THESIS

ENERGY USE AND EMISSIONS REDUCTION STRATEGIES FOR STRUCTURAL STEEL FABRICATORS: A CASE STUDY

Submitted by

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In partial fulfillment of the requirements

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY ERIK A. BERGSTROM ENTITLED: ENERGY AND EMISSIONS REDUCTION STRATEGIES FOR STRUCTURAL STEEL FABRICATORS: A CASE STUDY BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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ABSTRACT OF THESIS

ENERGY USE AND EMISSIONS REDUCTION STRATEGIES FOR STRUCTURAL STEEL FABRICATORS: A CASE STUDY

Energy price escalation, natural resource depletion, and wide-spread environmental degradation are driving demand for more sustainable construction methods and materials. Steel fabricators working to operate more sustainably require detailed energy and environmental analysis of operational practices in order to make informed improvements. Yet only limited research exists on the energy use and emissions associated with fabrication and material sourcing for structural steel used in building construction.

This research involves a life-cycle inventory assessment of structural members used in a case-study building to address this gap in research and identify high-impact areas for future process improvement at one fabrication facility. With a life-cycle inventory model developed, feasible process improvements are measured against standard practices, and the associated energy savings and environmental improvements are identified.

The main discovery of this research is that while the fabricator has the ability to make significant energy and emissions reductions by modifying operational process within their own facility, the most impactful opportunities are in material selection alternatives, such as sourcing reused materials. Structural steel fabricators can use these findings to reduce environmental impacts and operating costs, while delivering a more environmentally preferable product.

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1 INTRODUCTION

Resource conservation, energy efficiency, and emissions reduction efforts have become increasingly relevant topics in the fields of construction and development. Energy price escalation, natural resource depletion, and wide-spread environmental degradation are driving demand for more sustainable construction methods and materials. In response, mainstream building owners and developers are looking beyond first costs, to more dynamic metrics as the basis of design decisions and the determination of a project's overall success and value. These factors include issues associated with energy and water use in building operation, resource depletion from construction materials, impacts to natural ecosystems, and life-cycle environmental impacts and costs. The structural steel industry, as a primary upstream supplier to new development projects, has an interest in tailoring their products and services to meet this shift in values and the corresponding demands of the evolving marketplace. Industry leaders are realizing that incentives exist for organizations that can operate more sustainably and thereby deliver buildings with lower environmental impacts and a higher operational efficiency. This research adds to the understanding of energy consumption and emissions associated with the structural steel delivery process, specifically fabrication, and identify opportunities for future reductions.

1.1 Life Cycle Assessment

Organizations such as structural steel fabricators that are interested in reducing the negative environmental impact of a product or process must first have the necessary data with which to properly evaluate impacts and options. Access to reliable data is a prerequisite for informed decisions in the implementation of sustainability efforts. Life-cycle assessment (LCA) is a well-established tool for quantifying the energy use and environmental burdens associated with a product, service, or process (EPA, 2006). LCA is traditionally used to evaluate energy use and environmental impacts from "cradle-to-grave", including raw material acquisition, manufacturing, and the use and end-of-life phases (Keoleian, 1993; Guggemos & Horvath, 2003; EPA, 2006). Any meaningful effort to make a process more sustainable should evaluate all stages of a product's development to identify all impacts, both upstream and downstream in the supply chain. This research uses LCA methodology to develop an energy and emissions life-cycle inventory (LCI) for the material production and fabrication phases of the structural steel delivery process. This study is a segment of a larger project that involves the additional detailed inventory of structural steel design and erection impacts. The findings reported here are limited to the impacts primarily associated with fabrication, material procurement, and transportation from the mill to the fabricator.

1.2 Problem Statement and Goals

Only limited research exists on the energy use and emissions associated with fabrication and material sourcing for structural steel used in building construction. Steel fabricators working to operate more sustainably require detailed energy and environmental analysis of operational practices in order to make informed improvements. A comprehensive life-cycle inventory of structural members used in a case-study project addresses this gap in research and identifies high-impact areas for future process improvement. With a life-cycle inventory model developed, feasible process improvements are measured against standard practices, and the associated energy savings and environmental improvements are identified.

1.3 Research Questions

1. How much energy is used in the fabrication of structural steel for a case study building and what are the associated environmental emissions?

2. In what ways can the structural steel fabricator reduce energy use and emissions?

1.4 Background

In the United States, steel construction is a primary structural framing strategy for large government, institutional, commercial, and residential multi-story buildings, along with bridges. The material offers a relatively lightweight and flexible structural alternative to concrete. Prefabrication of the structural steel framing members off-site allows for rapid assembly in the field, giving steel a potential advantage for time-critical projects.

The structural steel industry is comprised of five primary stages: (1) mining, (2) manufacturing, (3) design and engineering, (4) fabrication, and (5) erection. Traditionally each stage is managed by a separate organization.

This study will focus on the steel fabrication phase, which involves manipulating stock materials to create structural members. Fabrication is an energy-intensive process involving heavy equipment for moving, cutting, bending, drilling, welding, blasting, and coating large members. Fabricators are also responsible for sourcing material and transporting fabricated product to customers. This study addresses issues related to improving the overall environmental performance of structural steel by addressing each of these factors in the fabrication process where appropriate.

In recent years, the building industry as a whole has been pressured by building owners, developers, and occupants to increasingly incorporate sustainability efforts into building design, materials selection, and construction methods. Building rating systems, such as the United States Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED™) are defining the tenets of sustainable design. The LEED™ certification rubric provides a limited set of guidelines for designers and contractors to follow in order to reduce a building's overall environmental impacts, and improve occupant comfort (USGBC, 2009). Due to the influence of the LEED™ rating system and the acceptance of "green" building in general, many manufacturers of building products, especially interior finishes, have developed "green" product lines.

Structural steel is often credited as being an environmentally friendly building material due to its high recycled content and recyclability. According to the Steel Recycling Institute (SRI), 83.3% of US steel was recycled in 2008 (SRI, 2009). This represents over 82 million tons of material. According to the same report, structural steel made in North America contains a minimum 28% recycled content and some products contain over 90%. Structural steel has one of the highest recycling rates among steel products, reaching 97.5% in 2008. Despite these favorable statistics, further improvements to the processes of raw material extraction, transportation, fabrication, and installation of structural steel are undoubtedly possible and should be identified and evaluated through research.

At present, the portion of the LEED™ rating system related to energy conservation is primarily directed at encouraging reductions in life-cycle energy consumption for building operations. Energy use in operations has been shown to have the greatest impact over the life of a building (Guggemos & Horvath, 2005). However, the LEED™ certification credits related to materials selection designate minimal material toxicity and recycled and regional material content as the primary basis for characterizing an environmentally superior building material (USGBC, 2009). The rating system places less emphasis on reducing *embodied energy* of materials, or the total energy used to bring a product to market, including raw material acquisition, manufacturing, and transportation. Evaluating products based on total embodied energy has the potential to significantly improve a building's energy use and reduce pollution. However, this type of evaluation is a complex process, involving detailed accounting of material and energy inputs including raw material extraction, transportation, and installation.

The success of LEED™ has brought greater awareness to the need for environmentally-responsible design and construction. However, in regard to structural steel, the rating system generates little incentive to improve the production impacts beyond increasing recycled content percentages (Materials and Resources Credit 4) and reducing material transportation distances (Materials and Resources Credit 5). Throughout the steel industry, such practices have largely become a standard practice due to basic economic efficiency. The recycled and regional content of materials are important factors for reducing energy and emissions but do not reward or promote efforts to improve other process improvements or post-manufacturing phases such as fabrication and erection. Fabricators may have opportunities to reduce energy use and emissions generated during fabrication by reducing waste, as well as re-evaluating internal processes, equipment types, and the sourcing of stock materials. Steel erectors, downstream from fabricators in the steel delivery process, may have opportunities to limit emissions by better managing equipment use and reducing idle machinery time. A more comprehensive approach to sustainable building would include the evaluation of environmental impacts at all phases of the construction process.

As the green building movement grows, the demand for sustainably-manufactured building materials increases. Individual steel fabricators have a new market incentive to separate themselves from their industry competitors by developing more sustainable material options for customers.

Reducing the environmental impacts of the steel fabrication process may be achieved by first performing a detailed analysis of current practices to help identify key areas for improvement. Life-cycle assessment methodology offers a comprehensive evaluation model for energy consumption and emissions releases in steel delivery. The process of performing an LCA involves detailed accounting of environmental impacts associated with a product's life cycle. This research will focus on the development of an LCI analysis of the structural steel fabrication process, which includes material production and transportation. The results can then serve as the basis for informed action towards improving the sustainability of the overall steel delivery process. It should be noted that this study does not address the life-cycle impacts of steel erection, operation, or material demolition and end-of-life.

1.5 Acronym Definitions

ASTM: American Society for Testing and Materials

AISI: American Institute of Steel Recycling

BOF: basic oxygen furnace

BOH: basic oxygen hearth

CFC: chlorofluorocarbons

CH_4: methane

CMU: Carnegie Mellon University

CO: carbon monoxide

CO_2: carbon dioxide

Cr: chromium

DOE: Department of Energy

EAF: electric arc furnace

EIO-LCA: Economic Input-Output Life-cycle Assessment

EPA: Environmental Protection Agency

GDI: Green Design Institute

GWP: global warming potential

I-O: input-output

IPCC: Intergovernmental Panel on Climate Change

ISO: International Organization for Standardization

LCA: life-cycle assessment

LCC: life-cycle costing

LCI: life-cycle inventory

LEED™: Leadership in Energy and Environmental Design

NAICS: North American Industry Classification System

NO_x: nitrogen oxides

N_2O: nitrous oxide

NREL: National Renewable Energy Laboratories

O_3: ozone

PM: particulate matter

PM_{10}: particulate matter less than 10 microns in diameter

PVS: Paxton & Vierling Inc.

RSF: Research Support Facility

SETAC: Society of Environmental Toxicology and Chemistry

SO_2: sulfur dioxide

SO_x: sulfur oxides

SRI: Steel Recycling Institute

USGBC: United States Green Building Council

USGS: United States Geological Survey

VOC: volatile organic compounds

2 LITERATURE REVIEW

Chapter 2 contains the literature review research on the topics of life cycle assessment, sustainability, emissions, and the steel industry. These topics establish the need for additional research on the energy and emissions associated with structural steel fabricators. Life cycle assessment methodologies are evaluated and compared in order to identify which is most appropriate for this research.

2.1 Historical Energy Reductions in Steel Delivery

Iron and steel have long been primary building blocks for civilization. The original use of iron by man dates back over 4,000 years; iron production is estimated to have begun around 1300 BC with the use of simple ovens to heat ore to a point where it could be hammered into usable wrought iron shapes (De Beers, Worrell, & Blok, 1998). Steel, which is made by combining iron and carbon, dates back as far as 1000 BC (Bjorhovde, 2004). Although these original steel making practices focused on the production of simple tools and weapons, today the material has become nearly ubiquitous due to its strength, weight, and flexibility (De Beers et al., 1998). Throughout the history of iron and steel production, energy conservation and efficiency in production have been recurring signals of technological advancement and industrial progress.

2.1.1 Modern Day Steel Production

Modern structural steel manufacturing in the US consists of two primary production processes: electric arc furnace (EAF) and basic oxygen furnace (BOF). Both methods are used to produce products manufactured from rolled sheet, such as hollow structural shapes and plate steel (Jones, 2010). BOF is used mainly to produce drawn or extruded steel shapes. EAF is the primary production method used for beams, angles, and channels.

2.1.2 Basic Oxygen Furnace Production

Following World War II, the US steel industry achieved unprecedented levels of productivity and output. The demand for steel was high and input costs were relatively low. The American standard production process was the basic open hearth (BOH) furnace method. The process, compared to modern standards, was slow and required tremendous heating energy and manpower to function. The basic process involved producing ingots, reheating them to about 2,400F degrees, and rolling them into slabs or booms, then reheating again for final processing into bars and rod before going to finishing mills (Stubbles, 2000).

The contemporary BOF steel-making process is similar to the traditional hearth-type method of production but uses an oxygen blast furnace instead of air. The use of oxygen allows steel to be produced using 20-30% less energy by increasing the heat during the process. The BOF method reduced refining time by a factor of 10 when compared to the BOH process (De Beers et al., 1998). Due to this performance, the BOF process was deemed one of the great industrial advancements (Hogan, 1971). The first oxygen converter (used to upgrade BOH mills to the BOF system) was installed in the US in 1954. By 1969, 42% of the nation's total steel was made using this method. Modern steel furnaces are now capable of producing over 500 tons per hour and use an average of 25% recycled content (Stubbles, 2000).

2.1.3 Electric Arc Furnace Production

Electric arc furnace technology utilizes steel scrap as the main material input. The basic operation of the EAF follows a batch melting process that uses an electric arc to melt steel to a molten state. The process requires exceptional heating of up to 3500F degrees in a short period of time. The EAF is a seven-step process: furnace charging, melting, refining, de-slagging, tapping, and furnace turn-around (Jones, 2010).

The electric arc furnace began to take hold in the US market during World War II. In 1940, only 2% of steel produced in the US came from facilities using EAF production methods (Warren, 2008). Between 1946 and 1970, the total amount of steel produced in EAFs increased from 2,563 Mt to 19,931 Mt. The size of EAFs grew significantly over that period, with 70-ton units in the 1940s to 150-ton units in the 1960s and 200-ton units in the 1970s; the largest being capable of melting 327 tons in three hours. Over this time, efficiency continued to improve due to size and technology. The producers discovered that higher power and step-up capability allowed for better efficiency. Original furnaces operated using 30,000 KVA and by the 1970s that increased to over 65,000 KVA (Hogan, 1971).

The EAF method has been increasing in market share of production since the mid-20th century. Most steel shapes for construction are already produced by EAF mills. The process is now being used to produce plate, primarily from scrap, which is making iron ore a less-needed resource. Smaller EAF production plants can be located anywhere in the country that has ready access to scrap steel. EAF production is much more efficient overall, consuming less energy, labor and resulting in more environmentally superior product compared to BOF produced steel. The process allows for up to 100% of recycled scrap materials to be used and reprocessed. (Bjorhovde, 2004).

2.1.4 Energy Efficiency in Steel Production

The iron and steel industry has a long tradition of efficiency improvements and energy reductions in the production process. Historians have documented significant early efficiency improvements as far back as 1760 when the amount of charcoal required for pig iron production was reduced to two loads per ton from 5.5 loads per ton in 1540 (De Beers et al., 1998). Further energy reductions came with the introduction of coke, a product of the heating of bituminous coal in the absence of air, to the production process. The first documented use of coke occurred around 1718 and did not take hold in the industry until about 1750 (Bjorhovde, 2004). Process energy continued to be gradually reduced over the next hundred years.

In 1860, the Bessemer process was first put to use. This technology allowed for steel to be melted by exothermic oxidation of carbon and other impurities by blowing air through the molten iron as it was heated (De Beers et al., 1998). The new process allowed for significantly cheaper, more efficient steel production, made at rate of about one ton of steel per ton of coal. Despite the energy savings, the process was imperfect. It proved difficult to control and yielded varying qualities of product. Due to these factors, the open hearth furnace was more largely adopted which was slower and required greater energy inputs but produced a higher quality and more consistent product (De Beers et al., 1998). However, the Bessemer process was eventually advanced, and became the basis for the modern basic oxygen furnace.

For EAF production, scrap preheating, a process of using waste heat from the process to heat scrap material before it enters the furnace, yielded a large reduction in input energy. Not only did this reduce electricity but in some cases it increased productivity by over 30% (Worrell, Martin, & Price, 1999). Between 1960 and 1990, the electricity required to produce a ton of EAF steel was reduced from 630 kWh/t to about 350 kWh/t in 1990 (De Beers et al., 1998). Today, a combination of electricity and other energy sources such as blown gasses are used to optimize the refining stage and further reduce energy requirements (USGS, 2009).

Over the past 50 years, the steel industry has made significant reductions in the physical energy required for the steel production process. Between 1958 and 1994, excluding the impact of scrap recycling, the physical energy intensity decreased from 35.6 GJ/t to 25.9 GJ/t and carbon emissions decreased from 0.88 tC/t to 0.50 tC/t (Worrell et al., 1999).

2.1.5 Steel Scrap Utilization

Scrap steel has been used in steel production for over 170 years. The reuse of scrap in production reduces energy use, resource depletion, and landfill waste. Steel recycling in the US reduces the annual energy equivalent to that used in 18 million houses, or roughly one fifth of US residences (USGS, 2007). The primary source for recycled steel in the US is salvaged scrap from old vehicles. In 2007, 53.7 Mt of scrap was sold to domestic consumers and over 16 Mt was exported abroad; the combined value was just over $20 billion. Steel mills were the primary consumers, purchasing 87% of the total. The feedstock for electric arc furnaces was 90% scrap steel (USGS, 2007).

As nations develop, the production of scrap is projected to increase. The growth of developing nations such as China and India will lead to the expanded production of automobiles and appliances. In the next 25 years—more automobiles, which are the leading source of scrap steel— are expected to be produced than the total made over the life of the auto industry (USGS, 2007).

2.1.6 Salvage and Reuse

The salvage and reuse of steel building materials is an increasingly viable alternative to new processed steel. Reuse removes the material from the waste stream and reduces input energy required for scrap reprocessing. In addition, the reuse of materials helps to establish markets for such products. This is demonstrated by the growth of the US recycling market. In 1960, the US recycling rate for all materials was 6.4%; in 2006, the national rate was 32.5% (USGBC, 2009). These transformations have occurred in parallel with the rapid growth of development, waste, and resource depletion. In the span of time between 1980 and 2006, solid waste grew 65% in the US to over 251 million tons per year. Construction waste is responsible for about 40% of the total (USGBC, 2009).

2.1.7 Structural Steel Material Types

Steel was first used as a structural building material in the US in 1867 for the construction of the Eads Bridge over the Mississippi River in St. Louis, Missouri (Bjorhovde, 2004). The original grades of structural steel used in the early 1900s were American Society for Testing and Materials (ASTM) A7 grade for bridge construction and A9 for buildings. These grades contained a higher level of carbon than what would be used for structural steel today, which made them difficult to weld. Structural steel advanced in the 1930s with the development of the A36 grade, a lower carbon content steel with more favorable qualities for welding. Today common structural grades are A572 and A588. More recent high performance structural grades include A992 and A709, used primarily for bridge steel, which have better weldability, strength, and ductility (Bjorhovde, 2004).

2.1.8 Current State of Steel Production

The US steel production industry is comprised of a total of about 116 plants. These are concentrated in Indiana, Ohio, Pennsylvania, and Michigan. An estimated 19% of all steel produced is for construction (USGS, 2009).

In 2008, US steel prices reached record levels due to high demand for steel and ferrous raw materials in China. Falling consumption toward the end of 2008 led to price decreases and output decreases. This is demonstrated by the fact that the leading producer of iron-ore pellets reduced output by 65% (USGS, 2009).

In 2008, steel production totaled 93.7 mmt (USGS, 2009). Fifty-eight percent was produced by BOF, whereas 42% was produced using EAFs. In terms of global production, the US produced less than 10% of the world output of 1360 mmt in 2008 (USGS, 2009).

2.1.9 Fabrication

To identify energy conservation opportunities within a process, the starting point should be those areas with greatest potential reduction at the lowest cost and greatest ease of implementation. These "low-hanging fruit" require the lowest investment relative to energy use and environmental impacts.

Fabrication facilities consume large amounts of electricity due to energy-intensive production processes and operations. Electricity is a primary input to the steel delivery process. In exploring opportunities to reduce the environmental impacts which are within the control of the fabricator, on-site electricity reduction is the obvious starting point.

The reliance on electricity as a primary input to fabrication can be viewed as a type of risk. Over the past 10 years electricity costs have increased consistently (Figure 1) (EIA, 2009a).

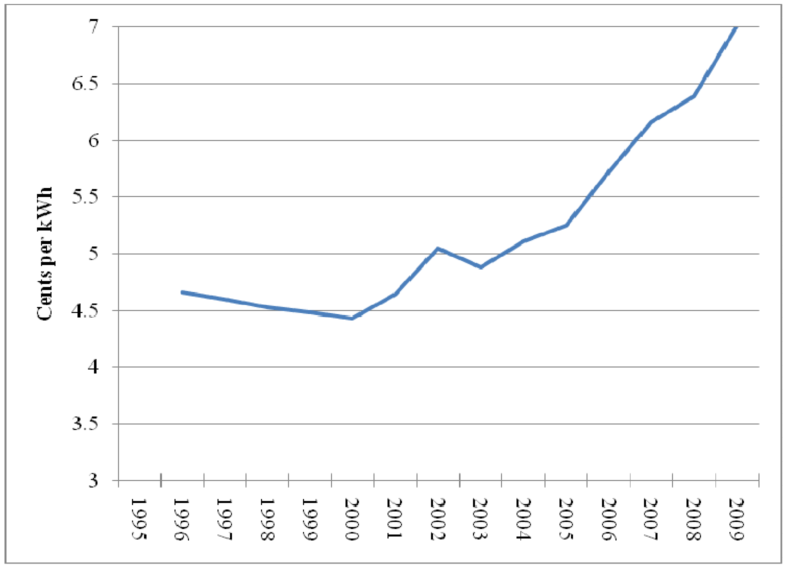

Figure 1. Average US Retail Price of Electricity: Industrial Sector (EIA, 2009a)

There is little indication that the trend will reverse. By making a modest investment in the short term, and therefore reducing the overall energy requirement for fabrication, the amount of risk associated with future electricity price fluctuations may be reduced. Reducing the amount of electricity use is also a primary means to reduce the carbon footprint for steel fabrication.

Little historical information is available related to the development of steel fabrication processes over time. No information was found related to energy performance of the fabrication phase. This may be due in part to much lower relative energy use and emissions from the fabrication phase relative to the material manufacturing phase. It is certain that energy efficiency improvements have been made to shop equipment. For example, automated plate cutting equipment has likely led to significant reductions in material waste as well as labor time involved in the template layout. However, no data are found quantifying the energy improvement associated with these advancements.

2.2 Life-Cycle Assessment

Life-cycle assessment (LCA) is a well-established tool for quantifying associated energy use and environmental burdens along the entire supply chain for a product or process. The method is used by researchers to quantify energy use and environmental impacts from "cradle-to-grave," including raw material acquisition, manufacturing, the use phase, and the end-of-life phase (Keoleian, 1993; Guggemos & Horvath, 2003; EPA, 2006).

The earliest LCA studies began in the 1960's to address concerns over shrinking supplies of natural resources. Over the years, numerous variations to LCA methodologies were developed and put into practice. However, due to lack of standardization and boundary definition, LCA studies were subject to misleading and incomplete data. In 1991, in response to demands for LCA consistency by State Attorney Generals and environmental organizations, the Society for Environmental Toxicology and Chemistry (SETAC) and the US EPA developed a consensus on the framework for conducting inventory analysis and impact assessment. The methodology was adopted internationally by the International Organization for Standardization (ISO) which developed the 14040 series to standardize the LCA framework (EPA, 2006).

According to the EPA LCA guide "Life-Cycle Assessment: Principles and Practice," there are four major components to the LCA study under the ISO framework: (1) goal definition and scoping, (2) inventory analysis, (3) impact assessment, and (4) interpretation (EPA, 2006).

The EPA defines these as follows:

> 1. *Goal Definition and Scoping* - Define and describe the product, process or activity. Establish the context in which the assessment is to be made and identify the boundaries and environmental effects to be reviewed for the assessment.
> 2. *Inventory Analysis* - Identify and quantify energy, water and materials usage and environmental releases (e.g., air emissions, solid waste disposal, waste water discharges).
> 3. *Impact Assessment* - Assess the potential human and ecological effects of energy, water, and material usage and the environmental releases identified in the inventory analysis.
> 4. *Interpretation* - Evaluate the results of the inventory analysis and impact assessment to select the preferred product, process or service with a clear understanding of the uncertainty and the assumptions used to generate the results. (EPA, 2006, p. 2)

There is broad acceptance of the ISO 14040 Series among the LCA research community. However, debate continues over LCA boundary definition and inventory data gathering methods (Joshi, 2000; Lenzen 2001; Lave, Cobas-Flores, Hendrickson & McMichael, 1995). Currently there are three primary methods for defining the boundaries to measuring inputs and outputs for an LCA. They are referred to as *process-flow* (or *process-based*), *input-output*, and *hybrid*, all of which are described herein.

2.2.1 Process-Based Life-Cycle Assessment

The process-based method allows the modeler to define the LCA boundary using process diagrams. These are used to capture the impacts and requirements of the entire process to a point where any excluded high-level impacts are negligible. Some critics argue that the subjectivity and unavoidable exclusion of inputs and outputs can lead to incomplete and inaccurate estimates of environmental impacts (Hendrickson, Horvath, Joshi, and Lave, 1998). Thus, any skeptical reviewer of a given study can argue that stages were omitted and results are therefore flawed. Process models have also been shown to suffer from truncation errors that can lead to the omission of as much as 50% of the process inputs, especially for service intensive industries (Lenzen, 2001). However, such omissions are generally assumed to be negligible relative to the primary direct inputs, but the omission nevertheless exists. The lack of a standardized process for establishing the boundary and the subjectivity allowed to the modeler are the primary reasons for a lack of confidence in process-based LCA results (Suh, et al. 2004).

2.2.2 Economic Input-Output Based Life-Cycle Assessment

The first alternative to the process model is economic input-output life-cycle assessment (EIO-LCA), which incorporates all the process inputs and outputs throughout the entire supply chain of the national economy. The economic input-output assessment methodology was developed in the 1930s by Harvard economist Wassily Leontief (EPA, 2006). The method used economic data, based on producer receipts for all goods and services throughout the entire direct and indirect supply chain, to estimate the nation-wide economic impacts of a given product or service. In the early 1990's, the Green Design Institute (GDI) at Carnegie Mellon University (CMU) created a tool to estimate environmental impacts as well as economic impacts across the economy. The GDI made this possible by applying modern computing capability to combine environmental with economic census data through Leontief's theoretical model. The GDI has developed this into a free public tool for performing EIO-LCA analysis that is accessible via the internet. In the past, the calculations had to be carried out manually, which was a highly time-intensive process. This method provides a robust inventory data set, which incorporates all the associated impacts across the entire US economy. It does not take into account the complete life-cycle of a given product, but provides a total embodied energy from "cradle to gate," starting with raw material and encompassing the entire direct and indirect supply chain. Since the data are based only on US economic reporting, product inputs that are made outside of the US are not included.

The EIO-LCA data set is entirely from 1997, which creates the potential for inaccuracies. Industries that have experienced either a high level of technological change or have improved production efficiencies, will be misrepresented due to the antiquated data. The updated 2002 dataset was released in 2009, but it provides incomplete emissions data. The 2002 data does not yet include the category "Conventional Air Pollutants", which reports SO_2, NO_x, CO, VOC, and PM (GDI, 2005). Because these pollutants are measured in outputs within the LCA inventory, the 1997 dataset was selected for this study.

The EIO-LCA methodology uses matrix algebra to capture the requirement for producers to produce a given product or service, as well as all upstream suppliers, and suppliers of suppliers, of that producer (GDI, 2005). In the input-output model, the matrix format is used to determine the inputs from 491 sectors associated with a dollar value of economic output in a given sector. The direct output from one sector can be represented as (GDI, 2005):

$$\mathbf{X_{direct} = (I + A)y}$$

$\mathbf{X_{direct}}$ = the direct output

y = the demand of goods,

A = represents the sector's relationships to all other sectors

I = the sector of demand

Given that **y** is the demand for goods, then **I** × **y** represents the amount of production required. In addition, **A** × **y**, represents the production in all other sectors required to meet that demand. This formula only accounts for the first level of supply to the final producer. The input-output model continues to identify output from additional levels of suppliers by multiplying the direct requirements by the final demand at each supplier level. The final output is then determined by combining tiered outputs at each supplier level:

$$\mathbf{X = (I + A + AA + AAA + \ldots)y}$$

X is now representative of all supplier outputs, beyond only the direct supplier outputs. This can also be represented as:

$$\mathbf{X = (I - A)^{-1}y}$$

The model available through the GDI then assigns various non-economic impact categories to each industry dollar of output. This is done by multiplying the total economic output at each sector by the associated environmental impacts.

Currently the impact categories available for the 1997 economic data are Conventional Air Pollutants, Greenhouse Gasses, Energy Toxic Releases, and Employment (GDI, 2005).

Classification categories for all products or services for the entire US economy are limited to the 491 predefined sectors. All products within each product sector have the same impacts per dollar of input. This aggregation of data can lead to the misrepresentation of products or services that have specialty characteristics or are difficult to place within a predefined sector (Hendrickson et al., 1998). Accordingly, aggregation limits one's ability to investigate a specific product within that sector. If a few very large organizations dominate the sector in terms of economic expenditure, their production process impacts will overshadow the impacts of smaller, possibly more efficient, producers in that same sector. When a specific product or process is evaluated, a process model can more accurately identify the direct process requirements (Lenzen, 2001).

The GDI tool's EIO-LCA sectors are defined by product types. The most reliable use of the tool is when products and services are well defined by the sector in which they are categorized. In some cases it can be difficult to accurately assign products to representative sectors. For example, for the analysis of a building's impacts, the database has sectors identified by type of construction (commercial, residential, highway, bridge, etc.) which offers only very aggregated, general information. However, the individual construction materials are captured in material categories (ready-mix concrete, millwork, etc.), which offer less aggregated information. In order to capture these impacts, the modeler is forced to analyze each building material individually, and then combine the results to establish building-wide material impacts. Once material impacts are determined through EIO-LCA analysis, a construction phase model would then be developed using a process-based approach. This combination of the two methods is typically referred to as a *hybrid* or *input-output based hybrid* LCA model.

2.2.3 Hybrid Life-Cycle Assessment

Since there are clear drawbacks to each of the LCA methods, the modeler can utilize a combination of both by creating a hybrid LCA. Bilec, Ries, Matthews, and Sharrard (2006) describe four primary hybrid methods in detail, including: tiered, input-output based hybrid, integrated hybrid and "augmented process-based hybrid". Each incorporates varying degrees of the EIO-LCA method (Bilec et al., 2006). The input-output hybrid model utilizes the EIO-LCA inventory data to effectively establish a complete economy-wide boundary around the study, incorporating both indirect and direct requirements into the model. At the most simplistic level, a hybrid input-output LCA uses a process-based approach for analysis of a specific component (e.g. steel fabrication), and the aggregated economic input-output data for upstream and indirect impacts outside the process-based boundary. The flexibility of the boundary allows for the model to be manipulated depending on available data and resources for the study (Suh et al. 2004).

2.2.4 Discussion of Life-Cycle Assessment Methodologies

In general, strict process LCA modeling serves as a useful tool for evaluating a specific industrial process or product manufacturing stage. In contrast, input-output analysis is more comprehensive and inclusive of all of the related indirect inputs for a given product. Process analysis involves defining a specific boundary of the study, where EIO-LCA models have a nearly complete scope, limited only by the exclusion of foreign data for foreign inputs. The quality of an input-output analysis can be limited due the aggregated nature of the data, which provides only as much detail as the 491 predetermined sectors offer. When a specific process evaluation is conducted, the process-based LCA can provide a more useful inventory of the process stages and impacts which the process manager can control and measure. For larger national issues and investigations of general rather than specific practices, EIO-LCA data can be more inclusive (Bullard, Penner, & Pilati, 1978).

When evaluating an industrial process, such as steel fabrication, a strict EIO-LCA analysis would provide average embodied energy and environmental discharges per dollar of steel product in a US Commerce Sector category, such as "Structural Steel Fabrication." This would include a somewhat diverse group of organizations, including but not limited to, some steel fabricators. Therefore, the EIO-LCA analysis would provide a good depth and breadth of information on the economy-wide impacts of the fabrication process, but not necessarily provide data that are directly representative of the process used by any one steel fabricator. If the goal of the study is to identify areas for improvement from among factors a specific organization has control over, then those processes should be disaggregated from the EIO-LCA analysis and their impacts quantified as accurately as possible using a process-based approach. The EIO-LCA data alone would be useful to approximate the net impact of the overall process, and to evaluate the impacts of changes to that process, but would not provide any useful data for the improvement of that process. A process model would have the potential to show greater detail at each stage, and therefore provide a more useful foundation for process improvement. Despite different approaches, the final tabulation of upstream impacts from a complete process model and EIO-LCA model, would in theory be identical (Bullard et al., 1978). A critical distinction is that the stand-alone EIO-LCA model does not capture the downstream life-cycle impacts, including the use- and end-of-life phases.

Much of the criticism surrounding the process LCA model stems from its failure to capture many of the associated inputs, such as indirect impacts and services. This criticism is well-founded; however, the process-based LCA design can be utilized to generate a more representative life-cycle inventory for a specific manufacturing process. Once the process LCA is established, additional inputs that cannot be easily quantified, such as indirect costs, can be evaluated using the EIO-LCA database. Given the trade-offs, a hybrid input-output analysis should offer the most accurate LCA data and appears suited to the steel fabrication process.

2.2.5 Life Cycle Assessment as a Tool for Building Design and Material Selection

The movement towards designing and building more sustainable structures has primarily followed established design criteria defined by the USGBC and other certification bodies. Rating systems such as LEED™ generally establish the greatest incentive to limit the energy consumption of the building in the operational phase, and to improve the environmental quality of the interior environment for occupants. Material selection criteria promote recycled and regional content and low toxicity products. These factors provide a starting point for evaluating some of the environmental tradeoffs between products. However, such factors fall short of providing a comprehensive environmental profile of a product. In some cases, materials that have high levels of recycled content are shipped great distances to the project site without any consideration paid to the transportation impacts.

The value of LCA in design is that it can help inform decisions that affect the project over the entire life-cycle of the building. The focus of sustainable building has traditionally been on the building-use phase because the greatest opportunity for net reduction in environmental impact with minimal required analysis is for this building-use phase. It is fairly simple to evaluate the 50-year life cycle value of high-efficiency lighting fixtures compared to a lower cost, lower efficiency alternative. However, currently it is much more difficult to determine the associated environmental impacts of the production of one lighting system versus the other. There is reason to make the assumption that the use-phase benefits outweigh the potential manufacturing, transportation, maintenance, or end-of-life impacts, but it is difficult to accurately determine.

In the past, and to a large extent in the present, the process of completing an LCA analysis was highly involved and complex, which made project-by-project material comparisons using LCA cost prohibitive. In addition, there are no universally agreed upon boundaries for life-cycle assessments which can lead to order of magnitude discrepancies in comparisons (Keoleian, 1993). The issue of the characterization of relative environmental effects further complicates the process of evaluating and comparing similar materials. This can force a design team to attempt to determine the relative impacts of natural resource depletion, versus CO_2 emissions, versus VOC emissions. This is neither their area of expertise nor a good use of their time. Technology is gradually improving the ability of a designer to access LCA information. In time, LCA may become a practical and easily accessible and design tool.

2.3 Emissions & Greenhouse Gasses

The production of structural steel is an energy-intensive process that generates emissions throughout various stages of production including material extraction, manufacturing, and transportation. According to the EPA, greenhouse gasses absorb terrestrial radiation that would otherwise escape the earth's atmosphere, causing the greenhouse effect (EPA, 2009). Common greenhouse gasses that increase global warming include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3). Other gasses with measurable effects on global radiation include carbon monoxide (CO), nitrogen oxides (NO_x), and sulfur dioxide (SO_2) (EPA, 2009). Table 1 shows the historical growth of greenhouse gas accumulations in the atmosphere.

Table 1. Historical Comparison Atmospheric Greenhouse Gas Concentrations (EPA, 2009)

Atmospheric Variable	CO_2	CH_4	N_2O
Pre-Industrial Concentration (1750)	278 ppm	0.715 ppm	0.270 ppm
Atmospheric Concentration (2007)	379 ppm	1.774 ppm	0.319 ppm

Carbon Dioxide (CO_2) is the largest contributor to the enhancement of terrestrial radiation (EPA, 2009). It is the oxidized form of carbon, being the primary building block for life on the planet. Since human industrialization, carbon dioxide concentrations in the atmosphere have increased by 35%. The combustion of fossil fuels is the primary anthropogenic contributor to increasing levels of CO_2 in the atmosphere. The increased amount of CO_2 in the atmosphere is leading to climate change and will result in the warming of the planet (EPA, 2009).

Methane (CH_4) is produced through anaerobic decomposition of organic matter. Methane is also emitted in the production of fossil fuels such as natural gas and petroleum as well as coal mining. Coal is the primary fuel source for electricity production in the United States. According to the EPA, atmospheric quantities of CH_4 have increased by 143% since 1750 (EPA, 2009).

Nitrous Oxide (N_2O) is released by synthetic fertilizer production, fossil fuel combustion, waste incineration, livestock manure, and nitrogen fixing plants. Atmospheric nitrous oxide levels have increased 18% from a pre-industrialized level of 270 ppb to 319 ppb in 2005 (EPA, 2009).

Carbon Monoxide (CO) is emitted from the combustion of fossil fuels. It has no direct radiative impact on the atmosphere. It does however have an indirect effect on the atmosphere by increasing levels of methane and ozone (EPA, 2009).

Global warming potential (GWP) is a measure of the relative impact of a given greenhouse gas. The measure allows for a relative impact comparison between different gasses. GWP is generally determined on a 100-year time frame. The calculation is based on the ratio of time-integrated direct and indirect radiative forcing for the release of 1 kg of a trace substance relative to 1 kg of a reference gas (EPA, 2009). Table 2 shows the GWP equivalents of common pollutants.

Table 2. Global Warming Potential Equivalents of Atmospheric Emissions (EPA, 2009)

Gas	Atmospheric Lifetime (yr)	100-year GWP
CO_2	50–200	1
CH_4	12±3	21
N_2O	120	310
HFC-23	264	11,700
HFC-143a	48.3	3,800
HFC-152a	1.5	140
HFC-4310mee	17.1	1,300
CF_4	50,000	6,500
C_2F_6	10,000	9,200
C_4F_{10}	2,600	7,000
C_6F_{14}	3,200	7,400
SF_6	3,200	23,900

2.4 Related Studies

Joshi (2000) describes five alternative models for using EIO-LCA framework to estimate energy and environmental burden across a range of product scenarios. Past studies have incorporated a combination of I-O and process-based LCAs, where I-O data was typically used to estimate upstream inputs and outputs, while a process-based estimate was used for the use phase and end-of-life phase. The new models show how, under certain circumstances, the EIO-LCA can be applied to the use-phase and the end-of-life phase.

Joshi (2000) uses the models to perform a life-cycle analysis and comparison of a steel vehicle fuel tank and a plastic tank. A previous study by the National Pollution Prevention Center at the University of Michigan was completed using the same product specification but using a process LCA model. The results of the two studies both showed that the plastic tank had lower embodied energy as well as environmental impacts. The author made the notable observation that a limitation of the EIO-LCA tool is that emissions are only reported from fuel combustion sources and other process pollutants are not included. Lastly, despite incorporating the full economy-wide boundary, the EIO-LCA tool did not show higher burden across all categories.

Bullard, Penner, & Pilati (1978) provide a hybrid LCA approach incorporating process analysis and input-output analysis in a hybrid tiered approach. The tiered approach uses multiple approximations of embodied energy by iteratively categorizing input goods and services by applicable I-O category. The good or service under study is divided into expense categories by an industry expert identifying high value expenses under major sector categories. These purchases are then evaluated for embodied energy in the I-O model and associated process energy for the disaggregated stage is added to the sum. Using uncertainty analysis, the result is evaluated to determine if it reaches an acceptable threshold. If the uncertainty percentage is not acceptable, additional analysis of the process components is undertaken and additional lower cost purchases are added to the I-O model. This process continues until an acceptable level of uncertainty is achieved (Bullard et al., 1978). The study's authors apply this approach to evaluate energy cost for a coal power plant. The same methodology could be applied using the EIO-LCA tool while incorporating the iterative process and uncertainty analysis.

In order to quantify and compare the environmental impacts of a structural steel building system versus a structural concrete building system, Guggemos (2003) developed a “cradle-to-grave” life-cycle assessment model for structural frames. The LCA used a process model to map and estimate energy use and environmental effects for the construction, maintenance, and end-of-life phases. The material acquisition operation stages were evaluated using EIO-LCA methodology.

For this study, building materials costs were estimated using R.S. Means and then applied to the EIO-LCA database tool which generated energy and environmental impact estimates based on product category. The study offers an example of a detailed process analysis that utilizes multiple LCA tools to develop a research model that is highly inclusive of all primary life-cycle inputs and outputs. Figure 2 is the structural steel construction phase process diagram from the research, identifying those activities included in the analysis.

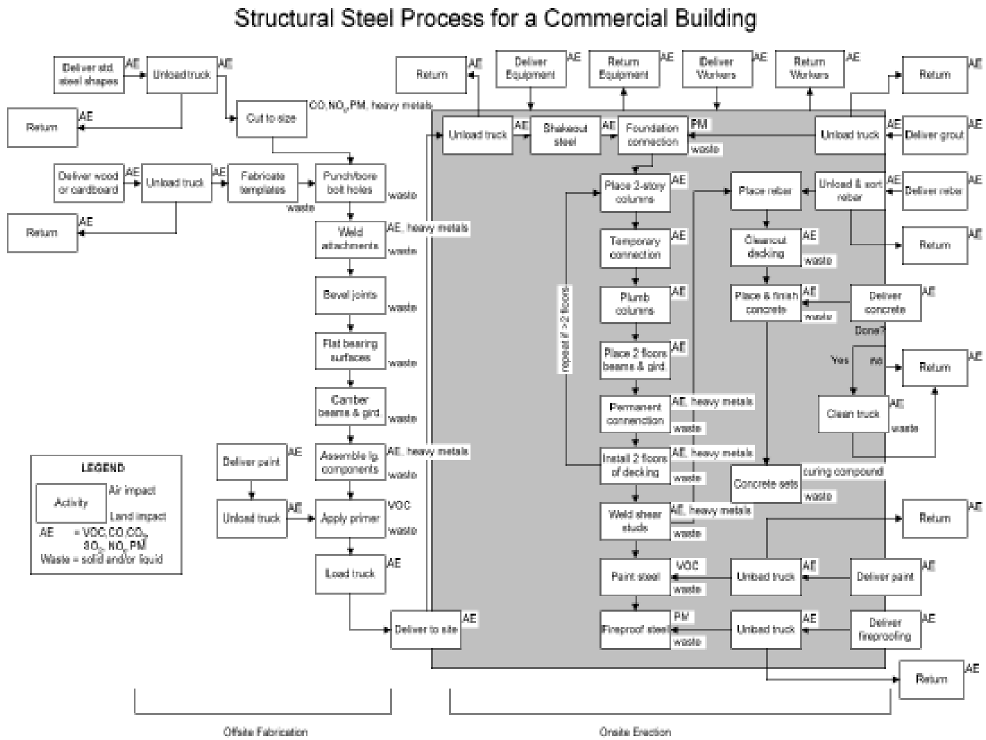

Figure 2. Construction Phase Process Diagram for Structural Steel LCA (Guggemos, 2003)

Guggemos (2003) found that the construction phase, including fabrication, of a steel frame building accounted for only 1% of the total life cycle energy. The use and maintenance phases of the steel framed building accounted for 88% of the total energy over the entire life-cycle of the building and materials accounted for 11%. The fabrication phase consumed 156 GJ of energy and generated 12.2 mt CO_2, where on-site construction accounted for 1603 GJ of energy and 120.5 mt CO_2.

Cole and Kernan (1996) evaluate life-cycle impacts of wood, concrete and steel structural systems for a case study building. Estimates of initial embodied energy of the building materials and construction were similar at 4.54, 5.13, 4.79 GJ/m^2 for wood, steel, and concrete respectively. In this case, the study was based in Canada and the environmental attributes were calculated using a corporate database. No detail was provided for how manufacturing, fabrication, and erection phase impacts were estimated. No process diagrams for steel fabrication are included in the methodology section.

Norgate, Jahanshah, and Rankin (2007) provide a summary and comparison of past studies done by the authors for CSIRO Minerals in Australia. The purpose of the studies was to use "cradle-to-gate" life-cycle inventory of various metal production processes. The researchers used a traditional process flow model, mapping broad production stages such as, mining, crushing, blast furnace, etc. Inventory data was based on processing data available from literature. Environmental impact categories were based on the IPCC (Intergovernmental Panel on Climate Change) characterization model. The results are limited to the total embodied energy in the direct production phases and only CO_2 and SO_2 environmental emissions. The researchers found that the gross energy requirement for steel production was 23 MJ/kg and 2.3 kg CO_{2e}/kg. A limited process map provides little detail of what is included within the project boundary making it unclear what inputs were evaluated. Although the results provide a compelling comparison of various metal production processes, it would be useful to identify energy requirement and emissions data for each stage of the production process. Lastly, the process model could be augmented by including economic input-output data to address the supply chain. The study offers useful information related to the emissions and energy use for the material production phase, but does not address downstream stages such as fabrication, transport, and erection.

3 RESEARCH METHODOLOGY

Chapter 3 defines the research methodology used for the study. Here the project-specific LCA methodology is outlined and specific data sources are identified. This research utilizes LCA methodology within a case-study project.

3.1 Case Study Research

This research relies on quantitative LCA evidence from a case study project to develop and report findings. Case study research is a useful means of contributing to the base of knowledge through improved understanding of real world events and phenomena (Yin, 2008). Detailed case-specific studies serve as single experiments that contribute to a larger developing body of research. At its essence, case study research is a way of investigating a research topic by systematically following a set of predetermined methods. The case study results will provide energy use and emissions data from a facility-specific steel fabrication process that can be compared to existing aggregate industry data. The alternative process improvements developed in this research are most appropriately determined by evaluating an existing real-world process. A representative case study provides detailed data from a fabrication facility that can inform future research. However, a limitation of this approach is that it only provides information from one facility and structural steel for one project.

3.2 Life-Cycle Assessment

This study uses hybrid life-cycle assessment methodology to complete a comprehensive inventory of inputs and byproducts for the fabrication of structural steel members, including beams, columns, and subcomponents. Various LCA models are discussed in detail in Chapter 2. A hybrid input-output LCA model allows for detailed process data to be combined with economic input-output data, resulting in a comprehensive life-cycle inventory. The process-based component of the hybrid model involves process mapping of operations related to the fabrication of primary structural members within the fabrication facility as well as the associated transport. Mapping involves documenting equipment specifications and process durations for each step in production in order to determine process requirements for the fabrication stage. Elements outside the process boundary are then captured using EIO-LCA data, which is based on producer cost. Following hybrid input-output methodology, indirect costs and upstream stages are quantified using the Carnegie Mellon University (CMU) Green Design Institute (GDI) online tool for economic input-output life-cycle assessment (GDI, 2005).

3.2.1 Goal Definition and Scoping

The goal of this study is to identify key areas for the reduction of energy consumption and emissions in the fabrication phase of the structural steel delivery process for building construction. Since structural steel members vary significantly from building to building, the data gathered for this LCA will use a single case study building and a single steel fabricator. The LCA model will provide a detailed inventory of energy use and environmental emissions associated with each stage of fabrication, material sourcing, and transport. Energy use in fabrication will be measured using process-based analysis and utility records from the fabricator. Atmospheric emissions associated with energy use will be calculated using public sources including, Environmental Protection Agency (EPA) emissions data, the National Renewable Energy Laboratories' (NREL) Life-Cycle Inventory Database, and the Carnegie Mellon University Green Design Institute's (GDI) Economic Input-Output Life-Cycle Assessment (EIO-LCA) database (a tool used to estimate both direct and upstream supply chain impacts) (GDI, 2005; NREL, 2009). With a life-cycle inventory model developed, feasible process improvements will be compared to existing practices and the associated energy savings and emissions reductions will be reported.

3.2.2 Research Boundary

Given the complexity of any comprehensive product life-cycle inventory, the determination of the assessment boundary can be highly subjective. Therefore it is critical that the boundary be clearly defined for the study. In this case, the boundary of the study is located as far as possible up the steel delivery supply chain. This is possible through the use of EIO-LCA methodology which theoretically accounts for all direct and indirect upstream supplier impacts, beginning with raw material acquisition (Hendrickson et al., 1998). At the opposite end of the production process, the research boundary ends at the point the material departs the fabrication plant. For this research, the analysis is used to determine a baseline against which alternative fabrication, transportation, and material sourcing strategies are compared.

Figure 3 shows the general boundary definitions used for this research.

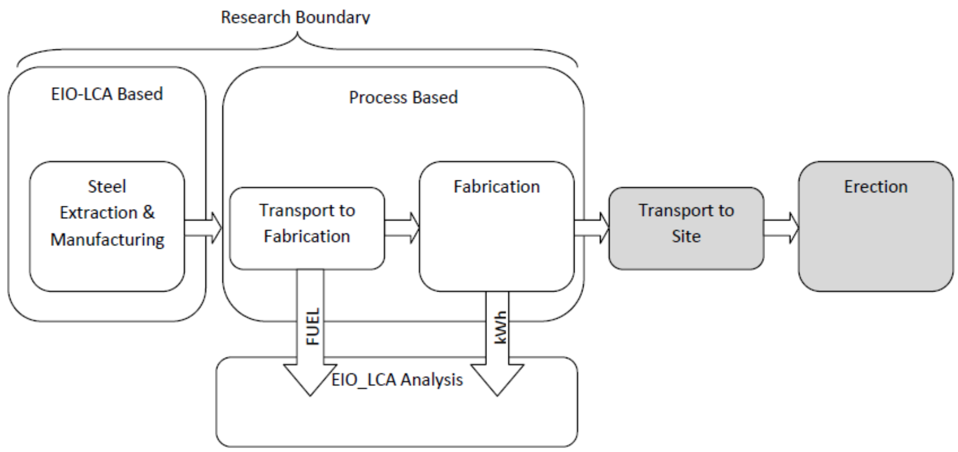

Figure 3. Research Boundary for Structural Steel Fabrication.

The construction phase impacts associated with the case study project are in the process of being quantified by another researcher involved in the same larger research project. Those results however, are not included in this report.

3.2.3 Study Phases

Impact assessment involves the evaluation of impacts on the environment, including pollution and resource depletion (USEPA, 2006).

The structural steel delivery process involves multiple stages that require impact assessment in order to develop a comprehensive analysis. In a typical LCA study, the primary life-cycle phases include material extraction, manufacturing, transport, assembly, use, and end-of-life. Given that the purpose of this research is to identify opportunities for improvement of the structural steel fabrication process, the erection, building use-phase, and end-of-life phase are excluded from research boundary.

3.2.4 Framework

The framework of the LCA model is comprised of inputs from the case study project and tools for determining the associated emissions and life-cycle energy use. Inputs include measured figures related to the case study project such as material cost, fuel cost, and electricity cost. Outputs are energy use and environmental emissions. The Research Model in Figure 4 details the framework for evaluating inputs and outputs in the delivery of steel members.

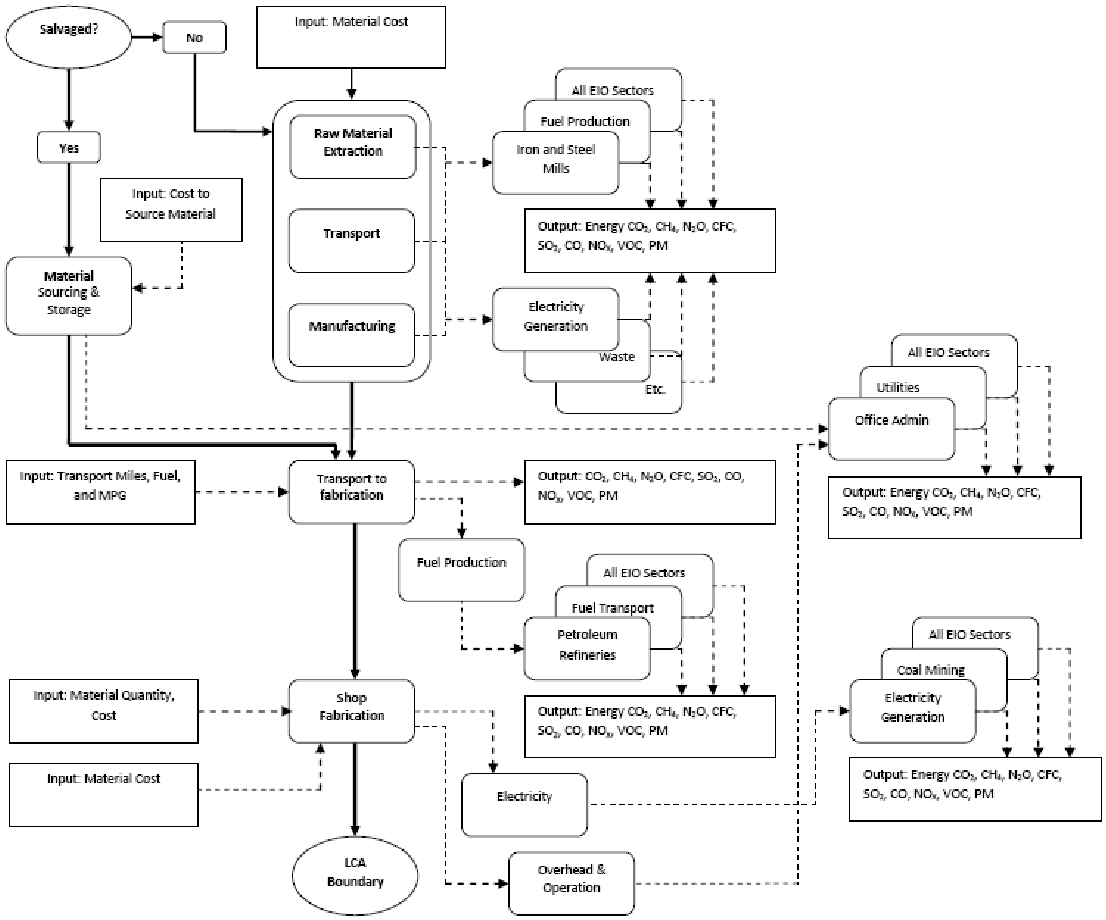

Figure 4. LCA Research Model for Steel Fabrication

3.2.5 Emissions and Energy Use

The direct and supply chain impacts associated with the structural steel used in the case study project are calculated using fabrication facility data, EPA emissions of sources depending on the level of direct process data available. The steel elements include: new manufactured structural columns, salvaged columns, beams, and associated subcomponents. Direct impacts include the emissions associated with material extraction, steel manufacturing, transportation, and fabrication processes. Additional upstream supply chain impacts are also accounted for using EIO-LCA data.

3.2.6 Impact Assessment

Impact assessment is an important step in the analysis of LCA results. The LCA inventory analysis is intended to quantify energy use and emissions environmental associated with a given product. The impact assessment stage then relates those impacts to environmental degradation and human health in order to weigh various outcomes and evaluate the consequences. This stage of analysis is left for a future research project. This study is limited to the inventory phase, and includes only emissions quantities and energy consumption rates.

3.2.7 Interpretation

Interpretation involves systematic evaluation of the results to reach conclusions and identify limitations. It also ensures that the findings are understandable, complete and consistent (USEPA, 2006).

The completed LCI model provides a detailed inventory of energy use and emissions associated with each stage of steel delivery through fabrication. The fabrication process is then evaluated to identify steps high in energy consumption and/or emissions releases. With high-impact areas identified, process modifications are suggested. These hypothetical changes to the delivery process are then incorporated into the updated model to evaluate and quantify improvements. This study goes beyond only quantifying the impacts from the fabrication process, but tests alternative scenarios for impact reduction potential. Limitations of the study are identified and discussed.

3.3 Data Sources for the Case Study LCI

The case study project includes multiple data input sources as well as tools to determine the associated emissions and energy use. Here these sources are detailed for the case-study project in the context of the larger LCA methodology.

3.3.1 Fabrication Process Inputs

A process map has been developed for beam and column fabrication at the fabrication facility of Paxton & Vierling Steel (PVS). A process map identifies the primary steps in the flow of material through the fabrication facility. At each step, work durations are recorded through observation and the associated equipment energy usage is calculated using published energy consumption rates from equipment specifications. Due to the high level of variability in the fabrication process, only the primary steps common to all columns of similar type are included. The process data are used to identify the impact of each primary step relative to the total energy used in fabrication. Figure 5 details the steps that are included in the inventory.

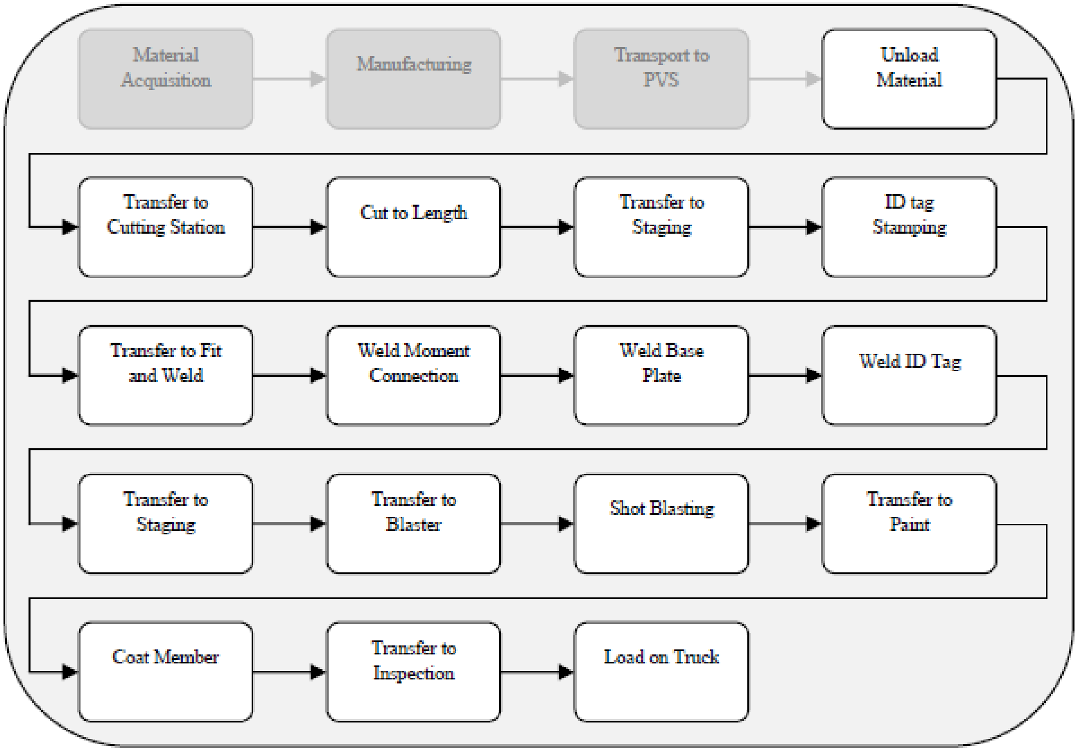

Figure 5. PVS Steel Fabrication Process Map

Total electricity used in the fabrication process is estimated based on kilowatt-hours per ton of fabricated steel using 2008 electricity consumption and steel fabrication records provided by PVS. This data is more reliable than the process-based data for total energy use because it includes all electricity related to the fabrication process including lighting, office operations, and other miscellaneous equipment. The combination of the process-based analysis and the actual 2008 consumption data allows for each process step to be evaluated relative to the total energy, both directly and indirectly related to the process.

To determine energy use and emissions totals, energy use is converted into dollar value of kilowatt-hours and input into the GDI EIO-LCA tool using North American Industry Classification System (NAICS) Sector #221100 “Power Generation and Supply” data.

Welding emissions are calculated based on electricity consumed by welding equipment. No emissions associated with the direct melting of welding rod are included as emissions are different than those measured in other areas of the study. The primary emissions from welding rod are chromium, manganese, nickel, and particulate matter. (Kura, Judy, Wisbith, & Stone, 2000).

3.3.2 Fabrication: Overhead

In addition to the direct process impacts of fabrication, other indirect impacts associated with the process are included. These include impacts associated with indirect purchases such as office equipment, consumables, heating fuel, etc. The energy use and emissions are estimated and included in the inventory by applying 5% of the contract cost to the NAICS Sector #561100 “Office Administration” in the GDI tool.

3.3.3 Material Sourcing: New Stock Material Fabricated by PVS

Embodied energy and emissions are calculated by applying material cost to the GDI tool for NAICS Sector #321111 “Iron and Steel Mills”. The estimated material cost of the manufactured columns, beams, and subcomponents is determined based on material weight. Cost for the steel materials is a price per ton average established through correspondence with the PVS Project Manager (S. Jundt, personal communication, January 13, 2010).

3.3.4 *Alternative Material Sourcing by the Fabricator*

In addition to new steel, many of the case study columns were salvaged pipes from the oil and gas industry. The raw material manufacturing impacts for the salvaged pipe columns are assigned to the previous life of the material and are excluded from the inventory. The justification for this approach is based on the assumption that the material served its full intended product life as gas pipe, the purpose for which it was originally produced. The pipe column material cost has been provided by PVS for the research project (S. Jundt, personal communication, December 2, 2009).

Many of the pipe columns used on the project were filled with concrete due to structural requirements. Since a typical equivalent alternative column, such as a W-shape would not have a concrete component, the emissions associated with the material production are included in the comparison. The energy use and emissions associated with concrete production and transport are determined using the GDI tool for NAICS sector #327320 “Ready-Mix Concrete”. Concrete Costs are based on RS Means regional delivered concrete prices (R.S. Means, 2008).

3.3.5 *Material Sourcing and Storage*

The salvaged piping is considered to have completed a life cycle after serving its useful life as oil and gas piping. Salvaged pipe columns began the new life cycle associated with the NREL project at the point they entered the salvage storage yard. Therefore, the impacts associated with the material manufacturing phase are excluded from the inventory. However, there are measurable impacts associated with sourcing and handling of the columns. Under EIO-LCA methodology, the impacts of a product are directly related to cost. For a typical manufactured column, much of the cost of production is associated with the raw material processing and steel manufacturing phases. The emissions per unit of cost are therefore much greater than the emissions associated with an equivalent unit cost from a salvage facility. A salvage operation's costs are primarily associated with the purchase and sourcing of scrap materials, which is a much less energy intensive and polluting process per ton of steel. The impacts associated with the salvage process were captured by assigning 20% of the material cost spent on the salvaged pipe columns to the GDI database using the category for Office and Administrative Services, (NAICS Sector #561100). This represents the estimated energy use and emissions associated with the sourcing and handling of salvaged materials.

3.3.6 Transportation

The transportation of steel originates from the mill or salvage yard and terminates at the fabrication shop. The transportation impacts are derived from the NREL Life Cycle Inventory Database category for *Heavy-Heavy Duty Truck* transport. Impacts are determined by total gallons of diesel combusted (NREL, 2009). The fuel production and associated upstream impacts are determined by applying wholesale fuel cost to the NAICS sector #324110 "Petroleum Refineries" within the GDI tool. Fuel cost per gallon was determined using historical data from the US Energy and Information Administration on wholesale diesel prices (EIA, 2009).

A full truck load is assumed to be 21,772 kg of steel. The fuel consumption rate of 6.6 miles/gallon (mpg) for heavy-heavy trucks is based on research from the California Air Resources Board (Huai, Shah, Miller, Younglove, Chernich, and Ayala, 2006). The mileage of truck travel is determined by the average distance between all project steel suppliers and PVS. Each truck was estimated to travel half the return distance empty to account for the complete delivery impacts. One half of the return distance is how far the truck is estimated to travel empty before receiving the next load. Therefore, the full round-trip impacts are not included.

3.3.7 Inflation Adjustment

As previously described, the GDI tool requires that products or services to be evaluated are assigned to a NAICS sector and converted into dollar values. However, a limitation of the GDI dataset is that the most current base year for data on the pollution categories used in this research is 1997. In order to calculate relative impacts of current input data using 1997 emissions figures, the corresponding dollar value of inputs must be adjusted back to 1997 prices. The sources for converting US dollars back to 1997 values vary by product type.

Steel manufacturing prices are based on the stock material prices paid by the fabricator. For raw material prices, the wholesale price of stock steel is adjusted based on values given in the Commodities Prices Yearbook 1999 & 2009 (CRB, 2009; CRB, 1999).

Fuel production impacts are calculated from the cost of fuel consumed during material transport. The price of wholesale fuel is adjusted based on values given in the US Energy and Information Administration Report titled; *Weekly Midwest No 2 Diesel Wholesale Sales by All Sellers (Cents per Gallon) 1994-2009* (EIA, 2009b).

Electricity prices are adjusted using the industrial sector retail prices given in the Energy Information Administration Report titled: *1990-2008 Average Price by State Provider* (EIA, 2008).

Office and administrative services data are adjusted based on the "All Services" categories of the Consumer Price Indexes for 2009 and 1997 (USCB, 2009).

3.3.8 Data Source Summary

Table 3 Summarizes the data sources used to calculate emissions and embodied energy for the case study.

Table 3. Case Study Emissions and Energy Use Input Data Summary Matrix

	New Columns and Beams	**Reused Pipe Columns**
Raw Material Acquisition	EIO-LCA "Iron and Steel Mills"	EIO-LCA "Ready-Mix Concrete"
Manufacturing	EIO-LCA "Iron and Steel Mills"	Salvaged Material sourcing, Sales and Storage: EIO-LCA "Office and Administrative Services"
Transport to Fabrication	NREL Life Cycle Inventory Database	NREL Life Cycle Inventory Database
Fuel production	EIO-LCA "Petroleum Refineries"	EIO-LCA "Petroleum Refineries"
Fabrication Process Energy	PVS Steel 2008 Electricity consumption per ton	PVS Steel 2008 Electricity consumption per ton
Fabrication Overhead	EIO-LCA "Office and Administrative Services"	EIO-"Office and Administrative Services"

3.4 Reporting

The impacts reported in this study include total embodied energy and emissions. Embodied energy is presented in megajoules (MJ) or terajoules (TJ). The specific types of emissions presented include CO_2, CH_4, N_2O, CFC, SO_2, CO, NO_x. All emissions quantities are in kilograms (kg).

3.5 Validity

The process assumptions and input estimates for the study are reviewed and validated through face validity, which is a process of establishing relevance through the opinions of industry experts and research professionals (Anastasi, 1998). Face validity establishes that the test or measurement appears to be valid, logical and accurate based on its face value or appearance. The process maps for the LCA are reviewed by steel industry professionals with intimate knowledge of the process. The research methodology and data analysis are presented to a university research committee, and reviewed.

4 CASE STUDY: ENERGY AND EMISSIONS FOR PAXTON & VIERLING STEEL FABRICATION AND MATERIAL SOURCING FOR NREL RSF BUILDING

Chapter four introduces the case study project and details the specific case-study inputs that were used to measure energy use and emissions. Here a baseline inventory is established for energy and emissions related to the case study steel. This data provides a current state for energy and emissions associated with the steel fabrication process. Alternative methods for reducing emissions and energy use are tested in order to identify potential reduction strategies. These alternative methods include opportunities within the fabrication facility as well as other stages within the steel delivery process that are under the control of the steel fabricator.

4.1 Case Study Project Overview

The Research Support Facilities (RSF) at the National Renewable Energy Laboratory's (NREL) campus in Golden, Colorado was designed to be a model for energy-efficient design and environmental sustainability. The project team targeted a Platinum level certification under the USGBC's LEED™ rating system. The 220,000 square foot, steel framed, $64-million design-build project was awarded to Haselden Construction and their partners RNL Architects. Haselden Construction hired Paxton & Vierling Steel (PVS) of Omaha, NE as the structural steel subcontractor for the project. PVS completed the fabrication of columns and W-beams for the building and subcontracted out erection and fabrication of other components such as the decking, stairs, and truss girders and joists.

PVS, originally Paxton & Vierling Iron Works, has been in the steel processing and fabrication industry since 1855 (PVS, 2009). It is now owned by Owen Industries. PVS specializes in heavy industrial projects, including nuclear, mid-to-heavy bridge, and complex seismic connections. PVS projects typically range in size from 2,000 to 20,000 tons. Some high profile PVS projects include: Union Pacific Center, Hanford Nuclear Waste Facility, Haynes Generation Station, First National Tower, and the Temco Ship Cover.

In support of the NREL project's sustainability goals, the project team made adjustments to the building design. Examples include day-lighting of interior spaces, building integrated renewable energy systems, water efficient fixtures, and low toxicity materials. The team also modified the structural design to accommodate the use of reclaimed oil and gas pipes as structural columns (S. Franklin, personal communication, May 22, 2009).

This case study research evaluates the energy use and emissions associated with the portion of NREL project steel that is fabricated by PVS. It also investigates opportunities to reduce energy use and emissions within the portion of the steel delivery process over which the fabricator has control, including material sourcing. The material fabricated by PVS for the NREL project is summarized in Table 4.

Table 4. PVS Material Fabricated for the NREL Project

	Weight (kg)	Raw Material Cost ($US)
Fabricated Columns	147,474	$ 214,582
Fabricated Beams	262,885	$ 364,000
Total PVS Fabricated Steel	**410,359**	**$ 578,582**

4.2 Baseline Energy and Emissions from Fabrication, Materials Sourcing, and Transportation by PVS for the NREL Project

The structural steel fabrication process is energy intensive and generates significant emissions. Yet, this phase of the steel delivery process has received little direct research attention related to resource efficiency and pollution reduction. This may be due to the relatively low energy use and emissions compared to the raw material production phase. However, steel fabrication does have measurable environmental impacts that can be evaluated. The fabricator can impact energy use, and therefore emissions, by adjusting operating practices within its control. These factors not only include the equipment and processes within the fabrication facility, but also material selection, and therefore the production method. Thus, the fabricator has the ability to select environmentally-preferable material alternatives, such as salvaged materials.

In order to develop an inventory of energy use and emissions, this research evaluates both the internal delivery process within PVS as well as material sourcing and transportation.

The existing fabrication process is observed and equipment energy consumption rates are measured for the fabrication of columns and beams. The data are used to determine the high impact stages in the fabrication process in terms of energy consumption and emissions. In addition, PVS has provided electricity consumption and steel fabrication data for 2008, which are used to establish a baseline rate of energy consumption per ton of steel fabricated. With a baseline developed, alternative scenarios are determined and measured against the baseline consumption. These scenarios are presented as energy reduction opportunities to improve the overall energy consumption in the steel delivery process. The net steel delivery impacts for the NREL project are developed for material production, fabrication, and erection as part of a joint project that combined other research. The research presented in this thesis is limited to the fabrication phase impacts, and material sourcing options over which the fabricator has control.

4.3 Inputs for Fabrication Phase Analysis

The total fabrication phase baseline energy and emissions are determined based on 2008 electricity consumption per ton data for the PVS facility. These figures are shown in Table 5.

Table 5. PVS Fabrication Phase Energy Consumption for 2008

2008 PVS Fabrication	Weight (kg)	Electricity (kWh)
Steel Received	11,314,422	
Waste (scrap)	877,249	
Steel Fabricated	10,437,173	
Annual Electricity Consumption (kWh)		4,092,022
Electricity per Kilogram Fabricated (kWh/kg)		2.55

The 2008 fabrication data is used to determine the life-cycle energy use and emissions by applying the cost per kWh of electricity consumed to NAICS Sector #221100 "Power Generation and Supply" using the GDI tool.

4.4 Inputs for Transportation Phase Analysis

Transportation mileage and fuel consumption from the steel supplier to the PVS facility are determined based on total material weight, supply distance, estimated return distance, and fuel consumption rate. Trucks were assumed to be fully loaded. Transportation inputs for the RSF project are shown in Table 6.

Table 6. NREL RSF Project Transportation Inputs from Steel Supplier to the PVS Facility

	Raw Material Weight (kg)	**Full Truck Load (kg)**	**Average Supply Distance to Fabricator (mi)**	**Average Fuel Consumption (mpg)**	**Trips (ea)**	**Calculated Fuel Consumption (gal)**
Truck Transport to PVS	444,830	21,772	884	6.6	23	4,225

4.5 Inputs for Material Production Phase Analysis

Material production inputs are determined by the total material weight, cost, and production method. Material weights are measured by weight of final fabricated member. A waste factor for fabrication is included to accurately represent the raw material weight required for final fabricated members. The waste factor (8.4%) is estimated from 2008 PVS production data. Table 7 shows the material production inputs for the PVS steel on the NREL RSF project.

Table 7. Material Production Inputs for PVS Steel on the NREL RSF Project

	Raw Material Weight (kg)	Raw Material Cost ($US)
Fabricated Columns	147,474	$214,582
Fabricated Beams	262,885	$382,511
Waste Material In Fabrication (8.4%)	34,470	$50,156
Total PVS Material	444,830	$647,249

4.6 Energy Use and Emissions from NREL Steel Fabricated by PVS

A baseline evaluation of energy use and emissions is determined. This represents the estimated life-cycle impacts of the case study steel fabricated at PVS. Table 8 shows the impacts associated with the steel fabricated by PVS for the NREL project.

Table 8. Energy and Emissions for NREL RSF Structural Steel Fabricated by PVS

	CO_2 (kg)	CH_4 (kg)	N_2O (kg)	CFC (kg)	SO_2 (kg)	CO (kg)	NO_X (kg)	Energy (MJ)
Material Production	502,000	2,090	6.29	13.4	1,000	5,180	939	6,160,000
Transportation	49,500	89.9	1.30	0.03	20.8	88.2	312	665,000
Fabrication	132,000	310	2.26	1.30	655	240	341	1,660,000
Total	**683,500**	**2,490**	**10**	**15**	**1,676**	**5,508**	**1,592**	**8,485,000**

Material production is responsible for 74% of the total CO_2 emissions. Transportation and fabrication are 7% and 19% respectively.

4.7 Alternative Scenarios: Fabrication

The structural steel elements of the RSF building are comprised of numerous, and often unique components and subcomponents. In fabrication, these require various equipment inputs and processes in order to produce what are largely custom products. Although there are many steps subject to variation, the majority of significant energy-intensive steps throughout the process are constant from member to member (e.g. shot blasting, transferring, cutting, and welding). Due to the high level of variability in production, the process-based analysis of fabrication is limited to a representative structural column and a beam fabricated at PVS. This allows for the process stages to be evaluated and prioritized within the facility without analyzing each unique component and over-complicating the study. Since these primary inputs are associated with all primary structural steel members, they provide representative data for improvement for all steel processed in the fabrication shop. With a representative model established, improvement opportunities are tested and evaluated for energy use and emissions reductions. These improvement opportunities include local factors, such as equipment operation schedules and shop lighting efficiency, as well as external factors such as raw material selection and transportation alternatives. Structural steel fabricated for the project by contractors other than PVS have been excluded from the research.

4.7.1 PVS Detailed Fabrication Process Analysis

The primary purpose for the fabrication process observations is to identify high-impact stages within the common process. Table 9 shows the energy and emissions associated with the primary processes that are required to fabricate a column or beam.

Table 9. Process Energy and Emissions per Column and Beam at PVS Facility

	Electricity (kWh)	CO_2 (g)	CH_4 (g)	N_2O (g)	CFC (g)	SO_2 (g)	CO (g)	NOx (g)	Energy (MJ)
Unload From Truck	0.10	71.2	0.13	0.00	0.00	0.39	0.04	0.18	0.87
Transfer to Cutting Station	0.04	25.1	0.05	0.00	0.00	0.14	0.01	0.06	0.03
Cut to length	0.57	390	0.70	0.00	0.00	2.11	0.22	1.00	0.47
Transfer to Staging	0.27	183	0.33	0.00	0.00	0.99	0.10	0.47	0.22
ID tag stamping	0.01	8.52	0.02	0.00	0.00	0.05	0.01	0.02	0.01
Transfer all to fit and weld	0.13	91.6	0.16	0.00	0.00	0.50	0.05	0.24	0.11
Weld moment connection	11.4	7,810	14.0	0.01	0.07	42.2	4.31	20.0	9.48
Weld base plate	5.53	3,790	6.79	0.01	0.04	20.5	2.09	9.71	4.60
Weld name tag	1.32	905	1.62	0.00	0.01	4.90	0.50	2.32	1.10
Transfer to staging	0.13	91.6	0.16	0.00	0.00	0.50	0.05	0.24	0.11
Transfer to Blaster	0.15	102	0.18	0.00	0.00	0.55	0.06	0.26	0.12
Shot Blast	160	110,000	197	0.18	1.04	594	60.5	281	133
Transfer to staging	0.15	102	0.18	0.00	0.00	0.55	0.06	0.26	0.12
Transfer to paint	0.15	102	0.18	0.00	0.00	0.55	0.06	0.26	0.12
Coat member	4.40	3,014	5.40	0.01	0.03	16.3	1.66	7.72	3.66
Transfer to inspection	0.15	102	0.18	0.00	0.00	0.55	0.06	0.26	0.12
Load on truck	0.30	205	0.37	0.00	0.00	1.11	0.11	0.52	0.25

The shot blasting equipment was found to be responsible for 86% of the process energy use by equipment in fabrication. This is the result of the blasting equipment using 12(ea) 25-horse power motors and eleven others ranging from 5 to 40 HP in full operation. The second largest energy consumer in the process was the welding equipment, which accounted for 6% of the equipment energy use.

4.7.2 Alternative Scenario #1: Reduced Operating Schedule for Shot Blasting Equipment

Analysis of the fabrication process and associated energy use and emissions impacts shows the steel shot blaster is a primary consumer of energy. This is, in part, due to the numerous large electric motors used to strip the surface of each fabricated member before coating. The process involves blasting the steel with small irregular steel pellets using high-velocity blowers. Unlike many other pieces of equipment used in the process, the blaster is running at all times. However, it does have an idle mode for when the machine is not actively in use, which shuts off twelve 25-horsepower electric motors.

The blaster is in operation for a total of 16 hours per day. It is estimated to operate in idle mode for 6 hours per day and be in full operation for the remaining 10 hours (S. Jundt, personal communication, January 12, 2010). At the time of the visit to the fabrication shop, the blaster operated in idle mode during breaks and between shift changes.

This analysis evaluates the impact of a two-hour per day reduction in idle time relative to the overall electricity consumption per year for PVS. The operating time reduction results in a net estimated energy reduction of over 60,000 kWh per year, which is detailed in Table 10.

Table 10. Annual Energy and CO_2 Reduction from Shot Blaster Idle Time Reduction at PVS

	Annual kWh	CO_2 (kg)	Energy (MJ)	Cost ($US)
Existing Blasting	1,060,000	728,000	8,850,000	$99,900
Reduced Idle Schedule	1,000,000	687,000	8,350,000	$94,200
Reduction	**60,000**	**41,000**	**500,000**	**$5,700.00**

4.7.3 Alternative Scenario #2: Lighting Retrofit in Fabrication Facility

One of the "low-hanging fruits" for electricity reduction is the fabrication facility lighting. It is a constant operational requirement for all processes within the shop. The PVS shop lighting currently utilizes 454 high pressure sodium 400W lights and 60 metal halide 1000W fixtures. The operating schedule for the facility requires approximately 18 hours of full lighting per day. Currently, the estimated electricity consumption for a full year of 18-hour working days is over 1 million kilowatt-hours.

Upgrading shop lighting will require an initial investment cost, but this may be offset by tax incentives and rebates through the local utility and government. These factors have a significant impact on the cost-benefit equation, which were not included in the evaluation.

A lighting upgrade would require the removal and replacement of all fixtures with 6 and 10-lamp F32T8 high lumen output, vapor tight, high bay fixtures at a cost of approximately US $178,000 (E. Neisel, Colorado Lighting, personal communication, February 12, 2010). The resulting estimated annual electricity savings would be 591,000 kWh and over US $55,000, with a simple payback of 3.2 years and an annual net CO_2 reduction of over 405,000 kg. Table 11 details the costs and impacts associated with a lighting upgrade for one year of operation.

Table 11. Annual Energy Use and Emissions Reduction from Fabrication Facility Lighting Retrofit

	Energy (kWh)	CO_2 (kg)	Energy (MJ)	Cost ($US)
Existing Shop Lighting	1,050,000	719,000	8,730,000	$98,400
Upgraded Lighting	459,000	314,000	3,820,000	$43,100
Reduction	**591,000**	**405,000**	**4,910,000**	**$55,300**
Percent Reduction	56%			
Upgrade Cost	$178,000			
Simple Payback (yrs.)	**3.2**			

4.7.4 Alternative Scenarios: Material Selection by the Fabricator

The analysis of the steel delivery process for PVS identifies that the material production phase is responsible for approximately 74% of the total embodied energy and CO_2 emissions for installed structural steel material (Table 8). In recent years, studies have shown that significant manufacturing efficiencies have been achieved in the steel production industry, reducing energy consumption by as much as 33% per ton in the period between 1990 and 2007 (AISI, 2008). These improvements are the result of the combined effort of the steel industry associations, producers, and the government to eliminate waste and improve efficiency. Although additional improvements are possible, many of the primary technological advancements that result in lower energy use and emissions have already been adopted by producers (Stubbles, 2000; Bjorhovde, 2004).

Further impact reductions are possible by organizations downstream from the production mills. However, it is important to consider that the production phase reductions have the potential for the greatest impacts. Fabricators and designers may have opportunities to make significant contributions to energy use and emissions reductions by simply reducing the amount of steel needed to be produced or by purchasing steel made using an environmentally-preferable method. This study analyses two possible ways that raw material production impacts may be reduced by the fabricator: the use of salvaged steel in lieu of new material and waste reduction in fabrication.

4.7.5 Alternative Scenario #3: Salvaged Material Sourcing

Salvaged oil and gas piping are incorporated into the structural steel design for the NREL RSF project. The structural steel designer and the fabricator worked together to source the material and incorporate the material into the structural frame. Here the embodied energy and emissions associated with the use of salvaged columns are compared to those associated with newly manufactured columns. This analysis serves to inform the industry and the research community of the environmental attributes of each option.

Salvaged columns are considered to have been manufactured for an alternative purpose, put to use, and reclaimed and put to use for a new purpose. The alternative to reuse is that the material would serve its useful life, be scrapped, melted down, and remanufactured into new steel products. The columns are removed from this typical material cycle, allowing for the material acquisition and manufacturing stages to be excluded from the life-cycle inventory.

According to the NREL project's structural engineer, pipe columns are not a typical design strategy. Thus, the structural engineer was asked to provide standard design alternatives to the pipe columns to inform the comparison. A number of the 16" diameter pipe columns were filled with concrete in order to meet structural support requirements. Given that the concrete is a primary component of the structural member, the concrete material impacts were also included in the evaluation. The placement impacts are not included in the comparison. The alternative design options (w-columns) are based on the structural engineer's determination of a newly manufactured alternative (See Table 12).

Table 12. NREL RSF Project Salvaged Pipe Column Sizes and Standard Column Equivalents

Salvaged column type	**Manufactured alternative**
16"x.375 pipe column	W14x74
16"x.375 concrete filled	W14x120
10"x.50 pipe column	W12x53

The net impacts associated with the salvaged columns are detailed in Table 13.

Table 13. Total Energy Use and Emissions for Salvaged Pipe Columns Fabricated by PVS for the NREL RSF Project

	CO_2 (kg)	CH_4 (kg)	N_2O (kg)	CFC (kg)	SO_2 (kg)	CO (kg)	NO_X (kg)	Energy (MJ)
Steel Columns Manufacturing	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Concrete Manufacturing	19,100	36.1	0.31	0.07	62.3	168	78.1	214,000
Transportation	13,500	24.2	0.33	0.01	5.67	24.0	84.9	181,000
Salvage Process	3,830	20.0	0.37	0.05	10.4	31.8	10.5	16,300
Fabrication Equipment Energy	16,700	33.2	0.12	0.16	87.6	16.6	42.9	193,000
Total	**53,130**	**114**	**1.13**	**0.29**	**166**	**240**	**216**	**604,000**

The net impacts associated with the use of structurally equivalent alternative non-salvaged columns are detailed in Table 14.

Table 14. Total Energy Use and Emissions for Structurally Equivalent Alternative Non-Salvaged Columns

	CO_2 (kg)	CH_4 (kg)	N_2O (kg)	CFC (kg)	SO_2 (kg)	CO (kg)	NO_X (kg)	Energy (MJ)
Steel Columns	140,000	593	1.64	3.88	270	1,450	247	1,730,000
Concrete	-	-	-	-	-	-	-	-
Transportation	20,500	106	0.44	0.00	3.84	27.6	116	253,000
Salvage Process	-	-	-	-	-	-	-	-
Fabrication Equipment Energy	16,300	31.2	0.08	0.16	86.6	13.6	41.8	190,000
Total	**176,800**	**730**	**2.16**	**4.04**	**360**	**1,490**	**405**	**2,170,000**

The use of salvaged pipe columns is shown to be an environmentally-superior alternative when analyzed through the fabrication stage, and without including the additional concrete placement energy and emissions. When compared to equivalent manufactured pipe columns, the use of salvaged columns reduced CO_2 emissions by 123,000 kg or 70%. Total energy is reduced by 1.5 TJ, a reduction of 69% (Table 15).

Table 15. Comparison of Energy Use and Emissions for Column Types for NREL RSF Project

Emissions Categories (Kilograms)	**CO_2 (kg)**	**CH_4 (kg)**	**N_2O (kg)**	**CFC (kg)**	**SO_2 (kg)**	**CO (kg)**	**NO_X (kg)**	**Energy (MJ)**
Salvaged Pipe Column	53,130	114	1.13	0.29	166	240	216	604,300
Standard W-Column	176,800	730	2.16	4.04	360	1,490	405	2,170,000
Reduction	**123,670**	**616**	**1.03**	**3.75**	**194**	**1,250**	**189**	**1,565,700**
Percent Reduction	**70%**	**84%**	**48%**	**93%**	**54%**	**84%**	**47%**	**69%**

In addition to the reduction of manufacturing-related impacts, the analysis shows that there is actually a net decrease in transportation of the steel, because the new manufactured columns are significantly heavier than the pipe columns. The new manufactured column weight is 170,000 kg, where the salvaged columns are 95,000 kg. The additional concrete, being a locally sourced material that is installed onsite, generates minimal impacts from transportation.

4.7.6 Alternative Scenario #4: Material Waste Reduction in Fabrication

Demand for new steel can be reduced through achieving a lower margin of waste in the fabrication phase. One example of a waste reduction strategy is through optimizing material cut lengths. The effort would involve expanded coordination between fabricator and designer to evaluate steel sizing options early in the design phase. Early review of structural dimensions and connections by the fabricator may identify opportunities for member sizing that better aligns with standard manufactured sizes. The result would be a lower waste factor in fabrication and potentially a lower overall price. The estimated waste factor for the steel fabricated by PVS in 2008 was 8.4%.

The reduction in fabrication not only reduces the energy use and emissions associated with process impacts within the fabrication plant, but it also reduces the upstream impacts associated with producing and transporting that waste material. Reducing waste in fabrication reduces the amount of steel needed to be produced by a mill, a phase with much higher energy use and emissions impacts per ton. If the resulting material demand reduction is attributable to the fabricator, then those associated impact reductions should be assigned to the fabricator. Table 16 represents the impacts associated with 8.4% of the NREL RSF project steel, and the impacts of total waste, relative to only the fabrication phase.

Table 16. Steel Production Impacts with Waste Factor Reduction for the NREL RSF Steel Fabricated by PVS

	CO_2 (kg)	CH_4 (kg)	N_2O (kg)	CFC (kg)	SO_2 (kg)	CO (kg)	NO_X (kg)	Energy (MJ)
Total PVS Steel Fabrication Phase Impacts	49,500	88.9	1.20	0.03	20.8	88.2	312	670,000
Waste factor impacts in fabrication phase (8.4%)	4,160	7.46	0.10	0.00	1.75	7.41	26.2	60,000
Waste factor impacts in material production phase (8.4%)	42,000	176	0.53	1.13	84.1	435	78.9	520,000
Waste factor impacts in transportation (8.4%)	11,100	26.1	0.19	0.11	55.0	20.1	28.7	140,000
Net Impacts of waste factor	**57,300**	**210**	**0.82**	**1.24**	**141**	**463**	**134**	**720,000**
Net Impacts of waste factor compared to total fabrication shop impacts	**116%**	**236%**	**68%**	**4130%**	**677%**	**524%**	**43%**	**107%**

The process energy used during the fabrication phase for the entire project is 670,000 MJ. Whereas, the energy used throughout the entire steel delivery process (material acquisition, manufacturing, transportation, and fabrication) for only 8.4% of NREL RSF project steel is 520,000 MJ. The data show that the total embodied energy of 8.4% of the project's steel is equivalent to over 107% of the energy used at the fabrication facility for the entire project. Therefore, a waste reduction of 8.4% would equate to the same energy decrease as would the reduction of energy use at the fabrication facility by 107%. This highlights the impact of material reduction efforts by the fabricator relative to the impacts of fabrication process improvement. In evaluating the opportunities a fabricator has to reduce energy and emissions, this shows that the material production phases are most impactful.

5 DISCUSSION

5.1 Discussion of Results

The results of the research have been presented and discussed within the case study section. However, key findings related to PVS steel fabrication are further developed here.

5.1.1 Energy Use and Emissions in the Steel Fabrication Process

The evaluation of the fabrication process yields feasible opportunities to reduce energy use and emissions. Given the variability of the fabrication process from steel member to member, this study identifies opportunities that impact environmental performance regardless of the project in fabrication. The process-based analysis identifies that the shot blasting equipment is the largest energy consumer of the primary fabrication process steps. Further analysis shows that shop lighting is a nearly constant consumer of energy and highly inefficient compared to alternative lighting options. A lighting upgrade can significantly reduce consumption at low cost, saving the PVS facility over $55,000 dollars per year. The energy and cost savings associated with lighting would further increase with the use of natural lighting features, such as skylights and light tubes.

5.1.2 Material Selection

Analysis of PVS steel fabrication identifies that the material production phase is responsible for approximately 74% of the total embodied energy and CO_2 emissions up to the point steel departs the fabrication facility (Table 8). The findings highlight the importance of material reduction and the reuse efforts on the part of the fabricator. The use of salvaged pipe columns for the NREL building in lieu of newly manufactured alternatives is shown to reduce CO_2 emissions by over 123,000 kg (Table 15). Other considerations related to material sourcing, such as waste reduction in fabrication can lead to significant impact reductions. Material waste in fabrication is over 8% of the total raw material entering the PVS facility. The waste steel for the NREL project is responsible for over 57,000 kg of CO_2 (Table 16). Because material production phase emissions are much greater per unit of steel than the fabrication phase impacts, waste reduction, and therefore a reduction in steel produced, is a highly impactful way to reduce total emissions by the fabricator.

5.1.3 Process Improvement within the PVS Fabrication Facility

In fabrication, a steel member requires a variety of equipment and resources depending on its design. This variability throughout the process makes it difficult to achieve uninterrupted flow of material through the facility. At present, production planners struggle to determine the exact equipment requirements in advance and schedule material flow without conflict. The transfer of material to an equipment station is determined by other ongoing projects that require the same resources including skilled operators. Based on observations of the process, there is a high frequency of stalled work in production. Such stoppages can be due to material either waiting on equipment or labor resources, or waiting on the completion of other subcomponents required for assembly of the final product. The time the material spends waiting to move to the following step in the process can be considered waste. This waste crowds the shop floor, leading to an underutilization of resources. It also requires workers' time to manage the material as it stands still or gets transferred to waiting, stored and again transferred back into the fabrication process. The waste associated with stop-and-go production is very difficult to quantify. Accordingly, it is difficult to quantify the energy consumption and emissions resulting from the waste. Therefore, the impacts of this are not calculated. However, PVS should evaluate the production flow and identify if there are opportunities for improvement, or determine if the existing waste factor is inherent to the nature of the fabrication system, and therefore unavoidable.

5.2 Research Findings

This study quantifies energy use and environmental impacts associated with early stages of structural steel delivery for a case study project. The study set out to answer specific research questions. Here the results are compared against the original research questions to determine if the study successfully met the intended goals.

Question 1. How much energy is used in the fabrication of structural steel for a case study building and what are the associated environmental emissions?

This study uses hybrid life-cycle assessment methodology to quantify the energy and emissions associated with the material acquisition, production, transportation and fabrication for one structural steel fabricator. Table 17 summarizes the results of the LCA analysis for each phase in the process through fabrication for the NREL RSF project's 410,000 kg of steel fabricated by PVS as shown earlier in (Table 17 was shown earlier as Table 8).

Table 17. Energy and Emissions for NREL RSF Structural Steel Fabricated by PVS

	CO_2 (kg)	CH_4 (kg)	N_2O (kg)	CFC (kg)	SO_2 (kg)	CO (kg)	NO_X (kg)	Energy (MJ)
Material Production	502,000	2,090	6.29	13.4	1,000	5,180	939	6,160,000
Transportation	49,500	89.9	1.30	0.03	20.8	88.2	312	665,000
Fabrication	132,000	310	2.26	1.30	655	240	341	1,660,000
Total	**683,500**	**2,490**	**10**	**15**	**1,676**	**5,508**	**1,592**	**8,485,000**

This information can be used in future studies to establish the phase impacts related to fabrication of structural steel buildings. The value, as well as the limitation of this analysis, is that it relies on very specific data from one company and may not represent the equivalent production process used in other facilities. However, it provides detailed empirical data for an actual process that until now has received little research attention.

Question 2. In what ways can the structural steel fabricator reduce energy use and emissions?

This study presents feasible ways to reduce energy use and emissions in the fabrication phase and through material selection alternatives within the fabricator's control. These include fabrication process and equipment improvements, such as improved efficiency in the operation schedule of the shot blaster, material waste reduction, and a shop lighting retrofit. Since material selection has the largest relative impact in the process, the benefit associated with fabricator choosing to use salvaged material is also evaluated and presented as an opportunity to reduce emissions and energy use.

5.3 Uncertainty

Uncertainty is an important consideration when reviewing the findings presented in this research. The LCI model, developed to estimate the impacts of a complex system, requires many data sources that rely on various disparate methodologies to determine content. The known uncertainties are identified here.

5.3.1 Process Observation

Observation of steel fabrication is affected by the conditions at that point in time. Due to time constraints, only limited observation took place. Observation of the facility process involved one 8-hour day on the production floor. Beams and columns were observed in process at various stages of fabrication. Depending on the conditions of fabrication and project specifications, the equipment used, as well as the duration of use, are subject to a high level of variability. For this reason, the process analysis is primarily relied on to identify high impact process stages, whereas historical utility information is used to estimate fabrication impacts on a per ton basis.

5.3.2 Single Project Case Study

This research relies on a single fabrication shop working on one project to develop findings. These findings are intended to inform the sustainability efforts of the industry as a whole. The approach has inherent uncertainty due to a single case study for a process that is likely to vary greatly from organization to organization and project to project. These findings cannot be assumed to represent other fabricators, only to inform them of opportunities found at one fabrication facility for steel on one case study project.

5.3.3 EIO-LCA

As discussed earlier, the EIO-LCA methodology results in the aggregation of data. This aggregation can result in uncertainty. In addition, other uncertainties can affect the reliability of data (GDI, 2005):

- Old data – the data are from the 1997 base year. Impacts can vary greatly over time for some products and services. Industries that experience a high level of change and technological advancement have the highest variability, and therefore the highest data uncertainty.

- Uncertainty in original data – the data used to estimate impacts is often based on voluntary reporting which can be unreliable.

- Incomplete Data – In some cases, due to lack of information, or availability of data, the model data are incomplete.

- Other issues – the dataset reports only limited emissions categories that are available and determined to be relevant. Other types of emissions may have significant impacts but may be excluded.

5.3.4 Boundary Definition

The boundary of the study is determined by the investigator. This can lead to the exclusion of important stages in product delivery. There are stages in the fabrication process that are excluded in this study. Such exclusions include direct welding rod emissions, direct paint emissions, and the impact associated with workers in the facility and the impact they themselves have in the complete delivery process.

Welding emissions are calculated based on electricity consumed by welding equipment. No emissions associated with the direct melting of welding rod are included as emissions are different than those measured in other areas of the study. The primary emissions from welding rod are chromium, manganese, nickel, and particulate matter. (Kura, Judy, Wisbith, & Stone, 2000).

Direct paint emissions were excluded because the primary pollutants are Volatile Organic Compounds (VOC), which are not included in other emissions measurements throughout this study.

No data was found regarding worker impacts outside of the fabrication facility, such as personal consumption. No analysis of the transportation of workers to the fabrication facility was done because the writer assumed that most workers live in close proximity to the facility and only limited emissions reduction would be achieved through strategies such as increased carpooling.

5.3.5 Uncertainly Analysis

There are no known data sources for determining or estimating uncertainty for the data sources used in this research. Due to the lack of such data, no error analysis is conducted.

5.4 Comparison to Related Studies

LCA studies identified in Chapter 2 present the life-cycle impacts of buildings and products throughout the entire life cycle. This study terminates the analysis at the point the steel departs the fabrication facility. Only one study was found to provide detailed energy and emissions data for the fabrication phase. Guggemos (2003) found that the construction phase, including fabrication, of a steel frame building accounted for only 1% of the total life cycle energy. The use and maintenance phases of the steel frame accounted for 88% of the total energy over the entire life-cycle of the building and materials accounted for 11%. The fabrication phase consumed 156 GJ of energy and generated 12.2 mt CO_2, where on-site construction accounted for 1603 GJ of energy and 120.5 mt CO_2. These results are compared to the results in this research in Table 18.

Table 18. PVS Fabrication Impacts Compared to "Steel Framed Building" Fabrication Impacts (Guggemos, 2003)

	Structural Steel (kg)	Fabrication Energy (MJ)	Fabrication CO_2(kg)	Energy (MJ) per kg Steel	CO_2 (kg) per kg Steel	CO_2 (kg) per MJ Energy
Steel Framed Building (Guggemos, 2003)	207,346	155,000	12,200	0.75	0.06	0.078
PVS Steel	410,359	1,662,426	131,855	4.05	0.32	0.079

Guggemos (2003) estimated fabrication energy and emissions to be approximately 20% of those identified in this study. This discrepancy is possibly due to limited equipment included in the research boundary of this 2003 study. The only equipment types accounted for in the comparison study were crane, forklift, grinder, power saw, rebar bender, rebar cutter, spray equipment, steel punch, steel torch, and welder. This excludes the shot blaster and other operational factors such as lighting. In contrast, this current research used actual annual energy consumption and total annual steel production data to estimate economy wide impacts using EIO-LCA. It is unclear if Guggemos (2003) included only the direct emissions associated with equipment operation, and electricity generation, without accounting for the economy wide impacts of electricity generation using EIO-LCA methodology.

5.5 Summary

Only limited research exists on the energy use and emissions associated with fabrication and material sourcing for structural steel used in building construction. As natural resource depletion accelerates, there is an increasing relevance for the improved understanding of the life-cycle environmental characteristics of building materials. More important, there is a need within the industry to identify feasible real-world opportunities to reduce environmental impacts and move towards more sustainable steel delivery. This research addresses this void by providing a detailed inventory of energy use and emissions associated with steel fabrication and material selection for a case study project. The main discovery of this research is that while PVS can make significant energy and emissions reductions by modifying operational process within their own facility, the most impactful opportunities are in raw material selection alternatives, such as sourcing reused materials.

5.6 Future Research

Future research should be carried out to address the production processes within Paxton & Vierling's fabrication facility in order to eliminate waste and improve efficiency. Other types of waste aside from energy and material waste, such as underutilization of equipment and manpower, or excessive inventory at the fabrication facility can be measured and improved.

Secondly, the results presented here should be compared to similar future studies at other plants to validate the findings. Other fabrication facility operations should be analyzed and the results compared to the findings of this study.

Lastly, given that material production has the greatest potential environmental impacts in the overall steel delivery process, future research should address better connecting fabricators with salvaged materials through centralized databases or other means.

5.7 Acknowledgements

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7 APPENDICES

7.1 PVS Fabrication Facility Process Data Map

Fabrication Process: Standard Pipe Columns

Description	Manufacture Columns
Equipment	(EIO) LCA DATA
Energy Demand	
Time	
Process Energy	
Labor	

Description	Transport pipe to buyer
Equipment	Heavy Combo Truck
Energy Demand	5 MPG
Time	varies
Process Energy	varies
Labor	1 Operator

Description	Manufacture Plate Steel
Equipment	(EIO) LCA DATA
Energy Demand	
Time	
Process Energy	
Labor	

Description	Transport to PVS
Equipment	Tractor Trailer
Energy Demand(MPG)	5
Time	Varies
Process Energy	Varies
Labor	1 Driver

Description	Unload at PVS Laydown Yard
Equipment	Forklift
Energy Demand	n/a
Time	n/a
Process Energy	n/a
Labor	n/a

Description	Transport Plate to PVS
Equipment	Heavy Combo Truck
Energy Demand	Various
Time	Various
Process Energy	Various
Labor	1 operator

Description	Load to Fab Shop Truck
Equipment	Truck: Tractor trailer
Energy Demand	
Time	.1 miles
Process Energy	
Labor	1 Operator

Description	Unload plate to fab shop
Equipment	10 ton overhead crane
Energy Demand	
Time	
Process Energy	
Labor	

Description	Unload From Truck
Equipment	10 ton overhead crane
Energy Demand (Watts)	10688.36667
Time (Hr)	0.009722222
Process Energy (kWh)	0.103914676
Labor	1 operator

Description	Transfer to Cutting station
Equipment	300lb/ft transfer arm
Energy Demand (Watts)	6000
Time (Hr)	0.006111111
Process Energy (kWh)	0.036666667
Labor	1 operator

Description	Cut to length
Equipment	Mavel Band Saw 2125 (7.5HP)
Energy Demand (Watts)	5685.9625
Time (Hr)	0.1
Process Energy (kWh)	0.56859625
Labor	2 workers

Description	Transfer to Staging
Equipment	10 ton bridge crane
Energy Demand (Watts)	10688.36667
Time (Hr)	0.025
Process Energy (kWh)	0.267209167
Labor	1 operator

Description	ID tag stamping
Equipment	135 ton cincinati break press (1940s)
Energy Demand (Watts)	22371
Time (Hr)	0.000555556
Process Energy (kWh)	0.012428333
Labor	1 operator

Description	Transfer column to fit and weld
Equipment	10 ton bridge crane
Energy Demand (Watts)	10688.36667
Time (Hr)	0.0125
Process Energy (kWh)	0.133604583
Labor	1 operator

Description	Transfer plate to plasma punch
Equipment	
Energy Demand	
Time	
Process Energy	
Labor	

Description	Cut angle
Equipment	AngleMaster, Messer Titan
Energy Demand	
Time	
Process Energy	
Labor	

Description	Transfer subcomponents to staging
Equipment	
Energy Demand	
Time	0.0125
Process Energy	
Labor	

Description	Weld moment connection
Equipment	IdealArc CV-400
Energy Demand (Watts)	13200
Time (Hr)	0.8625
Process Energy (kWh)	11.385
Labor	1 welder

Description	Weld base plate
Equipment	IdealArc CV-400
Energy Demand (Watts)	13200
Time (Hr)	0.418666667
Process Energy (kWh)	5.5264
Labor	1 welder

Description	Weld name tag
Equipment	IdealArc CV-400
Energy Demand (Watts)	13200
Time (Hr)	0.1
Process Energy (kWh)	1.32
Labor	1 welder

Description	Transfer to staging
Equipment	10-ton bridge crane
Energy Demand (Watts)	10688.36667
Time (Hr)	0.0125
Process Energy (kWh)	0.133604583
Labor	1 operator

Description	Transfer to Blaster
Equipment	15 ton bridge (1.5hr/ton)
Energy Demand (Watts)	11931.2
Time (Hr)	0.0125
Process Energy (kWh)	0.14914
Labor	1 operator

Description	Blasting
Equipment	Blastec Shot Blaster
Energy Demand (Watts)	339293.5
Time (Hr)	0.471620097
Process Energy (kWh)	160.0176333
Labor	1 operator

Description	Transfer to staging
Equipment	15 ton bridge
Energy Demand (Watts)	11931.2
Time (Hr)	0.0125
Process Energy (kWh)	0.14914
Labor	1 operator

Description	Transfer to paint
Equipment	15 ton bridge crane
Energy Demand (Watts)	11931.2
Time (Hr)	0.0125
Process Energy (kWh)	0.14914
Labor	1 operator

Description	Coat member
Equipment	Compressor pump
Energy Demand (Watts)	93212.5
Time (Hr)	0.04716201
Process Energy (kWh)	4.396088828
Labor	1 operator

Description	Transfer to inspection
Equipment	15 ton bridge crane
Energy Demand (Watts)	11931.2
Time (Hr)	0.0125
Process Energy (kWh)	0.14914
Labor	1 operator

Description	Load on truck
Equipment	15 ton bridge crane
Energy Demand (Watts)	11931.2
Time (Hr)	0.025
Process Energy (kWh)	0.29828
Labor	1 operator

7.2 PVS Fabrication Facility Equipment and Energy Consumption

Blastec Descaler	Custom Blastec			
Description	HP	Watts	Type	Manufacturer
Electric Motor	25	18,643	Blaster Wheel	Baldor
Electric Motor	25	18,643	Blaster Wheel	Baldor
Electric Motor	25	18,643	Blaster Wheel	Baldor
Electric Motor	25	18,643	Blaster Wheel	Baldor
Electric Motor	25	18,643	Blaster Wheel	Baldor
Electric Motor	25	18,643	Blaster Wheel	Baldor
Electric Motor	25	18,643	Blaster Wheel	Baldor
Electric Motor	25	18,643	Blaster Wheel	Baldor
Electric Motor	25	18,643	Blaster Wheel	Baldor
Electric Motor	25	18,643	Blaster Wheel	Baldor
Electric Motor	25	18,643	Blaster Wheel	Baldor
Electric Motor	25	18,643	Blaster Wheel	Baldor
Electric Motor	5	3,729	Drag Train	Eurodrive
Electric Motor	5	3,729	Drag Train	Eurodrive
Electric Motor	5	3,729	Drag Train	Eurodrive
Electric Motor	5	3,729	Drag Train	Eurodrive
Electric Motor	15	11,186	Variable Drive	Eurodrive
Electric Motor	15	11,186	Variable Drive	Eurodrive
Electric Motor	5	3,729	Screw	Eurodrive
Electric Motor	20	14,914	Fan	Baldor
Electric Motor	20	14,914	Fan	Baldor
Electric Motor	20	14,914	Fan	Baldor
Electric Motor	40	29,828	Fan	Baldor
Total		339,294	Watts	

Welder (Standard)	IDEAL ARC CV-400			
	Voltage	Amps	Watts	
	220	60	13,200	
	100% duty cycle			
	Total		13,200	Watts

Transfer Arm	300lb			
	VA	Volts	Power Factor (estimated)	Watts
Pump Motor	10,000	480	0.6	6000
Total				6000

Transfer Arm	800lb			
	VA	Volts	Power Factor (estimated)	Watts
Pump Motor	20,000	480	0.6	12000
Total				12000

Shop Lighting

	Qty	Watts (ea)	Watts (total)
HP Sodium	454	400	181,600
Metal Halide	60	1,000	60,000
Total			241,600

Bandsaw		Marvel 2150	
Description	HP	Watts	
Electric Motor	7.5	5,593	Blade Drive
Electric Motor	0.125	93	Coolant Motor
Total		5,686	

Plasma		Messer Titan	
	Voltage	Amps	Watts
Machine	480	10.4	4992
Hyper Therm	480	107	51360
Dust Collector	480	27	12960
Total			69312

Crane (10 TON)	Whiting	
	HP	Watts
Hoist	25	18,643
Bridge	15	11,186
Trolley	3	2,237
Total		10,688

Crane (15 TON)	Whiting	
	HP	Watts
Hoist	30	22,371
Bridge	15	11,186
Trolley	3	2,237
Total		11,931

Crane (20 TON)	Whiting		
	HP	Watts	
Hoist	30	22,371	
Bridge	15	11,186	
Trolley	3	2,237	
Total		11,931	

Paint Compressor			Ingersoll/Rand SSR-125
	HP	Watts	
Comp Motor	125	93,213	
Total		93,213	Watts

Name Plate Stamp			Cincinnati Break Press 21x12
	HP	Watts	
Pump	30	22,371	
Total		22,371	Watts

7.3 Truck Transport Energy and Emissions

Transport Emissions (Truck/Train)

Converted to Kgs/gallon (TRUCK)

CO2 kgs	CH4 kgs	N2O kgs	CFCs kgs	SO2 kgs	CO kgs	NOx kgs	VOC kgs	PM kgs	Energy TJ
11.10636899	0.000179134	0.000277151		0.00244583	0.017653544	0.074011162	0.003655804	0.001277914	0.000146117

lbs/kg = 2.20462262

PROCESS NAME: **Combination Truck - Diesel**

REFERENCE FLOW: **1,000** **Units:** **gallons**

PROCESS SUMMARY Environmental emissions for 1,000 gallons of diesel used in combination truck

Emission Factors of Fuel Combustion by Transportation Mode (lbs/1,000 gallons burned)

	Ocean Tanker		Barge		Locomotive	Heavy-Heavy-Du	Medium-Heavy-Duty Truck
	Residual Oil	Diesel	Residual Oil	Diesel	Diesel	Diesel	Diesel
VOC	27.22165761	25.22140221	12.42828346	11.51504954	23.7748333	8.059668489	12.04480605
CO	72.49927485	67.17200683	33.10017161	30.66796127	63.24105658	38.91940212	35.14514733
NOx	735.2592242	681.2321603	335.6889645	311.0224407	641.9204992	163.166681	174.354642
PM10	18.23094565	16.89133041	8.323496075	7.711883137	15.92913831	2.817317746	3.366991892
SOx	85.49575205	5.392132193	85.49575205	5.392132193	5.392132193	5.392132193	5.392132193
CH4	1.333861223	1.235848708	0.60898589	0.564237427	1.164966832	0.394923756	0.590195496
N2O	0.659471366	0	0.659471366	0	0.611013216	0.611013216	0.885137044
CO2	27070.70852	24385.15541	27180.72082	24487.08397	24396.03602	24485.35231	24478.32594

NREL (2009)

7.4 Steel Production Energy Use and Emissions

Steel Materials

EIO-LCA Sector 321111: Iron and Steel Mills
Accessed 11/2/2009

	GWP MTCO2E	CO2 MTCO2E	CH4 MTCO2E	N2O MTCO2E	CFCs MTCO2E	SO2 mt	CO mt	NOx mt	VOC mt	Lead mt	PM10 mt	Total TJ
Total for all sectors	2745.239	2431.584	217.0314	8.832052	87.79139	4.717381	25.29406	4.317371	2.484837	0.014245	2.505013	30.1
Mt per $1 Dollar	0.002745	0.002432	0.000217	8.83E-06	8.78E-05	4.72E-06	2.53E-05	4.32E-06	2.48E-06	1.42E-08	2.51E-06	3.01E-05
kg/$	2.745239	2.431584	0.217031	0.008832	0.087791	0.004717	0.025294	0.004317	0.002485	1.42E-05	0.002505	0.0301

(GDI, 2005)

7.5 Electricity Production Energy Use and Emissions

Electricity

Accessed 12/12/2009

EIO-LCA Sector 221100: Power Generation and Supply

	GWP MTCO2E	CO2 MTCO2E	CH4 MTCO2E	N2O MTCO2E	CFCs MTCO2E	SO2 mt	CO mt	NOx mt	VOC mt	Lead mt	PM10 mt	Total TJ
Total for all sectors	10514.16	10008.96	376.697	5.009	122.828	54.174	5.521	25.636	0.872	0	1.333	121.559
Mt Per $1 Dollar	10.51416	10.00896	0.376697	0.005009	0.122828	0.054174	0.005521	0.025636	0.000872	0	0.001333	0.000122
Total Kgs per 1 kWh	0.72022	0.685613	0.025804	0.000343	0.008414	0.003711	0.000378	0.001756	5.97E-05	0	9.13E-05	8.33E-06

(GDI, 2005)

7.6 Fuel Production Energy Use and Emissions

Fuel Production

Accessed 12/12/2009

EIO-LCA Sector 324110: Petrolium Refineries

	GWP MTCO2E	CO2 MTCO2E	CH4 MTCO2E	N2O MTCO2E	CFCs MTCO2E	SO2 mt	CO mt	NOx mt	VOC mt	Lead mt	PM10 mt	Total TJ
Total for all sectors	2200	1440	727	7.14	16.8	4.22	6.02	2.46	2.73	0	0.436	24.6
Mt per $1 Dollar	0.0022	0.00144	0.000727	7.14E-06	1.68E-05	4.22E-06	6.02E-06	2.46E-06	2.73E-06	0	4.36E-07	2.46E-05
kg/$	2.2	1.44	0.727	0.00714	0.0168	0.00422	0.00602	0.00246	0.00273	0	0.000436	0.0246

(GDI, 2005)

7.7 Concrete Production and Delivery Energy Use and Emissions

Pipe Column Concrete

Accessed 12/18/2009

EIO-LCA Sector 327320: Ready Mix Concrete

Total for all sectors	GWP	CO2	CH4	N2O	CFCs	SO2	CO	NOx	VOC	Lead	PM10	Total
	MTCO2E	MTCO2E	MTCO2E	MTCO2E	MTCO2E	mt	mt	mt	mt	mt	mt	TJ
Per US$1 Million	2025.558	1929.565	76.67119	9.734455	9.587495	6.29421	16.94469	7.89655	5.642234	0.001079	1.028357	21.57687
MT per $1 Dollar	0.002026	0.00193	7.67E-05	9.73E-06	9.59E-06	6.29E-06	1.69E-05	7.9E-06	5.64E-06	1.08E-09	1.03E-06	2.16E-05
kgs/$	2.025558	1.929565	0.076671	0.009734	0.009587	0.006294	0.016945	0.007897	0.005642	1.08E-06	0.001028	0.021577

(GDI, 2005)

7.8 Overhead and Office Administration Energy Use and Emissions

Overhead

EIO-LCA Sector 561100: Office Administraitive Services
Accessed 12/12/2009

	GWP	CO2	CH4	N2O	CFCs	SO2	CO	NOx	VOC	Lead	PM10	Total
	MTCO2E	MTCO2E	MTCO2E	MTCO2E	MTCO2E	mt	mt	mt	mt	mt	mt	TJ
Total for all sectors	141.6051	122.5477	13.43845	3.675336	1.943727	0.331396	1.016559	0.335222	0.183956	0.000104	0.056836	1.835514
Mt per $1 Dollar	0.000142	0.000123	1.34E-05	3.68E-06	1.94E-06	3.31E-07	1.02E-06	3.35E-07	1.84E-07	1.04E-10	5.68E-08	1.84E-06
kg/$	0.141605	0.122548	0.013438	0.003675	0.001944	0.000331	0.001017	0.000335	0.000184	1.04E-07	5.68E-05	0.001836

(GDI, 2005)

7.9 Column Concrete Estimate

NREL Column Concrete

Total concrete (Cy)		100.7111256
cost (3500 PSI) per cy	$	104.00
local increase	$	14.56
Total Cost		118.56

Column Concrete Cost	11940.31105

quan	type	dim	gradename	ft	inches	frac	Ft total	weight
				10 in				
1	HSS	10-3/4x.500	A500-B	45	6	3/4	45.5	2494.09
1	HSS	10-3/4x.500	A500-B	45	6	3/4	45.5	2494.09
1	HSS	10-3/4x.500	A500-B	47	3	3/4	47.25	2589.89
1	HSS	10-3/4x.500	A500-B	52	7	1/4	52.58333333	2879.55
1	HSS	10-3/4x.500	A500-B	51	10		51.83333333	2837.36
				16 in				
3	HSS	16x.375	A500-B	5	2		15.5	969.99
1	HSS	16x.375	A500-B	5	2		5.166666667	323.33
4	HSS	16x.375	A500-B	5	2		20.66666667	1293.32
1	HSS	16x.375	A500-B	5	2		5.166666667	323.33
1	HSS	16x.375	A500-B	5	2		5.166666667	323.33
1	HSS	16x.375	A500-B	5	2		5.166666667	323.33
3	HSS	16x.375	A500-B	15	5	1/16	46.25	2895.3
3	HSS	16x.375	A500-B	15	5	1/16	46.25	2895.3
1	HSS	16x.375	A500-B	15	5	1/16	15.41666667	965.1
1	HSS	16x.375	A500-B	15	5	1/16	15.41666667	965.1
1	HSS	16x.375	A500-B	15	5	1/16	15.41666667	965.1
1	HSS	16x.375	A500-B	19	7	5/8	19.58333333	1228.78
1	HSS	16x.375	A500-B	19	7	5/8	19.58333333	1228.78
1	HSS	16x.375	A500-B	19	7	5/8	19.58333333	1228.78
4	HSS	16x.375	A500-B	19	7	5/8	78.33333333	4915.14
2	HSS	16x.375	A500-B	19	7	5/8	39.16666667	2457.57
1	HSS	16x.375	A500-B	19	7	5/8	19.58333333	1228.78
4	HSS	16x.375	A500-B	19	7	5/8	78.33333333	4915.14
1	HSS	16x.375	A500-B	29	6	3/4	29.5	1850.02
1	HSS	16x.375	A500-B	29	7		29.58333333	1851.33
1	HSS	16x.375	A500-B	29	7		29.58333333	1851.33
1	HSS	16x.375	A500-B	29	10	15/16	29.83333333	1871.86
3	HSS	16x.375	A500-B	29	11		89.75	5616.56
1	HSS	16x.375	A500-B	29	11		29.91666667	1872.19
1	HSS	16x.375	A500-B	29	11		29.91666667	1872.19
1	HSS	16x.375	A500-B	29	11		29.91666667	1872.19
1	HSS	16x.375	A500-B	29	11		29.91666667	1872.19
1	HSS	16x.375	A500-B	29	11		29.91666667	1872.19
1	HSS	16x.375	A500-B	29	11		29.91666667	1872.19
1	HSS	16x.375	A500-B	37	6	3/4	37.5	2350.66
3	HSS	16x.375	A500-B	37	6	3/4	112.5	7051.98
2	HSS	16x.375	A500-B	37	6	3/4	75	4701.32
1	HSS	16x.375	A500-B	37	6	3/4	37.5	2350.66
1	HSS	16x.375	A500-B	37	6	3/4	37.5	2350.66
1	HSS	16x.375	A500-B	37	6	3/4	37.5	2350.66
3	HSS	16x.375	A500-B	37	6	3/4	112.5	7051.98
1	HSS	16x.375	A500-B	37	6	3/4	37.5	2350.66
1	HSS	16x.375	A500-B	37	6	3/4	37.5	2350.66

2	HSS	16x.375	A500-B	37	6 3/4	75	4701.32
1	HSS	16x.375	A500-B	37	6 3/4	37.5	2350.66
1	HSS	16x.375	A500-B	37	6 3/4	37.5	2350.66
1	HSS	16x.375	A500-B	37	6 3/4	37.5	2350.66
2	HSS	16x.375	A500-B	37	6 3/4	75	4701.32
1	HSS	16x.375	A500-B	37	6 3/4	37.5	2350.66
1	HSS	16x.375	A500-B	37	6 3/4	37.5	2350.66
1	HSS	16x.375	A500-B	37	6 3/4	37.5	2350.66
1	HSS	16x.375	A500-B	37	6 3/4	37.5	2350.66
1	HSS	16x.375	A500-B	37	6 3/4	37.5	2350.66
1	HSS	16x.375	A500-B	37	7	37.58333333	2351.97
2	HSS	16x.375	A500-B	37	7	75.16666667	4703.93
1	HSS	16x.375	A500-B	37	7	37.58333333	2351.97
2	HSS	16x.375	A500-B	37	7	75.16666667	4703.93
1	HSS	16x.375	A500-B	37	7	37.58333333	2351.97
1	HSS	16x.375	A500-B	37	7	37.58333333	2351.97
1	HSS	16x.375	A500-B	37	7	37.58333333	2351.97
1	HSS	16x.375	A500-B	37	7	37.58333333	2351.97
1	HSS	16x.375	A500-B	37	7	37.58333333	2351.97
2	HSS	16x.375	A500-B	37	7	75.16666667	4703.93
1	HSS	16x.375	A500-B	37	7	37.58333333	2351.97
1	HSS	16x.375	A500-B	37	7	37.58333333	2351.97
1	HSS	16x.375	A500-B	37	7	37.58333333	2351.97
1	HSS	16x.375	A500-B	37	7	37.58333333	2351.97
2	HSS	16x.375	A500-B	37	7	75.16666667	4703.93
1	HSS	16x.375	A500-B	37	7	37.58333333	2351.97
1	HSS	16x.375	A500-B	49	9 1/8	49.75	3114.01
1	HSS	16x.375	A500-B	49	9 1/8	49.75	3114.01
1	HSS	16x.375	A500-B	52	2	52.16666667	3264.59
1	HSS	16x.375	A500-B	52	7 9/16	52.58333333	3293.6
1	HSS	16x.375	A500-B	52	7 9/16	52.58333333	3293.6
	Total			**2143.75**	**Radius (ft)=**	**0.63541667**	
			Area (ft)=	**1.26843167**	**Volume (CY)=**	**100.711126**	