energy gained when the materials are used as biofuel to generate electricity. In this case, Ere will be negative because it is a carbon offset in the embodied energy calculation.

Embodied Energy = Eex + Etran + Epro + Einst + Ere

Equation 14 Total Embodied Energy

A study by Australian government showed that metal products have higher embodied energy than other construction materials. To lower the embodied energy of a construction, they recommended using materials with lower embodied energy, such as concrete, bricks, and timber (Milne & Reardon, 2010). The same study indicated that transportation energy is location dependent. Construction materials manufactured from different cities have different embodied energy even within the same country. Therefore, transportation embodied energy should be calculated separately depending on the material original location. The equation of the transportation-embodied energy is shown in Equation 13. The proposed embodied energy and carbon emissions model is shown in Figure 37.

Transportation Energy Etran=Etran1 + Etran2 +Etran3

Equation 15 Total Transportation Energy

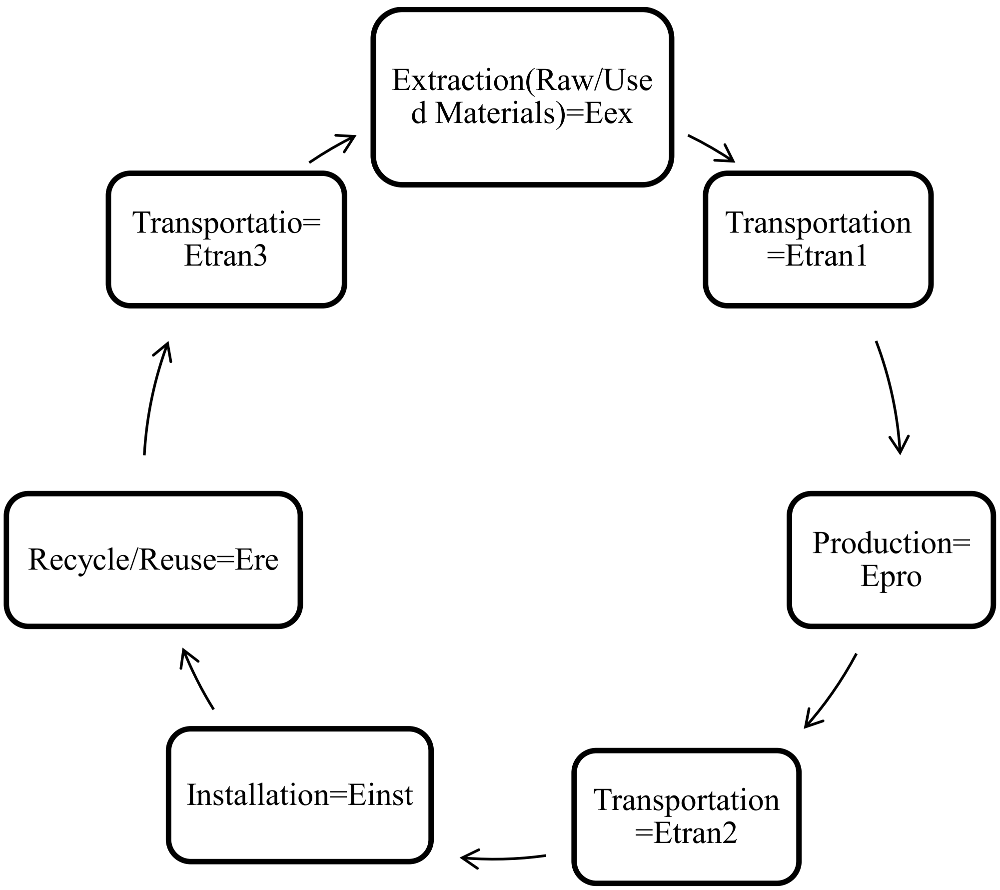


Figure 37 Embodied Energy Model for Construction Materials

CHAPTER 8: RESEARCH FINDINGS: COMPREHENSIVE MODEL

The purpose of this research was to determine a comprehensive framework to quantify carbon emissions throughout the building lifecycle. The findings showed that the initial step to determine carbon emissions of a building was to consider the building lifecycle based on the idea of "Cradle-to-Cradle" by McDonough & Braungart 2002 and the process needed to start from the ground up (McDonough & Braungart, 2002). Therefore, the building lifecycle carbon emissions estimation first focused on the raw materials and construction materials that were used in a building. At the same time, the fuel consumption by construction equipment and vehicles should have also been considered in the process.

The study concluded two methods could be used to investigate the embodied carbon emissions of the building. The first method was to collect data from transactions and purchase orders between engineers/architects, owners, and contractors. If data had not been available, especially for existing buildings, blueprints, drawings, Google Street View, and Google Maps could be used to determine the materials in a building. Figure 38 shows the framework to determine the embodied energy and embodied carbon emissions of a building. The research at Eaton Hall and with KDOT showed that the methods proposed in the framework could be used to estimate the carbon emissions from the embodied energy of a building. The framework also showed that it could be used even when the data was not available like the case of the KDOT buildings.

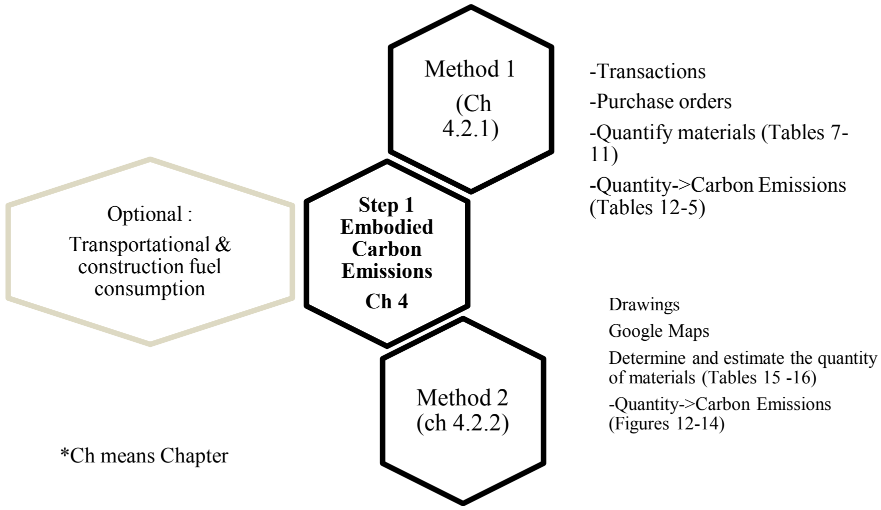


Figure 38 Step 1 of the Overall Framework

The research also showed that the building operational carbon emissions could be determined by the utility use and Figure 39 shows the framework of determining the utility consumption and the related carbon emissions of a building. If all the utility data, such as electricity, water, steam, and natural gas are available, the framework could be used to compare the national average based on the EIA CBECS publication. The utility data collected from Eaton Hall showed that the framework could be applied in real life data analysis. This result indicated that the framework could be used alone for one type of data when only electricity data was available like the case of KDOT. To run this part of the comprehensive framework, utility data, such as electricity, water, steam, and natural gas were required to determine the building operation carbon emissions. Also, the framework could be used to estimate multi-building cases and the framework could be applied to computer coding to compose a webpage for carbon emission calculation. The single and multi-building computer testing models will be shown in Chapter 9.

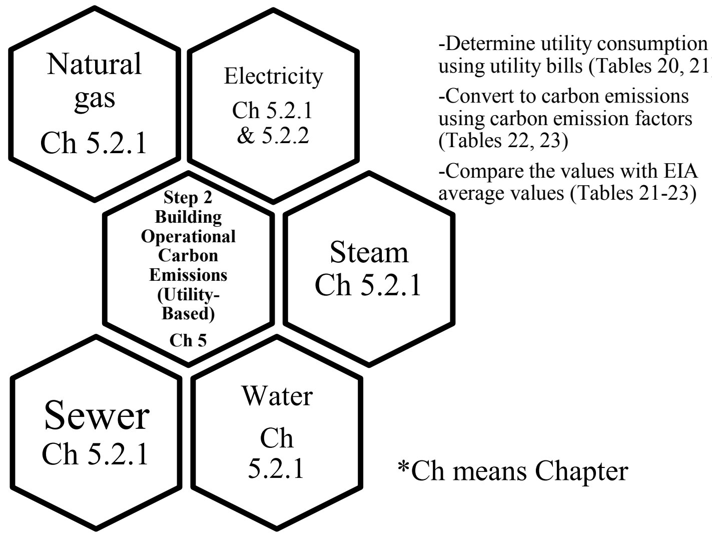


Figure 39 Step 2 of the Overall Framework

Utility data alone did not show how and where the utilities were consumed. Therefore, Step 3 of the comprehensive framework, as shown in Figure 40, was to use an equipment-based estimation method to determine building operational carbon emission and to investigate utility-consuming locations in a building. The equipment-based framework was to break down each appliance into smaller parts and estimate the power consumption and carbon emissions of each part of a component. The equipment-based method in this research only focused on building envelope (ETTV), HVAC, renewable energy and greenery, lighting, elevator and escalator, water consumption and irrigation, and means of transportation. The method proposed in the framework was run as a test at Eaton Hall. The result showed that energy consumption could be predicted even without local metering. Like the case of an elevator, when the type of gear and the power of the motor were determined, the power consumption could be calculated. Since the base of this part of the framework was to break down appliances into components, the framework could be extended to other electronic appliances, such as computer, television, and stove top, using the same methodology.

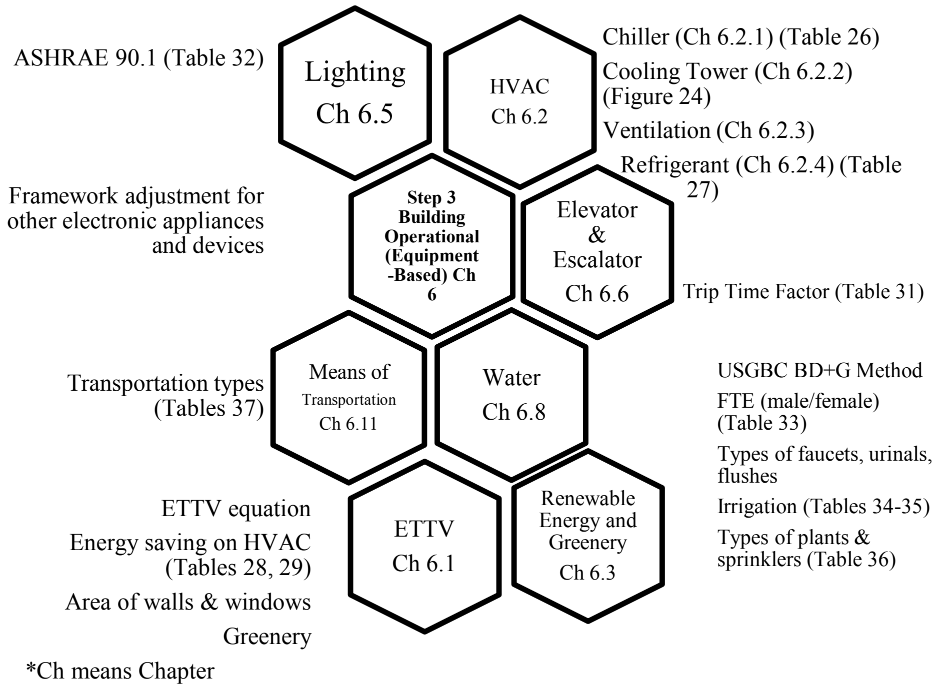


Figure 40 Step 3 of the Overall Framework

In the last step of the comprehensive framework, as shown in Figure 41, the end-of-life analysis was used to find the carbon emissions, and environmental impact of building demolition debris. Two methods were discovered in this research. The first method was the Bulk Weight Method that only considered the total weight of demolition debris and this method estimated the carbon emissions of the debris if it was shipped to landfill. The second method was to determine the carbon offset that could be created when the construction debris was used as biomass fuel for power generation. In the future, this part of the framework could be extended to use a CHNS analyzer to estimate the emissions when the building demolition debris was incinerated for power generation.

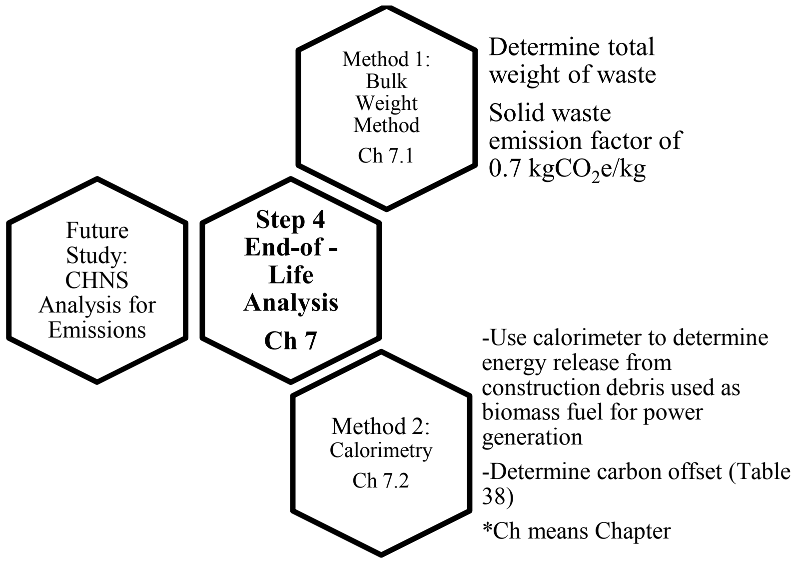


Figure 41 Step 4 of the Overall Framework

The research concluded that the proposed framework could be applied to reality. On some occasions, some crucial data may not be available, the framework includes backup alternative methods to estimate the carbon emissions from specific parts of a building. The summary of the building lifecycle carbon emissions framework is shown in Figure 42 and the total proposed framework is shown in Figure 43.

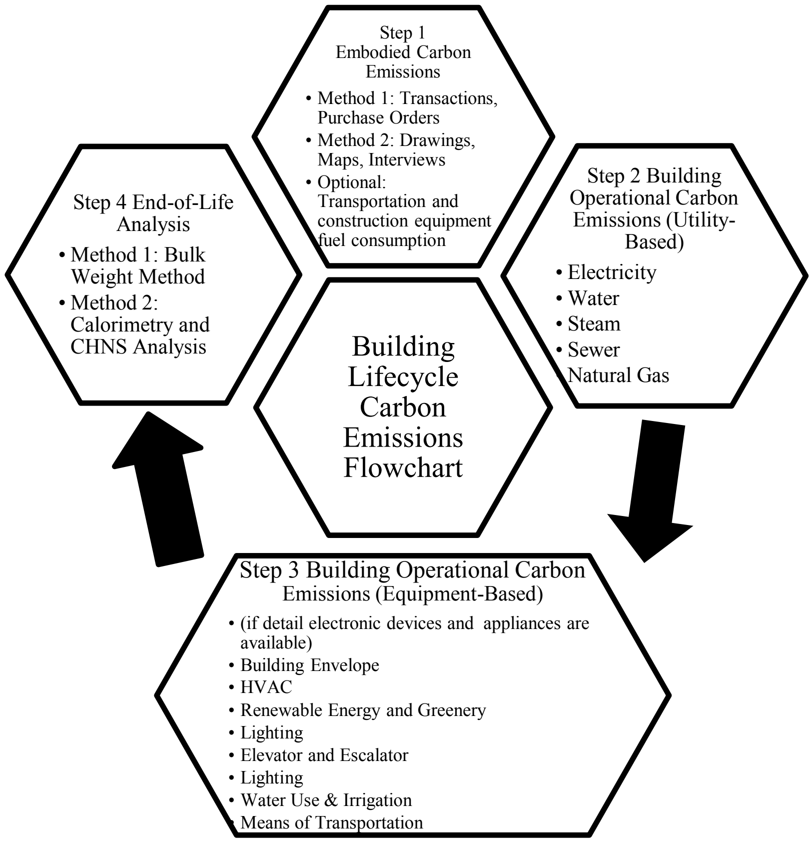


Figure 42 Summary of the Building Lifecycle Carbon Emissions Framework

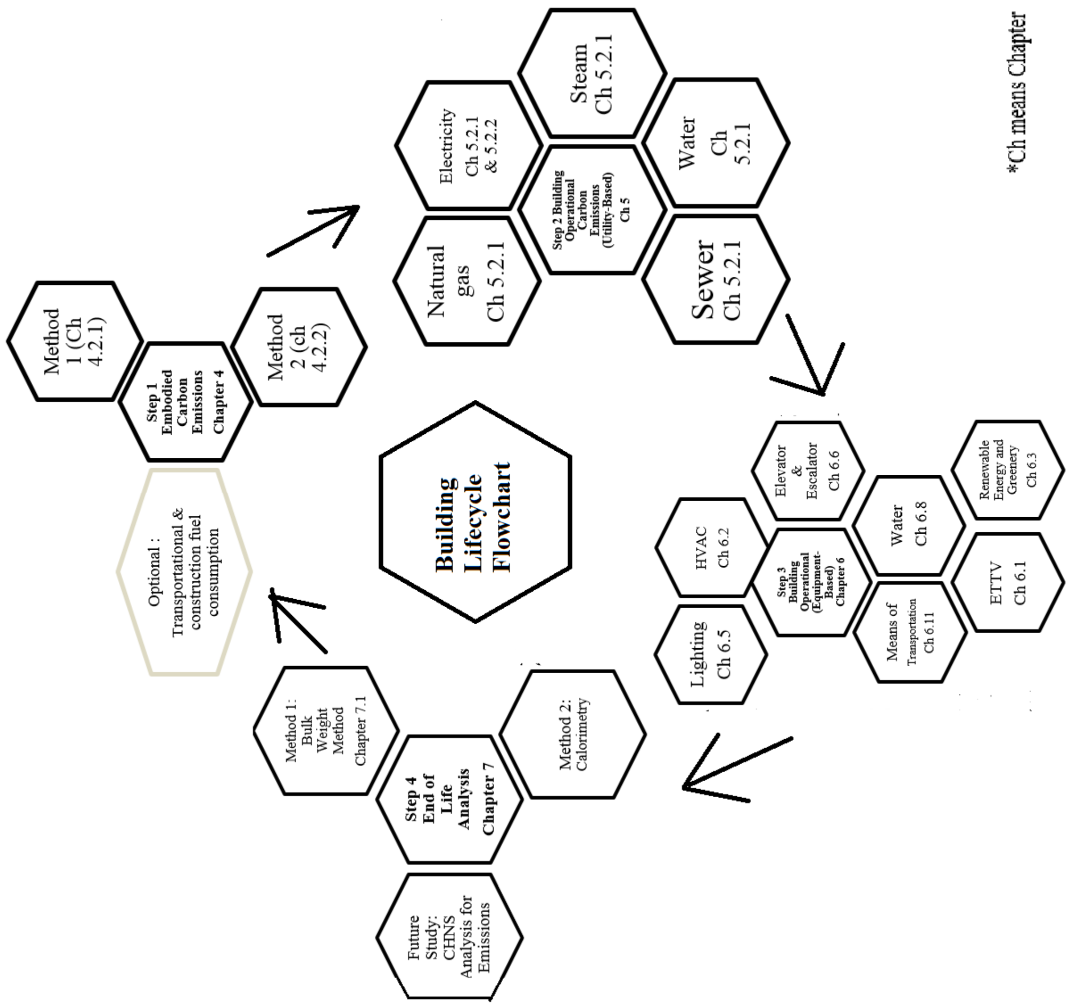


Figure 43 the Complete Proposed Framework of the Research

8.1 Model Testing

This research did not have data from one single building throughout its whole building lifecycle. However, M2SEC and Eaton Hall were both located at the University of Kansas and the construction of the building and energy consumption pattern were similar and they were both occupied by the School of Engineering. In this test model, data from Eaton Hall and M2SEC were used to run the model assuming there was a building similar to Eaton Hall and M2SEC called Building X with similar features and square footage of Eaton Hall.

Chapter 4.2.1 determined that the embodied carbon emissions was 2677050 $kgCO_2e$. Suppose Building X has similar square footage as Eaton Hall, the embodied carbon emissions would be:

Embodied carbon emissions = 2677050 x (7872/4366) = 4826783 $kgCO_2e$

Chapter 5.1 showed the detail calculation of the utility-based building operational carbon emissions for Eaton Hall. If Building X had similar pattern of utility use, the carbon emissions would be 794789, 285764, 1984, 914969, 718188 $kgCO_2e$ per year for electricity, natural gas, water, sewer, steam respectively. The total utility carbon emissions would be 3790216 $kgCO_2e$ per year.

Assuming the electronic devices and appliances were known in Building X and they were similar to Eaton Hall, the carbon emissions calculation could be borrowed from Chapter 6.7.1. The carbon emissions from HVAC to cool the building envelope would range from 25.92 to 82.48 $kgCO_2e$ per operating hour depending on the orientation of the walls. The carbon emissions from the chiller would be 92.64 $kgCO_2e$ per hour and the refrigerant contributed 431.25 $kgCO_2e$ per kW assuming the refrigerant was R410A. The ventilation would contributed 29.61 $kgCO_2e$ per hour in the HVAC system of Building X. The lighting contributed 101.15 $kgCO_2e$ per hour. Since Building X, like Eaton Hall, had only an elevator. Assuming the elevator was made by Kone that was gearless with similar motor, the carbon emissions would be 1.24 $kgCO_2e$ per hour of building operation. The water consumption carbon emissions would be 1.45 $kgCO_2e$ per day based on the detail calculation was shown in Chapter 6.9.1

Assuming the same students and staff members are using Building X, there were 1464 people that were regular users of the building and 70% were driving to school. The rest of the people either took the bus or walked to school. Therefore, the carbon emissions from the occupants' personal vehicles was 1941.09 kgCO_2e per day and the carbon emissions from buses was 1635.60 kgCO_2e per day. The total would be 3576.69 kgCO_2e per day. The detailed calculations were shown in Chapter 6.11.1.

No bulk weight demolition data could be collected since Eaton Hall and M2SEC were still operating during this study. However, according to USEPA, the average demolition of a building was 845 kg per m^2 (USEPA, 2013b). Therefore, the demolition debris of Building X would weigh 6,651,840 kg. From the method proposed in Chapter 7.1, the carbon emissions from the demolition debris would be:

$$\text{Building X demolition debris carbon emissions} = (0.7\ \text{kgCO}_2\text{e per kg}) \times (6651840\ \text{kg})$$
$$= 4656288\ \text{kgCO}_2\text{e}$$

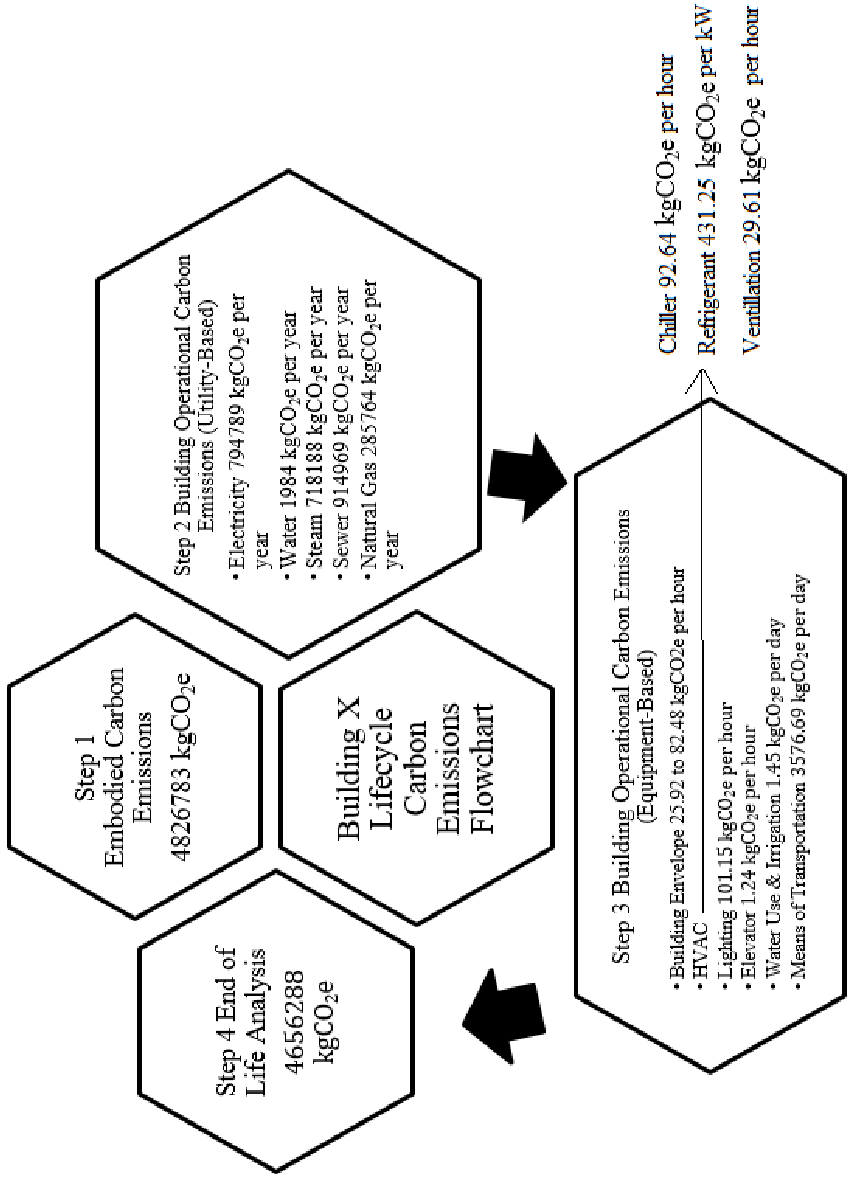


Figure 44 Framework for Building X

CHAPTER 9: COMPUTER BASED MODEL TESTING

Due to the huge number of buildings and the user-friendly interface of the result of the data analysis, the data was analyzed by website language PHP and MySQL database in the same manner for the Eaton Hall data. The data, such as building address, square footage, and power consumption, was stored on a MySQL server at the University of Kansas as shown in Figure 45. PHP was used to program the website and calculated the total power consumption of each district, city, zip code, and county and the results were compared to the EIA average values. An input webpage was composed for a user to find their desired data analysis for each studied year as shown in Figure 46. A sample result was shown in Figure 47. A detail result is enclosed in Appendix F.

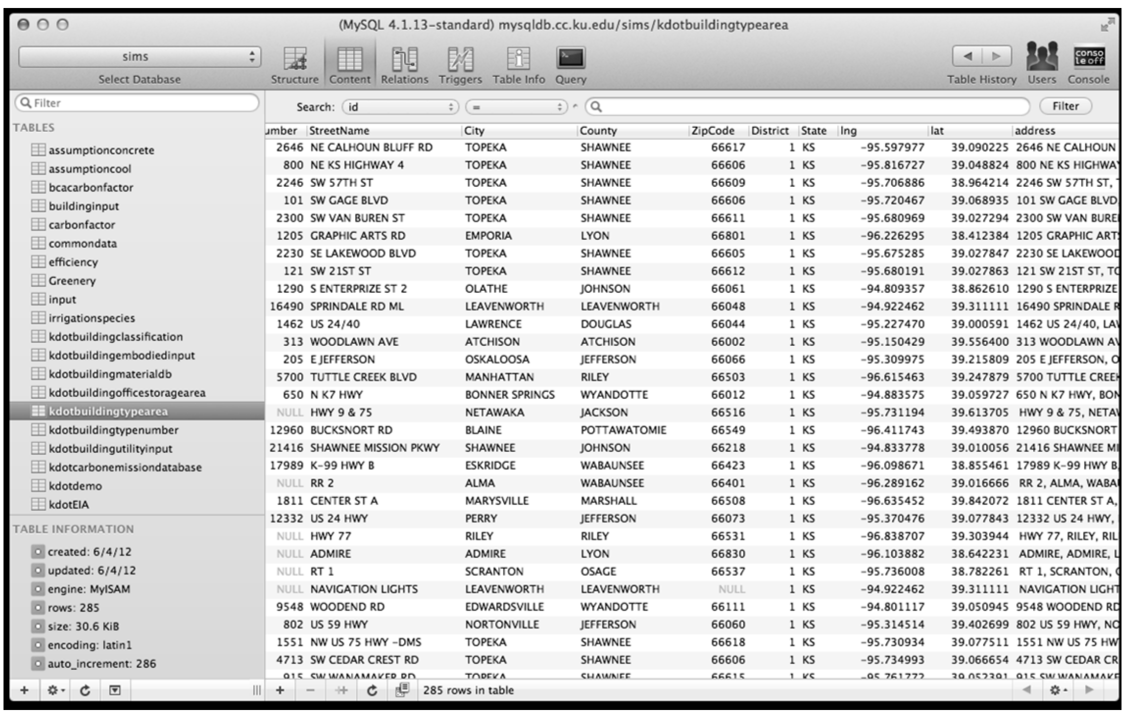


Figure 45 MySQL database for KDOT Utility Research

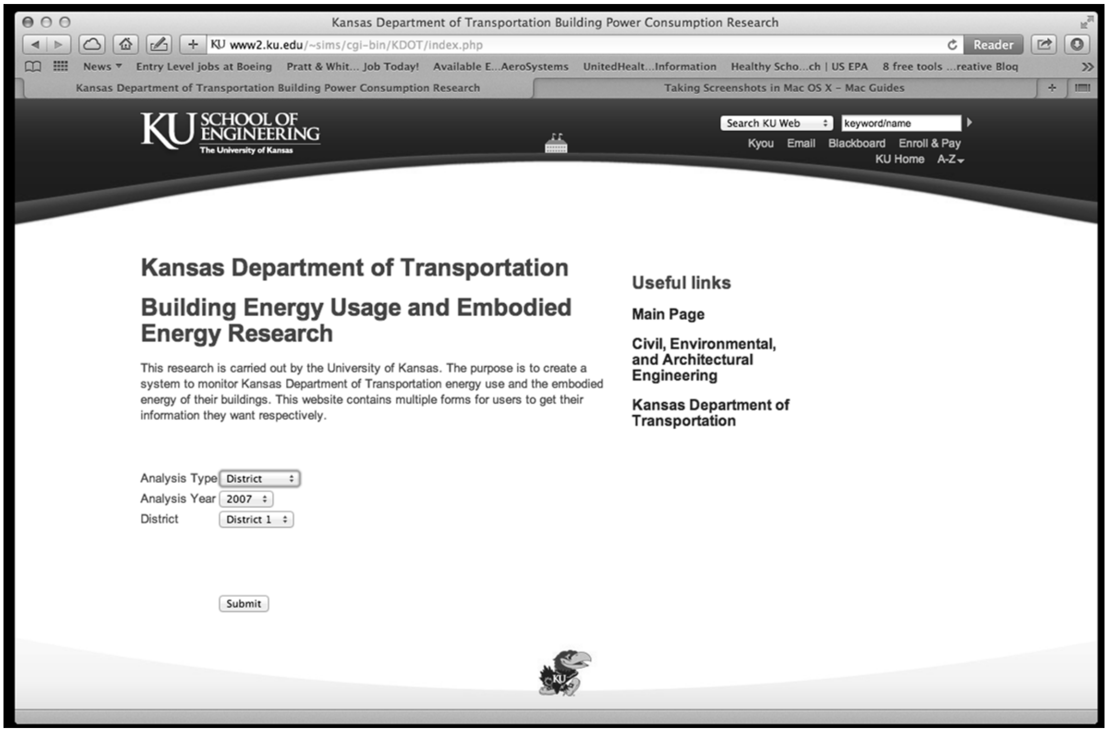


Figure 46 KDOT Utility Data Analysis Input Page

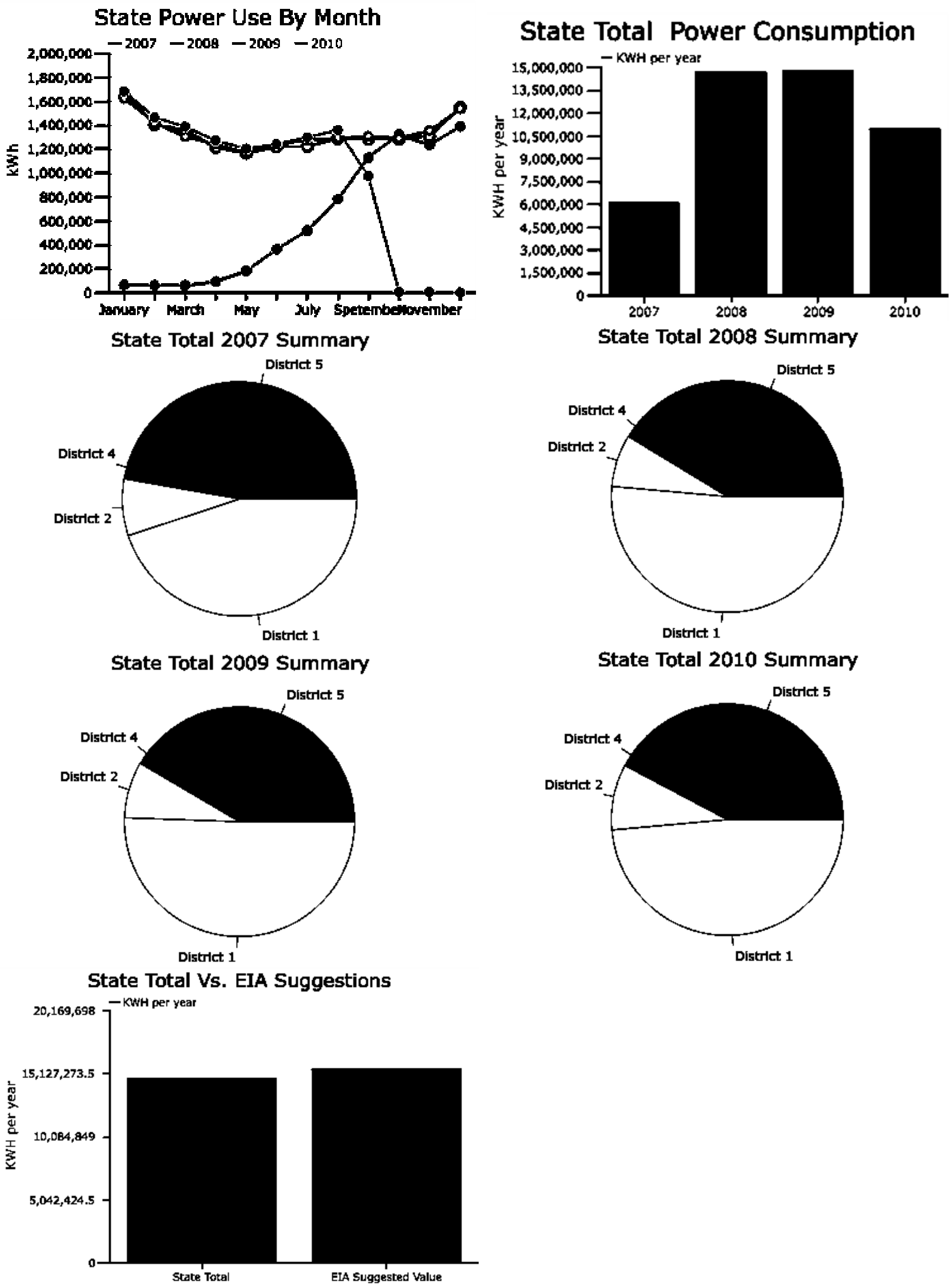


Figure 47 Sample Result from KDOT Utility Research

Using the MySQL server and PHP coding, the equipment based carbon emissions calculation of building operation was also calculated of a building as shown in Figure 48 and Figure 49. The two examples of carbon emissions calculations using MySQL and PHP coding indicated that the modeling methods discussed in Chapter 3 to 7 could be applied in real life applications. It could provide a real time calculation of carbon emissions during building operations and the users of buildings could see the carbon footprints of their activities inside their buildings.

To improve the computerized modeling methods, intensive Java coding should be used to improve the graphical output and more equipment should be considered in the calculation to increase the accuracy of the results.

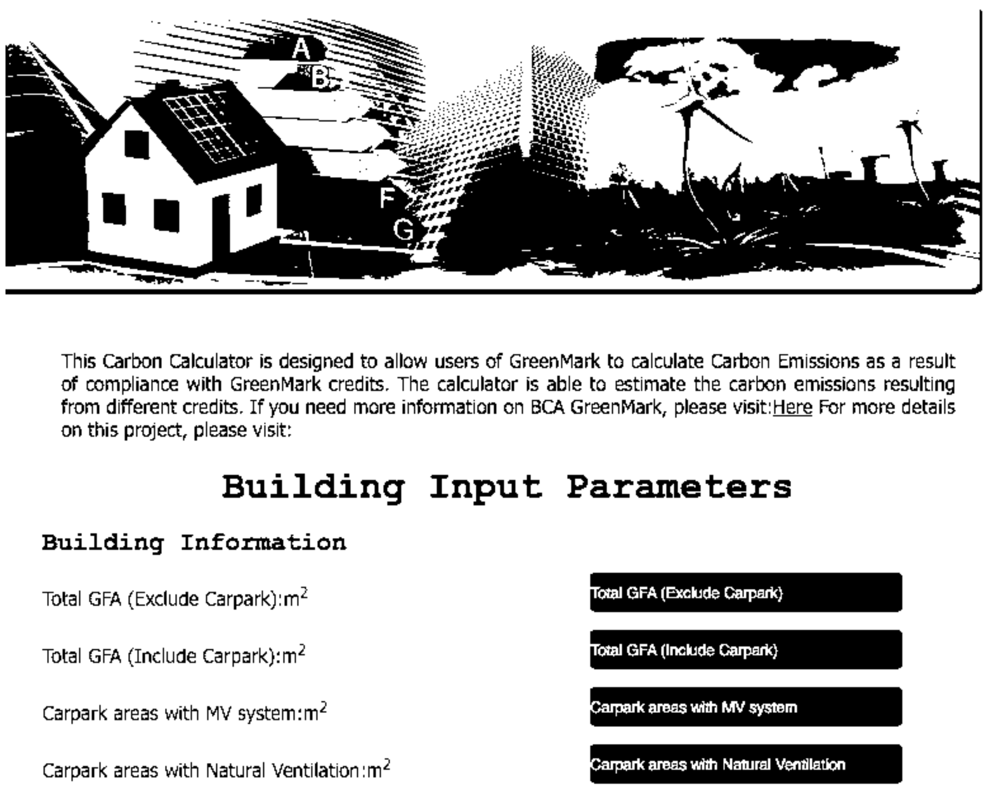


Figure 48 Screenshot of the Input Page of the Equipment Based Carbon Emissions Calculation of Building Operation

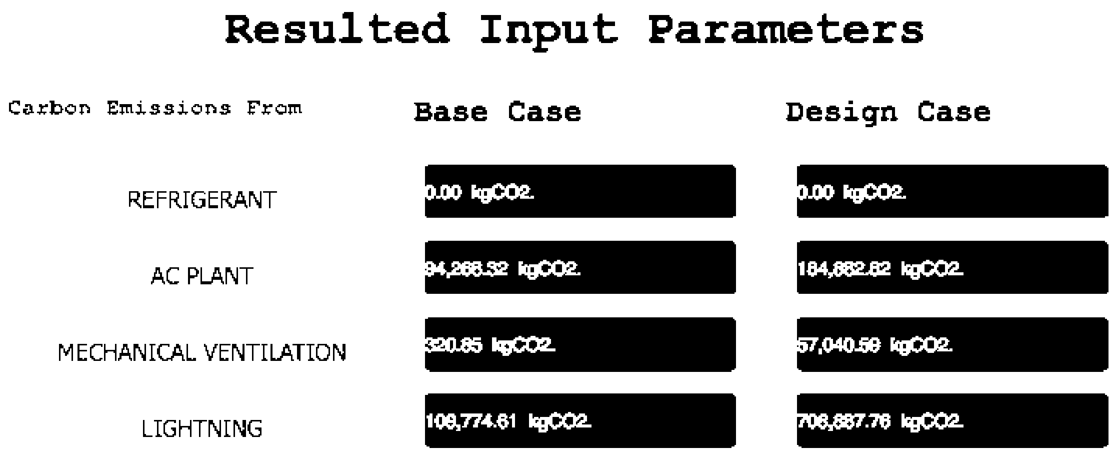


Figure 49 Screenshot of the Result Page of the Equipment Based Carbon Emissions Calculation of Building Operation

CHAPTER 10: CONCLUSIONS AND RECOMMENDATION

10.1 Summary

Green Building Certification is a good start for the construction industry to benchmark the environmental impact of their products. However, the current Green Building Certification around the world disregards the carbon footprint calculation for certified buildings. The positive significance of green building designs may not be reflected on the points and rating in the certification. It is hard to understand the environmental impact through points. In 2008, the New Building Institute did a study on energy performance on LEED certified new construction buildings. It showed that the calculation might not have been accurate due to the variability of lifecycle cost evaluation (Turner & Frankel, 2008). A similar study showed that LEED certified buildings are 29% less energy efficient (Gifford, 2008). The author of this report filed a $100 million lawsuit against USGBC and requested them to pay the victims for alleged fraud under the Sherman Anti-Trust Act. The lawsuit argued that the author and USGBC used different energy methods to determine the energy performance of buildings. It is difficult to have similar results using different methodologies, and it highlighted the imperfection of the current rating systems.

This research shows that carbon emissions, a well-known factor, can be deliberated on and related to the building systems in future development in this area using the modeling methods mentioned in this dissertation. The proposed models should be used as guidelines to calculate the carbon emissions, including the embodied carbon emissions, for buildings throughout the building lifecycle. The proposed modeling methods should be extended to the areas that are not covered in this dissertation, such as electronic devices and appliances, on site renewable energy sources (wind, solar, and geothermal), compressor, evaporator, and condenser in the HVAC system, and outdoor lighting. A summary of the models throughout a building lifecycle is shown in Figure 50.

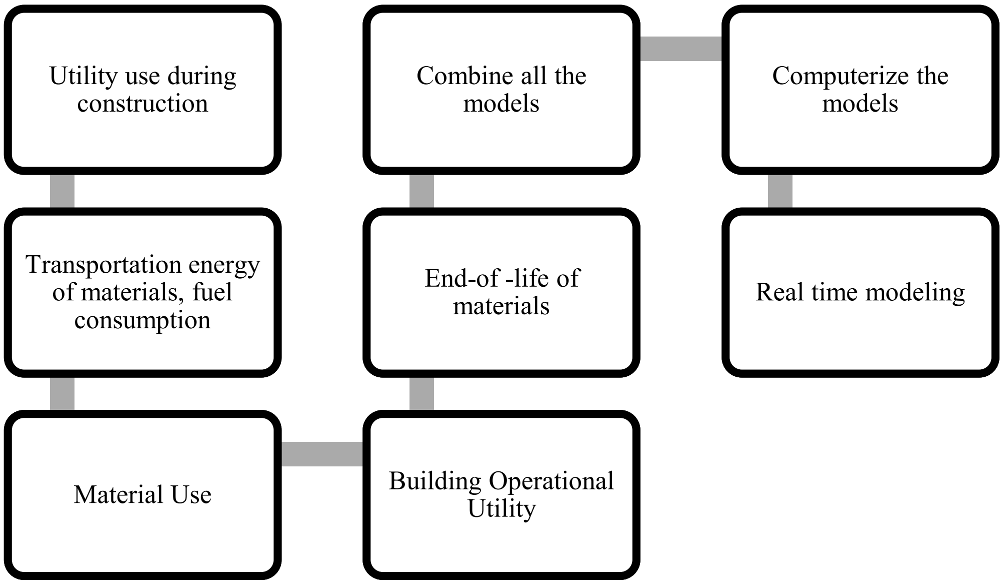


Figure 50 Summarized Models and Future Uses in Buildings

10.2 Recommendation

For future research, data and models need be adjusted to fit the needs in specific countries due to geographic, political, technological and lifestyle differences and a localized city-based methodology should be established. In addition, the average value from the United States Energy Information Administration should be adjusted to reflect the fact that many commercial buildings do not switch off the light during non-office hours so that the public has a closer-to-reality benchmark to compare to.

The proposed energy and carbon emission accounting models can combine into building information modeling (BIM). The calculations of each individual model can be computerized using computer script and it can be incorporated with building information modeling software such as ArchiCAD, Autodesk Revit, and Autodesk Navisworks. These programs have already been used to organize the drawings and the materials of a building. If proposed models are incorporated into these programs, they can accurately calculate the environmental impact, including toxin release, carbon emissions, and energy consumption, of a building in real-time. The construction industry can easily monitor the environmental impact of their activities and lower their footprint. Also, a web-based system should be made to show users their environmental impact due to their activities in a building.

The Kansas Department of Transportation (KDOT) research was to determine the energy usage and carbon emissions (operational energy and emissions) of buildings. In the U.S., building users always leave their lights, air-conditioning, and computers on even after office hours and the data shows this practice. The regional offices consume the most energy and contribute the most carbon emissions. From the KDOT research, there is a challenge to monitor the operational energy and carbon emissions of government agencies. KDOT is a customer of hundreds of power suppliers, and it is difficult to get their power consumption through them. Also, a power meter may serve a campus of different buildings and it is difficult to determine power consumption of each building considering the large variety of uses of these buildings. The other challenge is that the current drawings of these building do not reflect the reality. A lot of old buildings have had a few renovations and the drawings are not updated. It is not easy to know the power consuming appliances and machines inside each building. This part of the research determined that book keeping, including power bills and updated drawings is vital for energy consumption and carbon emissions monitoring. This research suggests that KDOT should have a bookkeeping system like the Eaton Hall, and the Measurement, Materials and Sustainable Environment Center (M2SEC) at the University of Kansas for existing and future buildings.

To improve the end-of-life analysis in this research, more common construction materials should be analyzed in order to find the energy release of these materials as biofuel. However, some construction materials contain hazardous elements and the benefit of their energy release may be offset by their environmental impact during incineration. To determine the emissions during incineration, carbon, hydrogen, nitrogen, sulfur (CHNS) elemental analysis should be carried out to construction materials as well. This analysis can find out the amount of carbon, hydrogen, nitrogen, and sulfur released during oxidation through chromatography. The laboratory testing will establish frameworks of environmental impact study and testing for other materials within or outside the construction industry. In the next phase of this research, the six most popular construction materials, such as concrete, wood, gypsum, carpet, aluminum, and steel, should be analyzed to determine their carbon emission factor by lifecycle analysis. The carbon emission factors of them should be put on a database that is location dependent according to transportation and geographical differences.

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Appendix A. M2SEC Embodied Carbon Emissions Calculation

Description	Quantity	Unit	Weight (kg)	Carbon Factor ($kgCO_2e/kg$)	kg CO_2e
Drilled Piers, 40' Long	1,301	CY	2287453.97	0.107	244757.57
Haul Pier Spoils	1,301	CY	2287453.97	0.107	244757.57
Grade Beam & Ftg Excavate	742	CY	1304789.32	0.107	139612.46
Crushed Rock @ SOG, 18" Thick	1,025	CY	959915.15	0.01	9599.15
Granular Backfill	2,657	CY	2487501.37	0.01	24875.01
Perimeter Foundation Drains	839	LF	258.89	3.23	836.22
				Total	664437.99

Table 39 Summary of Excavation Carbon Emissions Calculation for M2SEC

Description	Quantity	Unit	Weight (kg)	Carbon Factor ($kgCO_2e/kg$)	$kgCO_2e$
Drilled Pier Concrete	1,548	CY	2722847.12	0.107	291344.64
Pier Caps	216	CY	379830.85	0.107	40641.90
Tie Beams	160	CY	281356.19	0.107	30105.11
Grade Beams; 2'x3', Form 100%	366	CY	643602.28	0.107	68865.44
Elevator Pit Walls	200	SF	8683.81	0.107	929.17
Foundation Walls & Pilasters	9,693	SF	578685.14	0.107	61919.31
Fdn Wall 24" premium	1,092	SF	1172.20	0.107	125.43
Slab on Grade - 6"	12,748	SF	293.07	0.107	31.36
Slab on Grade - 4"	5,705	SF	195.39	0.107	20.91
7" Slab Premium	2,509	SF	341.93	0.107	36.59
Floor Trench @ Lab, 18"x18"	87	LF	38246.86	0.107	4092.41
Isolation Slab Premium	1,381	SF	23490.40	0.107	2513.47
Concrete Columns	292	CY	513898.40	0.107	54987.13

HVAC Penthouse Roof Framing	29	TN	26308.37	1.46	38410.21
Anechoic Chamber Steel	6	TN	5443.11	1.46	7946.94
Lightwell Framing	1	TN	1349.89	1.46	1970.84
Greenscreen Framing	3	TN	2905.26	1.46	4241.68
1.5" Type B Steel Roof Deck	5,991	SF	7337.54	1.46	10712.80
2 EA Exit Stairs, 4.00' Wide	46	VF	5858.24	1.46	8553.03
1 EA Bsmt Stairs, 4.00' Wide	16	VF	2003.20	1.46	2924.67
Roof Egress Stair	16	VF	2003.20	1.46	2924.67
Stair Railings, Mesh Panel Style	125	LF	227.06	1.46	331.50
Ext Stair Railings, Mesh Panel Style	84	LF	153.18	1.46	223.65
Wall Railings	195	LF	177.03	1.46	258.46
Ornamental Metal Railing	59	LF	107.05	1.46	156.29
Suspended Masonry Supports	252	LF	2286.48	1.54	3521.19
Masonry Lintels or Shelf Angles	250	LF	2270.41	1.54	3496.43
Curtainwall Support Steel, 5#/SF	182	SF	413.49	1.46	603.70
Other Miscellaneous Steel	4	TN	3188.30	1.46	4654.92
Housekeeping Pads, Etc	1,367	SF	1201742.62	0.107	128586.46
Equipment Foundations	713	SF	626896.76	0.107	67077.95
Pan Stair Fill	785	SF	230009.15	0.107	24610.98
Penthouse & Misc Curbs	357	LF	6072.46	0.107	649.75
Strongwall Piers EX	10	CY	18414.70	0.107	1970.37
Strongwall Piers Haul Spoils	10	CY	18414.70	0.107	1970.37
Strongwall Piers	13	SF	1710.00	0.107	182.97
Strongwall	501	SF	68106.84	0.107	7287.43
Strongwall Base	54	CY	94957.71	0.107	10160.48
Dyno Base	9	CY	15826.29	0.107	1693.41

Strongwall Lid	485	SF	65997.64	0.107	7061.75
Strongwall Column	7	CY	13134.30	0.107	1405.37
				Total	899201.16

Table 40 Summary of Structural Carbon Emissions Calculation for M2SEC

Description	Quantity	Unit	Weight (kg)	Carbon Factor ($kgCO_2e/kg$)	$kgCO_2e$
Building Skin					
Brick Veneer	7,784	SF	150622.2271	0.24	36149.33
Precast Panels Veneer	5,381	SF	93563.17783	0.107	10011.26
Metal Wall Panels Accent	1,407	SF	764.5151413	0.107	81.80
Modular Brick and 8" CMU	2,728	SF	47049.39037	0.073	3434.61
Metal Wall Panels at Penthouse	4,757	SF	2584.789287	0.107	276.57
HVAC Louvers	283	SF	153.7724129	0.107	16.45
Sheet Metal Soffits,Flat	479	SF	260.2720346	0.107	27.85
Interior Masonry					
8" CMU Partitions - Reverb	3,532	SF	60915.85292	0.073	4446.86
8" CMU Partitions	11,482	SF	198028.2625	0.073	14456.06
Ground Face CMU Premium	4,191	SF	72281.5231	0.073	5276.55
				Total	74177.35

Table 41 Summary of Masonry Carbon Emissions Calculation for M2SEC

Description	Quantity	Unit	Weight (kg)	Carbon Factor ($kgCO_2e/kg$)	$kgCO_2e$
Rough Carpentry					
Roof Blocking	4,142	BF	2739.89	1.07	2931.6823
Plywood at Parapet	2,714	SF	2462.326193	1.07	2634.689026
Finish Carpentry and Millwork					
Corian (Top Only) Vanities	24	LF	87.8154112	2.54	223.0511444
6" Wood Base, One Piece	134	LF	334.297304	1.07	357.6981153
Corian Window Sills, 8" Avg Width	279	LF	371.2196928	2.54	942.8980197
Closet Shelving	90	LF	224.52804	1.07	240.2450028
Plastic Laminate Base Cabinets	41	LF	130.180904	0.63	82.01396952
Plastic Laminate Countertops	124	LF	393.717856	0.63	248.0422493
Plastic Laminate Upper Cabinets	43	LF	136.531192	0.63	86.01465096
MAP Wall Panel System	244	SF	664.058688	9.16	6082.777582
SS Wall Panels @ Emerg Eyewash	123	SF	223.167264	9.16	2044.212138
Cement Board Panels	736	SF	1001.531136	1.09	1091.668938
				Total	16964.99314

Table 42 Summary of Carpentry Carbon Emissions Calculation for M2SEC

Description	Quantity	Unit	Weight (kg)	Carbon Factor ($kgCO_2e/kg$)	$kgCO_2e$

Membrane Roofing					
TPO Fully Adhered Membrane	20,760	SF	112998.84	0.0952	10757.49
Densdeck Insulation Cover Board	17,769	SF	13701.79	0.13	1781.23
Roof Crickets, Interior	888	SF	49437.27	2.03	100357.65
Tapered Insulation Prem	15,992	SF	2350.26	2.85	6698.24
Roof Walkway Pads	600	SF	353.80	2.85	1008.34
Parapet Flashing	2,714	SF	75516.47	1.9	143481.29
Sheet Metal and Louvers					
Sheet Metal Flashings	2,071	LF	766.79	9.08	6962.43
Overflow Roof Scuppers	3	EA	43.55	9.08	395.39
Gutters & Downspouts	60	LF	10.27	9.08	93.25
Painted Standing Seam Roof	200	SF	136.08	1.38	187.79
Nail Base & Insulation, R20	200	SF	181.44	1.86	337.47
Sheet Metal Sunscreen, Hor	56	LF	43.28	9.08	392.97
Sheet Metal Sunscreen,Vert	168	LF	129.84	9.08	1178.92
Caulking and Waterproofing					
Spray Foam Insulation & Flashing	22,536	SF	5111.07	0.98	5008.85

Building Skin & Window Caulking	7,169	LF	48.26	0.98	47.29
Caulk CMU Control Joints	621	LF	4.18	0.98	4.09
Caulk HM Frames at CMU	451	LF	3.04	0.98	2.97
Dampproof Elevator Pits	200	SF	2.52	3.43	8.64
Waterproof/Drain Mat at Fdn Walls	9,693	SF	122.12	3.43	418.89
				Total	279123.21

Table 43 Summary of Roofing & Flashing Carbon Emissions Calculation for M2SEC

Description	Quantity	Unit	Weight (kg)	Carbon Factor ($kgCO_2e/kg$)	kg CO_2e
Doors, Frames and Hardware					
Hollow Metal Frames	92	EA	1710.95	1.46	2497.99
HM SL/BL Frames, 36 SF/EA	32	EA	602.55	1.46	879.73
Hollow Metal Doors	32	EA	1168.45	1.46	1705.94
Solid Core Wood Doors, Oak, 7'	81	EA	2250.38	0.87	1957.83
42" Lab Door Premium	38	EA	1932.33	1.46	2821.20
Stair Exit Doors 3.00' Wide	5	EA	219.08	1.46	319.86
Finish Hardware, Cylinder Locks	113	EA	307.54	9.08	2792.42
Unload & Distribute Dr, Frame, Hdwe	108	EA	9.33	12.4	115.70
Sound Door @ Test Cell	1	EA	124.90	1.35167	168.82
Reverb & Dyno Door Premium	2	EA	49.62	5.7	282.83
Double 5' Leaf Door	1	EA	278.22	1.46	406.20
Glass and Glazing Systems					

Curtainwall	2,279	SF	107508.56	0.91	97832.79
Window Wall and Storefront	221	SF	10425.36	0.91	9487.08
Ribbon Windows	951	SF	22431.03	0.91	20412.24
Punch Windows	373	SF	8797.87	0.91	8006.06
Entrance Doors	5	EA	181.44	0.91	165.11
HC Door Operators	2	EA	27.22	1.46	39.73
Interior Storefront	416	SF	9812.10	0.91	8929.01
Light Monitors	64	SF	116.12	1.38	160.24
Mirrors	96	SF	827.35	0.91	752.89
Glaze Sidelites & Borrow Lites	1,166	SF	2116.28	0.91	1925.81
Door Lites and Misc Glazing	28	EA	168.00	0.91	152.88
Fire Lite Glazing	365	SF	662.24	0.91	602.64
				Total	162415.03

Table 44 Summary of Doors & Glazing Carbon Emissions Calculation for M2SEC

Description	Quantity	Unit	Weight (kg)	Carbon Factor ($kgCO_2e/kg$)	kg CO_2e
Plaster and Drywall Systems					
Structural Stud Wall Framing	14,790	SF	13417.25	1.54	20662.57
Exterior Wall Furring	4,650	SF	3163.95	1.54	4872.48
Struct Stud Walls at Penthouse	4,345	SF	3941.71	1.54	6070.24
Perimeter Drywall	14,780	SF	22793.91	0.13	2963.21
Non-Organic Wall Board Premium	2,847	SF	4390.68	0.13	570.79
Quad-Layer Drywall Prem @ Reverb Rm.	596	SF	1054.33	0.13	137.06
Shaft Wall, Incl Fire Caulk	340	LF	3084.43	1.54	4750.02
One Hour Walls, Incl Fire Caulk	499	LF	4526.85	1.54	6971.35
Abuse Resistant Drywall Premium	12,669	SF	34478.59	0.13	4482.22
Drywall @ Columns	1,000	SF	1542.21	0.13	200.49
Suspended Drywall Ceilings	5,378	SF	304.93	0.13	39.64
Drywall Bulkheads	65	LF	400.98	0.13	52.13
Aluminum Reveal Premium	1,022	LF	9908.83	9.08	89972.18

Fireproofing @ Penthouse	7,615	SF	8635.26	1.54	13298.30
Metal Panel Cover - Painted	20	SF	193.91	9.08	1760.71
Safing Insulation	1,306	LF	2369.74	1.12	2654.11
Ceramic Tile					
Ceramic Tile	807	SF	1720.43	0.78	1341.93
Ceramic Tile Walls	2,438	SF	5197.53	0.78	4054.07
Tile Base	305	SF	650.22	0.78	507.17
Misc Stone & Tile	38,818	SF	82756.37	0.78	64549.97
Acoustical Treatment					
2x2 Acoustic Ceilings	4,672	SF	2119.18	0.13	275.49
2x2 Acoustic Ceilings (Washable)	3,478	SF	1577.59	0.13	205.09
Acoustic Cloud Ceilings	550	SF	249.48	0.13	32.43
Metal Ceiling System	622	SF	34610.82	1.66	57453.95
Perforated MWP & Insulation	234	SF	212.55	1.46	310.33
Painting and Wall Coverings					
Stair & Service Room Walls	4,920	SF	457.05	0.87	397.64
Paint Stairs and Handrails	115	LF	7.13	0.87	6.20
Finish Doors & Frames	92	EA	5244.00	0.87	4562.28
CMU Partitions (Incl Blk Filler)	30,028	SF	2789.60	0.87	2426.95
Paint Drywall Walls	47,820	SF	4442.46	0.87	3864.94
Epoxy Paint Walls	16,614	SF	25.40	2.91	73.92
Whiteboard Paint	365	SF	1.78	3.76	6.70
Polymix Wall Coatings	5,981	SF	555.63	0.87	483.40
Drywall Ceilings	5,443	SF	505.65	0.87	439.92
				Total	300449.88

Table 45 Summary of Plaster & Ceilings Carbon Emissions Calculation for M2SEC

Description	Quantity	Unit	Weight (kg)	Carbon Factor ($kgCO_2e/kg$)	kg CO_2e
Flooring					
Clear Floor Sealer, One Coat	24,067	SF	156.47	3.76	588.34
Resilient Base	4,426	LF	652.51	3.19	2081.51
Metal Base	102	LF	9.46	6.15	58.18

Sealed & Diamond Polished Concrete	8,118	SF	44059.49	0.107	4714.37
Resinous Flooring	7,596	SF	10336.45	0.12	1240.37
Resinous Cove Base	743	LF	351.06	1.93	677.55
Carpet Tiles	383	SY	320.24	7.75	2481.84
				Total	11842.15

Table 46 Summary of Flooring Carbon Emissions Calculation for M2SEC

Description	Quantity	Unit	Weight (kg)	Carbon Factor ($kgCO_2e/kg$)	kg CO_2e
Specialties					
Marker & Bulletin Boards	231	SF	154.03	0.86	132.46
Toilet Partitions	10	EA	1061.41	1.93	2048.51
Dust Strip Curtain @ Rm 1544	25	LF	8.50	3.16	26.88
Unistrut Tank Supports	102	LF	161.42	1.46	235.68
Unistrut TV Supports	9	EA	40.82	1.46	59.60
Corner Guards	44	EA	139.02	2.85	396.21
Access Flooring	309	SF	981.12	1.46	1432.43
Access Flooring A. Chamber	119	SF	377.84	1.46	551.65
Door Signs	92	EA	92.00	8.1	745.20
Fire Extinguishers and Cabinets	8	EA	62.29	1.46	90.94
Toilet Accessories Public Toilets	4	EA	328.00	1.61	528.08
Equipment and Furnishings					
Projection Screens	2	EA	30.84	3.1	95.62
Movable Wall (Glass & Wood)	143	LF	3632.36	1.09	3959.28
Sliding Barn Doors	9	EA	498.04	1.46	727.14
Edge of Dock Leveler	1	EA	503.00	5.896	2965.69
Material Hoist, 3 ton	1	EA	900.00	6.15	5535.00
Dyno Bedplate, 4'x15'	1	EA	226.80	1.46	331.12
Lab Cswrk, Mtl, resin top, Base & Wall	560	LF	8890.40	2.029	18038.63
Lab Cswrk, Mobile, Mtl, resin top, Base & Wall	633	LF	10049.33	2.029	20390.09
Lab Cswrk, Shelving	239	LF	16.06	1.46	23.45
Lab Cswrk, Tall Storage Cabinets	62	LF	2531.04	1.295	3277.70

Fume Hoods Low flow, hi-eff.,72 in.	13	EA	2948.35	1.46	4304.59
Bio Safety Cabinet	4	EA	1616.60	1.46	2360.24
Entrance Mats	152	SF	9.09	3.19	29.01
Black out Shades	122	SF	165.99	3.19	529.50
Meccho Shades	963	SF	1310.22	3.19	4179.60
				Total	72994.30

Table 47 Summary of Equipment Carbon Emissions Calculation for M2SEC

Description	Quantity	Unit	Weight (kg)	Carbon Factor ($kgCO_2e/kg$)	kg CO_2e
Plumbing					
Fixtures	56	EA	762.04	2.71	2065.12
EWC	4	EA	5.44	6.15	33.48
Emergency Eyewashes	1	EA	1.36	6.15	8.37
Drains/Carriers	40	EA	27.22	6.15	167.38
Instantaneous Water Heaters - Steam to Water	2	EA	4.49	2.1835	9.81
Circ Pump DHW Return	1	EA	3.24	2.03	6.58
Clear Water Duplex Sump Pumps	1	EA	17.35	2.03	35.22
Duplex Sewage Ejector Pumps	1	EA	247.21	1.46	360.92
Air Compressors	3	EA	157.85	2.03	320.44
Air Receiver	1	EA	394.63	1.46	576.15
Air Dryer	2	EA	14.51	1.46	21.19
Roof Drains (see A-105)	14	EA	107.95	2.03	219.15
Roof Drain Piping	14	EA	203.21	2.03	412.52
Water Softener Skid	2	EA	191.42	1.35	258.41
Waste Effluent Sample Port	1	LS	0.45	3.23	1.47
Natural Gas Meter Station	1	EA	2.70	1.46	3.94
PVF - RO 316L SS Humidif. Piping	200	LF	202.12	3.23	652.85
PVF - RO PPE Circ. Loop w/ U-bend end Use Points	600	LF	606.36	3.23	1958.55
Domestic Water Pre-Heat Exchanger	1	EA	254.01	1.46	370.86
Domestic Water Backflow Preventer	4	EA	9.07	2.64	23.95
BioDiesel Storage Tank 40 Gal	1	EA	11.79	1.93	22.76
				Total	7529.10

Table 48 Summary of Fire Protection & Plumbing Carbon Emissions Calculation for M2SEC

Description	Quantity	Unit		Weight (kg)	Carbon Factor ($kgCO_2e$/kg)	$kgCO_2e$
HVAC Systems						
Chiller - Modular (Climacool UCW)	157	TON		3224.16	1.54	4965.21
Chiller - Air Cooled (York YMC)	289	TON		7348.19	1.54	11316.21
Chiller Air Cooled Condensing Unit	8	TON		611.44	2.71	1657.01
Chilled Water - Pumps	80	HP	INC. ABOVE			
Chilled Water - VFD	80	HP	INC. ABOVE			
Chilled Glycol - Pumps	40	HP	INC. ABOVE			
Chilled Glycol - VFD	40	HP	INC. ABOVE			
Chilled Beam (Tertiary) - Pumps	15	HP		136.08	2.03	276.24
Chilled Beam (Tertiary) - VFD	15	HP		136.08	2.03	276.24
Misc In-Line Pumps (9,10,11,12, & 15)	7	HP		82.10	2.03	166.66
Server - Pump (13, 14 & 15)	12	HP		82.10	2.03	166.66
Server - VFD	10	HP		82.10	2.03	166.66
AHU-1, -2 Labs	40,000	CFM		10777.35	1.54	16597.11
AHU-1, -2 - VFD	80	HP	INC. ABOVE			
AHU-3 Composites Lab	2,160	CFM		768.38	1.54	1183.31
AHU-4 Dyno Comb.	1,200	CFM		603.28	1.54	929.05
AHU-4 - VFD	15	HP	INC. ABOVE			
AHU-5 Dyno Vent	10,000	CFM		1799.85	1.54	2771.77
HRU-1, -2	36,000	CFM	INC. ABOVE			
Humidifiers (AHU & Atomizing)	500	LB		99.79	1.54	153.68
Liebert Unit @ Server Room	10	TON		907.18	1.54	1397.06
FCU	14	EA		1079.55	2.1835	2357.20
CUH	7	EA		555.65	1.54	855.70

Fin Tube Radiation Panels	155	LF		246.07	2.1835	537.30
VAV Terminal Units - Hydronic	62	EA		2390.43	2.1835	5219.50
Chilled Beams	33	EA		1471.80	1.54	2266.57
Phoenix Air Valves	60	EA		244.94	1.54	377.21
Sound Attenuators (Duct Stream)	28	EA		139.71	1.54	215.15
6" Steam Meter	1	EA		42.73	1.54	65.80
HE-1, -2 (Plate & Frame)	3	EA	INC IN AHU			
HE-3, -4 (Shell & Tube (Test Cell))	2	EA	INC IN AHU			
HHW - Converters (Steam to Water)	3	EA		289.85	2.03	588.39
HHW - Pumps	40	HP		210.01	2.03	426.33
HHW - VFD	40	HP		210.01	2.03	426.33
Steam Condensate Pump	1	EA		69.40	2.03	140.88
Air Separators>10"	5	EA		226.80	1.54	349.27
Expansion Tanks	4	EA		181.44	1.46	264.90
Air Intake Louver/Damper @ Penthouse	1	EA		16.33	1.54	25.15
Intake Hood	1	EA		90.72	1.54	139.71
Relief Hood	2	EA		181.44	1.54	279.41
Chemical Treat Pots / PVF Allow.	3	EA		124.50	2.03	252.74
Water Filters	3	EA		714.41	1.46	1043.03
Hydraulic Pumps (By Owner)	6	EA		62.60	2.03	127.07
					Total	57980.50

Table 49 Summary of HVAC Carbon Emissions Calculation for M2SEC

Description	Quantity	Unit	Weight (kg)	Carbon Factor ($kgCO_2e/kg$)	$kgCO_2e$
Electrical					
2000A Feeder	75	LF	0.05	2.71	0.13
480/277V 2000A Swbd W/ Metering & (10) C/B	1	EA	2267.96	1.54	3492.66
120/208V 225A 42Ckt. Pwr. Panel	20	EA	1270.06	2.125	2698.87
120/208V 400A 42Ckt. Pwr. Panel	1	EA	94.35	2.125	200.49
480/277V 100A 42Ckt. Ltg.	3	EA	183.70	2.125	390.37

Panel					
120/208V 800A 42Ckt. Pwr. Panel	2	EA	204.12	2.125	433.75
480/277V 225A 42Ckt. Ltg. Panel	4	EA	254.01	2.125	539.77
480/277V 400A 42Ckt. Dist. Panel	1	EA	94.35	2.125	200.49
480/277V 600A 42Ckt. Dist. Panel	3	EA	283.04	2.125	601.46
480/277V 800A 42Ckt. Ltg. Panel	2	EA	204.12	2.125	433.75
60A NEMA1 F Disc. Switch	5	EA	129.27	2.125	274.71
112.5KVA Dry Type Transformer	1	EA	333.39	2.1835	727.96
225KVA Dry Type Transformer	2	EA	1732.72	2.1835	3783.40
330KVA Dry Type Transformer	1	EA	929.86	2.1835	2030.36
SATEC PM174 Feeder Breaker Meters (AEI Comment)	5	EA	6.12	1.54	9.43
100A EMT Feeder	1,200	LF	232.96	2.71	1136.45
150A EMT Feeder	2,470	LF	939.43	2.71	4089.17
200A EMT Feeder	200	LF	116.89	2.71	461.47
225A EMT Feeder	1,170	LF	875.66	2.71	3450.36
300A EMT Feeder	120	LF	183.38	2.71	607.45
400A EMT Feeder	210	LF	339.20	2.71	1202.38
450A EMT Feeder	160	LF	374.92	2.71	1231.76
600A EMT Feeder	450	LF	1560.47	2.71	4968.80
800A EMT Feeder	230	LF	1052.65	2.71	3412.39
100A NEMA1 F Disc. Switch for Oven and Autoclave	2	EA	51.71	1.54	79.63
Chiller Hook-up 500A EMT Feeder	120	LF	416.13	2.71	1289.50
Pumps Hook-up 100A EMT Feeder	700	LF	2427.40	2.71	6872.90
2x4 Light Fixtures	45	EA	46.35	9.18	425.49
Can Lights	37	EA	38.11	9.18	349.85
Indirect Ltg Fixtures	86	EA	88.58	9.18	813.16
Misc Fixtures	177	EA	182.31	9.18	1673.61
20A EMT Feeder	3,470	LF	124.66	2.71	65381.90
Light Switches	187	EA	16.96	2.625	44.53
Motion Detectors	94	EA	10.66	2.625	27.98
Photocell (Daylighting	23	EA	2.61	2.625	6.85

Control)					
IR Sensor (Daylighting Control)	23	EA	2.61	2.625	6.85
Power Pack (Daylighting Control)	23	EA	31.30	2.625	82.16
Wall Outlets	426	EA	38.65	2.625	101.45
Wiremold 4000 Series	1,000	LF	181.44	2.54	460.85
400kW Generator (W/ Enclosure)	1	EA	3303.96	2.1835	7214.21
300A Transfer Switch	1	EA	179.17	2.1835	391.22
600A Transfer Switch	1	EA	179.17	2.1835	391.22
800A Feeder	100	LF	293.74	2.71	1039.39
3/4 Inch EMT Empty Conduit	5,355	LF	1554.55	2.71	4212.83
Cable Tray	1,060	LF	192.32	2.54	488.50
4 Inch EMT Empty Conduit	450	LF	755.23	2.71	2046.68
Cable TV Outlets (Conduit Stub & Wiring)	35	EA	3.18	1.54	4.89
				Total	129783.45

Table 50 Summary of Electrical Carbon Emissions Calculation for M2SEC

Appendix B. Kansas Department of Transportation Building Categories

Building Type	Description	Number of Buildings	Type of Usage	EIA Type	Energy Intensity (kWh/ft^2)
A1	Chemical Domes Standard, Dome, and Cone	209	Storage	Storage	1.75017
B4	Wash bays	89	Service	Service	6.28149
C5	Equipment Storage 4 Bay less than 2000 ft^2	9	Storage	Storage	1.3262
D6	Equipment Storage 6 Bay 2000 to 4000 ft^2	13	Storage	Storage	1.3262
E7	Equipment Storage 10 Bay 4000 to 6000 ft^2 O	43	Storage	Storage	0.68323
F8	Equipment Storage 6000 to 8000 ft^2	55	Storage	Storage	0.68323
G9	Equipment Storage 8000 to 10000 ft^2 Open side	8	Storage	Storage	0.68323
H10	Area Office 2000 to 4000 ft^2 (none in existance	4	Office w/ service	Other	67.07199
I11	Area Office 4000 to 6000 ft^2	18	Office w/ service	Other	67.07199
J12	Area Office 6000 to 8000 ft^2 No info	3	Office w/ service	Other	67.07199
K13	Area Office 8000 to 10000 ft^2 No info	1	Office w/ service	Other	67.07199
AA14	Storage Salt Bunker	111	Storage	Storage	0.29645
AA15	Storage Salt Loader	79	Storage	Storage	0.29645
L17	Sub Area 2000 to 4000 ft^2	69	Office w/ storage	Other	14.33486
M18	Sub Area 4000 to 6000 ft^2 Garage portion	31	Office w/ storage	Other	3.04395
N18	Sub Area 4000 to 6000 ft^2	31	Office w/ storage	Other	48.56008
O19	Sub Area 6000 to 8000 ft^2 Garage	6	Office w/ storage	Other	3.04395
P19	Sub Area 6000 to 8000 ft^2	6	Office w/ storage	Other	48.56008
Q20	Sub Area 8000 to 10000 ft^2	8	Office w/ storage	Other	17.91305
R21	Transmission Tower	1	Service	Service	1.80076
S22	Storage less than 2000 ft^2	83	Storage	Storage	0.48258
T23	Storage 2000 to 4000 ft^2	10	Storage	Storage	0.48258
U24	Storage 4000 to 6000 f^2	4	Storage	Storage	0.38206
V25	Storage 6000 to 8000 ft^2	3	Storage	Storage	0.38206

W26	Storage 8000 to 10000 ft^2	1	Storage	Storage	0.38206
X27	Weighing Station	5	Service	Service	13.42421
Y28	Loader Storage	11	Storage	Storage	39.26352
Z29	Old District Shop	3	Service	Service	39.50992
2A30	New District Shop	3	Service	Service	27.12614
2B31	Laboratory less than 2000 ft^2	6	Office	Office	19.56014
2C32	Laboratory 2000 to 4000 ft^2	4	Office	Office	21.12669
2D33	Laboratory 4000 to 6000 ft^2	2	Office	Office	15.48593
2D34	Laboratory 6000 to 8000 ft^2 Garage	1	Office	Office	15.48593
2F34	Laboratory 6000 to 8000 ft^2	1	Office	Office	39.26352
2G36	Laboratory Larger than 10000 ft^2	2	Office	Office	30.1603
2H33	District Office District 3	1	Office	Office	42.93382
2I38	District Office District 1	1	Office w/ service	Other	33.54688
2J39	Construction Office District	0	Office	Office	39.26352
2K40	Salt Brine	2	Storage	Storage	39.26352
2L41	Radio Shop	3	Service	Service	0
2M42	District Office District 2	1	Office	Office	41.87104
2N43	District Office District 5	1	Office	Office	42.93382
2O44	District Office District 6 (similar to 2 and 4)	3	Office	Office	41.87104
2P45	Warehouse District 2	1	Storage	Storage	21.54109
2Q46	KHP HQ/Construction D6 D2 Annex	1	Office	Office	16.00904
2R47	KHP Office District 3 & 5	1	Office	Office	41.87104
2S48	KHP Office District 4	1	Office	Office	41.87104
2T49	HDQ Material	1	Office	Office	39.26352
2U50	Geology	1	Office	Office	39.26352
2V51	KHP District 1	1	Office	Office	41.87104
2W52	Area Office District 1	1	Office	Office	67.07199
2X53	Area Office District 1 Olathe	1	Office	Office	67.07199
2Y54	Metro Office Shop Contractions	1	Office	Office	27.12614
2Z55	Conference Room/Storage	1	Office w/ storage	Office	19.56014
AA56	Stock Room	1	Storage	Storage	0.48258
AA57	Underground Concrete Blocks	1	None	None	0

Appendix C. Appendix C Kansas Department of Transportation Building Embodied Carbon Emissions By Building Type

		Material ft²	Total Carbon	Material ft²	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon		
TYPE B4		Wash bays															
	Material	Concrete		Reinforced Concrete		Concrete Block		Metal		Glass - Skylight		Doors Sandard		Doors Garage			
	Wall 1 N	156	698.4124	0	0	0	0	364	4648.719	0	0	0	0	0	0		
	Wall 2 E	270	1208.791	0	0	0	0	708	9042.014	0	0	42	37.19722	0	0		
	Wall 3 S	72	322.3442	0	0	0	0	252	3218.344	0	0	0	0	196	2626.939		
	Wall 4 W	306	1369.963	0	0	0	0	714	9118.641	0	0	0	0	0	0		
	Roof	0	0	0	0	0	0	1270	16219.43	96	62.80192	0	0	0	0		
		804	3599.51	0	0	0	0	3308	42247.15	96	62.80192	42	37.19722	196	2626.939	48573.596	Carbon Per Building
Totals per Type		71556	320356.4	0	0	0	0	294412	3759996	8544	5589.371	3738	3310.553	17444	233797.6		
Buildings of Type	89															4323050.1	Total Carbon per Type

		Material ft²	Total Carbon	Material ft²	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon		
TYPE A1		Chemical Domes - Standard, Dome, and Cone															
	Material	Concrete		Reinforced Concrete		Concrete Block		Metal		Glass		Doors - Reinf. Wood		Fiberglass			
	Wall	0	0	1605	7185.589	0	0	0	0	0	0	155	137.2755	0	0		
	Roof	0	0	0	0	0	0	0	0	0	0	78	69.08056	5375	3754.649		
		0	0	1605	7185.589	0	0	0	0	0	0	233	206.356	5375	3754.649	11146.595	Carbon Per Building
Totals per Type		0	0	335445	1501788	0	0	0	0	0	0	48697	43128.41	1123375	784721.7		
Buildings of Type	209															2329638.3	Total Carbon per Type

		Material ft²	Total Carbon	Material ft²	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon		
TYPE C5		Equipment Storage - 4 Bay - less than 2000 ft^2															
	Material	Concrete		Reinforced Concrete		Concrete Block		Metal		Glass Insul.		Doors Garage		Gravel			
	Wall 1 N	0	0	0	0	822	3680.096	0	0	70	91.58614	0	0	0	0		
	Wall 2 E	0	0	0	0	409	1831.094	0	0	0	0	0	0	0	0		
	Wall 3 S	0	0	0	0	316	1414.733	0	0	0	0	576	7719.983	0	0		
	Wall 4 W	0	0	0	0	409	1831.094	0	0	0	0	0	0	0	0		
	Roof	0	0	0	0	0	0	0	0	0	0	0	0	1960	2271.523		
		0	0	0	0	1956	8757.017	0	0	70	91.58614	576	7719.983	1960	2271.523	18840.11	Carbon Per Building
Totals per Type		0	0	0	0	17604	78813.15	0	0	630	824.2752	5184	69479.85	17640	20443.71		
Buildings of Type	9															169560.99	Total Carbon per Type

		Material ft²	Total Carbon	Material ft²	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon		
TYPE D6		Equipment Storage - 6 Bay - 2000 to 4000 ft^2															
	Material	Concrete		Reinforced Concrete		Concrete Block		Metal		Glass Insul.		Doors Garage		Gravel			
	Wall 1 N	0	0	1220	5461.943	0	0	0	0	104	136.0708	0	0	0	0		
	Wall 2 E	0	0	409	1831.094	0	0	0	0	0	0	0	0	0	0		
	Wall 3 S	0	0	461	2063.898	0	0	0	0	0	0	864	11579.97	0	0		
	Wall 4 W	0	0	409	1831.094	0	0	0	0	0	0	0	0	0	0		
	Roof	0	0	0	0	0	0	0	0	0	0	0	0	2910	3372.517		
		0	0	2499	11188.03	0	0	0	0	104	136.0708	864	11579.97	2910	3372.517	26276.592	Carbon Per Building
Totals per Type		0	0	32487	145444.4	0	0	0	0	1352	1768.921	11232	150539.7	37830	43842.72		
Buildings of Type	13															341595.7	Total Carbon per Type

		Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon		
TYPE E7	Equipment Storage - 10 Bay - 4000 to 6000 ft^2 - Open Sided																
	Material	Concrete		Reinforced Concrete		Concrete Block		Metal		Glass		Doors Garage		Corr. Iron			
	Wall 1 N	0	0	0	0	0	0	0	0	48	31.40096	0	0	3024	24627.1		
	Wall 2 E	0	0	0	0	0	0	0	0	48	31.40096	0	0	432	3518.157		
	Wall 3 S	0	0	0	0	0	0	0	0	24	15.70048	144	1929.996	803	6539.536		
	Wall 4 W	0	0	0	0	0	0	0	0	0	0	0	0	480	3909.063		
	Roof	0	0	0	0	0	0	0	0	0	0	0	0	5760	46908.75		
		0	0	0	0	0	0	0	0	120	78.5024	144	1929.996	10499	85502.61	87511.105	Carbon Per
Totals per Type		0	0	0	0	0	0	0	0	5160	3375.603	6192	82989.82	451457	3676612		
Buildings of Type	43															3762977.5	Total Carbo

		Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon		
TYPE F8	Equipment Storage - 6000 to 8000 ft^2																
	Material	Concrete		Reinforced Concrete		Concrete Block		Metal		Glass		Doors Garage		Corr. Iron			
	Wall 1 N	0	0	0	0	0	0	0	0	0	0	0	0	2114	17216.16		
	Wall 2 E	0	0	0	0	0	0	0	0	0	0	23	308.2632	480	3909.063		
	Wall 3 S	0	0	0	0	0	0	0	0	0	0	1680	22516.62	434	3534.444		
	Wall 4 W	0	0	0	0	0	0	0	0	0	0	23	308.2632	480	3909.063		
	Roof	0	0	0	0	0	0	0	0	0	0	0	0	5436	44270.14		
		0	0	0	0	0	0	0	0	0	0	1726	23133.14	8944	72838.87	95972.016	Carbon Per Building
Totals per Type		0	0	0	0	0	0	0	0	0	0	94930	1272323	491920	4006138		
Buildings of Type	55															5278460.9	Total Carbon per Type

		Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon		
TYPE G9	Equipment Storage - 8000 to 10000 ft^2 - Open sided																
	Material	Concrete		Reinforced Concrete		Concrete Block		Metal		Glass		Doors		Corr. Iron			
	Wall 1 N	0	0	0	0	0	0	0	0	0	0	0	0	3290	26793.37		
	Wall 2 E	0	0	0	0	0	0	0	0	0	0	23	20.36991	480	3909.063		
	Wall 3 S	0	0	0	0	0	0	0	0	0	0	2688	2380.622	602	4902.616		
	Wall 4 W	0	0	0	0	0	0	0	0	0	0	23	20.36991	480	3909.063		
	Roof	0	0	0	0	0	0	0	0	0	0	0	0	8460	68897.23		
		0	0	0	0	0	0	0	0	0	0	2734	2421.362	13312	108411.3	110832.71	Carbon Per Building
Totals per Type		0	0	0	0	0	0	0	0	0	0	21872	19370.9	106496	867290.7		
Buildings of Type	8															886661.65	Total Carbon per Type

		Material ft²	Total Carbon	Material ft²	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon		
TYPE I11								Area Office - 4000 to 6000 ft^2									
	Material	Concrete		Reinforced Concrete		Concrete Block		Metal		Glass		Doors		Garage Door			
	Wall 1 N	0	0	0	0	1712	7664.629	0	0	163	106.6324	0	0	0	0		
	Wall 2 E	0	0	0	0	1596	7145.296	0	0	290	189.7141	45	39.85417	0	0		
	Wall 3 S	0	0	0	0	1477	6612.533	0	0	193	126.258	22	19.48426	418	5602.349		
	Wall 4 W	0	0	0	0	1442	6455.838	0	0	250	163.5467	0	0	418	5602.349		
	Roof	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
		0	0	0	0	6227	27878.3	0	0	896	586.1513	67	59.33843	836	11204.7	39728.483	Carbon Per Building
Totals per Type		0	0	0	0	112086	501809.3	0	0	16128	10550.72	1206	1068.092	15048	201684.6		
Buildings of Type	18															715112.7	Total Carbon per Type

		Material ft²	Total Carbon	Material ft²	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon		
TYPE L17								Sub Area - 2000 to 4000 ft^2									
	Material	Concrete		Reinforced Concrete		Concrete Block		Metal		Glass Insul.		Doors Insul w glass		Garage Door			
	Wall 1 N	0	0	0	0	1015	4544.158	0	0	104	136.0708	0	0	0	0		
	Wall 2 E	0	0	0	0	423	1893.772	0	0	18	23.55072	24	31.40096	0	0		
	Wall 3 S	0	0	0	0	480	2148.961	0	0	15	19.6256	49	64.1103	576	7719.983		
	Wall 4 W	0	0	0	0	465	2081.806	0	0	0	0	0	0	0	0		
	Roof	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
		0	0	0	0	2383	10668.7	0	0	137	179.2472	73	95.51126	576	7719.983	18663.439	Carbon Per Building
Totals per Type		0	0	0	0	164427	736140.1	0	0	9453	12368.05	5037	6590.277	39744	532678.8		
Buildings of Type	69															1287777.3	Total Carbon per Type

		Material ft²	Total Carbon	Material ft²	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon		
TYPE M-18								Sub Area - 4000 to 6000 ft^2 - Garage portion									
	Material	Concrete		Reinforced Concrete		Concrete Block		Metal		Glass		Doors Garage		Other			
	Wall 1 N	0	0	0	0	1284	5748.471	0	0	72	47.10144	0	0	0	0		
	Wall 2 E	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
	Wall 3 S	0	0	0	0	493	2207.162	0	0	0	0	864	11579.97	0	0		
	Wall 4 W	0	0	0	0	409	1831.094	0	0	0	0	0	0	0	0		
	Roof	0	0	0	0	0	0	0	0	0	0	0	0	2167			
		0	0	0	0	2186	9786.728	0	0	72	47.10144	864	11579.97	2167	0	21413.804	Carbon Per Building
Totals per Type		0	0	0	0	67766	303388.6	0	0	2232	1460.145	26784	358979.2	67177	0		
Buildings of Type	31															663827.93	Total Carbon per Type

		Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon		
TYPE N18		Sub Area - 4000 to 6000 ft^2															
	Material	Concrete		Reinforced Concrete		Concrete Block		Metal		Glass		Doors		Other			
	Wall 1 N	0	0	0	0	617	2762.311	0	0	72	47.10144	24	21.25556	0	0		
	Wall 2 E	0	0	0	0	223	998.3716	0	0	72	47.10144	48	42.51111	0	0		
	Wall 3 S	0	0	0	0	568	2542.937	0	0	73	47.75563	72	63.76667	0	0		
	Wall 4 W	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
	Roof	0	0	0	0	2167	9701.665	0	0	0	0	0	0	2980			
		0	0	0	0	3575	16005.28	0	0	217	141.9585	144	127.5333	2980	0	16274.776	Carbon Per Building
Totals per Type		0	0	0	0	110825	496163.8	0	0	6727	4400.714	4464	3953.534	92380	0		
Buildings of Type	31															504518.06	Total Carbon per Type

		Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon		
TYPE P19		Sub Area - 6000 to 8000 ft^2															
	Material	Concrete		Reinforced Concrete		Concrete Block		Metal		Glass		Doors		Other			
	Wall 1 N	0	0	0	0	617	2762.311	0	0	72	47.10144	24	21.25556	0	0		
	Wall 2 E	0	0	0	0	223	998.3716	0	0	24	15.70048	48	42.51111	0	0		
	Wall 3 S	0	0	0	0	568	2542.937	0	0	72	47.10144	73	64.65232	0	0		
	Wall 4 W	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
	Roof	0	0	0	0	0	0	0	0	0	0	0	0	2167			
		0	0	0	0	1408	6303.62	0	0	168	109.9034	145	128.419	2167	0	6541.9421	Carbon Per Building
Totals per Type		0	0	0	0	8448	37821.72	0	0	1008	659.4202	870	770.5139	13002	0		
Buildings of Type	6															39251.652	Total Carbon per Type

		Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon		
TYPE R21		Transmission Tower															
	Material	Concrete		Reinforced Concrete		Concrete Block		Shingles		Glass		Doors		Brick			
	Wall 1 N	0	0	0	0	0	0	0	0	32	20.93397	24	21.25556	162	676.041		
	Wall 2 E	0	0	0	0	0	0	0	0	16	10.46699	0	0	130	542.502		
	Wall 3 S	0	0	0	0	0	0	0	0	32	20.93397	0	0	189	788.7145		
	Wall 4 W	0	0	0	0	0	0	0	0	16	10.46699	0	0	130	542.502		
	Roof	0	0	0	0	0	0	416	133.9744	0	0	0	0	0	0		
		0	0	0	0	0	0	416	133.9744	96	62.80192	24	21.25556	611	2549.76	2767.7915	Carbon Per Building
Totals per Type		0	0	0	0	0	0	416	133.9744	96	62.80192	24	21.25556	611	2549.76		
Buildings of Type	1															2767.7915	Total Carbon per Type

		Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon		
TYPE S22		Storage - less than 2000 ft^2															
	Material	Concrete		Reinforced Concrete		Concrete Block		Metal		Garage Door		Doors Metal		Corr. Metal			
	Wall 1 N	0	0	0	0	0	0	0	0	0	0	0	0	480	3909.063		
	Wall 2 E	0	0	0	0	0	0	0	0	0	0	21	281.4577	339	2760.776		
	Wall 3 S	0	0	0	0	0	0	0	0	100	1340.275	0	0	380	3094.675		
	Wall 4 W	0	0	0	0	0	0	0	0	0	0	0	0	360	2931.797		
	Roof	0	0	0	0	0	0	0	0	0	0	0	0	1200	9772.657		
		0	0	0	0	0	0	0	0	100	1340.275	21	281.4577	2759	22468.97	24090.7	Carbon Per Building
Totals per Type		0	0	0	0	0	0	0	0	8300	111242.8	1743	23360.99	228997	1864924		
Buildings of Type	83															1999528.1	Total Carbon per Type

		Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon		
TYPE T23		Storage - 2000 to 4000 ft^2															
	Material	Concrete		Reinforced Concrete		Concrete Block		Door		Glass Skylight		Doors Garage		Corr. Metal			
	Wall 1 N	0	0	0	0	0	0	0	0	0	0	0	0	640	5212.084		
	Wall 2 E	0	0	0	0	0	0	24	21.25556	0	0	120	1608.33	1455	11849.35		
	Wall 3 S	0	0	0	0	0	0	48	42.51111	0	0	0	0	591	4813.034		
	Wall 4 W	0	0	0	0	0	0	0	0	0	0	0	0	160	1303.021		
	Roof	0	0	0	0	0	0	0	0	0	0	0	0	3768	30686.14		
		0	0	0	0	0	0	72	63.76667	0	0	120	1608.33	6614	53863.63	55535.725	Carbon Per Building
Totals per Type		0	0	0	0	0	0	720	637.6667	0	0	1200	16083.3	66140	538636.3		
Buildings of Type	10															555357.25	Total Carbon per Type

		Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon		
TYPE U24		Storage - 4000 to 6000 f^2															
	Material	Concrete		Reinforced Concrete		Concrete Block		Door		Glass - Skylight		Doors Garage		Corr. Metal			
	Wall 1 N	0	0	0	0	0	0	0	0	0	0	0	0	840	6840.86		
	Wall 2 E	0	0	0	0	0	0	24	21.25556	0	0	120	1608.33	1655	13478.12		
	Wall 3 S	0	0	0	0	0	0	48	42.51111	0	0	0	0	391	3184.257		
	Wall 4 W	0	0	0	0	0	0	0	0	0	0	0	0	180	1465.899		
	Roof	0	0	0	0	0	0	0	0	231	151.1171	0	0	4568	37201.25		
		0	0	0	0	0	0	72	63.76667	231	151.1171	120	1608.33	7634	62170.39	63993.601	Carbon Per Building
Totals per Type		0	0	0	0	0	0	288	255.0667	924	604.4685	480	6433.319	30536	248681.5		
Buildings of Type	4															255974.4	Total Carbon per Type

		Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon		
TYPE V25		Storage - 6000 to 8000 ft^2															
	Material	Concrete		Corr. Metal		Concrete Block		Ins. Metal Door		Glass		Doors Garage		Other			
	Wall 1 N	0	0	1955	15921.29	0	0	48	643.3319	0	0	556	7451.928	0	0		
	Wall 2 E	0	0	720	5863.594	0	0	0	0	0	0	0	0	0	0		
	Wall 3 S	0	0	2533	20628.45	0	0	0	0	27	17.66304	0	0	0	0		
	Wall 4 W	0	0	720	5863.594	0	0	0	0	0	0	0	0	0	0		
	Roof	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
		0	0	5928	48276.93	0	0	48	643.3319	27	17.66304	556	7451.928	0	0	56389.85	Carbon Per Building
Totals per Type		0	0	17784	144830.8	0	0	144	1929.996	81	52.98912	1668	22355.78	0	0		
Buildings of Type	3															169169.55	Total Carbon per Type

		Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon		
Type X-27		Weighing Station															
	Material	Concrete		Reinforced Concrete		Concrete Block		Metal		Glass		Doors		Lap Siding			
	Wall 1 N	0	0	0	0	0	0	0	0	80	52.33494	0	0	144	178.3181		
	Wall 2 E	0	0	0	0	0	0	0	0	12	7.85024	24	21.25556	140	173.3648		
	Wall 3 S	0	0	0	0	0	0	0	0	12	7.85024	0	0	212	262.5238		
	Wall 4 W	0	0	0	0	0	0	0	0	32	20.93397	0	0	144	178.3181		
	Roof	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
		0	0	0	0	0	0	0	0	136	88.96939	24	21.25556	640	792.5247	902.74967	Carbon Per Building
Totals per Type		0	0	0	0	0	0	0	0	680	444.847	120	106.2778	3200	3962.624		
Buildings of Type	5															4513.7483	Total Carbon per Type

		Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon		
TYPE Z29		Old District Shop															
	Material	Stone		Reinforced Concrete		Concrete Block		Garage Door		Glass		Doors		Other			
	Wall 1 N	1423	5430.262	0	0	0	0	0	0	181	118.4078	26	23.02685	0	0		
	Wall 2 E	2471	9429.5	0	0	0	0	0	0	835	546.2459	53	46.93935	0	0		
	Wall 3 S	1186	4525.855	0	0	0	0	288	3859.992	157	102.7073	0	0	0	0		
	Wall 4 W	2330	8891.435	0	0	0	0	253	3390.895	231	151.1171	0	0	0	0		
	Roof	0	0	0	0	0	0	0	0	542	354.5692	0	0	0	0		
		7410	28277.05	0	0	0	0	541	7250.887	1946	1273.047	79	69.96621	0	0	36870.953	Carbon Per Building
Totals per Type		22230	84831.16	0	0	0	0	1623	21752.66	5838	3819.142	237	209.8986	0	0		
Buildings of Type	3															110612.86	Total Carbon per Type

		Material ft²	Total Carbon	Material ft²	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon		
TYPE 2A30		New District Shop															
	Material	Concrete		Reinforced Concrete		Concrete Block		Metal		Glass		Doors		Other			
	Wall 1 N	0	0	0	0	0	0	0	0	1554	1016.606	0	0	3124			
	Wall 2 E	0	0	0	0	0	0	0	0	206	134.7625	257	227.6116	2705			
	Wall 3 S	0	0	0	0	0	0	0	0	659	431.109	1030	912.2176	2988			
	Wall 4 W	0	0	0	0	0	0	0	0	121	79.15659	822	728.0028	2254			
	Roof	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
		0	0	0	0	0	0	0	0	2540	1661.634	2109	1867.832	11071	0	3529.4663	Carbon Per Building
Totals per Type		0	0	0	0	0	0	0	0	7620	4984.903	6327	5603.496	33213	0		
Buildings of Type	3															10588.399	Total Carbon per Type

		Material ft²	Total Carbon	Material ft²	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon		
TYPE 2B31		Laboratory - less than 2000 ft^2															
	Material	Concrete		Reinforced Concrete		Concrete Block		Metal		Glass		Doors		Other			
	Wall 1 N	968	4333.739	0	0	0	0	0	0	149	97.47382	70	61.99537	0	0		
	Wall 2 E	461	2063.898	0	0	0	0	0	0	55	35.98027	23	20.36991	0	0		
	Wall 3 S	969	4338.216	0	0	0	0	0	0	149	97.47382	69	61.10973	0	0		
	Wall 4 W	485	2171.346	0	0	0	0	0	0	55	35.98027	0	0	0	0		
	Roof	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
		2883	12907.2	0	0	0	0	0	0	408	266.9082	162	143.475	0	0	13317.582	Carbon Per
Totals per Type		17298	77443.19	0	0	0	0	0	0	2448	1601.449	972	860.85	0	0		
Buildings of Type	6															79905.491	Total Carbo

		Material ft²	Total Carbon	Material ft²	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon		
TYPE 2C32		Laboratory - 2000 to 4000 ft^2															
	Material	Concrete		Reinforced Concrete		Concrete Block		Metal		Glass		Doors		Brick			
	Wall 1 N	0	0	0	0	0	0	0	0	263	172.0511	23	20.36991	578	2412.048		
	Wall 2 E	0	0	0	0	0	0	0	0	38	24.85909	0	0	467	1948.834		
	Wall 3 S	0	0	0	0	0	0	0	0	182	119.062	46	40.73982	598	2495.509		
	Wall 4 W	0	0	0	0	0	0	0	0	13	8.504427	46	40.73982	393	1640.025		
	Roof	0	0	0	0	0	0	0	0	52	34.01771	0	0	0	0		
		0	0	0	0	0	0	0	0	548	358.4943	115	101.8495	2036	8496.417	8956.7604	Carbon Per
Totals per Type		0	0	0	0	0	0	0	0	2192	1433.977	460	407.3982	8144	33985.67		
Buildings of Type	4															35827.042	Total Carbo

		Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon		
TYPE 2D33		Laboratory - 4000 to 6000 ft^2															
	Material	Concrete		Reinforced Concrete		Concrete Block		Garage Door		Glass		Doors		Other			
	Wall 1 N	0	0	0	0	1902	8515.259	0	0	0	0	24	21.25556	0	0		
	Wall 2 E	0	0	0	0	223	998.3716	0	0	0	0	48	42.51111	0	0		
	Wall 3 S	0	0	0	0	1061	4750.1	864	11579.97	0	0	73	64.65232	0	0		
	Wall 4 W	0	0	0	0	409	1831.094	0	0	0	0	0	0	0	0		
	Roof	0	0	0	0	0	0	0	0	0	0	0	0	5147			
		0	0	0	0	3595	16094.82	864	11579.97	0	0	145	128.419	5147	0	27803.218	Carbon Per Building
Totals per Type		0	0	0	0	7190	32189.65	1728	23159.95	0	0	290	256.838	10294	0		
Buildings of Type	2															55606.437	Total Carbon per Type

		Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon		
TYPE 2D34		Laboratory - 6000 to 8000 ft^2 - Garage															
	Material	Concrete		Reinforced Concrete		Concrete Block		Metal		Glass		Doors Garage		Other			
	Wall 1 N	0	0	0	0	1711	7660.152	0	0	96	62.80192	0	0	0	0		
	Wall 2 E	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
	Wall 3 S	0	0	0	0	655	2932.437	0	0	0	0	1152	15439.97	0	0		
	Wall 4 W	0	0	0	0	409	1831.094	0	0	0	0	0	0	0	0		
	Roof	0	0	0	0	0	0	0	0	0	0	0	0	3969			
		0	0	0	0	2775	12423.68	0	0	96	62.80192	1152	15439.97	3969	0	27926.451	Carbon Per
Totals per Type		0	0	0	0	2775	12423.68	0	0	96	62.80192	1152	15439.97	3969	0		
Buildings of Type	1															27926.451	Total Carbo

		Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon		
TYPE 2F34		Laboratory - 6000 to 8000 ft^2															
	Material	Concrete		Reinforced Concrete		Concrete Block		Metal		Glass		Doors		Other			
	Wall 1 N	0	0	0	0	617	2762.311	0	0	72	47.10144	24	21.25556	0	0		
	Wall 2 E	0	0	0	0	223	998.3716	0	0	24	15.70048	48	42.51111	0	0		
	Wall 3 S	0	0	0	0	568	2542.937	0	0	72	47.10144	73	64.65232	0	0		
	Wall 4 W	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
	Roof	0	0	0	0	0	0	0	0	0	0	0	0	2167			
		0	0	0	0	1408	6303.62	0	0	168	109.9034	145	128.419	2167	0	6541.9421	Carbon Per Building
Totals per Type		0	0	0	0	0	0	0	0	0	0	0	0	0	0		
Buildings of Type	0															0	Total Carbon per Type

		Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon		
TYPE 2G36		Laboratory - Larger than 10000 ft^2															
	Material	Concrete		Reinforced Concrete		Garage Door		Metal		Glass		Doors		Other			
	Wall 1 N		0	0	0	0	0	0	0	0	0	0	0	0	0		
	Wall 2 E		0	0	0	0	0	0	0	0	0	0	0	0	0		
	Wall 3 S	2635	11796.9	0	0	144	1929.996	0	0	27	17.66304	117	103.6208	0	0		
	Wall 4 W	419	1875.864	0	0	0	0	0	0	24	15.70048	23	20.36991	0	0		
	Roof		0	0	0	0	0	0	0	0	0	0	0	0	0		
		3054	13672.77	0	0	144	1929.996	0	0	51	33.36352	140	123.9907	0	0	15760.116	Carbon Per Building
Totals per Type		0	0	0	0	0	0	0	0	0	0	0	0	0	0		
Buildings of Type	0															0	Total Carbon per Type

		Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon		
TYPE 2H33		District Office - District 3															
	Material	Brick		Reinforced Concrete		Concrete Block		Metal		Glass		Doors		Other			
	Wall 1 N	0	0	0	0	0	0	0	0	216	141.3043	0	0	0	0		
	Wall 2 E	0	0	0	0	0	0	0	0	377	246.6284	0	0	0	0		
	Wall 3 S	0	0	0	0	0	0	0	0	264	172.7053	0	0	0	0		
	Wall 4 W	0	0	0	0	0	0	0	0	355	232.2363	0	0	0	0		
	Roof	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
		0	0	0	0	0	0	0	0	1212	792.8743	0	0	0	0	792.87428	Carbon Per Building
Totals per Type		0	0	0	0	0	0	0	0	1212	792.8743	0	0	0	0		
Buildings of Type	1															792.87428	Total Carbon per Type

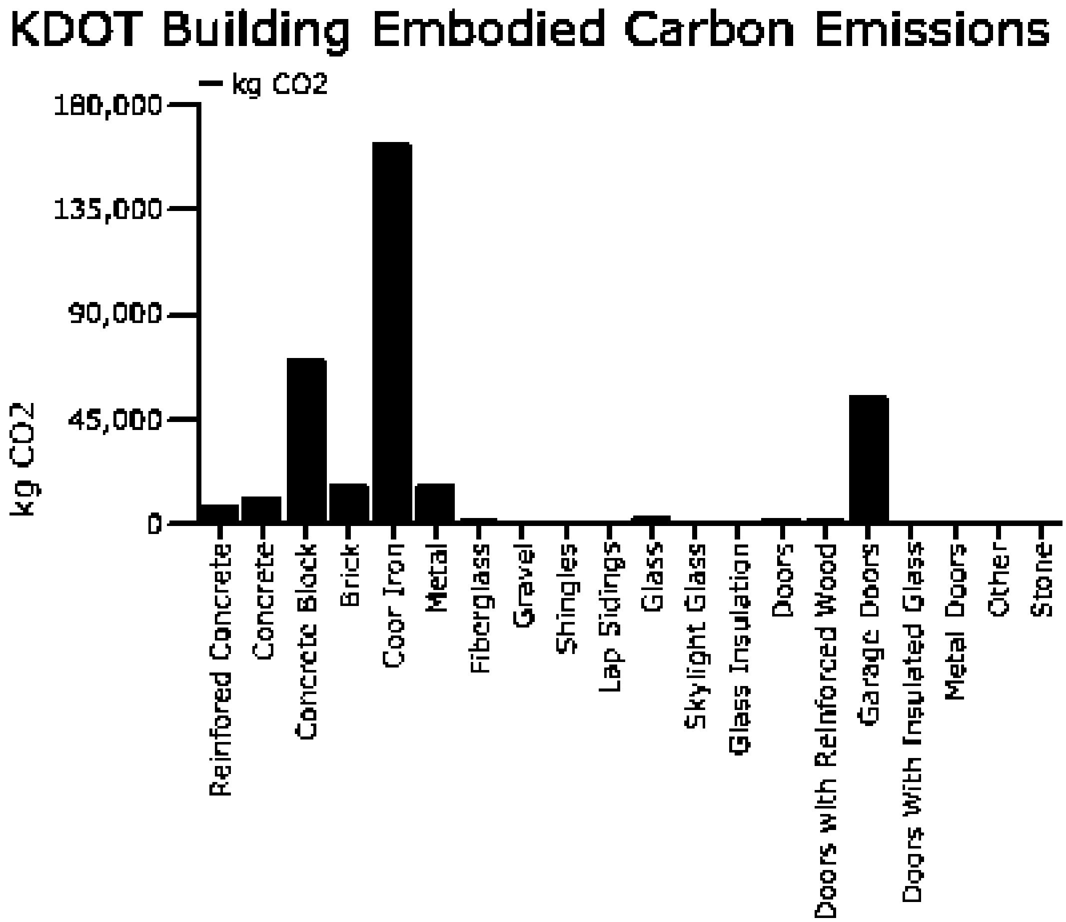
		Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon		
TYPE 2M42		District Office - District 2															
	Material	Brick		Reinforced Concrete		Concrete Block		Metal		Glass		Door w glass		Other			
	Wall 1 N	767	3200.762	0	0	0	0	0	0	398	260.3663	46	60.18518	0	0		
	Wall 2 E	490	2044.815	0	0	0	0	0	0	179	117.0994	0	0	0	0		
	Wall 3 S	1386	5783.906	0	0	0	0	0	0	183	119.7162	46	60.18518	0	0		
	Wall 4 W	373	1556.564	0	0	0	0	0	0	58	37.94283	0	0	0	0		
	Roof	0	0	0	0	0	0	0	0	238	155.6964	0	0	0	0		
		3016	12586.05	0	0	0	0	0	0	1056	690.8212	92	120.3704	0	0	13397.239	Carbon Per Building
Totals per Type		3016	12586.05	0	0	0	0	0	0	1056	690.8212	92	120.3704	0	0		
Buildings of Type	1															13397.239	Total Carbon per Type

		Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon		
TYPE 2N43		District Office - District 5															
	Material	Brick		Reinforced Concrete		Concrete Block		Metal		Glass		Doors		Other			
	Wall 1 N	1470	6134.446	0	0	0	0	0	0	280	183.1723	0	0	0	0		
	Wall 2 E	1275	5320.693	0	0	0	0	0	0	227	148.5004	23	20.36991	0	0		
	Wall 3 S	1467	6121.927	0	0	0	0	0	0	261	170.7427	21	18.59861	0	0		
	Wall 4 W	1261	5262.27	0	0	0	0	0	0	154	100.7448	42	37.19722	0	0		
	Roof	0	0	0	0	0	0	0	0	70	45.79307	0	0	0	0		
		5473	22839.34	0	0	0	0	0	0	992	648.9532	86	76.16574	0	0	23564.455	Carbon Per Building
Totals per Type		5473	22839.34	0	0	0	0	0	0	992	648.9532	86	76.16574	0	0		
Buildings of Type	1															23564.455	Total Carbon per Type

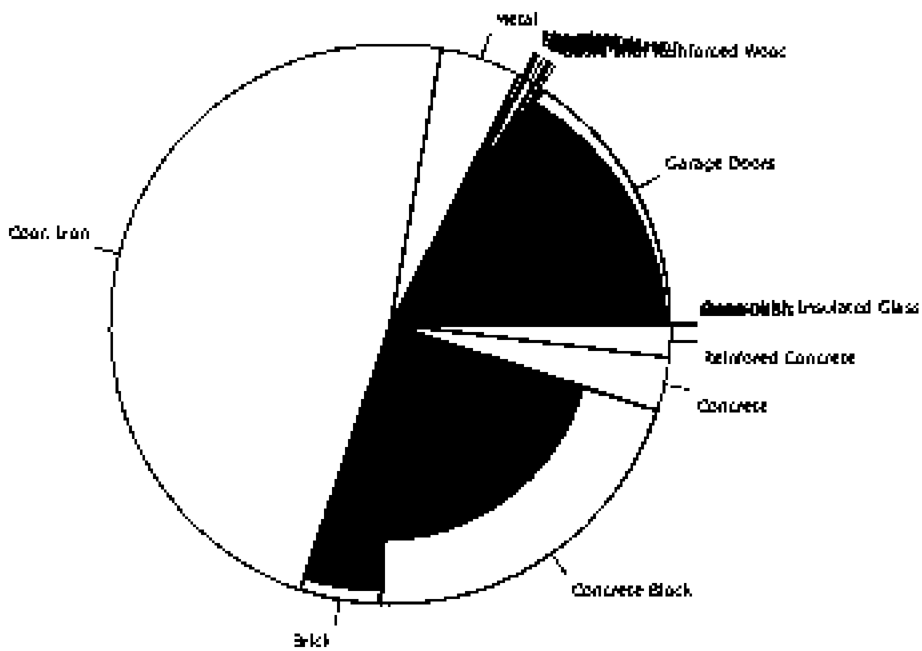
		Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon		
TYPE 2O44		District Office - District 6 (similar to 4)															
	Material	Brick		Reinforced Concrete		Concrete Block		Metal		Glass		Door w Glass		Other			
	Wall 1 N	578	2412.048	0	0	0	0	0	0	81	52.98912	0	0	0	0		
	Wall 2 E	1036	4323.324	0	0	0	0	0	0	151	98.78219	23	30.09259	0	0		
	Wall 3 S	590	2462.125	0	0	0	0	0	0	70	45.79307	0	0	0	0		
	Wall 4 W	1353	5646.194	0	0	0	0	0	0	186	121.6787	46	60.18518	0	0		
	Roof	0	0	0	0	0	0	0	0	28	18.31723	0	0	0	0		
		3557	14843.69	0	0	0	0	0	0	516	337.5603	69	90.27776	0	0	15271.529	Carbon Per Building
Totals per Type		7114	29687.38	0	0	0	0	0	0	1032	675.1207	138	180.5555	0	0		
Buildings of Type	2															30543.057	Total Carbon per Type

		Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon	Material ft^2	Total Carbon		
TYPE R21		Transmission Tower															
	Material	Concrete		Reinforced Concrete		Concrete Block		Shingles		Glass		Doors		Brick			
	Wall 1 N	0	0	0	0	0	0	0	0	32	20.93397	24	21.25556	162	676.041		
	Wall 2 E	0	0	0	0	0	0	0	0	16	10.46699	0	0	130	542.502		
	Wall 3 S	0	0	0	0	0	0	0	0	32	20.93397	0	0	189	788.7145		
	Wall 4 W	0	0	0	0	0	0	0	0	16	10.46699	0	0	130	542.502		
	Roof	0	0	0	0	0	0	416	133.9744	0	0	0	0	0	0		
		0	0	0	0	0	0	416	133.9744	96	62.80192	24	21.25556	611	2549.76	2767.7915	Carbon Per Building
Totals per Type		0	0	0	0	0	0	416	133.9744	96	62.80192	24	21.25556	611	2549.76		
Buildings of Type	1															2767.7915	Total Carbon per Type

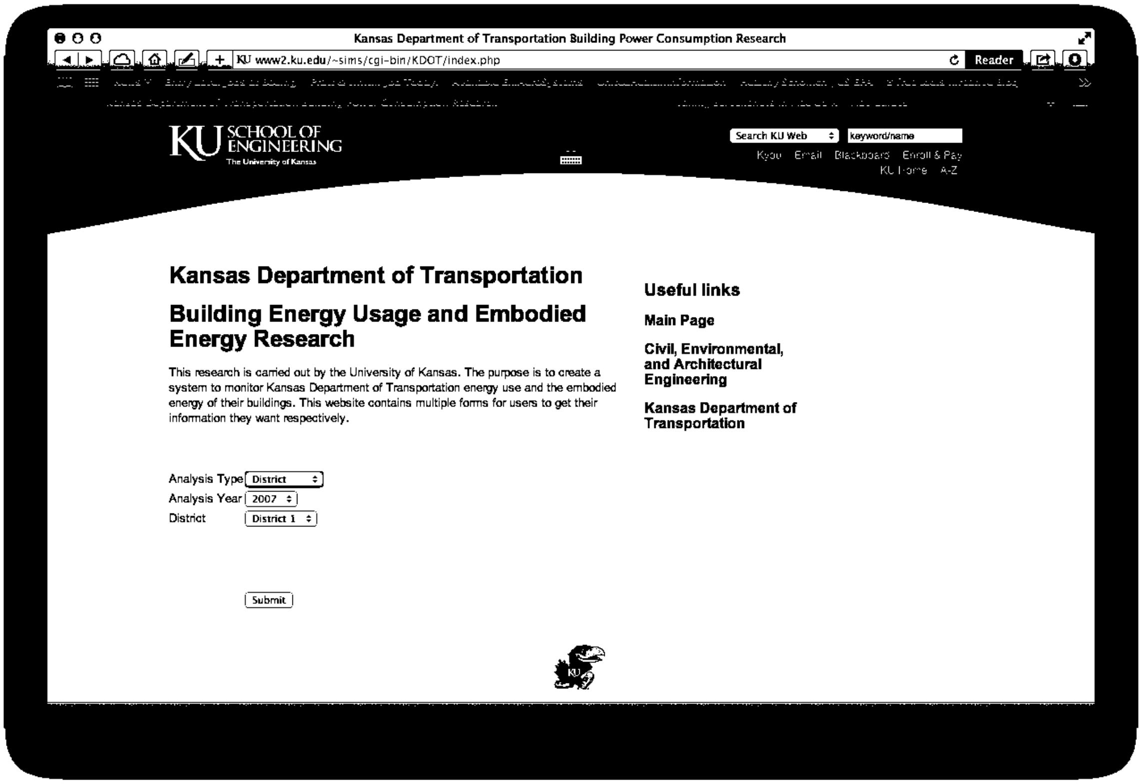
Appendix D. KDOT Building Embodied Carbon Emissions Result

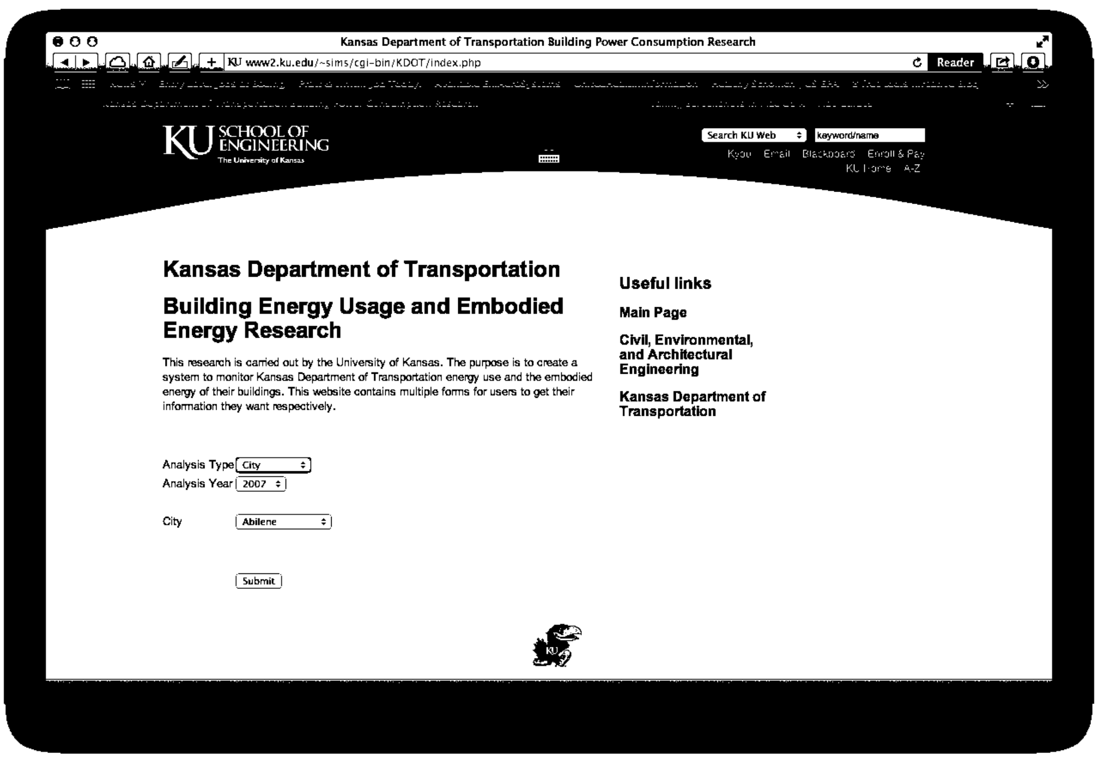


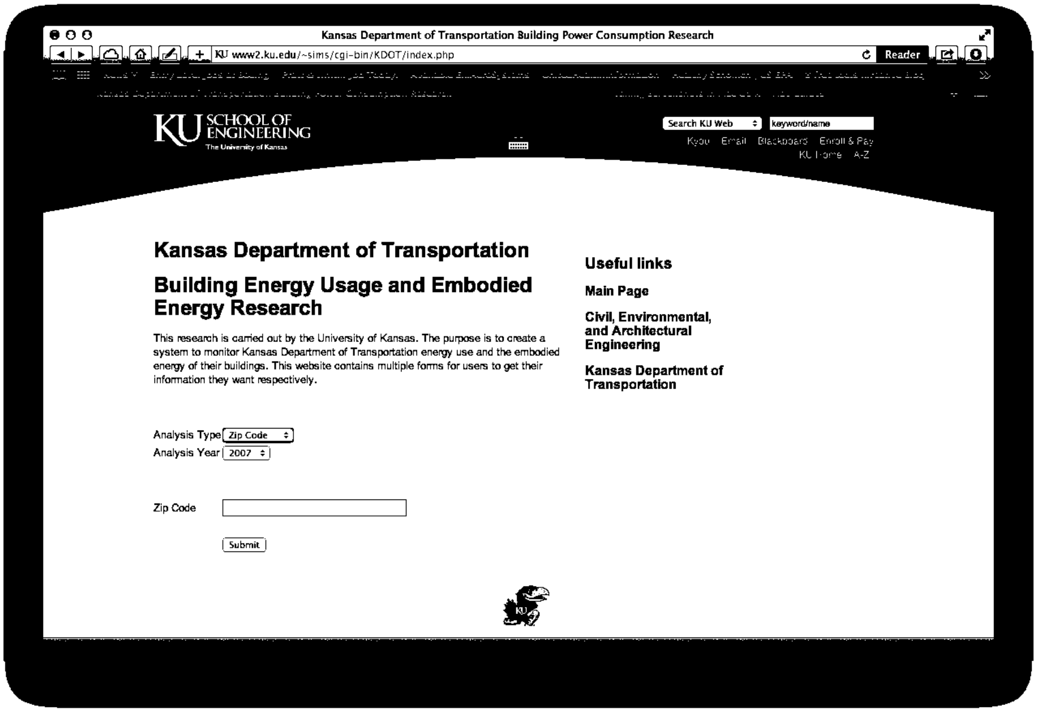
State Total Embodied Carbon Emissions

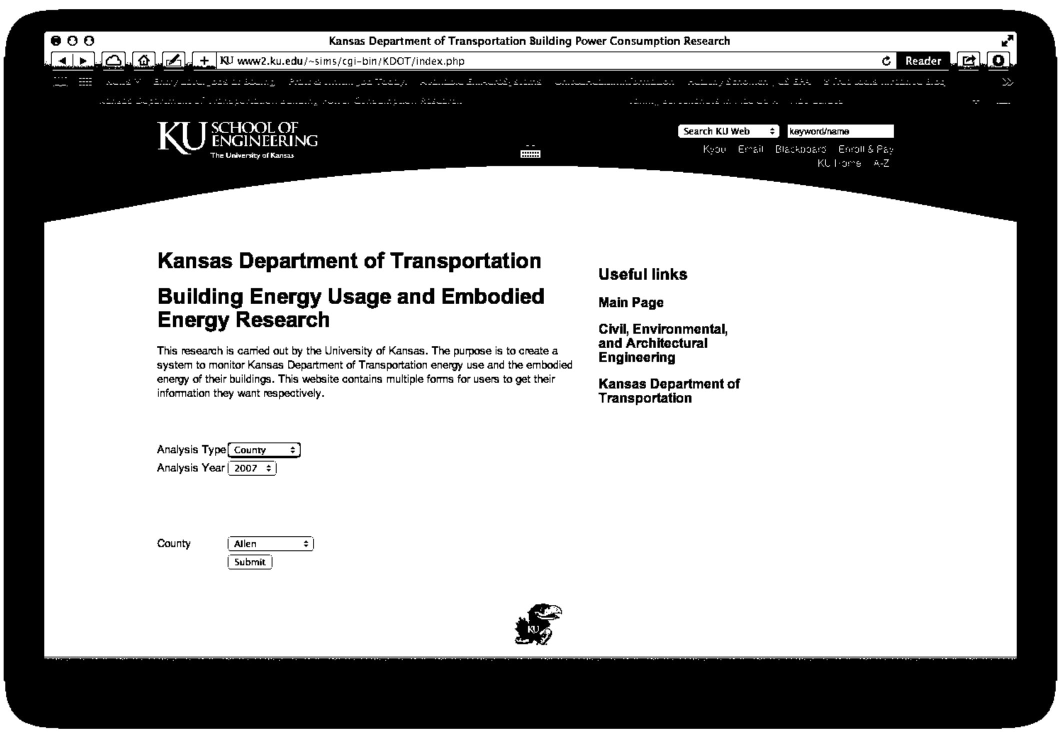


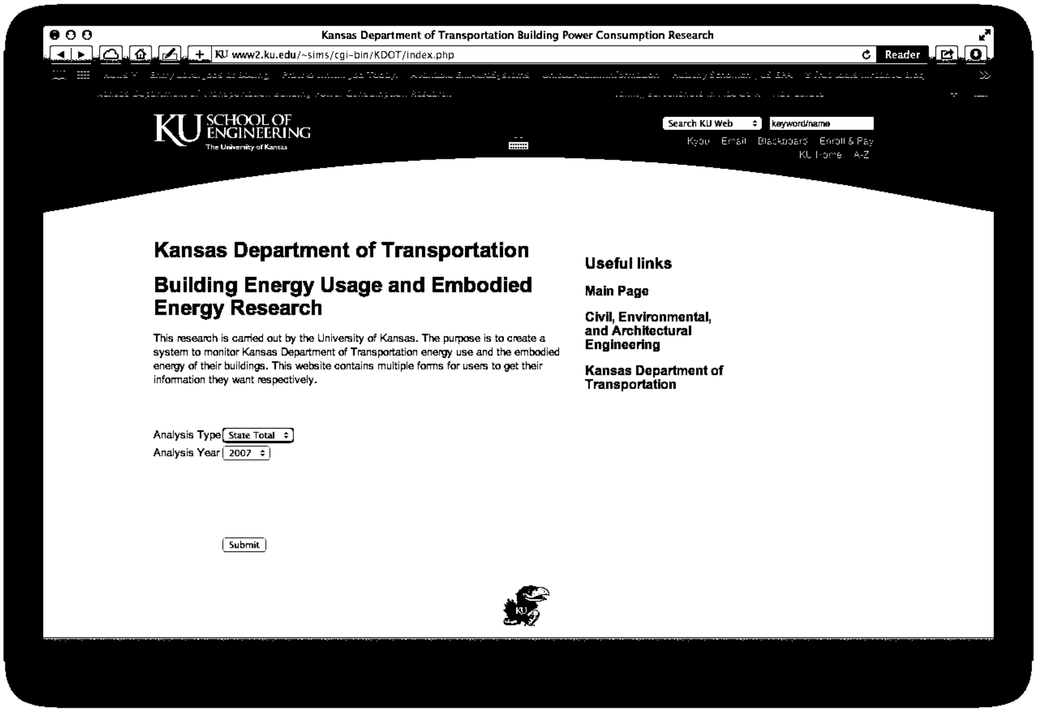
Appendix E. KDOT Building Utility Summary Input page



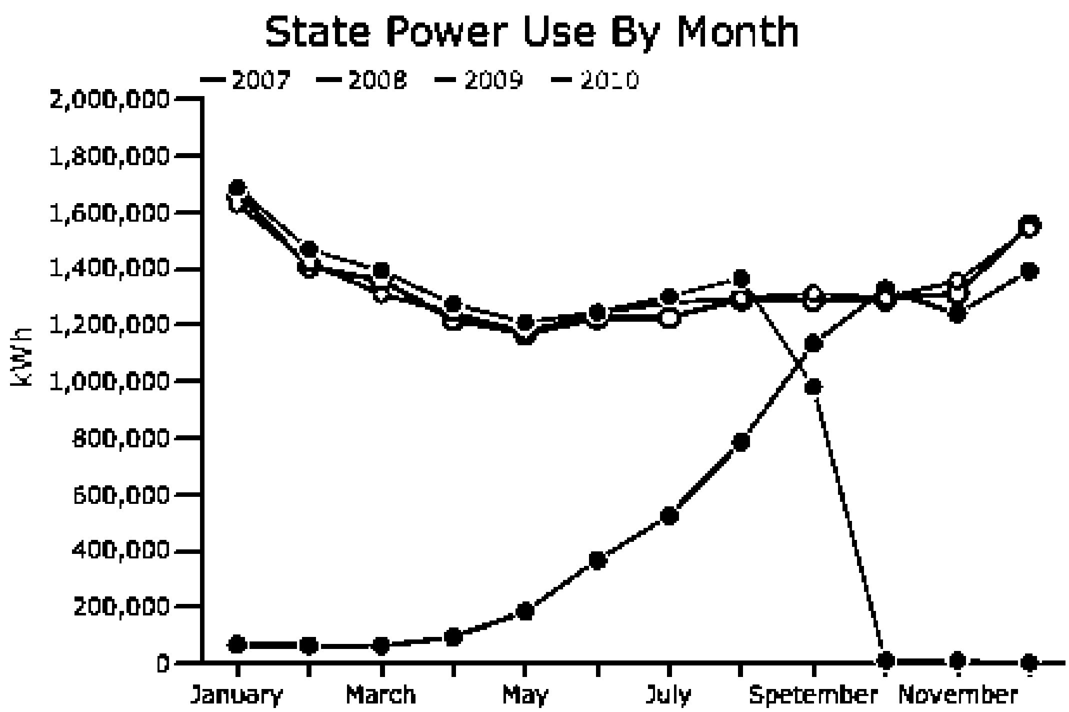


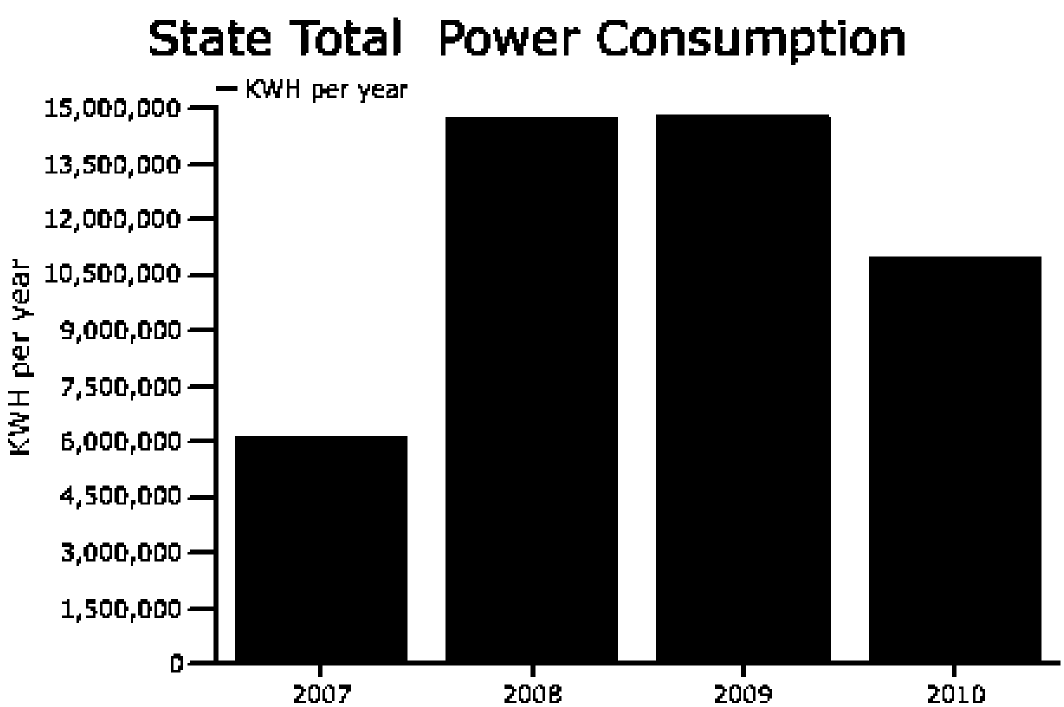

Kansas Department of Transportation Building Power Consumption Research
www2.ku.edu/~sims/cgi-bin/KDOT/index.php
Reader
KU SCHOOL OF ENGINEERING
The University of Kansas
Search KU Web
keyword/name
Kansas Department of Transportation
Building Energy Usage and Embodied Energy Research
This research is carried out by the University of Kansas. The purpose is to create a system to monitor Kansas Department of Transportation energy use and the embodied energy of their buildings. This website contains multiple forms for users to get their information they want respectively.
Analysis Type
Zip Code
Analysis Year
2007
Zip Code
Submit
Useful links
Main Page
Civil, Environmental, and Architectural Engineering
Kansas Department of Transportation

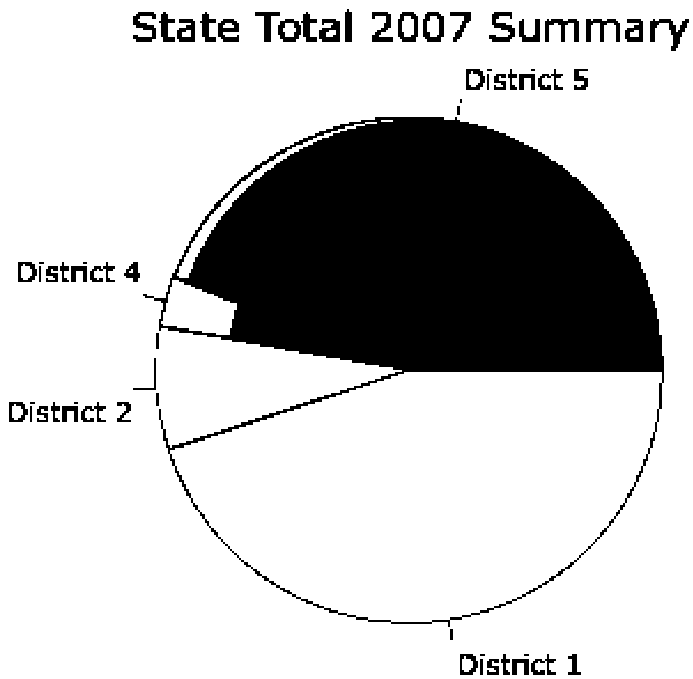

Kansas Department of Transportation Building Power Consumption Research
www2.ku.edu/~sims/cgi-bin/KDOT/index.php
Reader
KU SCHOOL OF ENGINEERING
The University of Kansas
Search KU Web
keyword/name
Kansas Department of Transportation
Building Energy Usage and Embodied Energy Research
This research is carried out by the University of Kansas. The purpose is to create a system to monitor Kansas Department of Transportation energy use and the embodied energy of their buildings. This website contains multiple forms for users to get their information they want respectively.
Analysis Type
County
Analysis Year
2007
County
Allen
Submit
Useful links
Main Page
Civil, Environmental, and Architectural Engineering
Kansas Department of Transportation

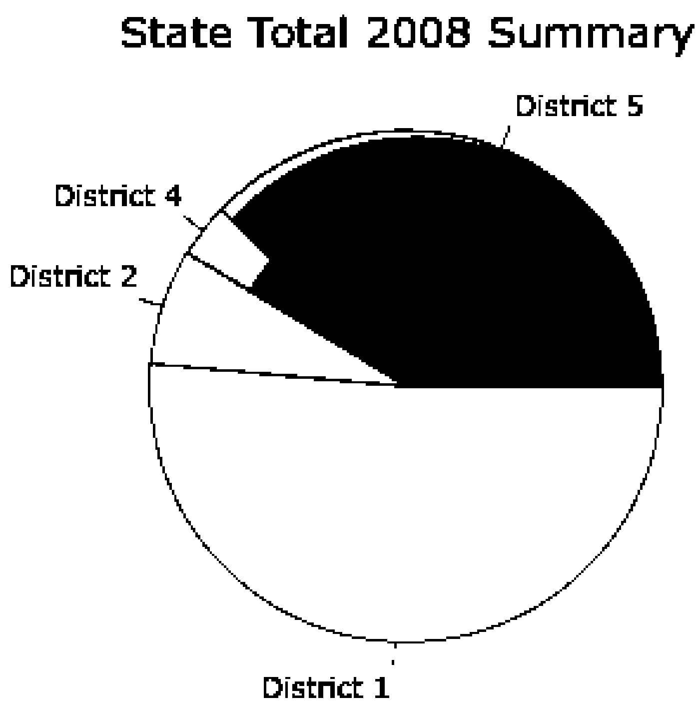

Kansas Department of Transportation Building Power Consumption Research
KU www2.ku.edu/~sims/cgi-bin/KDOT/index.php
Reader
KU SCHOOL OF ENGINEERING
The University of Kansas
Search KU Web
keyword/name
Kansas Department of Transportation
Building Energy Usage and Embodied Energy Research
This research is carried out by the University of Kansas. The purpose is to create a system to monitor Kansas Department of Transportation energy use and the embodied energy of their buildings. This website contains multiple forms for users to get their information they want respectively.
Analysis Type
State Total
Analysis Year
2007
Submit
Useful links
Main Page
Civil, Environmental, and Architectural Engineering
Kansas Department of Transportation

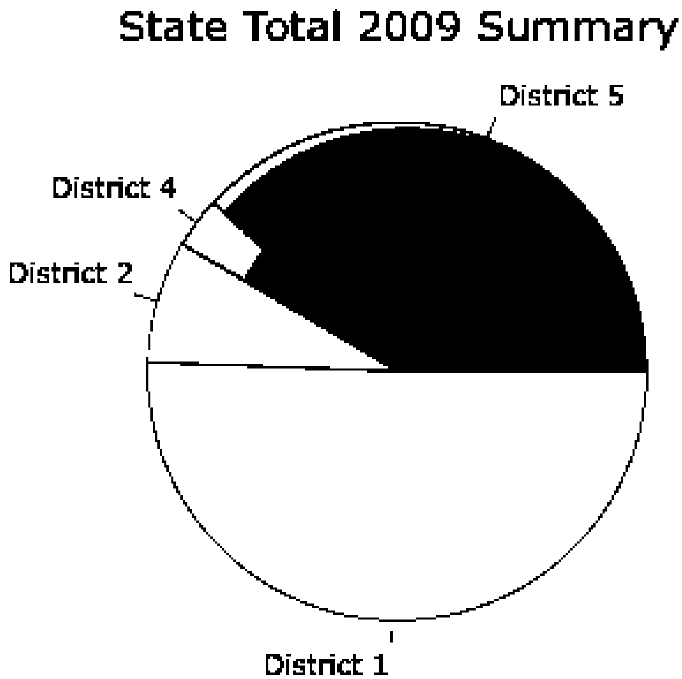
Appendix F. KDOT Building Usage Summary (Website)

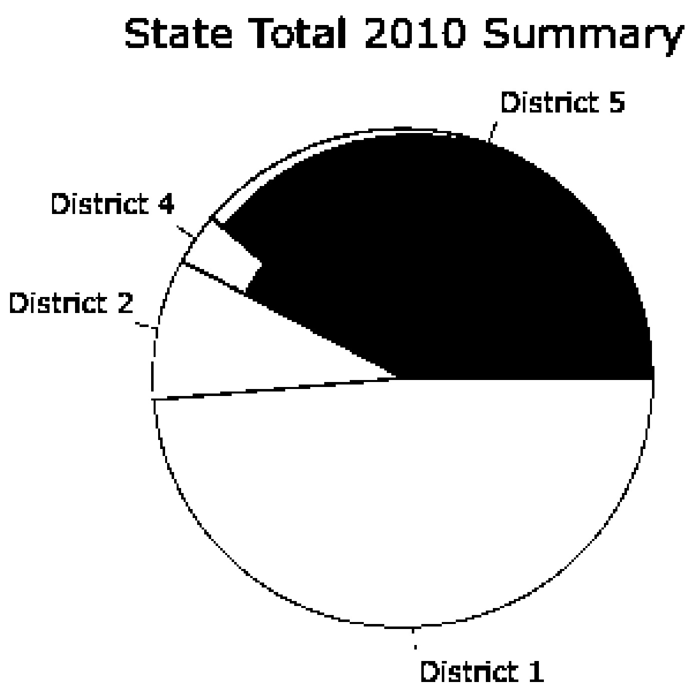


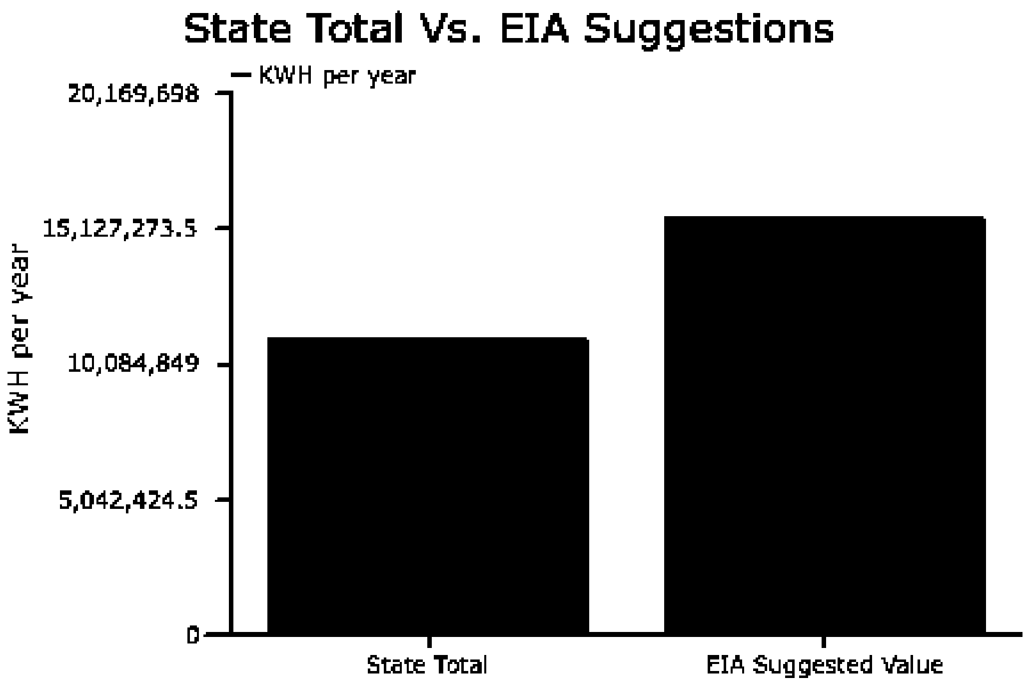



State Total 2007 Summary
District 5
District 4
District 2
District 1


State Total 2008 Summary
District 5
District 4
District 2
District 1


State Total 2009 Summary
District 5
District 4
District 2
District 1


State Total 2010 Summary
District 5
District 4
District 2
District 1


State Total Vs. EIA Suggestions
KWH per year
20,169,698
15,127,273.5
10,084,849
5,042,424.5
0
KWH per year
State Total
EIA Suggested Value

Appendix G. Eaton Hall Energy Data and EIA Data Comparison

Year	Power (kWh)	Power Carbon Emissions (kgCO2e)	Gas (MCF)	Natural Gas Carbon Emissions (kgCO2e)	Water (Mgal)	Water Carbon Emissions (kgCO2e)	Sewer (Mgal)	Sewer Carbon Emissions (kgCO2e)	Steam (gal)	Steam Carbon Emissions (kgCO2e)	Total Carbon Emissions(kgCO2e)
2004	2107750.00	1797278.43	6.20	425216.40	1329.15	1731291.86	301.73	856627.97	1331100.00	1084601.33	5895015.98
2005	2132220.00	1818143.99	1.50	102874.93	1354.47	1764281.78	277.34	787392.44	1262700.00	1028867.93	5501561.08
2006	2065800.00	1761507.66	10.00	685832.90	1139.78	1484631.36	264.41	750670.37	714800.00	582430.34	5265072.63
2007	2335270.00	1991284.73	7.10	486941.36	1338.90	1743995.72	277.01	786449.02	381100.00	310526.31	5319197.13
2008	2267080.00	1933139.12	2.30	157741.57	1296.51	1688780.22	324.61	921583.90	1008400.00	821660.27	5522905.07
2009	2250720.00	1919188.94	2.20	150883.24	1627.03	2119297.00	391.26	1110809.92	1267800.00	1033023.49	6333202.59
2010	2321100.00	1979201.97	3.10	212608.20	2342.44	3051168.97	324.30	920702.37	1134900.00	924734.47	7088415.98
2011	2109760.00	1798992.35	2.40	164599.90	1207.17	1572416.06	360.97	1024806.35	441700.00	359904.15	4920718.80
2012	2140336.00	1825064.51	2.70	185174.88	2074.02	2701535.92	378.89	1075682.83	390200.00	317941.13	6105399.28
EIA Average Value	932085.00	794788.88	3.13	214440.85	7.69	10014.05	N/A	N/A	1020934.20	831873.33	N/A