THESIS

ENVIRONMENTAL EMISSIONS AND ENERGY USE FROM THE STRUCTURAL STEEL ERECTION PROCESS: A CASE STUDY

Submitted by

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ABSTRACT

ENVIRONMENTAL EMISSIONS AND ENERGY USE FROM THE STRUCTURAL STEEL ERECTION PROCESS: A CASE STUDY

Over the last two decades, sustainable (or green) building has been proven effective at reducing the environmental impact of buildings in an economically efficient way. In the United States, the Leadership in Energy and Environmental Design (LEED) building rating system has been at the forefront of the green building movement. LEED accomplishes breadth at the expense of depth and, as a result, many facets of the construction industry are not explicitly addressed by this standard. Specifically, structural steel has been championed as an environmentally responsible building material because of its high recycled content, but only limited investigation has been done into the erection phase environmental implications of the material. To reduce the environmental impact of structural steel construction operations, practitioners must first understand which activities are the most impactful, so that improvement efforts can be properly targeted.

Using life cycle assessment (LCA), this case study quantifies the energy consumption and environmental emissions resulting from the erection of the structural steel frame for a mid-sized office building on the campus of the National Renewable Energy Laboratory (NREL) in

Golden, Colorado. Those data are then used to explore recommendations for environmentally-preferable methods of steel construction.

The magnitude of total energy use and pollution emitted during the steel erection process is found to be significant, with CO_2 generation totaling 342,000 kg. According to the case study, the major sources of emissions (in descending order of magnitude) are materials transportation to the site, operation of the 100-ton crane, and worker transportation to the site. The most effective strategies for reducing energy consumption and emissions identified by the study are: 1) sourcing materials within 500 miles, 2) shipping only full loads of materials, 3) improving site logistics and crane-sizing to reduce erection time, and 4) switching from an 8-hour to a 10-hour work day. These strategies resulted in reductions in total erection phase energy consumption and CO_2 emissions of approximately 17.5%, 8.5%, 6.4%, and 3% respectively.

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1 Introduction

In the last twenty years, evidence has mounted that human activities are doing irrevocable damage to global biogeochemical systems (Pachauri & Reisinger, 2007). Sustainable development offers an alternative to current business practices by promoting qualitative change that focuses on a triple bottom line of economic, ecological and social benefit. The 1987 report of the Brundtland Commission, *Our Common Future*, defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, p. 27). Sustainability has since matured from a radical fringe idea to a commonly promoted best practice.

Beyond the moral and social implications, sustainability has been widely recognized as making good business sense. An influential report from the World Business Council for Sustainable Development (Holliday & Pepper, 2001) identified two primary ways in which sustainability can make firms more financially competitive: by saving money through reducing waste and risk, and by making money through access to new markets and differentiation from competition. Additionally, it has been noted that "…even where there is no direct economic gain, there is often a business case for sustainable development, since society increasingly expects companies and market sectors to contribute to social progress and to the wider good, i.e. a better quality of life." (Steel Construction Sector Sustainability Committee [SCSSC], 2002, p. 9)

Despite the spread of sustainable thought, substantial action has been slow to follow and the scale of human consumption still greatly exceeds the regenerative capacity of the natural world. Green building has been identified by many as one of the low-hanging fruits of sustainability (McLennan, 2004); great opportunity exists for reducing the environmental impact of buildings in an economically efficient way and with minimal restructuring of industry. The potential benefit is huge, since the built environment is responsible for a substantial portion of the global environmental burden. In the United States, 30% of total energy consumption, 60% of electricity use and 16% of potable water goes to operating buildings (U.S. Green Building Council [USGBC], 2009). Globally, building construction accounts for 40% of raw material flows (3 billion tons annually) and a similar percentage of solid waste. Additionally, humans now spend the vast majority of their time indoors, resulting in a close relationship between the quality of the built environment and human health (Burgan & Sansom, 2006).

In the United States, the Leadership in Energy and Environmental Design (LEED) building rating system developed by the USGBC has been at the forefront of the green building movement. LEED is designed to address the sustainability of entire buildings and thus accomplishes breadth at the expense of depth. As a result, many facets of the construction industry may be influenced, but not specifically addressed, by LEED. For instance, many LEED projects receive credit for specifying steel with a high percentage of recycled content, yet the standard does not speak to the actual steel design or construction process. This leaves each trade to develop its own sustainability policy that compliments, but does not compete with, LEED.

1.1 Statement of the Problem

One tool that has been successfully utilized to understand and improve the performance of the built environment is life cycle assessment (LCA). LCA quantifies all resource inputs and environmental outputs associated with a product or process's entire life from cradle to grave (Perez-Garcia et al., 2006). For building construction, these life cycle phases include: 1) raw materials extraction, 2) material manufacturing, 3) product fabrication, 4) construction, 5) operation, 6) maintenance and 7) end-of-life (reuse, demolition and/or recycling).

Existing LCAs of buildings conclude that the operational phase is responsible for the vast majority of environmental impacts over the course of a building's existence (Scheuer, Keoleian & Reppe, 2003; Burgan & Sansom, 2006; Junnila, Horvath & Guggemos, 2006), thus discounting the importance of the harvesting, manufacturing, construction and end-of-life phases. As a result, sustainable building practitioners have understandably focused their efforts on designing buildings which are less resource intensive to operate. These efforts have met with some success and buildings are constantly being designed to higher standards of energy and water efficiency. However, as the operational phase becomes less damaging, the relative importance of other life cycle stages increases (Guggemos & Horvath, 2006).

A number of public and private initiatives are focused on creating mainstream buildings that are "net zero" (U.S. Department of Energy [DOE], 2009; Architecture 2030, 2009). "Net zero" is typically used to describe a building that produces as much energy and water from onsite renewable sources as it uses. For such a building, the non-operational life cycle phases will be responsible for the majority of life cycle energy consumption and pollution. This shift in the distribution of environmental impacts through a building's lifespan increases the need to evaluate and improve the materials manufacturing and construction phases.

The design decision with the greatest impact on the pre-operational phases of a building is the choice of a structural system (Ochsendorf, 2005). Structural steel has been championed as an environmentally responsible building material because of its high recycled content (Steel Recycling Institute, 2009), but only limited investigation has been done into the erection phase environmental implications of the material. To reduce the environmental impact of structural steel construction operations, practitioners must first understand which activities are the most impactful, so that improvement efforts can be properly targeted. This case study quantifies the energy consumption and environmental emissions resulting specifically from the erection of a structural steel frame for a mid-sized office building in Golden, Colorado and then uses those data to explore recommendations for environmentally-preferable methods of construction.

1.2 Research Questions

- What are the major sources of energy consumption and environmental emissions associated with a typical steel erection process during the construction phase of a mid-sized office building?

-What strategies can be used to reduce these impacts and what are the effects of those strategies on energy consumption and environmental emissions during the steel erection process?

2 Literature Review

This chapter provides a brief review of prior research on the history and sustainability of steel as a construction material, followed by a review of general LCA and its specific application within the construction industry. The final section discusses some categories of pollutants commonly tracked LCA.

2.1 Steel

Humans have been putting iron to productive use for at least 5,000 years and the metal has had a profound impact on the course of history. Until the mid-19th century, this influence was predominantly in the realm of weaponry, but in 1855 Henry Bessemer patented a new process which reduced the cost of producing steel by 80% (McCormac & Nelson, 2003). As inexpensive structural steel became readily available by the 1870's, it replaced cast iron, which was first used as a structural material in 1779 for the Coalbrookdale Arch Bridge in England (Martin & Purkiss, 2008). Cast iron's usefulness in construction was limited by its weakness in tension, but steel has significantly higher tensile strength. As a result, by 1890 steel was the most common structural material for nonresidential construction in the United States (McCormick & Nelson, 2003).

Steel has several, well-known advantages as a construction material. It does not warp or twist noticeably like wood can. It has a very high strength-to-weight ratio, is durable and can be produced with very uniform quality, so its properties are well understood by engineers (Greyhawk North America, Inc., 2000). Additionally, the majority of components for structural steel buildings can be manufactured off site, facilitating quality and consistency. The long spans possible with structural steel can produce flexible spaces that are easily modified to extend the life of a building. At the end of a structure's useful life, steel components can be easily dismantled for reuse or recycling (SCSSC, 2002). Disadvantages of steel include initial cost, maintenance costs of exposed members, fireproofing requirements, and the possibility of fatigue or brittle fracture (McCormac & Nelson, 2003).

2.2 Structural Steel and Sustainability

Until the last quarter of the twentieth century, steel production had a reputation as the quintessential polluting, energy-intensive industrial process. Cities such as Pittsburg, Pennsylvania and Gary, Indiana were notoriously unhealthy and unattractive due to their steel mills.

However, in the last thirty years, extraction, production, and fabrication processes have dramatically improved. Motivated by a mix of international competition and tougher environmental regulation, the industry has actively sought to increase efficiency. The result has been a shift towards sustainability (SCSSC, 2002). At the global level, the World Steel Association (WSA) released a sustainable development policy in 2002 that included directives on environmental protection, health and safety, local communities, ethical standards, stakeholder engagement, and transparency (WSA, 2010). Currently, WSA is developing a sector-specific approach to reducing CO_2 emissions. Scheduled for release in 2010, the strategy will include provisions for collecting and reporting plant-by-plant CO_2 emissions data for all major steel producing countries (WSA, 2008). In 1990, the Canadian Steel Producers Association made a commitment to aggressively address energy usage and has since improved efficiency by 25%, resulting in a 20% decrease in CO_2 emissions (Boulanger, 2008a).

The average recycled content of structural steel has also steadily increased over time and is now often above 90% (USGBC, 2009). Steel's high monetary value and the ease with which it can be separated from other building components have also made it the most commonly recycled construction material, with diversion rates reaching 94% in the UK (SCSSC, 2002). In 2004, 70 million tons of steel were recycled in North America, 57% of which came from construction and demolition waste. The environmental benefits from recycling on this scale are enormous—compared to virgin steel, one ton of recycled steel conserves 1100 kg of iron ore, 600 kg of coal, 50 kg of limestone and 25,000 MJ of energy (Gorgolewski, 2006).

Gorgolewski (2006) suggests that construction steel recycling has developed to such a level that the next incremental improvement to be made is the direct reuse of old structural members in new buildings. Reuse offers more environmental benefit than recycling due to the relatively high energy intensity of recycling steel, even using the more efficient electric arc furnace method. To date, reuse has been limited by the difficultly of coordinating demand with supply and because the use of reclaimed materials can increase the complexity of design. Fabrication phase efficiency has been improved by common sense measures, such as scrap metal recycling and paint recovery systems, and by new technologies, like onsite cogeneration (Boulanger, 2008a).

Although the high rate of recycling in the steel industry is commendable, recycled content and an efficient production process only address the sustainability of steel as a *material* and a sustainable material does not automatically result in a sustainable building *practice*. As the green building movement matures from trying to do less harm to having a net positive effect, it will become crucial to examine all phases of the structural steel life cycle, including erection and end-of-life (Ochsendorf, 2005).

Acknowledging this idea, Ian Christmas, Director General of the WSA, has stated that:

> We are shifting our focus from increasing the volume of steel in use to maximizing the contribution of steel over product life cycles, especially the use phase. This is done by providing lighter, safer, long-lasting and more intelligent structures for transport and construction. We also continue to work with designers to create products that are easy to reuse and recycle at the end of their life, to maximize steel recycling. The recyclability of steel is one of its most valuable properties, saving precious raw materials and significant energy for future generations. (WSA, 2008, p. 3)

A comprehensive look at structural steel construction from an environmental perspective may be *Sustainable Steel Construction: Building a Better Future*, a 2002 strategy developed by the UK's Steel Construction Sector Sustainability Committee. The report serves as an implementation document for the sector-wide *Towards Sustainability: A Strategy for the Construction Industry* (Sustainable Construction Task Group/Construction Confederation, 2000) and consists of two primary sections: the current state of sustainability in steel construction and recommendations for the future. Construction process-specific recommendations include implementation of environmental management systems, noise reduction, waste minimization strategies and recovery, recycling and reuse initiatives.

Burgan and Sansom (2006) have also examined structural steel throughout its life cycle and they identify solid waste and impact on the local community (noise, dust, pollution and traffic congestion) as the primary sustainability concerns of the construction phase. They suggest that maximizing offsite assembly could reduce all of these impacts, while improving job stability for workers. While the inclusion of the human aspect of sustainability is commendable, their suggested solution is off target, as steel frames are already typically fabricated offsite to the extent allowed by transportation factors.

The sustainability of structural steel frames has also been addressed by LCAs of entire building systems, and these studies will be covered in the following section of this literature review.

2.3 Life Cycle Assessment (LCA)

Life cycle assessment is a tool for collecting and analyzing the relevant environmental data from all stages of a product or service's life span. LCA is one of many approaches to evaluating environmental impact, but differentiates itself because of a strong emphasis on a product or process's cradle-to-grave implications (Forsberg & von Malmborg, 2004) and quantitative evaluation. As explained by Hunkeler (2005), LCA "represents a shift from pollution prevention and gate-to-gate concepts, which focus on single facilities of industrial enterprises, to a view of incorporating the supply chain as well as downstream processes related to a product (p. 306)."

LCA has its roots in studies of cumulative energy requirements for manufacturing done in the late 1960's by academics and later by corporations including the Coca-Cola Company (Ciambrone, 1997). In 1972 Meadows, Meadows, Randers and Behrens published *The Limits of Growth*, which brought public attention to the looming conflict between a rapidly expanding global population and a finite natural world. The book has since been criticized for making false predictions, but at the time it significantly furthered public awareness of life cycle thinking. Boustead and Hancock's (1981) book *Energy and Packaging* has been cited as the first example of LCA as it is now defined (Johnston, 1997). This volume provided both methodological guidance and data sets for determining energy and raw material requirements for manufacturing various types of containers.

2.3.1 Process-Based Life Cycle Assessment

The first serious international effort to standardize LCA methodology was initiated by the Society of Environmental Toxicology and Chemistry (SETAC) and produced the 1990 SETAC Code of Practice (Russell, 2005). SETAC defines LCA as follows:

> The life-cycle assessment is an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and material usage and environmental releases, to assess the impact of those energy and material uses and releases on the environment, and to evaluate and implement opportunities to effect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing extracting and processing raw materials; manufacturing, transportation, and distribution; use/reuse/maintenance; recycling; and final disposal. (Graedel & Allenby, 2003, p. 183)

Interest in and use of LCA accelerated rapidly in the early 1990's, leading to special issues of the Journal of Cleaner Production starting in 1993 and the creation of the International Journal of LCA in 1996 (Russell, 2005). In 1993, the International Organization for Standardization (ISO) launched an intense effort to develop their own LCA standard that would strike a balance between detailed instruction and practicality of implementation (Marsmann, 2000). The ISO 14040 series of standards was released in June 1997 (ANSI/ISO, 1997) and has since become the consensus framework for LCA (Rebitzer et al., 2004).

Today, LCA is a well-established (although not entirely static) field in academia and industry. LCA methodology consists of three basic steps: 1) goal and scope definition, 2) inventory analysis, and 3) impact analysis (Ciambrone, 1997). Goal and scope definition delineates a boundary around the product or process being studied and articulates the purpose of the LCA. Inventory analysis quantifies all energy and material inputs and outputs of the system with those boundaries. Impact analysis then translates these inputs and outputs into measures of environmental, economic, or human impact, such as global warming potential or toxicity. Improvement analysis – a systematic effort to reduce the negative impacts of the system being studied – is occasionally treated as a standalone fourth step, but is more commonly applied during each of the three basic stages.

Once the system to be studied has been defined during scope definition, an appropriate *functional unit* must be selected. ISO 14040 defines functional unit as the “quantified performance of a product system for use as a reference unit in a life cycle assessment study” (Hendrickson, Lave, & Matthews, 2006, p.226). The concept helps distinguish between a product and the service the product provides to facilitate comparison. For instance, in LCAs of construction, the functional unit is often a square foot of finished floor space, so that statements can be made about the building’s performance *per square foot*. This type of LCA, which attempts to meticulously account for every input and output within a clearly delineated system boundary, is referred to as *process-based LCA* to differentiate it from other methodologies.

LCA can serve a wide variety of purposes from design guidance to third party verification of a product or process’s environmental performance. When used to support design decisions, LCA is often an iterative process with an interpretation of results after each stage to suggest possible improvements (Graedel & Allenby, 2003). The procedure is more linear when used to evaluate a product already on the market. In some instances, LCA may not be the most appropriate environmental assessment tool available and should not be used. For instance, the quantitative nature and complexity of LCA results may make them difficult to use in marketing campaigns for consumer goods (Jonsson, 2000).

One danger posed by the difficulty of conducting process-based LCA using the SETAC/ISO method according to Johnston (1997): "It is tempting to simply model that part of the system of most immediate concern and about which we know the most… decision-makers using such models will be lured into making decisions that are at best suboptimal." Johnston also points out that there are political and competitive disadvantages that act to discourage industry from participating in LCA; much of the information required for an accurate LCA has business intelligence value to competitors and the findings may be used to attack the industry or firm studied. LCA has also been criticized for failing to adequately address local environmental issues and the human aspect of sustainability (Hunkeler, 2005).

2.3.2 Economic Input-Output Life Cycle Assessment (EIO-LCA)

An alternative to the time and resource intensity of traditional LCA is the economic input-output life cycle assessment (EIO-LCA) approach (Rebitzer et al., 2004). This method is based on tables released by the U.S. Department of Commerce which aggregate the production of all goods and services in the U.S. economy into approximately 500 sectors (U.S. Department of Commerce, 1997). These complex matrixes describe the amount that each industrial sector spends on services from every other sector, so it becomes possible to track all direct and indirect inputs required for each unit of production from a single sector. The tables were first conceptualized in the 1930's by Harvard economist Wassily Leontief, who won the Noble Prize in Economics in 1973 for his work. Leontief (1970) also pioneered the idea that pollution statistics could be linked to input-output tables to estimate the upstream environmental impacts of any product or service.

In the mid 1990's, researchers at The Green Design Institute of Carnegie Mellon University realized that developments in technology and pollution reporting would allow for the creation of computer-based EIO-LCA tools. The resulting eiolca.net website was made available to the public and has since been used in a variety of research applications (Hendrickson et al., 2006). The tool was originally based on economic data from 1997, but was recently updated using the 2002 data (Green Design Institute, 2009).

EIO-LCA has the effect of broadening the boundaries of the analysis, while also reducing the level of detail within those bounds. Hendrickson et al. (2006) are careful to point-out that EIO-LCA can be used complimentarily with the SETAC/ISO framework in a variety of ways. This hybrid form of LCA has been used successfully in a number of construction industry studies (Treloar, Love & Crawford, 2004; Junnila et al., 2006; Bilec, 2007). One method of hybrid LCA uses EIO-LCA to estimate processes that fall outside the system boundary of a process-based LCA.

2.3.3 Applying LCA to Construction

A number of LCA challenges unique to the building and construction industry have been identified. Peuportier (2008) explains that selecting an appropriate functional unit is highly complex because different alternatives vary greatly in their contribution to aesthetics, energy performance, flexibility of space, building lifespan, occupant health and comfort. Unlike other manufactured goods for which a single design serves as the basis for thousands of identical units, the majority of buildings are unique and site-specific. Ries and Mahdavi (2001) note that building industry LCA in particular requires computational support tools, because the final product relies on such an intricate network of individuals, firms, equipment, materials and assemblies.

A challenge specific to the United States is the lack of sophisticated LCA databases geared toward the industry. The Netherlands, Germany, Switzerland, France, the UK, Austria and

Finland all have building-specific LCA programs— many developed through public, or joint public/private efforts (Peuportier, 2008). The BEES (Building for Environmental and Economic Sustainability) software developed by the National Institute of Standards and Technology's (NIST) Building and Fire Research Laboratory is the United States' best effort, but covers only 230 products and was last updated in 2007 (NIST, 2007).

Despite challenges, a large and varied body of work has been published on the application of LCA to the building and construction industry since the early 1990's. A recent meta-analysis of LCA in the construction industry (Ortiz, Castells, & Sonnemann, 2009) analyzes 25 case studies published from 2000 to 2007 and found them to be not fully comparable because of variations in their final output and target audience. The study concludes that, although it is often difficult and expensive, "LCA of BMCC (building materials and component combinations) and WPC (whole process of construction) definitely represent an innovative methodology which improves sustainability… throughout all stages of the building life cycle". (2009, pg. 34)

The distinction made by Ortiz et al. between LCA of components and LCA of whole buildings is also made by Kotaji, Schuurmans, and Edwards (2003) and is useful in organizing and examining the existing literature. Dozens of LCAs of specific building products have been completed; however the majority does not give serious consideration to construction phase impacts, but instead focus on the materials manufacturing or operation phases of a building's life cycle. There are a handful of exceptions. Nebel, Simmer, and Wegener (2006) measured average commuting distance for construction workers, average waste factors on-site, electricity consumption during installation and volatile organic compound (VOC) production in an analysis of three types of parquet flooring. The construction phase was identified as the unit process with the second largest potential for improvement due to the high level of VOCs resulting from sanding and finishing. In a comparison of residential heating systems, Glick (2007) also calculated commuting miles for workers and provided a rough approximation of electrical use for job site equipment.

LCAs of the whole process of construction (WPC) aim to catalog the environmental impacts of an entire building from design through demolition and therefore must attempt to accurately capture construction phase activities. Cole (1999) made one of the first detailed examinations of a building from cradle to grave with the stated purpose of determining "the relative proportion that the construction process represents of the total initial embodied energy and greenhouse gas emissions (pg. 335)." Using published data and phone interviews, the construction processes for wood, steel and concrete framed buildings were modeled and analyzed for their contribution to energy use and greenhouse gas (GHG) emissions from five sources: 1) worker transportation to and from the site, 2) materials transportation to site from distribution center, 3) equipment transportation to site, 4) on-site use of equipment, and 5) supporting processes such as temporary heating. Worker transportation was found to be the largest contributor to embodied energy and greenhouse gas emissions, regardless of building type. Steel assemblies were found to typically have the lowest construction energy, due to requiring fewer worker days. All construction activities combined were found to account for between 6.5% and 10% of a building's embodied energy.

Scheuer, Keoleian, and Reppe (2003) modeled the lifespan of a 7300 m^2 six-story university building and concluded that manufacturing of building materials, transportation and construction were responsible for only 2.2% of total energy use, with other impact categories showing similar results. This low number can be partially explained by the long use phase (50 years) and the omission of worker transportation from the model. Additionally, the researchers did not have access to actual construction data and instead assumed that construction energy use was equal to 5% of the building's total embodied energy.

Guggemos and Horvath (2005) developed a more comprehensive model for quantifying construction phase impacts in a comparison of two otherwise identical steel and concrete framed buildings. In addition to the processes examined in previous studies, the authors included impacts from temporary and consumable materials used at the fabrication shop and job site. During the construction phase, the concrete building was found to require more energy and produce more air emissions due to its larger transportation mass and more equipment use, while the steel framed building produced more VOCs and heavy metal emissions because of painting, torch cutting and welding.

Construction of a new structural steel framed building at the University of California, Santa Barbara was analyzed by Guggemos and Horvath (2006) using the Construction Environmental Decision-Support Tool (CEDST) developed in Guggemos (2003). Onsite equipment use was found to be the most significant source of all environmental impacts, except VOCs and heavy metals. Temporary materials were found to be the second largest contributor, while material and equipment transportation to the site were not significant. Equipment use was again identified as the largest contributor to energy use and emissions during the construction phase in Junnila et al. (2006).

2.4 Inventory Analysis Categories

Five pollutants and energy consumption are utilized as the six indicator categories for this study's inventory analysis. The following sections discuss the five selected pollutants—carbon dioxide, sulfur oxides, carbon monoxide, nitrogen oxides, and particulate matter—in terms of environmental and human health concerns.

2.4.1 Carbon Dioxide (CO_2)

CO_2 is a gas that is naturally produced by plants and animals during respiration. It is also produced by human activities, such as the burning of fossil fuels, the clearing of forested land, and industrial processes like cement manufacturing. CO_2 is also a greenhouse gas (GHG) due to its ability to trap heat inside earth's atmosphere (EPA, 2010b). It is the single most significant anthropogenic GHG, with human activities releasing over 38 gigatonnes into the atmosphere annually (International Panel on Climate Change (IPCC) 2007, p. 36). As a result, atmospheric concentrations of CO_2 averaged 379 ppm in 2005, up from 280 ppm in pre-industrial times (p. 37). The IPCC now believes that "most of the observed increase in global average temperatures since the mid-20th century is *very likely* (their emphasis) due to the observed increase in anthropogenic GHG concentrations (p. 39)."

Stringent emission standards for construction equipment were not adopted at the national level until 1998, much later than for other major sources of air pollution like passenger vehicles and power plants. These rules are expected to reduce exhaust emissions from nonroad engines by more than 90%, preventing 12,000 premature deaths, 8,900 hospitalizations, and one million work days lost by 2030 (EPA, 2007). However, due to the fact that EPA standards only regulate new engines and construction equipment often lasts twenty to thirty years, nonroad diesel engines continue to be responsible for a disproportionate level of emissions per unit of fuel consumed (EPA, 1998b) and contribute significantly to localized air quality problems.

2.4.2 Sulfur Oxides (SO_x)

SO_x represents all sulfur oxides, including sulfur dioxide (SO_2), the primary cause of acid rain. SO_x particles lodge in sensitive parts of the lungs, resulting in emphysema, bronchitis, and heart disease. Coal-fired power plants and industrial facilities are responsible for the majority of SO_x emissions, but construction equipment also produces SO_2 because of the higher sulfur content of nonroad diesel fuel. Due in part to the EPA's highly successful cap and trade program for SO_2 emissions, ambient concentrations have been reduced by 70% since 1980 (EPA, 2010f). Recent standards limiting nonroad diesel fuel to 500 ppm sulfur should also contribute to the decline in atmospheric SO_x (EPA, 2007).

2.4.3 Carbon Monoxide (CO)

CO is a byproduct when the carbon in fossil fuels is only partially burned. It reduces the body's ability to absorb oxygen and can be dangerous to humans at relatively low levels. CO also combines with other pollutants to form ground-level ozone, which worsens in colder climates when pollution is held near the ground by a layer of warmer air above. Nonroad engines are responsible for approximately a quarter of CO emissions in the U.S. (EPA, 2010c).

2.4.4 Nitrogen Oxides (NO_x)

NO_x refers to the group of gases known as nitrogen oxides. From an air pollution prospective, the most important nitrogen oxides are nitrogen dioxide (NO_2), nitric oxide (NO), nitrous acid, and nitric acid, which have been linked to crop damage, acid rain, and reductions in visibility. Human health concerns from NO_x include airway inflammation, increased symptoms for people with asthma, and increased emergency room visits for respiratory issues. At the national level, NO_2 levels have been decreasing steadily since the early 1980's due to more strict regulations. Localized concentrations remain a public health concern, especially near highways, railroads, and airports (EPA, 2010d). NO_x and CO also contribute to the formation of ground-level ozone, a pollutant linked to coughing, wheezing, aggravation of asthma, and permanent lung damage. Jefferson County, Colorado, the location of the NREL project, is considered a "nonattainment area" by the EPA for having levels of ozone that persistently exceed the national ambient air quality standards (EPA, 2010a).

2.4.5 Particulate Matter (PM_{10})

Particulate matter, or particle pollution, is the generic name for an assortment of organic chemicals, metals, acids, soil, and dust particles that have been identified as potentially harmful to human health. Particulate matter is classified by size and PM_{10} refers to those particles ten micrometers in diameter or less. These smaller particles are regulated by the Clean Air Act because they are more easily inhaled and can damage the heart and lungs (EPA, 2010e). Internal combustion engines and construction sites are both major sources of man-made particulate matter, which is responsible for smog and haze in urban areas (Oklahoma Department of Environmental Quality, 2006).

3 Research Methodology

The activities involved in the erection of a structural steel building frame are numerous and varied. A systematic approach to data collection and analysis is crucial to precisely inventory energy consumption and environmental emissions from each of these activities. A combination of process diagramming and LCA is used in this study to assure every relevant process is accounted for and that the resulting impacts are accurately captured. A single case study approach is utilized and is sufficient to support this research, due to the relative consistency of the steel erection process throughout the industry.

The results of the baseline life cycle inventory are analyzed to identify the activities with the most significant contribution to environmental loads. Through a literature review and concurrent research consisting of interviews with case study project members (Gotthelf, 2010), environmentally preferable alternatives are identified and modeled to quantify their potential savings. An assessment of these alternatives is conducted based upon feasibility of implementation, ability to impact life cycle environmental performance and cost.

3.1 Case Studies

According to Creswell (2008), a case study is "an in-depth exploration of a bounded system (e.g., an activity, event, process, or individuals) based on extensive data collection" (p. 476). The in-depth nature of case studies limits the number of systems that can be studied, but provides data on details that might be missed by a broader scope of research. *Intrinsic* case studies focus on a particularly noteworthy or exceptional system, while *instrumental* case studies use a typical example to illustrate a more universal trend or issue. Ideally, the researcher provides an exploration of the relationship between their specific case study and the broader societal context or significance.

The subject of this case study is a new mid-sized office building, currently under construction on the campus of the National Renewable Energy Laboratory (NREL) in Golden, Colorado. The details of the case study building are discussed in greater detail in Chapter 4, but it is important to note that the project is targeting LEED Platinum certification and is designed to be one the most sustainable office spaces in the nation, if not the world. As a research subject, the NREL building's steel erection combines elements of both intrinsic and instrumental case studies. The cutting-edge sustainable design of the overall project makes it intrinsically interesting for research on environmental best practices in steel erection, yet the standardized erection process used suggests an instrumental case study of environmental impacts from typical steel erection techniques.

3.2 Life Cycle Assessment

A hybrid of process-based LCA and EIO-LCA is used to capture both the direct and supply-chain environmental impacts for each activity in the erection process. Process-based estimates are used for those impacts that take place specifically during the erection process, while the EIO method is used to determine upstream inputs and impacts. For instance, direct CO_2 emissions from a crane used onsite are calculated from observation of the crane's usage and published emissions rates for that equipment; while CO_2 emissions resulting from the extraction, refinement and transportation of the diesel fuel used in the crane are approximated using EIO-LCA. Below is an itemization of the impacts calculated using each LCA methodology.

Impacts calculated using process-based LCA:

- Direct emissions from on-site equipment usage during erection
- Direct emissions from worker transportation to and from job site
- Direct emissions from material and equipment transportation to site

Impacts calculated using EIO-LCA:

- Emissions from generation of electricity used on site during erection
- Emissions from production of gas and diesel fuel consumed by on-site equipment and transportation of workers, material, and equipment to site
- Emissions from manufacturing of welding rod and wire used during erection

3.2.1 Goal and Scope Definition

The first step in LCA is to define the purpose and boundaries of the study. Goal and scope definition can be a highly complex process and involves consideration of the available resources, the purpose of the study, and the target audience. The aim is to establish a system boundary which is sufficiently wide to capture all meaningful impacts, yet is narrow enough to keep the study feasible. One approach to limiting scope is to only include certain life stages in the study. Some LCAs focus exclusively on the extraction and manufacturing of a product, while others follow the product through to the end-of-life stage. Scope can also be limited by the level of detail that is included (Graedel & Allenby, 2003).

This study’s scope is limited to the transportation of structural steel members to the job site and on-site steel erection activities for the case study building. See Section 4.1 for a more detailed description of the case study’s goal and scope definition.

3.2.2 Process Diagrams

Once the boundaries of the system to be studied are clearly defined, a process diagram detailing every activity and the relationships between activities is developed for the full lifespan of the product or process. The process diagram is a graphical representation with each activity shown as a box and the sequence of activities illustrated by arrows connecting the boxes. Creation of a process diagram helps prevent the omission of activities critical to the larger systems and organizes the research into more manageable units for subsequent steps. (Guggemos, 2003). Process diagramming or modeling is a technique utilized within the goal and scope definition stage of the basic LCA frame work and does not constitute a separate step.

3.2.3 Inventory Analysis

Resource inputs and environmental outputs are calculated and aggregated for each activity during the inventory analysis. According to Graedel and Allenby, "The aim is to list, at least qualitatively but preferably quantitatively, all inputs and outputs of materials and energy throughout all life stages (2003, p.191)". Data for the inventory analysis can come from three sources: primary data collection, secondary data collection, and assumptions. Primary data collection often requires taking representative samples of emissions from a particular activity, which can be difficult and expensive to do accurately. Secondary data collection utilizes published information such as articles and studies that are applicable to the system in question. Assumptions rely on logic to bridge the gap between existing data and the process being studied. This method is used when neither primary nor secondary data collection is feasible (Ciambrone, 1997, p. 50-53).

This study uses a combination of primary data (site observation and communication with project team members) and secondary data (published emissions factors and fuel consumption for equipment) to quantify energy consumption and emissions of five pollutants: carbon dioxide, sulfur oxides, carbon monoxide, nitrogen oxides, and particulate matter. Selection is based on a combination of each pollutant's contribution to environmental concerns and the availability of necessary emissions data from publicly available sources. A major limiting factor in the number of categories selected is variation in the pollutants supplied by different secondary sources; methane, chlorofluorocarbons, volatile organic carbons, hydrocarbons, and lead emissions are all reported inconsistently between databases. The specific sources of emissions and energy consumption data for each activity are provided in Section 4.4.

Researcher observation of the erection process was used to determine the equipment usage durations associate with activity identified in the process model. An instrument was developed to accurately record inputs and outputs during observation of each activity. Figure 1 shows the instrument used to record observations on the unloading of materials from delivery trucks at the jobsite. Appendix 7.1 contains the observational instruments used for all other activities.

Delivery From:		
Load Description/ # of Pieces:		
Equipment:	#1	#2
Use/Job:		
Total Operating Time for Load:		
% Idling:		
Associated Personnel:		
Notes:		

Figure 1 Instrument used to record observation of unloading activities

A study, such as this one, that stops at the inventory analysis stage is known as a life cycle inventory (LCI), not an LCA.

3.2.4 Economic Input-Output LCA

EIO-LCA provides a more comprehensive, but less precise, method for estimating the environmental impact of a good or service (Rebitzer et al., 2004). EIO-LCA combines aggregated national data on purchases made by each of the economy's approximately 500 sectors with pollution statistics for each of those sectors. This reveals the indirect emissions and energy consumption that result from one unit of production from a given sector. The advantage of EIO-LCA is that it provides information on nation-wide systems that may otherwise be inaccessible to the researcher (Hendrickson et al., 2006). The main disadvantage of EIO-LCA is that it does not differentiate between goods from different sources within the same sector of the economy; for example, a tomato purchased directly from a local organic farm would produce the same estimated impacts as a conventionally-grown, plastic-wrapped tomato transported 1500 miles before reaching the grocery store shelf. For this reason, EIO-LCA is more effective for determining baseline impacts from a process than for comparison of similar processes (Green Design Institute, 2009).

This study utilizes two EIO-LCA sources to determine upstream impacts from the production of items consumed during the erection process: NREL's *U.S. Life-Cycle Inventory Database* (2005) and the Green Design Institute's (2009) online EIO-LCA tool.

4 Case Study: Energy and Emissions from Structural Steel Erection of a Mid-sized Office Building

The topic of the case study is the Research Support Facility (RSF) at NREL's South Table Mountain Campus in Golden, Colorado. The 218,000 square foot building is designed to accommodate 700 employees and cost \$64 million (\$27.31 per m^2) to build (Simon, 2009). The project's twenty three sustainability goals include LEED Platinum certification, net-zero energy performance, exceptional occupant comfort, and visible use of renewable energy systems. As part of the building's integrated design process, the many disciplines involved in the design and construction process—architects, engineers, consultants, contractors, subcontractors, manufacturers, and occupants—were brought onboard earlier and collaborated more extensively than in a typical design-bid-build process (Gotthelf, 2010).

The three-story building utilizes a unique H-shaped floor plan to maximize interior daylight and solar heat gain during the winter months. These efforts have led the building to be called "the greenest office building in the country" (Simon, 2009) and "a model for future sustainable office buildings" (Leslie, 2009). The RSF's structural design is typical of a modern steel-framed office building, but with two notable exceptions: reclaimed natural gas pipes, some filled with concrete, were used as structural columns in place of new wide-flange columns and the integrated design process lead to the layout of horizontal members being redesigned to better accommodate mechanical components.

4.1 Study Boundaries

The scope of this study was limited by a life-stage boundary around the construction phase of the NREL building. Furthermore, the scope only included the major components of the structural steel frame of the building. The scope definitions combined to delineate a process referred to as *structural steel erection for the NREL building.* The process begins with the steel frame components leaving various fabrication plants and ends with all of the members being permanently welded or bolted in place. The indirect impacts of extracting and manufacturing goods *consumed* during the erection process, such as gasoline, diesel fuel, welding rod, and electricity, were included in the scope. Additionally, electricity used by the contractor's on-site office trailer was included.

Auxiliary processes excluded from the study's scope include fabrication of the steel members, placement of structural concrete and concrete reinforcement, light gauge steel framing of interior partition walls, and the erector's home office operations.

The erection activities were further divided into three groups: transportation activities, raising gang activities, and detailing activities. *Transportation activities* include delivery of materials to the jobsite, delivery of equipment to and from the jobsite, worker transportation to and from jobsite, and the production of the fuel used during transportation activities. *Raising gang activities* are defined as those performed by the erector's raising crew and include the unloading of materials at the jobsite, preparing components for installation (shakeout, organization of lay-down area, moving steel around site), placing structural members, and temporarily connecting those members. *Detailing activities* are those done by the erector's detailing crew and consist primarily of bolting and welding the permanent connections between members.

4.2 Process Diagram

A preliminary process diagram of the steel erection process was developed from a review of existing literature (Emmitt & Gorse, 2006; Andres & Smith, 2004) and diagrams of similar systems (Bilec, 2007; Guggemos, 2003). Through consultation with employees of the steel erection company and site observations made on September 4, 2009, the draft diagram was modified to reflect the specific process used to erect the steel frame of the NREL building. The resulting process diagram is shown in Figure 2. Activities that took place on the NREL job site are shown within the large box to the right and activities that occurred off-site are shown to the left of the box. Arrows show the progression of on-site activities.

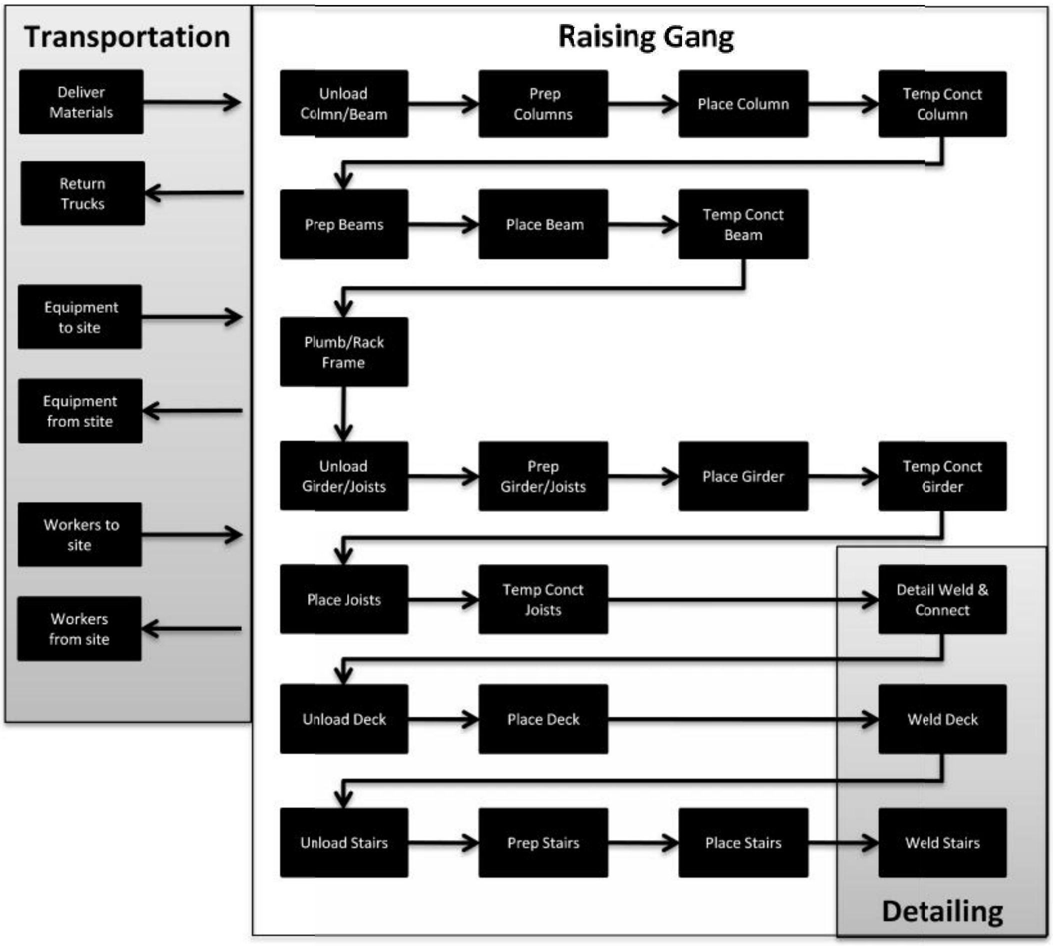

Figure 2 Process diagram of structural steel erection for NREL RSF building

4.3 Site Observations

Site observations occurred concurrently with and informed the development of the process model. Once complete, the process diagram was populated with equipment usage and resource consumption quantities for each activity through additional site observation and consultation with the erector's project management team. Site observations occurred on September 4, October 6-7, and November 11, 2009, during the erection of structural steel in Area "F" of the NREL building.

All site observations of equipment usage were made on a time per unit basis. The mean of the observed times was then multiplied by the total number of units in the building to estimate the total time each piece of equipment spent on the specific activity. For example, the observed times for the 100-ton crane to place a girder were 19 min 48 sec, 7 min 33 sec, and 11 min 41 sec, which have a mean of 13 min 1 sec. There are 109 girders in the building, so 109 x 13.02 min = 1420 min total spent by the 100-ton crane placing girders. The number of times the researcher observed each process was dictated by actual construction activities on the days that site visits were made. Thus, sample size varies considerably between activities.

4.3.1 Equipment

The make and model of all equipment used for off-site transportation and on-site erection activities were recorded during site observations. Table 1 shows a sample of the vehicles used by the steel erector's employees for personal transportation to and from the jobsite. Fuel efficiencies are highway estimates provided by DOE (2010). The median of all fuel efficiencies for that model year was used when the specific engine type was unknown.

Table 1 Fuel efficiency of worker vehicles from DOE, 2010

Make	Model	Year	Engine Type	Fuel	mpg
Honda	Civic	1996	4 cyl, 1.6L	Gasoline	33
Volkswagen	Jetta	2006	4 cyl, 1.6L	Gasoline	28
Chevy	2500 HD	2007	V8, 6.0L	Gasoline	19
Ford	F-150 4WD	2002	8 cyl, 4.6L	Gasoline	17
Toyota	Camry	2000	6 cyl, 3L	Gasoline	26
Dodge	Dakota 4WD	2004	8 cyl, 4.7L	Gasoline	17

The make and model of each piece of construction equipment used during steel erection were determined through site observation and conversations with the erector's project management team. The make, model, and horsepower (HP) of each piece of equipment's engine were taken from manufacturers' product information sheets and are shown in Table 2.

Table 2 Diesel-powered construction equipment used during erection by horsepower (Manitowoc, 2009; Kobelco Cranes North America, 2009; JLG Industries, 2009b; Genie United States, 2009; JLG Industries, 2009a; Red-D-Arc Welderentals, n.d.a)

Type	Model	Model	Year	Engine	Fuel	HP
275-ton Crane	Manitowoc	999	>2004	Cummins QSM11	Diesel	400
100-ton Crane	Kobelco	CK1000-III	>2004	Hino P11C-UN	Diesel	331
Forklift	JLG	944 E-42	>2004	Cummins QSB4.5T	Diesel	110
80ft Man Lift	Genie	S-80	>2004	Deutz TD2011 L04i	Diesel	74
60ft Man Lift	JLG	600 AJ	>2004	Caterpillar 3044C	Diesel	63.3
Diesel Welder	Red-D-Arc	D302K 3+12	>2004	Kubota V1505	Diesel	20.2

Likewise, the make and model of electric hand tools used regularly during erection were recorded. The power rating of each tool was gathered from manufacturers' published product data and is shown in Table 3.

Table 3 Electric tools used during erection (Makita, n.d.; Hilti USA, n.d.; Red-D-Arc Welderentals, n.d.b)

Type	Brand	Model	Power (W)
Impact Wrench	Makita	6906	1980
Hammer Drill	Hilti	TE 70-ATC	1600
4 Pak Welder	Red-D-Arc	Extreme 360	Variable

4.3.2 Transportation Inputs

During site observations, workers were questioned about commuting habits to estimate fuel inputs for transportation to and from the jobsite. The drivers of six vehicles were asked the route of their work commute and typical carpooling practices. This information was combined with the fuel efficiency values for their vehicles in Table 1 to calculate average fuel consumption per worker per day of 2.92 gallons of gasoline. 1759 worker days were spent on steel erection according to the erector's records (D. Cohen, personal communication, November 11, 2009), so total fuel consumption for worker transportation was estimated at 5133 gallons (2.92 x 1759). These input values are shown in Table 4.

Table 4 Worker transportation input values. Fuel efficiency values from DOE, 2010

	MPG	Round Trip (mi)	Fuel/Day (gal)	Occupants	Fuel/Day/Worker (gal)
Vehicle #1	33	138	4.18	2	2.09
Vehicle #2	28	222	7.93	3	2.64
Vehicle #3	19	102	5.37	1	5.37
Vehicle #4	17	71	4.18	1	4.18
Vehicle #5	26	159	6.12	2	3.06
Vehicle #6	17	24	1.41	1	1.41
Average Daily Totals:	**23.3**	**119**	**29.2**	**10**	**2.92**

All materials were assumed to be delivered to the site by heavy-duty diesel trucks pulling flatbed trailers. Both site observations and project team members' comments supported this assumption. Since actual fuel usage could not be captured for each delivery, the location of fabrication shops and number of deliveries for each component type were used to calculate total miles traveled. In total, 23 loads of columns and beams came from PVS in Omaha, Nebraska; 35 loads of girders and joists came from Quincy Joist in Buckeye, Arizona; 12 loads of decking came from Wheeling Corrugating in Houston, Texas; and 17 loads of stair assemblies came from CorTek, Inc. in Loveland, Colorado.

A return factor was used to allocate the proper portion of impacts from the delivery trucks' return trip to steel erection activities. Discussions with out-of-state delivery drivers suggested that approximately 50% of the time they returned to the fabrication plant without a load and 50% of the time they picked-up another load near the project site before returning. This is represented by a 0.5 return factor for column, beam, truss, and decking deliveries. The proximity of the stair fabricator increased the likelihood that their truck would return empty, so a return factor of 1 was used for this component. An average fuel efficiency for heavy diesel trucks was then used to estimate total fuel consumption (Huai et al., 2006). Table 5 summarizes the materials transportation inputs.

Table 5 Materials transportation by heavy diesel truck input values. Fuel efficiency from Huai et al., 2006

Component	MPG	1-Way Mileage (mi)	Return Factor (0-1)	Fuel/Trip (gal)	Total Trips (#)	Total Fuel (gal)
Columns & Beams	6.6	551	0.5	125	23	2,880
Girders & Joists	6.6	921	0.5	209	35	7,330
Decking	6.6	1,140	0.5	258	12	3,100
Stair Assemblies	6.6	63	1	19.1	17	325
Project Total	**-**	**-**	**-**	**-**	**87**	**13,600**

Heavy diesel trucks pulling flatbed trailers also delivered all equipment to the site. The number of trips required to transport the equipment to and from the jobsite was multiplied by the distance between the site and the equipment rental company’s yard to calculate total equipment transportation mileage. A usage factor was used to account for the portion of the equipment’s time on the NREL project that was for steel erection activities and thus the portion of transportation impacts that should be attribute to steel erection. A usage factor of one indicates that 100% of the equipment’s project usage was dedicated to steel erection, while a usage factor of .25 would be used when only a quarter of usage was for steel erection purposes. Usage factors were determined by worker input and billing records from equipment rental companies (D. Cohen, personal communication, December 10, 2009). Table 6 summarizes the equipment transportation inputs.

Table 6 Equipment transportation by heavy diesel truck input values. Fuel efficiency from Huai et al., 2006

Equipment	MPG	Round Trip Mileage (mi)	Fuel/Trip (gal)	Total Trips (#)	Usage Factor (0-1)	Total Fuel (gal)
275-ton Crane	6.6	28.0	4.24	32	0.25	33.9
100-ton Crane	6.6	28.0	4.24	14	1	59.4
Forklift	6.6	21.0	3.18	2	1	6.4
80ft Man Lift	6.6	21.0	3.18	2	1	6.4
60ft Man Lift	6.6	21.0	3.18	2	1	6.4
Job Trailer	6.6	118	17.9	2	1	35.8
Project Total	-	-	-	-	-	**148**

Fuel consumption for worker, materials, and equipment transportation were added to calculate total transportation related fuel consumption. Total fuel cost was calculated with U.S. Energy Information Administration data for retail prices (US EIA, 2010b; US EIA, 2010c) and used as an input for the EIO-LCA. Total transportation fuel consumption and cost are shown in

Table 7.

Table 7 Total transportation fuel consumption and cost

Fuel	Total Fuel (gal)	Cost/Gal ($)	Total Cost ($)
Diesel	13,800	2.66	36,700
Gas	5,130	2.63	13,500
Total	**18,930**	**-**	**50,200**

4.3.3 Raising Gang Inputs

Once the steel frame's components arrived onsite, the raising gang was responsible for unloading and placing each piece in the laydown area. The researcher observed at least one load of each component type (columns, beams, joists, decking, and stair assemblies) being unloaded at the NREL site and recorded the time spent by equipment to unload each piece from the truck. The mean of these times was then calculated and multiplied by the total number of that component in the building to arrive at a value for the total time spent unloading each component type. Table 8 summarizes the inputs for unloading activities.

Table 8 Equipment inputs for unloading activities by component type

Component	Equipment	Average Time/Piece (min)	Total Pieces (#)	Total Time (min)
Columns (per section):				
	Forklift	7.58	172	1,300
Beams (per each):				
	Forklift	3.30	571	1,880
Girders & Joists (per each):				
	100-Ton Crane	1.05	928	974
Decking (per ton):				
	100-Ton Crane	2.82	171	482
Stair Units (per each):				
	Forklift	60.0	6	360

Before the raising gang could erect the steel for a section of the building, significant effort went into finding, organizing, and relocating structural members so that they could be picked-up and put in place without the crane having to move each time. These activities have been combined under the label *preparation activities* for the sake of this study. Preparation activities were complicated by the relatively small laydown area at the NREL site, which often required components to be stacked one on top of another. In some cases, two pieces of equipment were used simultaneously for preparation activities: one to locate pieces in the laydown area and another to move the pieces to the proper section of the building. Additionally, the large footprint of the NREL building extended the time required to relocate steel members around the site.

The process for calculating the time per piece and total equipment usage during preparation activities was identical to that used for unloading activities. The researcher observed preparation activities for every component type, except decking. Conversations with the erector's superintendents determined that there was little or no preparation work involved with decking. Typically the decking was stacked in a separate section of the laydown area and then, while still bundled, moved directly from there to the floor on which it was used. This was determined to be a *placing* activity, not a preparation activity. Table 9 summarizes the inputs for preparation activities.

Table 9 Equipment inputs for preparation activities by component type

Component	Equipment	Time/Piece (min)	Total Pieces (#)	Total Time (min)
Columns (per section):				
	100-Ton Crane	2.85	172	490
Beams (per each):				
	Forklift	5.37	571	3,070
Joists (per each):				
	100-Ton Crane	4.38	819	3,590
	275-Ton Crane	0.45	819	369
Girders (per each):				
	100-Ton Crane	6.15	109	670
	Forklift	0.84	109	91.6
Stair Stringers (per each):				
	100-Ton Crane	10.8	30	325
Stair Landings (per each):				
	100-Ton Crane	5.78	30	173
Stair Railings (per each):				
	100-Ton Crane	1.98	30	59.4

Once the necessary pieces were assembled, the crane operator worked with three to five members of the raising gang to place components in their permanent position within the frame and temporarily secure them with bolts or tack welds. Typically, two workers were on the ground rigging the next piece and two or three more were on the steel frame landing and connecting pieces. Although placing and temporary connection activities are shown separately in the process diagram, they occur simultaneously and are indistinguishable from an equipment usage perspective.

The process for calculating the time per piece and total equipment usage during preparation activities was identical to that used for unloading and preparation activities. The diesel-powered welder was used as a generator to power the impact wrench during placement of columns because the impact wrench repeatedly tripped the breakers on the site electricity connection. Table 10 summarizes the inputs for placing and temporary connection activities.

Table 10 Equipment inputs for placing and temporary connection activities by component type

Equipment	Time/Piece (min)	Total Pieces (#)	Total Time (min)
Columns (per section):			
100-Ton Crane	11.8	172	2,020
Forklift	5.10	172	877
Diesel Welder	11.8	172	2,020
W-Beams (per each):			
100-Ton Crane	6.01	521	3,130
Forklift	1.80	521	938
Other Beams (per each):			
100-Ton Crane	15.2	50	759
60ft Man Lift	14.7	50	735
Joists (per each):			
100-Ton Crane	5.22	819	4,280
275-Ton Crane	5.48	819	4,490
Girders (per each):			
100-Ton Crane	13.0	109	1,420
Decking (per ton):			
100-Ton Crane	3.00	171	513
Stair Stringers (per each):			
100-Ton Crane	8.64	30	259
Stair Landings (per each):			
100-Ton Crane	26.3	30	788
Hammer Drill	3.50	30	105
Stair Railings (per each):			
100-Ton Crane	1.98	30	59.4

The inputs from each individual raising gang activity were combined to provide a picture of total equipment use associated with these steps. These values are shown in Table 11. Diesel consumption was calculated using the brake specific fuel consumption (BSFC) method outlined in Section 4.4.1. Both time of use and fuel consumption are dominated by the 100-ton crane, which was used almost exclusively for raising activities while onsite. Electricity usage by the erector's job trailer was grouped with the raising gang because the majority of supervisory work is focused on raising-related activities and the associated equipment.

Table 11 Total raising gang equipment and fuel usage by equipment type

Equipment	Total Use (hrs)	Electricity (kWh)	Diesel (gal)
275-Ton Crane	80.9	-	1,550
100-Ton Crane	333	-	5,290
Forklift	142	-	756
60ft Man Lift	12.2	-	51.1
Diesel Welder	33.7	-	44.9
Hammer Drill	1.75	2.80	-
Job Trailer	-	1,160	-
Raising Gang Totals	**604**	**1,163**	**7,690**

4.3.4 Detailing Inputs

During site observations, the detailing crew consisted of at least 10 employees spread throughout the jobsite, completing different tasks, either alone or in pairs. The variety and inconsistency of detailing activities on the project necessitated that inputs be determined on an aggregated basis. The erector used invoices to calculate the total quantity of welding rod and wire used by the detailing crew (D. Cohen, personal communication, November 30, 2009). The detailing crew used two 350 amp welders connected to site electricity for the majority of welding and hand tool use, but occasionally used two 300 amp diesel-powered welders for smaller tasks or when site power could not be reached. The erector's superintendent estimated that 90% of welding on the project was done with the electric welders, while the remaining 10% was done with the diesel welders (R. Nelson, personal communication, October 7, 2009). The quantity of electrode used by the electric welders was calculated by multiplying the known total quantity of each electrode type by the 90% factor. The quantity of each electrode was then multiplied by standard feed rates (ESAB Welding and Cutting Products, Inc., 2000) to yield total welding time. Welding times were coupled with the appropriate welder power setting for each electrode type to calculate total electricity use. The feed rates account for typical deposition efficiency and stub losses. Inputs for the electric welders are shown in Table 12.

Table 12 Electrode and electricity consumption by electric welders. Feed rates from ESAB Welding and Cutting Products, Inc. (2000)

Electrode	Rod/Wire (lbs)	Feed Rate (lbs/min)	Time (min)	Power (W)	Electricity (kWh)
Rod:					
E7018 1/8"	900	0.070	12,800	9,060	1,940
E7018 5/32"	1,440	0.115	12,500	13,500	2,810
E7028 5/32”	720	0.115	6,270	13,500	1,410
Wire:					
NR233 1/16"	810	0.092	8,790	13,500	1,970
XLR-8	180	0.092	1,950	13,500	438
Electric Welding Total	**4050**	**-**	**42,400**	**-**	**8,570**

The remaining 10% of detail welding was combined with all other miscellaneous detailing activities (permanent bolting, grinding, cutting for field repairs) because they all primarily utilized the diesel welders for power. The mobility of the diesel welders and their ability to handle the power drawn by impact wrenches made them the logical choice for smaller, dispersed detailing jobs.

Fuel consumption for diesel welders is primarily a function of time running, not the quantity of work performed, so use was approximated from the researcher’s observations of when the welders were turned on and off each day. During each site visit, one diesel welder ran the vast majority of the day and occasionally a second was turned on; the amount of time in which two welders were running was similar to that in which neither was, so total use was determined to approximately equal the detailing crew’s work hours. The logic of this assumption was confirmed by the erector's project engineer and superintendent. Diesel welder use and fuel consumption for detailing activities are shown in Table 13.

Table 13 Diesel welder use and fuel consumption for detailing activities.

Equipment	Total Project Use (hrs)	Raising Gang Use (hrs)	Detailing Use (hrs)	Diesel (gal)
Diesel Welder	464	34	430	573

The cost of all welding consumables was provided by the erector's project engineer and equaled $8454 (D. Cohen, personal communication, December 7, 2009 & January 12, 2010). The total cost for diesel consumed during detailing equaled $1520 (US EIA, 2010b).

4.4 Life Cycle Inventory Data Sources

After equipment and material inputs for each activity in the project's steel erection process are determined, a number of published sources are used to approximate energy consumption and environmental emissions resulting from each input. This section discusses each of these sources and how they are used to calculate project-specific impacts.

4.4.1 Construction Equipment Emissions Factors

EPA's *NONROAD 2008 Emissions Inventory Model* (2008) is the latest edition of a computer application designed to evaluate emissions from non-highway engines, such as those found in lawnmowers, motorboats, portable generators and construction equipment. Although the *NONROAD 2008* software is intended to quantify emissions at the county, state, or national level for policy development purposes, the emissions factors used to calculate regional totals are useful at a more micro level (EPA, 1998a). According to the EPA, an emissions factor "estimates the amount of pollution emitted by a particular type of equipment during a unit of use. Typically, emission factors for non-road sources are reported in grams per horsepower-hour (g/hp-hr), but they also may be reported in grams per mile, grams per hour, and grams per gallon (2004, p. 2)."

For diesel engines the *Exhaust and Crankcase Emission Factors for Nonroad Engine Modeling: Compression Ignition* (US EPA, 2004) was used and for gasoline engines the *Exhaust and Crankcase Emission Factors for Nonroad Engine Modeling: Spark Ignition* (US EPA, 2002) was used. These documents provide the quantity of hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), particulate matter (PM) and carbon dioxide (CO_2) produced by an engine as a function of its fuel type, rated horsepower, and the emissions standard by which it is governed (based on model year). Brake specific fuel consumption (BSFC) – the ratio of fuel consumption to power production – is also provided, so fuel consumption can be calculated if operating time is known. Because BSFC and the per-horsepower-hour rates for emissions are based on tests of idling engines, a *transient adjustment factor* adjusts for the difference between test conditions and typical in-use conditions for each type of equipment. For example the transient adjustment factor for hydrocarbon emissions from "Rough Terrain Fork Lifts" is 1.47, because research shows that a fork lift operating under actual jobsite conditions produces 1.47 times more hydrocarbons than the same forklift simply idling (EPA, 2004, p. A9).

The *NONROAD 2008* emissions factors were used to determine the emissions from the 275-ton crane, the 100-ton crane, the forklift, both man lifts, and the diesel-power welders. BSFC was multiplied by the heating value of diesel (19,300 Btu/lb) to calculate the energy consumption of these pieces of equipment.

Additionally, BSFC values were used to calculate total fuel consumption for each piece of equipment. Table 14 shows the emissions factors and BSFC values used for each type of construction equipment.

Table 14 Environmental emissions and energy consumption per hour of operation for construction equipment (EPA, 2004)

Equipment	BSFC (lb/h)	CO (g/h)	NO_x (g/h)	PM (g/h)	CO_2 (g/h)	SO_x (g/h)	Energy (MJ/h)
100-ton Crane	116	279	828	49.7	167,000	339	2,360
275-ton Crane	140	337	1000	60.0	202,000	409	2,850
Forklift	38.9	146	286	35.6	56,200	114	792
80ft Man Lift	35.6	450	421	42.1	51,400	104	725
60ft Man Lift	30.5	385	360	36.0	43,900	88.9	621
Diesel Welder	9.73	112	109	12.8	14,000	28.3	198

A weakness of these data sources is that the emissions factors are not given for specific makes or models of engines. Two pieces of equipment from the same year and with the same rated horsepower will have identical emissions rates, despite known discrepancies in fuel efficiency and pollution from different manufacturers' products.

4.4.2 Transportation Emissions Factors

Once diesel fuel consumption was quantified for truck transportation of materials and equipment, NREL's *U.S. Life-Cycle Inventory Database* (2005) was used to estimate emissions on a per gallon of fuel basis. The database is a collaborative effort between industry, government, and nongovernment organizations to make LCI data for basic goods and services publicly available.

Emissions factors from the “Transport, combination truck, diesel powered” category were extracted and used in the calculation of project-wide emissions from trucking. Table 15 shows the emission factor for each pollutant in grams per gallon of diesel consumed.

Table 15 Environmental emissions and energy consumption per gallon of diesel for truck transportation (NREL, 2005)

	CO (g/gal)	NO_x (g/gal)	PM (g/gal)	CO_2 (g/gal)	SO_x (g/gal)	Energy (MJ/gal)
Emissions per Gallon of Diesel	17.7	74.0	1.28	11,100	2.45	146

Emission factors for CO_2 and energy consumption for gasoline engines are from EPA’s *Emissions Facts: Average Carbon Dioxide Emissions Resulting from Gasoline and Diesel Fuel* (2005) and factors for the remaining pollutants are from the NREL (2005) database. Table 16 shows the emission factor for each pollutant in grams per gallon of gasoline consumed.

Table 16 Environmental emissions and energy consumption per gallon of gasoline for worker transportation (NREL, 2005; EPA, 2005)

	CO (g/gal)	NO_x (g/gal)	PM (g/gal)	CO_2 (g/gal)	SO_x (g/gal)	Energy (MJ/gal)
Emissions per Gallon of Gas	31.9	111	.512	8,790	4.41	131

4.4.3 Indirect and Electric Power Generation Emissions Factors

The indirect environmental emissions and energy consumption from the extraction of raw materials and manufacturing of goods consumed during the erection process were calculated using the Green Design Institute’s (2009) online economic input-output LCA tool: eiolca.net. Environmental emissions resulting from the generation of electricity used during erection were also calculated using the tool. Since the emissions factors for eiolca.net are presented in grams per dollar of economic activity and the source data is from 1997, all input values had to be converted to 1997 dollars. For diesel and gasoline this was achieved by multiplying the quantity of fuel consumed times the average 1997 wholesale price for each fuel (EIA, 2010b; EIA, 2010c). For electric power generation, the quantity of electricity used was multiplied by the average commercial rate for electricity in 1997 (EIA, 2010a). For welding consumables, the 2009 dollar value was multiplied by the ratio of the 1997 consumer price index (CPI) for to the 2009 CPI for the same category. The CPI ratio was .80 and the category used was “all items less food and energy” (U.S. Census Bureau, 2010).

Table 17 shows the emissions factors used for calculating the indirect emissions and energy consumption for producing fuel and welding consumables for the steel erection process. Values are expressed as grams of emissions per 1997 dollar of economic activity. The category “welding equipment manufacturers” was assumed to include welding consumables manufacturers.

Table 17 Environmental emissions and energy consumption per dollar of production for petroleum refineries and welding equipment manufacturers (Green Design Institute, 2009; U.S. Census Bureau, 2010, p. 710)

EIO-LCA Category	CO (g/$)	NO_x (g/$)	PM (g/$)	CO_2 (g/$)	SO_x (g/$)	Energy (MJ/$)
Petroleum Refineries (NAICS #324110)	0.38	1.76	0.09	686	3.71	3.60
Welding Equipment (NAICS #333992)	5.41	1.14	0.40	465	1.48	6.56

Table 18 shows the direct and indirect emissions resulting from each kilowatt hour of electricity used during the erection process.

Table 18 Environmental emissions per kilowatt hour of electricity generated (Green Design Institute, 2009)

	CO (g/kWh)	NO_x (g/kWh)	PM (g/kWh)	CO_2 (g/kWh)	SO_x (g/kWh)	Energy (MJ/kWh)
Emissions per kWh	0.38	1.756	0.09	686	3.71	3.60

4.5 Erection Phase Emissions

Emissions and energy consumption for the NREL steel erection process were calculated using the inputs and emissions factors discussed in previous sections and are presented in Table 19. Transportation is responsible for the largest share of CO_2, CO, NO_x, and energy consumption. Raising gang activities are responsible for the largest share amount of SO_x and PM_{10}. Detailing contributes the least in every category except CO and SO_x, both of which it is responsible for the second largest contribution.

Table 19 Environmental emissions and energy consumption from structural steel erection

	CO (kg)	NO_x (kg)	PM_{10} (kg)	CO_2 (kg)	SO_x (kg)	Energy (GJ)
Transportation	407	1,430	29.4	216,000	97.4	2,990,000
	49%	69%	35%	63%	25%	63%
Raising Gang	182	428	30.1	90,800	193	1,290,000
	22%	21%	36%	27%	50%	27%
Detailing	234	207	24.0	35,600	98.3	457,000
	28%	10%	29%	10%	25%	10%
Total	**823**	**2,060**	**83.5**	**342,000**	**388**	**4,740,000**

4.5.1 Transportation Emissions

Emissions and energy consumption from transportation activities are shown in Table 20. The first three sections of the table show results for the transportation of materials, equipment, and workers. The fourth section, “Indirect Emissions”, represents pollution and energy consumption resulting from the production of diesel and gasoline for transportation. Materials transportation is responsible for the vast majority of emissions and energy consumption due to the extremely long distances some components were shipped. Equipment transportation is insignificant, representing less than 1% of transportation totals for each category.

Table 20 Environmental emissions and energy consumption from transportation activities

	CO (kg)	NO_x (kg)	PM_{10} (kg)	CO_2 (kg)	SO_x (kg)	Energy (GJ)
Materials Transport:						
Columns & Beams	50.8	213	3.68	32,000	7.04	422
Girders & Trusses	129	542	9.36	81,400	17.9	1,070
Decking	54.7	230	3.96	34,400	7.58	454
Stair Assemblies	5.73	24.0	0.42	3,600	0.79	47.5
Sub-Total	**241**	**1,010**	**17.4**	**151,000**	**33.3**	**2,000**
Equipment Transport:						
100-ton Crane	1.05	4.40	0.08	660	0.15	8.69
275-ton Crane	0.60	2.51	0.04	377	0.08	4.97
Forklift	0.11	0.47	0.01	70.7	0.02	0.93
Man Lift #1	0.11	0.47	0.01	70.7	0.02	0.93
Man Lift #2	0.11	0.47	0.01	70.7	0.02	0.93
Job Trailer	0.63	2.65	0.05	397	0.09	5.23
Sub-Total	**2.62**	**11.0**	**0.19**	**1,650**	**0.36**	**21.7**
Worker Transport:						
Erector's Employees	90.6	380	6.56	45,100	12.6	673
Indirect Emissions:						
Fuel Production	72.9	29.8	5.27	17,500	51.1	298
Transportation Total	**407**	**1,430**	**29.4**	**216,000**	**97.4**	**2,990**
% of Project Total	**49.4%**	**69.2%**	**35.2%**	**63.0%**	**25.1%**	**63.1%**

4.5.2 Raising Gang Emissions

The emissions generated by the raising gang activities are presented in Table 21. In the first section of the table emissions are listed according to the responsible piece of equipment and in the second section they are listed according to component type. The job trailer emissions could not be assigned by component type, so the sub-total for equipment is slightly higher than the sub-total by component type. Finally, the third section of the table shows the indirect emissions and energy consumption resulting from the production of the diesel fuel consumed by the raising gang.

Of the equipment, the two cranes produce the majority of emissions due to their large engines and extensive use during raising activities. The joists are the most energy and emissions intensive of the components simply due to the large number required for the project.

Table 21 Environmental emissions and energy consumption from raising gang activities organized by equipment type and structural component type

	CO (kg)	NO_x (kg)	PM_{10} (kg)	CO_2 (kg)	SO_x (kg)	Energy (GJ)
By Equipment Type:						
Job Trailer	0.44	2.04	0.11	795	4.30	4.18
275-Ton Crane	27.3	80.9	4.86	16,400	33.1	231
100-Ton Crane	92.9	276	16.50	55,800	113	786
Fork Lift	20.7	40.6	5.05	7,980	16.1	112
JLG Man Lift	4.71	4.41	0.44	538	1.09	7.60
Diesel Welder	3.78	3.66	0.43	472	0.96	6.68
Hand Tools	0.00	0.00	0.00	1.92	0.01	0.01
Sub-Total	**153**	**416**	**28.00**	**83,800**	**172**	**1,170**
By Component Type:						
Columns	23.8	57.6	4.34	11,300	22.9	160
Beams	37.1	86.1	7.15	16,900	34.2	238
Girders	12.2	36.0	2.19	7,270	14.7	102
Joists	66.1	196	11.80	39,700	80.3	559
Decking	4.63	13.7	0.82	2,780	5.62	39.1
Stairs	8.61	24.7	1.59	4,980	10.1	70.2
Sub-Total	**152**	**414**	**27.90**	**83,000**	**168**	**1,170**
Indirect Emissions:						
Fuel Production	29.2	11.9	2.11	7,000	20.5	120
Erection Total	**182**	**428**	**30.10**	**90,800**	**193**	**1,290**
% of Project Total	22.1%	20.7%	36.0%	26.5%	49.6%	27.3%

4.5.3 Detailing Emissions

The emissions generated by detailing activities are presented in Table 22. The first section shows emissions from welding and bolting activities, separated by power source. Welding done with electric welders is further divided by the type of electrode used: rod or wire. Within the “Welding and Bolting” subcategory, the diesel welder contributes 50% of CO_2, 94% of CO, and 88% of PM_{10} emissions, despite only being used for approximately 10% of total welding. The second section shows results from the construction equipment used to support detailing activities. The third section shows indirect emissions from the production of fuel and welding consumables.

Table 22 Environmental emissions and energy consumption from detailing activities

	CO (kg)	**NO_x (kg)**	**PM_{10} (kg)**	**CO_2 (kg)**	**SO_x (kg)**	**Energy (GJ)**
Welding & Bolting:						
Rod w/ Electric Welder	2.33	10.8	0.56	4,220	22.9	22.2
Wire w/ Electric Welder	0.91	4.23	0.22	1,650	8.94	8.67
Diesel Welder	48.3	46.7	5.49	6,030	12.2	85.2
Sub-Total	**51.5**	**61.7**	**6.27**	**11,900**	**44.0**	**116**
Equipment:						
80ft Man Lift	65.5	61.3	6.13	7,480	15.1	106
60ft Man Lift	51.4	48.0	4.81	5,860	11.9	82.8
Fork	11.5	22.5	2.80	4,420	8.95	62.3
Sub-Total	**128**	**132**	**13.70**	**17,800**	**35.9**	**251**
Indirect Emissions:						
Fuel Production	8.40	3.43	0.61	2,010	5.89	34.4
Welding Consumables	45.8	9.66	3.41	3,930	12.5	55.5
Sub-Total	**54.2**	**13.1**	**4.02**	**5,950**	**18.4**	**89.9**
Detailing Total	**234**	**207**	**24.00**	**35,600**	**98.3**	**457**
% of Project Total	28.4%	10.0%	28.8%	10.4%	25.3%	9.6%

4.6 Alternative Scenarios

Based on the results of the baseline inventory presented in Table 19, discussions with project team members, and a literature review of best management practices for steel erection, the researcher developed a comprehensive list of alternative strategies for improving the environmental performance of the steel erection process on the NREL project. This list was evaluated by project team members, including representatives of the general contractor, the architect, the fabricator, the steel detailer, the structural engineer, and the erector. The project team members provided qualitative analysis of the cost, feasibility, and perceived benefit of each proposed alternative strategy (Gotthelf, 2010).

Based on this feedback, six alternative strategies were selected by the researchers to have their emissions and energy consumption modeled and then compared to the baseline inventory for the project. Table 23 presents a summary of the erection phase energy and emission reductions from each alternative scenario and the following six sections provide a more in-depth look at each scenario.

Table 23 Summary of erection phase emissions and energy savings from 6 alternative strategies (as percent reduction from project as-built).

	CO Savings	**NO_x Savings**	**PM_{10} Savings**	**CO_2 Savings**	**SO_x Savings**	**Energy Savings**
#1: Improved Site Logistics & Crane Sizing	5.5%	5.9%	7.4%	6.4%	9.3%	6.7%
#2: No Diesel Generator Use	6.1%	2.2%	6.7%	1.7%	2.6%	1.9%
#3: Ten Hour Work Day	2.7%	3.8%	1.9%	2.9%	1.4%	3.2%
#4: Worker Carpooling Incentive	2.3%	3.1%	1.6%	2.5%	1.2%	2.7%
#5: No Partial Loads of Materials Shipped	6.4%	9.1%	4.6%	8.7%	3.2%	8.5%
#6: Materials Sourced Locally	13.2%	18.6%	9.4%	17.9%	6.6%	17.4%

4.6.1 Alternative Scenario #1: Improved Site Logistics and Crane Sizing

Due to site constraints and crane-sizing issues, steel erection activities took approximately three weeks longer than originally proposed by the erector. Had the erection crew been afforded a larger staging area and the preferred crane size, the erector believed that erection could have been compressed by fifteen working days, resulting in reduced emissions from worker transportation and site equipment. This alternative scenario quantifies these savings by eliminating 225 worker days (15 days at an average manpower of 15 employees) worth of commuting and 17% of raising gang related emissions (14 week versus 17 week schedule). It was assumed the materials transportation, equipment transportation, and detailing activities would remain unchanged in this scenario. Table 24 presents the resulting savings in CO_2 and energy, as well as the equivalent gallons of diesel and approximate cost savings compared the NREL project as-built. Cost calculations throughout all alternative scenarios assume \$2.66 per gallon of diesel, \$2.63 per gallon of gasoline, and \$0.094 per kilowatt hour of electricity (EIA, 2010a; EIA, 2010b; EIA, 2010c).

Table 24 Emissions and energy savings from reducing erection schedule by 3 weeks (EIA, 2010a; EIA, 2010b).

	CO_2 (kg)	**Energy (GJ)**	**Diesel (gal)**	**Cost (\$US)**
NREL As-Built Schedule	342,000	4,740	32,400	\$86,100
Erector's Preferred Schedule	320,000	4,420	30,000	\$80,300
Net Reduction	**21,900**	**317**	**2,170**	**\$5,760**
Percent reduction	6.4%	6.7%	6.7%	6.7%

4.6.2 Alternative Scenario #2: No Diesel Generator Use for Site Welding and Bolting

The diesel welders used during detailing were responsible for a disproportionate share of pollution relative to work accomplished. An alternative scenario was modeled to demonstrate the impact of using only electric welders and eliminating the diesel welders. It was assumed that this would have had no impact on productivity rates if additional 350 amp welders were used to provide access throughout the entire site. Table 25 shows the impact on CO_2, electricity consumption, diesel usage, and approximate cost compared to the as-built case. The CO_2 values are representative of the entire erection phase, while the electricity, diesel, and cost columns represent only the welder operation.

Switching to all electric welders increased electricity consumption for welding by 11%. The resulting 1.7% savings in erection-wide CO_2 emissions is fairly minor, but the 6.7% reduction in particulate matter generation could significantly improve jobsite air quality.

Table 25 Emissions and cost savings from not using diesel generators during erection (EIA, 2010a; EIA, 2010b).

	Erection Phase		**Welder Operations Only**		
	CO_2 (kg)	**PM_{10} (kg)**	**Electricity (kWh)**	**Diesel (gal)**	**Cost ($US)**
With Diesel Welders	342,000	83.5	8,570	573	$2,330
Without Diesel Welders	336,000	78.0	9,520	0.0	$895
Reduction	**5,890**	**5.56**	**-952**	**573**	**$1,440**
Percent reduction	1.7%	6.7%	-11.1%	100.0%	61.6%

4.6.3 Alternative Scenario #3: Ten Hour Work Day

One suggestion for reducing emissions from worker transportation was a ten-hours per day, four days per week work schedule for the erection crew. According to feedback from the project management team, decreased productivity during longer days is typically offset by reduced start-up and shut down activities, so the alternative schedule was assumed to have no impact on the number of man hours needed for completion. An alternative scenario was modeled with a 20% reduction in worker transportation to quantify the benefits of this four day work week. Results are shown in Table 26. The net effect is an approximately 3% reduction of total erection phase CO_2 emissions and energy consumption, resulting from a 20% reduction in worker gasoline consumption and expense.

Table 26 Emissions and energy savings from switching to a 10 hour work day

	Erection Phase		**Worker Transportation**	
	CO_2 (kg)	**Energy (GJ)**	**Gas (gal)**	**Cost ($US)**
8 x 5 Work Week	342,000	4,740	5,130	$13,500
10 x 4 Work Week	332,000	4,580	4,110	$10,800
Reduction	**10,100**	**152**	**1,030**	**$2,700**
Percent reduction	2.9%	3.2%	20.0%	20.0%

4.6.4 Alternative Scenario #4: Worker Carpooling Incentive

Due to an average commuting distance of 72.8 miles one way to the jobsite, many of the erector's employees carpooled during the project. Based on interviews and an analysis of the vehicles driven, the erection crew averaged 1.67 occupants per vehicle and 2.91 gallons of fuel consumed per worker per day. Carpooling resulted in a 9.8% reduction in worker transportation CO_2 emissions and gasoline savings of 3,422 gallons when compared to every worker driving a separate vehicle. To encourage additional ridesharing an employer-sponsored incentive was proposed and modeled as an alternative scenario. Assuming the incentive created a modest 20% increase in carpooling (2 workers per vehicle) there would be a 2.5% savings in total erection phase CO_2 emissions and $2,250 in fuel savings to employees. Table 27 shows the results of the increased carpooling scenario relative to the actual project values. The cost to the erector of the carpooling incentive could not be accurately calculated with existing information, so cost figures in Table 27 only represent employee fuel costs and not total costs for a carpooling incentive.

Table 27 Emissions and energy savings from worker carpooling incentive

	Erection Phase		**Worker Transportation**	
	CO_2 (kg)	**Energy (GJ)**	**Gas (gal)**	**Cost ($US)**
Current Practice	342,000	4,740	5,130	$13,500
With Carpooling Incentive	334,000	4,610	4,280	$11,250
Reduction	**8,380**	**127**	**856**	**$2,250**
Percent reduction	2.5%	2.7%	16.7%	16.7%

4.6.5 Alternative Scenario #5: No Partial Loads of Materials Shipped to Site

Site constraints, mid-construction design changes, and coordination issues between different parties led to a number of partially-full loads being trucked from the various steel fabricators to the jobsite. An analysis of 35 deliveries to the jobsite revealed that the average shipment of steel components weighed 35,250 lbs or 73% of a typical semitrailer's 48,000 lbs capacity. To quantify the benefits of a reduction in the number of partial loads, a hypothetical scenario was modeled in which all structural steel members were shipped to the site on fully-loaded trailers (48,000 lbs). It was found that the total number of truck loads could have been reduced from 87 to 66, and erection phase CO_2 emissions could have been cut by 8.7%. A smaller number of deliveries could also have a positive impact on the erector's productivity, as the arrival of each shipment requires the erection gang to switch from erecting to unloading tasks and back again.

Table 28 Emissions and fuel savings from not shipping partially full loads to site

	Erection Phase	Materials Transportation		
	CO_2 (kg)	**Trips Required**	**Diesel (gal)**	**Cost ($US)**
As-Built	342,000	87.0	13,600	$36,300
No Partial Loads	312,000	66.0	11,200	$29,700
Reduction	**29,800**	**21.0**	**2,480**	**$6,600**
Percent reduction	8.7%	24.1%	18.2%	18.2%

4.6.6 Alternative Scenario #6: Source Materials Regionally

The NREL project's steel trusses and decking were fabricated 921 miles and 1,137 miles from the site, respectively. Price and quality are primary factors in the selection of suppliers. However, transportation of materials is responsible for approximately 44% of erection phase CO_2 emissions and sourcing materials regionally or locally could have a significant impact on project-wide emissions. LEED defines local materials as those which come from within 500 miles of the jobsite (USGBC, 2009). An alternative scenario was tested in which the trusses and decking were sourced from 499 miles away. This minor change resulted in a 17.9% reduction in erection phase CO_2 emission and $13,600 in fuel cost savings. Table 29 illustrates the results for this scenario.

Table 29 Emissions and fuel savings from sourcing materials regionally

	Erection Phase	**Materials Transportation**		
	CO_2 (kg)	**Avg Distance (mi)**	**Diesel (gal)**	**Cost ($US)**
NREL As-Built	342,000	685	13,600	$36,300
Regional Suppliers	281,000	428	8,540	$22,700
Reduction	**61,100**	**258**	**5,100**	**$13,600**
Percent reduction	17.9%	37.6	37.4%	37.4%

5 Discussion and Summary

The magnitude of total energy use and pollution emitted during the steel erection process is significant. The 342,000 kg of CO_2 generated is equivalent to the annual emissions from 29 American homes (EPA, 2010b). This contribution to global and local environmental problems deserves industry attention and improvement, regardless of the impact of erection activities relative to the entire building's life cycle impacts.

Transportation activities, particularly transportation of materials, contribute a majority of erection phase emissions on the NREL building and thus are a logical starting point for process improvements on similar projects. However, transportation emissions are highly dependent on the project location, so this is by no means a universal reality for all structural steel projects. While the use of regional suppliers in Alternative Scenario 6 dramatically reduced erection phase emissions, it is feasible that reducing the distance from the fabrication plant to the building site will only increase the distance from the material manufacturer to the fabrication plant. It is necessary for firms at all levels of the supply chain to purchase local materials to guarantee a reduction in life cycle transportation emissions. In addition to limiting the number of trips made and distance traveled by trucks delivering steel to jobsites, the industry needs to continue exploring alternative modes of transportation, such as rail or biodiesel trucks.

Worker transportation also provides ample opportunity to decrease emissions in this case study, but may be a less significant factor on more urban sites. Currently, worker transportation decisions are determined almost exclusively by financial implications and any proposed improvements must appreciate this fact. Workers are more than willing to change commuting habits if it allows them to save money or spend more time with their families.

Raising and detailing activities are quite standardized across the industry and the emissions from these categories would be similar for most mid-sized, steel framed buildings. This reality can be viewed as a positive for the industry; environmentally-preferable methods employed on one project will generally be practical and reap similar benefits on other projects. For instance, the replacement of diesel welders with additional electric welders may be an inconvenience initially, but once a crew adjusts they could work without diesel welders on all future jobs.

As the second largest contributor to erection phase emissions, onsite equipment usage should also be constantly evaluated and improved. All equipment used during erection was compliant with the highest tier of air pollution standards, however standards for nonroad diesel engines remain significantly more lenient that standards for highway diesel engines. These lax standards for construction equipment explain why raising gang activities are responsible for the largest share of SO_x and PM_{10}.

For buildings, the energy use and emissions per unit of usable space are better metrics of environmental performance than total emissions or energy use and are also useful for comparing the relative sustainability of different sized buildings. For these reasons, the environmental indicators for erection of the NREL structural steel are presented per square meter in Table 30.

Table 30 Emissions and energy consumption from structural steel erection per square meter

	CO_2 (kg/m^2)	SO_x (kg/m^2)	CO (kg/m^2)	NO_x (kg/m^2)	PM_{10} (kg/m^2)	Energy (MJ/m^2)
Transportation	10.7	.005	.020	.071	.0015	148
Onsite Activities	6.24	.014	.021	.031	.0027	86.3
Total	**16.9**	**.019**	**.041**	**.102**	**.0041**	**234**

5.1 Comparison with Existing Literature

Much of the existing research on environmental sustainability in the structural steel industry has focused on manufacturing and fabrication (Boulanger, 2008a; Gorgolewski, 2006), and is thus not directly comparable to this study. Ochsendorf (2005) and the World Steel Association (2010) emphasize the importance of addressing sustainability throughout all phases of the structural steel life cycle, but do not propose specific erection phase improvements. This case study partially fulfills their recommendation by evaluating two important components of sustainability (energy consumption and air pollution) during a less often analyzed phase of the structural steel life cycle, erection. Burgan and Sansom (2006) determine solid waste generation and local community impacts from noise and dust creation to be the primary environmental concerns during the construction phase of structural steel frames. While the NREL case study does not track these same impact categories, a qualitative analysis suggests that very little solid waste was generated and the impact on the local community was negligible when compared to the energy consumption and air pollution created during erection.

Cole (1999) calculates construction phase energy use for 12 steel framed buildings in Canada with a mean of 6.5 MJ/m^2 and a range of 3 MJ/m^2 to 19 MJ/m^2. This figure is dramatically lower than the 234 MJ/m^2 calculated for the NREL case study. Cole includes worker, materials, and equipment transportation and onsite equipment use, but relies on published data and phone interviews to determine input quantities. The difference in the findings may be a result of the short distance used by Cole for materials transportation (40 km) and the inclusion of indirect energy use from fuel and welding consumable production in the NREL case study. Scheuer et al. (2003) determine construction activities for a 7300 m^2 steel-framed university building to use 632 MJ/m^2, but base the calculation entirely on an arbitrary ratio of construction phase energy use to total embodied energy of a building. Additionally, Scheuer et al. include all building construction activities, not just structural steel activities.

Guggemos (2003) and Guggemos and Horvath (2005) exclude worker transportation from their studies of structural steel frames and find onsite equipment use to be the largest contributor to emissions during the construction process. They calculate construction and transportation energy use for a five-story office building to be 418 MJ/m^2. However, the difference between this value and the figure for the NREL case study can be partially explained by the inclusion of structural concrete elements, such as floor slabs, in their scope. Guggemos (2003), Guggemos and Horvath (2005; 2006) and Junnila et al. (2006) all find materials transportation to be an insignificant contributor to construction phase energy use and emissions, while the NREL case study found it to be the single largest contributor. The long shipping distances for the steel components for the NREL building explain some of this discrepancy. For instance, steel decking for the NREL building traveled 1,137 miles from Houston, Texas to the jobsite, while Guggemos (2003) assumes a shipping distance of 150 miles for a hypothetical office building located in the Mid-West closer to steel fabrication facilities.

One crucial methodological difference between prior life cycle analyses of structural steel frames and this research is the use of actual site observation to determine input values for the NREL case study, as opposed to a reliance on published data or informed assumptions. The observational approach produces more accurate, but perhaps less universally applicable results.

5.2 Uncertainty

The environmental emissions and energy consumption values calculated in the study contain uncertainty from a number of sources. The limited scope of the site observation process only allowed for most activities to be observed a handful of times. The small sample size used to calculate mean times for these activities resulted in a significant level of uncertainty as to their accuracy. Additionally, uncertainty was created by the assumptions made during development of input values for detailing activities; including the assumption that one diesel welder was operating 40 hours per week during detailing and the assumption that 90% of welding work was completed by the electric welders. Other input values contain almost no uncertainty as they were taken from the erector's project records and covered discrete events. Input values in this category included total worker days on the project, the number of deliveries made to the site, and the cost of welding consumables.

The emissions factors, transient use factors, and brake specific fuel consumption rates used for construction equipment produced uncertainty in the results, as they are based on industry-wide emissions standards for each type of equipment, not the actual emissions produced by the specific models used on the NREL project. Likewise, the fuel efficiency and emissions factors used for heavy diesel trucks are based on national fleet averages, not the specific models used for transportation on the NREL project.

The EIO-LCA resource used to estimate upstream impacts from the production of electricity, liquid fuels, and welding consumables also introduces uncertainty on multiple levels. The tool is based on economic and pollution data from 1997 and despite adjustments for inflation, the data does not account for changes in the energy or pollution-intensity of each industry over the last decade. Additionally, emissions factors are only given on a sector-wide basis and might not accurately reflect the impact of each specific product within that sector.

5.3 Review of Research Questions

This section ties the research results back to the initial research questions asked in Section 1.2.

What are the major sources of energy consumption and environmental emissions associated with a typical steel erection process during the construction phase of a mid-sized office building?

The major sources of energy consumption and emissions from steel erection for a mid-sized office building are (in descending order of importance) materials transportation to the site, operation of the 100-ton crane, and worker transportation to the site.

What strategies can be used to reduce these impacts and what are the effects of those strategies on energy consumption and environmental emissions during the steel erection process?

The most effective strategies for reducing energy consumption and emissions identified by the study were sourcing materials within 500 miles, shipping only full loads of materials, and improving site logistics, as well as crane-sizing, to reduce erection time. These strategies resulted in reductions in total erection phase energy consumption and CO_2 emissions of approximately

17.5%, 8.5%, 6.4%, and 3.2% respectively. Switching to a 10-hour work day (3.0% reduction), providing worker carpooling incentives (2.5% reduction), and eliminating the use of diesel generators (1.7% reduction) were determined to be less effective strategies for reducing total erection phase CO_2 emissions.

For complete emissions reduction results see Appendix 7.2.

5.4 Future Research

For practical reasons, this research examines only a small portion of the NREL building during a single phase of its lifecycle. The narrow boundaries of the study beg for similarly detailed inventories to be conducted on all components and all life stages of this or other office buildings to form an accurate LCI of the larger system. By focusing on a single life stage, the research runs the risk of optimizing a part at the expense of the whole. Complimentary studies of the rest of the structural steel process could help avoid this pitfall. Specific to improving the steel erection process, this baseline study could serve as springboard for analysis of more innovative practices, such as the use of biofuels in construction equipment, or onsite renewable energy generation to power hand tools. As new construction techniques are developed in this field, research will also be needed to quantify their contribution to reducing environmental loads. For the environmentally preferable practices evaluated in the “Alternative Scenarios” section, there is a need for research into the economic and technological feasibility of adopting such improvements on a large scale. This would help bridge the gap between academic findings and actual industry guidelines or standards.

The effort and resources required to evaluate a single building component suggest that much research remains to be done into tools and methodologies for simplifying the LCI and LCA process. Accurate tools that could be used by architects and engineers to compare alternative designs would have a much shorter feedback loop than the current methodologies targeted at academics and professional researchers.

5.5 Conclusion

The Research Support Facility at NREL will be one of the most environmentally sustainable office buildings in the world when finished, but a lack of guidelines for environmentally-preferable steel erection techniques led the project's structural frame to be constructed using standard industry techniques. Baseline knowledge of the major sources of energy use and pollution generation during the process is needed as a preliminary step to developing alternative techniques and guidelines for improving the sustainability of steel erection. This research uses a case study of the NREL building and site observation of construction activities to develop an accurate picture energy use and emissions during erection.

The results indicate that transportation of materials to the site, use of construction equipment onsite, and worker transportation to the site are the most environmentally impactful activities. The results are used to test the environmental benefits of six hypothetical process improvements. Sourcing materials within 500 miles, shipping only full loads of materials, improving site logistics and crane-sizing to reduce erection time, and switching to a 10-hour work day were all determined to be strategies capable of significantly reducing energy use or emissions.

These findings will be useful to steel erectors, steel fabricators, general contractors, structural engineers, and architects as they continue to strive to improve the life cycle sustainability of steel-framed buildings. By understanding the relative and absolute contribution to energy use and air pollution of each activity in the steel erection process they can evaluate the potential impact of proposed process improvements.

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7 Appendix

7.1 Site Observation Instruments

Name	**Route/Distance**	**Vehicle/Year**	**Notes (company truck, carpooling, etc)**

Figure 3 Instrument used to record observation of worker transportation

Delivery From:		
Make/Model/Size:		
Route/Miles:		
Return Empty?		
Weight & Contents:		
Time Idling:		
Additional Notes:		

Figure 4 Instrument used to record observation of materials transportation to site

Equipment Make and Model	Miles/ Trip	# of Trips Required	Mode of Transportation	% of Use for Steel

Figure 5 Instrument used to record observation of equipment transportation and details

Activity:						
Equipment:	#1			#2		
Use/Job:						
Pieces per sequence:						
Time operating per sequence:						
% Idling:						
Associated Personnel:						
Notes:						

Figure 6 Instrument used to record observation of all preparation and placing activities

7.2 Complete Results from Alternative Scenarios

Table 31 Impact on emissions of alternative scenario #1: Improved site logistics and crane sizing

	CO (kg)	NO_x (kg)	PM (kg)	CO_2 (kg)	SO_x (kg)	Energy (GJ)
Transportation:						
NREL As-Built	407	1,430	29.4	216,000	97.4	2,990
Alternative #1	392	1,380	28.4	209,000	93.8	2,890
Reduction	**14.4**	**49.7**	**1.04**	**6,430**	**3.55**	**97.4**
% Reduction	**3.5%**	**3.5%**	**3.5%**	**3.0%**	**3.6%**	**3.3%**
Raising Gang:						
NREL As-Built	182	428	30.1	90,800	193	1,290
Alternative #1	151	355	25.0	75,300	160	1,070
Reduction	**30.9**	**72.8**	**5.11**	**15,400**	**32.8**	**220**
% Reduction	**17.0%**	**17.0%**	**17.0%**	**17.0%**	**17.0%**	**17.0%**
Detailing:						
NREL As-Built	234	207	24.0	35,600	98.3	457
Alternative #1	234	207	24.0	35,600	98.3	457
Reduction	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
% Reduction	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**
Project Totals:						
Reduction	**45.3**	**123**	**6.15**	**21,900**	**36.3**	**317.0**
% Reduction	**5.5%**	**5.9%**	**7.4%**	**6.4%**	**9.3%**	**6.7%**

Table 32 Impact on emissions of alternative scenario #2: No diesel generator use for site welding and bolting

	CO (kg)	NO_x (kg)	PM (kg)	CO_2 (kg)	SO_x (kg)	Energy (GJ)
Transportation:						
NREL As-Built	407	1,430	29.4	216,000	97.4	2,990
Alternative #2	407	1,430	29.4	216,000	97.4	2,990
Reduction	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
% Reduction	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**
Raising Gang:						
NREL As-Built	182	428	30.1	90,800	193	1,290
Alternative #2	182	428	30.1	90,800	193	1,290
Reduction	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
% Reduction	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**
Detailing:						
NREL As-Built	234	207	24.0	35,600	98.3	457
Alternative #2	184	161	18.5	29,700	88.2	366
Reduction	**50.0**	**45.9**	**5.56**	**5890**	**10.2**	**90.5**
% Reduction	**21.4%**	**22.2%**	**23.1%**	**16.5%**	**10.3%**	**19.8%**
Project Totals:						
Reduction	**50.0**	**45.9**	**5.56**	**5,890**	**10.2**	**90.5**
% Reduction	**6.1%**	**2.2%**	**6.7%**	**1.7%**	**2.6%**	**1.9%**

Table 33 Impact on emissions of alternative scenario #3: Ten hour work day

	CO (kg)	NO_x (kg)	PM (kg)	CO_2 (kg)	SO_x (kg)	Energy (GJ)
Transportation:						
NREL As-Built	407	1,430	29.4	216,000	97.4	2,990
Alternative #3	384	1,350	27.8	206,000	91.8	2,840
Reduction	**22.5**	**77.8**	**1.63**	**10,100**	**5.55**	**152.0**
% Reduction	**5.5%**	**5.4%**	**5.5%**	**4.7%**	**5.7%**	**5.1%**
Raising Gang:						
NREL As-Built	182	428	30.1	90,800	193	1,290
Alternative #3	182	428	30.1	90,800	193	1,290
Reduction	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
% Reduction	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**
Detailing:						
NREL As-Built	234	207	24.0	35,600	98.3	457
Alternative #3	234	207	24.0	35,600	98.3	457
Reduction	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
% Reduction	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**
Project Totals:						
Reduction	**22.5**	**77.8**	**1.63**	**10,100**	**5.55**	**152**
% Reduction	**2.7%**	**3.8%**	**1.9%**	**2.9%**	**1.4%**	**3.2%**

Table 34 Impact on emissions of alternative scenario #4: Worker carpooling incentive

	CO (kg)	NO_x (kg)	PM (kg)	CO_2 (kg)	SO_x (kg)	Energy (GJ)
Transportation:						
NREL As-Built	407	1,430	29.4	216,000	97.4	2,990
Alternative #4	388	1,360	28.1	207,000	92.7	2,860
Reduction	**18.7**	**64.8**	**1.35**	**8,380**	**4.63**	**127.0**
% Reduction	**4.6%**	**4.5%**	**4.6%**	**3.9%**	**4.8%**	**4.2%**
Raising Gang:						
NREL As-Built	182	428	30.1	90,800	193	1,290
Alternative #4	182	428	30.1	90,800	193	1,290
Reduction	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
% Reduction	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**
Detailing:						
NREL As-Built	234	207	24.0	35,600	98.3	457
Alternative #4	234	207	24.0	35,600	98.3	457
Reduction	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
% Reduction	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**
Project Totals:						
Reduction	**18.7**	**64.8**	**1.35**	**8,380**	**4.63**	**127**
% Reduction	**2.3%**	**3.1%**	**1.6%**	**2.5%**	**1.2%**	**2.7%**

Table 35 Impact on emissions of alternative scenario #5: No partial loads of materials shipped to site

	CO (kg)	NO_x (kg)	PM (kg)	CO_2 (kg)	SO_x (kg)	Energy (GJ)
Transportation:						
NREL As-Built	407	1,430	29.4	216,000	97.4	2,990
Alternative #5	354	1,240	25.6	186,000	84.8	2,590
Reduction	**53.0**	**187**	**3.84**	**29,800**	**13**	**401**
% Reduction	**13.0%**	**13.1%**	**13.0%**	**13.8%**	**12.9%**	**13.4%**
Raising Gang:						
NREL As-Built	182	428	30.1	90,800	193	1,290
Alternative #5	182	428	30.1	90,800	193	1,290
Reduction	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
% Reduction	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**
Detailing:						
NREL As-Built	234	207	24.0	35,600	98.3	457
Alternative #5	234	207	24.0	35,600	98.3	457
Reduction	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
% Reduction	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**
Project Totals:						
Reduction	**53.0**	**187**	**3.84**	**29,800**	**12.5**	**401**
% Reduction	**6.4%**	**9.1%**	**4.6%**	**8.7%**	**3.2%**	**8.5%**

Table 36 Impact on emissions of alternative scenario #6: Source materials regionally

	CO (kg)	NO_x (kg)	PM (kg)	CO_2 (kg)	SO_x (kg)	Energy (GJ)
Transportation:						
NREL As-Built	407	1,430	29.4	216,000	97.4	2,990
Alternative #6	298	1,040	21.6	154,000	71.6	2,160
Reduction	**109**	**385**	**7.88**	**61,100**	**25.7**	**824**
% Reduction	**26.8%**	**26.9%**	**26.8%**	**28.4%**	**26.4%**	**27.6%**
Raising Gang:						
NREL As-Built	182	428	30.1	90,800	193	1,290
Alternative #6	182	428	30.1	90,800	193	1,290
Reduction	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
% Reduction	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**
Detailing:						
NREL As-Built	234	207	24.0	35,600	98.3	457
Alternative #6	234	207	24.0	35,600	98.3	457
Reduction	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
% Reduction	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**	**0.0%**
Project Totals:						
Reduction	**109**	**385**	**7.88**	**61,100**	**25.7**	**824**
% Reduction	**13.2%**	**18.6%**	**9.4%**	**17.9%**	**6.6%**	**17.4%**