Greening Structural Steel Design, Fabrication and Erection: A Case Study of the National Renewable Energy Laboratory Research Support Facilities Project

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Final Report

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Executive Summary

This study seeks to identify and evaluate opportunities to reduce the environmental impacts of structural steel through case study research of the National Renewable Energy Laboratory's (NREL) Research Support Facility (RSF) in Golden, Colorado. The building was designed around 23 sustainability goals, including net-zero energy usage, and the US Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED™) Platinum certification.

The LEED™ Rating System, however, falls short in addressing and rewarding environmentally preferable practices in the structural steel design, fabrication, erection, and overall delivery process. This research identifies opportunities for reducing environmental impacts within these stages and quantifies the associated benefits. Key stakeholders from the structural steel industry have joined to support the research including KL&A Inc., Paxton & Vierling Steel (PVS), LPR Construction, Haselden Construction, and the American Institute of Steel Construction (AISC).

The research is divided into two distinct but interrelated parts: (1) individual and group interviews to identify potential contractual, relational, and environmental improvements for the structural steel delivery process and (2) a life-cycle inventory assessment of the structural steel for the project and alternative scenarios for additional environmental impact reductions in fabrication and erection.

Interviews

Individual interviews were conducted and a focus group discussion was held to gather input from stakeholders. The goal was to determine the level of integration the steel stakeholders used on the project and to allow participants to discuss any inefficiencies and opportunities for improvement for the steel delivery process based on their experiences on the NREL RSF project. As a result of these discussions, three primary process recommendations emerged:

Establish Direct Lines of Communication among the Structural Steel Team

- The existing contractual lines of communication did not allow for communication between all structural steel project team members, which led to inefficiencies and waste.
- An alternative contractual model is presented that allows for direct lines of communication among all structural steel project team members.

Ensure Early Involvement of the Erector and Fabricator in the Steel Design Process

- The focus group revealed that early involvement of the fabricator and erector would be beneficial to the overall efficiency of the structural steel design and delivery process.
- Early involvement and an integrated process would be null, however, if the exchange of information between phases are not smooth.

Utilize Appropriate Technology

- Building information modeling has the ability to track several project components including scheduling, sequencing, deliveries, and the erection progress. Utilizing a 3D model also allows for initial problem detection virtually rather than on site.
- One strong recommendation that came from KL&A and PVS was for the team to hold a technology planning meeting early in the project. A dedicated planning effort is the key to successful collaboration.

Life Cycle Inventory Assessment

In addition to conducting interviews, the research team performed life-cycle inventory assessments (LCIA) on seventeen scenarios to identify practical opportunities for energy and emissions reductions throughout the structural steel delivery process. The direct and supply chain environmental impacts of steel production, fabrication, erection, and transportation were estimated for all the structural steel used in the NREL project. The research methodology used captures all direct, indirect, and upstream supply chain impacts.

Results of the LCIA revealed several opportunities for improvement related to the manufacturing, fabrication and erection phases of the project. Samplings of the findings include:

Material Selection for NREL RSF Project

- Use of salvaged gas pipe columns resulted in a 69% reduction in CO_2 emissions compared to new manufactured columns.
- Waste reduction through cut-length optimization can reduce CO_2 emission by up to 75,000 kg.

Fabrication Process

- Fabrication shop lighting upgrade would result in an annual 400,000 kg reduction in CO_2 emissions and cost savings of over $55,000 dollars.
- Reducing average daily idle time of the main shot blaster would result in an annual 41,000 kg reduction in CO_2 emissions.
- Rail transport from fabrication to the RSF jobsite could reduce CO_2 emissions by 76%, when compared to truck transport.

Erection Process

- Increased carpooling of steel erection crews would result in a 8,380 kg reduction in CO_2 emissions for the RSF project.
- Reducing partial loads of steel materials to the RSF jobsite has the potential to reduce CO_2 emissions by 30,000 kg.
- Sourcing steel for the RSF project within a 500 mile radius would lead to a 17.9% reduction in erection phase CO_2 emissions and $13,600 in fuel cost savings.

Environmentally speaking, the NREL RSF project has had many successes. The building itself serves as a model of energy efficiency and sustainable design. The steel delivery team must be credited for working to enhance the sustainability efforts on this project. Incorporating reused gas pipes for structural columns was a unique contribution by the team and proved to be a superior environmental decision compared to using a newly manufactured alternative. The reused pipes reduced more than 69% of the energy that would have been required to produce new comparable materials. While there were challenges associated with the reused gas piping, there were measureable environmental benefits from this decision.

Beyond recycled content and reused materials, there is significant room for improvement in the design, fabrication, and erection of structural steel. The recommendations chronicled in this report are in part based on the notion that inefficiencies result in increased physical waste, which negatively impact sustainability efforts. The underlying assumption is that by increasing efficiencies throughout the structural steel delivery process, not only are costs reduced, but also waste, time, energy, materials, and the overall environmental impact of the structural steel industry.

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List of Abbreviations

AGC	Associated General Contractors
AIA	American Institute of Architects
AISC	American Institute of Steel Construction
AISI	American Iron and Steel Institute
BIM	Building Information Modeling
BOF	Basic oxygen furnace
DB	Design-Build
DBB	Design-Bid-Build
DOE	Department of Energy
EAF	Electric arc furnace
EIO-LCA	Economic Input-Output Life-Cycle Assessment
EPA	Environmental Protection Agency
LCIA	Life Cycle Inventory Assessment
LEED™	Leadership in Energy and Environmental Design
NREL	National Renewable Energy Laboratory
REC	Renewable energy certificate
RFI	Request for Information
RSF	Research Support Facilities
PVS	Paxton & Vierling Steel
USGBC	United States Green Building Council

Introduction

The Research Support Facilities (RSF) at the National Renewable Energy Laboratory's (NREL) campus in Golden, Colorado aims to be the prototype for the next generation of sustainable office space. The 220,000 square foot, $64-million building was designed around 23 sustainability goals, including the US Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED™) Platinum certification, net-zero energy usage and inclusion of visible alternative energy technologies. Haselden Construction partnered with RNL Architects, Stantec Consulting, and KL&A to win the performance-based, design-build contract and has also worked to improve the sustainability of onsite construction operations. The project will house approximately 700 employees at NREL's South Table Mesa Campus and will showcase many technologies developed in-house. The Department of Energy (DOE) and the Alliance for Sustainable Energy have high expectations for the building and the design-build team will be publishing a "how-to guide" for designing and constructing high performance office buildings on the DOE website.

The RSF project challenged the design team to find creative ways of improving the overall impact of the building process as well as operation. The structural design team, led by structural engineers KL&A, Inc., was inspired by the project's ambitious sustainability goals, but saw limited guidance for greening the structural steel process within the LEED™ framework. KL&A seized this opportunity to fill a void in green building knowledge by commissioning a study to investigate opportunities for reducing the environmental impacts of structural steel design, fabrication, and erection processes. Other key stakeholders in the structural steel industry have joined the initiative, including Paxton & Vierling Steel (PVS), LPR Construction, Haselden Construction, and the American Institute of Steel Construction (AISC).

This study seeks to reduce the environmental impacts of structural steel through a case study of the RSF project. The study is divided into two parts: (1) a series of interviews that identify potential sustainability and process improvements through integrated design and delivery of structural steel and (2) analysis of the structural steel fabrication and erection for the NREL project using life cycle inventory assessment (LCIA) methodology. Results will include estimation of energy use and CO_2 emissions for the RSF steel fabrication and erection processes, evaluation of scenarios to reduce environmental impacts from these processes, and potential benefits from transitioning towards a more integrated structural steel delivery process. Although this case study focuses solely on the RSF project, the results of the research will aim to inform a wider steel industry audience.

Background

NREL's new RSF project is targeting Platinum certification, which is symbolic of both the growth of green building as well as the government's commitment to sustainability efforts. The success of the LEED™ Rating System has brought greater awareness of the need for environmentally responsible design and construction. While LEED™ is an important tool for the green building industry, it does not account for all facets of the built environment.

Aside from credits related to recycled content and regional materials, LEED™ gives little guidance for reducing the environmental impacts associated with structural steel. In many cases, such efforts have already become standard practice throughout the industry, due to economic efficiency. While recycled content and sourcing local materials are important considerations, there are additional opportunities to reduce structural steel impacts during design, fabrication and erection. A comprehensive approach to sustainable building should include all phases of the construction process. During design, early participation from all members of the structural team allows for valuable collective input on design alternatives and has the potential to improve sustainability by reducing the amount of excess material produced, cutting back on erection errors, and requiring fewer Requests for Information (RFI). Fabricators may have opportunities to reduce waste generated in fabrication by re-evaluating internal processes, equipment types, or source of stock materials. Steel erectors may have opportunities to limit emissions by better managing equipment, transportation, and sources of electricity.

The RSF project incorporated an integrated design process by including the mechanical and structural engineers during the schematic design phase. As a result, the project team made adjustments to the building design in order to support the sustainability efforts of the whole project. An example of this optimization was the reorientation of structural members to better accommodate mechanical systems and improve daylighting to interior spaces. Reclaimed gas pipes were also utilized by the team as structural columns. Although the structural engineers were involved early in the design process, other stakeholders in the structural steel construction process (fabricators, erectors, joist manufacturers, etc.) were not engaged until after design was complete. Without key involvement from the fabrication and erection team during the design phase, there may have been lost opportunities for improving the sustainability of the structural steel system.

Methodology

The methodology for the study consisted of two distinct approaches: (1) individual and group interviews to identify potential environmental improvements for the structural steel delivery process and (2) analysis of the structural steel fabrication and erection for the NREL project using life cycle inventory assessment (LCIA) methodology. Based on the results from the interviews and LCIA, different scenario analyses were performed to identify ways to improve the sustainability of the structural steel delivery process for the NREL RSF project.

Interviews and Focus Group

CSU conducted individual interviews as well as a focus group session to gather input from stakeholders. Representatives for the owner, architect, steel detailer, structural engineer, contractor, fabricator, and erector all participated in individual interviews. The purpose was to determine the level of integration the steel stakeholders used on the project and to allow participants to discuss any inefficiencies and/or opportunities for improvement for the steel delivery process based on their experiences on the NREL RSF project.

Following the individual interviews, the same stakeholders participated in a focus group session to determine feasibility of their recommendations from the individual interviews. In order to determine the topics for the focus of the group session, comments from the individual interviews were synthesized into common themes. Themes were selected by two factors: (1) those noted most frequently in the individual interviews, and (2) their relevance to the structural steel industry. Three themes were selected for further discussion at the focus group: early involvement, communication, and technology.

Life Cycle Inventory Assessment

Through consultation with Paxton & Vierling Steel (PVS) and LPR Construction, process diagrams detailing the steps of the fabrication and erection processes were developed as the foundation of the LCIA. These diagrams depict each process necessary to get from generic steel shapes arriving at the fabrication plant to structural members installed in the RSF building. The materials, energy consumption, and equipment usage associated with each step were estimated using onsite observation at PVS and NREL, discussions with team members, electricity records, and published data.

The direct emissions from materials transportation, worker transportation, and site equipment use were calculated using quantities of inputs (travel miles, hours of operation, fuel usage) and data from the EPA, NREL, and equipment manufacturers (NREL, 2009; USEPA, 2004). The direct and upstream environmental impacts from the production of raw steel, diesel, welding rod, and electricity were calculated using the Carnegie Mellon University Green Design Institute's Economic Input-Output Life-Cycle Assessment (EIO-LCA) Tool (GDI, 2009).

The EIO-LCA methodology uses aggregated energy, pollution, and economic data for the entire US economy to estimate the emissions per unit of production for each of 497 economic sectors. It captures the inputs and outputs for the final production stage of a product, as well as all upstream suppliers, and suppliers of suppliers. The benefit of this methodology is that the data captures all direct, indirect, and supply chain impacts, rather than only those for a specific step within in the larger product delivery process. Once impacts for the entire life cycle of the steel structure were determined, the relative contribution of each individual activity was calculated and high-impact areas identified for improvement.

Alternative Scenarios

Opportunities for impact reductions were identified through process analysis, interviews, observations, and literature review. Where feasible, opportunities were tested in the LCIA process models to generate quantifiable results for specific efficiency and sustainability measures.

Results

The results of the individual interviews and focus group session are provided first, followed by the LCIA of the steel delivery process. This section concludes with the analysis of several alternative scenarios identified through the interview and LCIA processes.

The following recommendations and alternative scenarios are based on the notion that inefficiencies result in increased physical waste, which negatively impact sustainability efforts. The underlying assumption is that by increasing efficiencies throughout the structural steel delivery process, not only are costs reduced, but also waste, time, energy, materials, and the overall environmental impact of the structural steel industry.

Interviews and Focus Group

During the eight individual interviews, participants revealed thirty-six opportunities for improvement that could reduce environmental impacts from structural steel design and delivery processes. The suggestions were grouped into themes and the number of times each suggestion was reported was noted. Results of the individual interviews are listed in Table 1. The themes are ranked by frequency of occurrence.

Table 1. Number of Opportunities for Improvement by Theme

Theme	Number of Suggestions
On-Site Construction Issues	10
Lines of Communication Between Steel Stakeholders	7
Early Involvement of Fabricator & Erector	7
Coordination of Mechanical Systems	4
Interoperability of Technologies	3
Applying Lessons Learned to Future Projects	2
Implications of Design or Delivery Method	2
Transportation of Materials	1

During the focus group, participants had the opportunity to view the results of the individual interviews. Together they decided that the following process recommendations were the most common and relevant themes affecting the structural steel delivery process (personal communication, December 22, 2009):

1. Establishing direct lines of communication among the structural steel team.
2. Ensuring early involvement of the erector and fabricator in the steel design process.
3. Utilizing appropriate technology.

The following section summarizes the findings from the focus group. It is important to note that the following information was taken directly from the participants' feedback and was not influenced by the researcher or outside sources unless cited otherwise.

Process Recommendation #1: Establish Direct Lines of Communication among the Structural Steel Team

The communication hierarchy for the NREL project was determined first by the project's contractual arrangement and second by the trust dynamics within the team. The project was contracted as a Design-Build (DB) partnership between Haselden Construction and RNL Architects. Even though the project used a DB method, the fabrication and erection of the structural steel was more closely aligned with that of a Design-Bid-Build (DBB) method. Once Haselden was hired, the steel fabricator, detailer, and erector were brought on via a hard bid. Figure 1 illustrates the DB contractual arrangement used for this project.

The project team agreed that the DB contractual arrangement was more beneficial to the project than a traditional DBB model would have been. However, the structural steel team members including the structural engineers, steel detailer, fabricator and erector, felt that the delivery method was an inferior contractual arrangement (personal communication, December 22, 2009). The primary concern was that direct lines of communication did not exist between all structural steel project team members causing a series of inefficient interactions, one of which was unnecessary lag time processing Requests for Information (RFIs). While the fabricator encouraged open communication between parties, not all project team members had practiced such open lines of communication (personal communication, December 22, 2009). Thus, it took some time to trust in a system that varied from more traditional hierarchical methods.

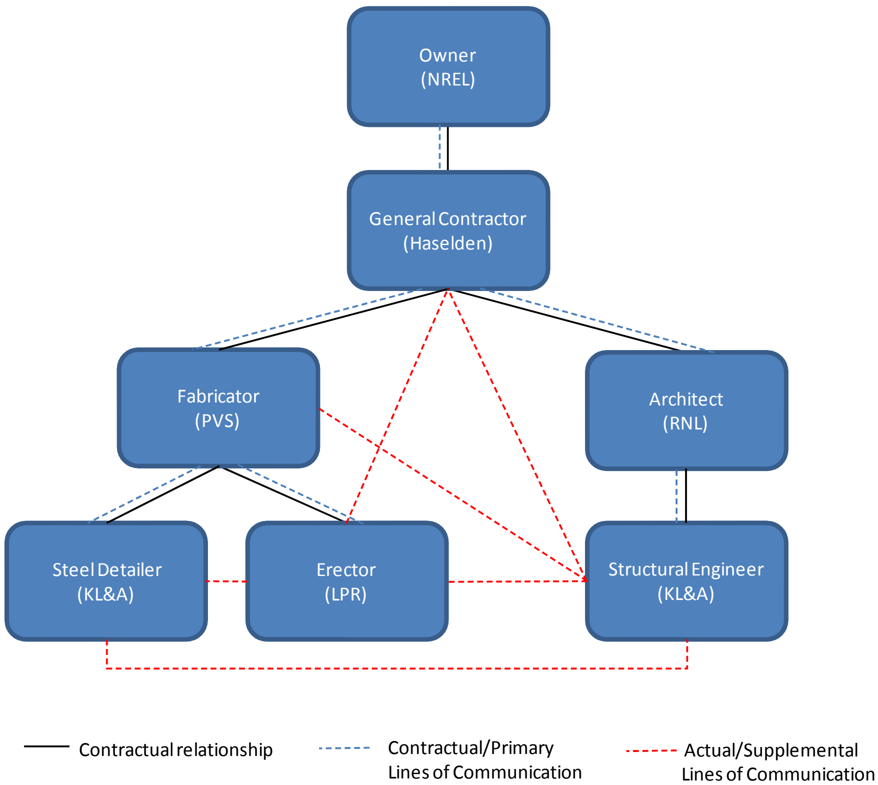

Figure 1. Contractual Arrangement for the Structural Steel Delivery of the NREL Project.

The DB delivery method posed challenges to the communication among project team members. DB allows for design and construction to occur simultaneously, with design consistently a few steps ahead of construction. The expedited DB schedule provides a limited time to review designs so that construction can stay on schedule. Hence, there was not always adequate time to make sure that communication needs were being met for all stakeholders.

Project team members agreed that although there were a handful of communication issues, there was still a relatively integrated steel design and delivery process because of the relationships among team members (personal communication, December 22, 2009). All of the team members' companies had worked together previously, which allowed for a level of trust that would be uncommon for a project team who had not worked together before. Once trust was established between all the individual project members, they were more willing to directly communicate with each other, despite the contractual arrangements (See “Actual Lines of Communication” in Figure 1). There was also a consensus that if a company unfamiliar to the steel team had been hired, the project would have encountered additional challenges. They believed that their team was able to avoid problems due to the established working relationships between companies (personal communication, December 22, 2009). This highlights the correlation between a trusting relationship within a project team and the success of a project. Although project members established some level of integrated communication throughout the project, it was not until after construction documents had been issued that the majority of direct communication between the structural steel team members took place.

Despite the team’s ability to work around their contractual arrangements, there were times that team members did not communicate directly with each other due to their contractual relationships. Given the possibility that a different project team may not have an established level of trust, and thus be willing to communicate outside the contractual arrangement, KL&A presented an alternative contractual model (see Figure 2). This model allows for direct lines of communication among all structural steel project team members and has been used successfully on another project with Haselden, PVS, and LPR.

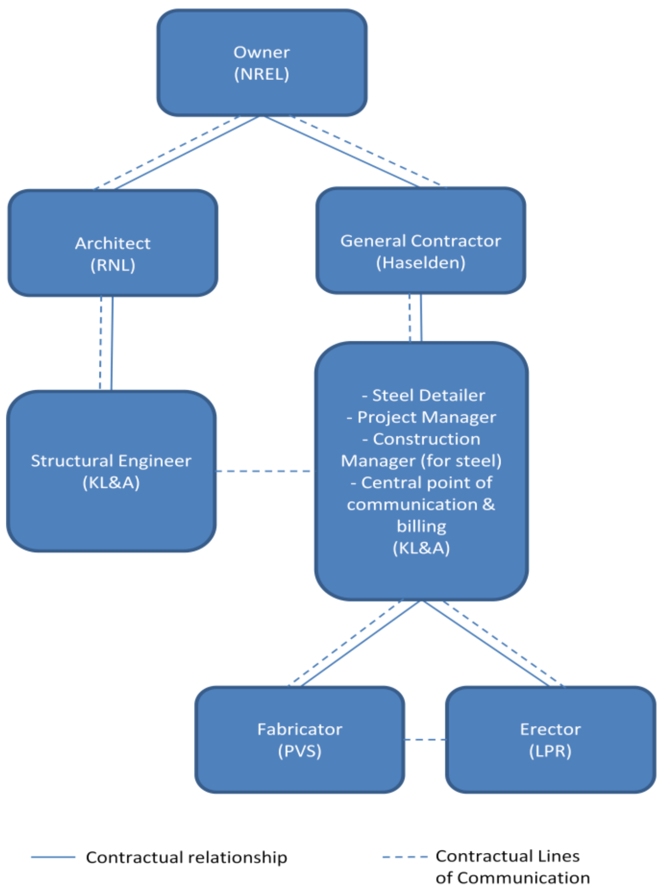

Figure 2. Proposed Integrated Steel Delivery Model.

This model establishes one firm as the structural engineer, steel detailer, project manager, construction manager (for steel), and the central point for communication and billing. The structural engineer hires the fabricator and erector directly, thus housing all structural steel team members under one party and establishing direct lines of communication. In this arrangement, the steel detailer would be able to directly communicate with the structural engineer. In contrast, the steel detailer would not need to go through the fabricator, general contractor and architect to communicate with the structural engineer in the contractual arrangement illustrated in Figure 1. One potential benefit of an integrated steel delivery method would be savings in paperwork, time and energy associated with RFIs (Requests for Information) for smaller design questions. It is important to note that RFIs would still be required on issues that affect the project budget and schedule. Smaller design questions, however, would be able to be answered in a matter of hours versus days or sometimes weeks. A savings in time equates to a savings in money, resources, and energy.

Process Recommendation #2: Ensure Early Involvement of the Erector and Fabricator in the Steel Design Process

During the focus group interview, there was a consensus that it would have been beneficial to include the fabricator and erector earlier in the design phase of the NREL project (personal communication, December 22, 2009). The fabricator and erector bring a unique perspective to the design process, as they are able to foresee design issues that other team members may not recognize. The fabricator, PVS, and erector, LPR, were not contractually brought onto the NREL Project until the end of the design development phase; therefore, the design was substantially complete before any input was gathered from PVS and LPR.

During the focus group interview, project team members spent a significant amount of time discussing a truss girder size change that occurred during erection (personal communication, December 22, 2009). Due to the increased member size, the crane that LPR was using was now too small to erect the new truss. Haselden had to get a bigger crane, which was inefficient for LPR, as there were cranes moving in and out of an already constrained job site. Switching cranes was a disruptive element to the process and LPR suffered at least a one week delay because of the issue.

Although there were several scenarios discussed that could have resulted in avoiding this issue, the group did agree that if LPR and PVS joined the steel delivery team earlier in the design, the team may have been able to get preliminary information about the joists and the team could have worked out girder allowances during preliminary design (personal communication, December 22, 2009). This would allow PVS to foresee any fabrication issues, Haselden to order the proper crane, and would have eliminated the delays LPR suffered during erection.

Beyond including the fabricator and erector earlier in the design of the project, the group also discussed the importance of involving all key stakeholders early in the project (personal communication, December 22, 2009). The early involvement of key stakeholders in the design of a project allows for holistic design decisions and the opportunity to work through issues early in the life a project. Changes in design that are explored during schematic design and design development are generally less expensive and have a smaller impact on the schedule. Conversely, changes made during the creation of construction documents and the construction phase can have a much greater effect on the project resulting in a series of events that will use more time, money, resources, and energy to compensate for the design change (AIA National & AIA California Council, 2007).

A broad discussion of the implications of involving key stakeholders early in a project can be exemplified through Figure 3 as provided by KL&A (AIA National & AIA California Council, 2007; Rutledge, 2009).

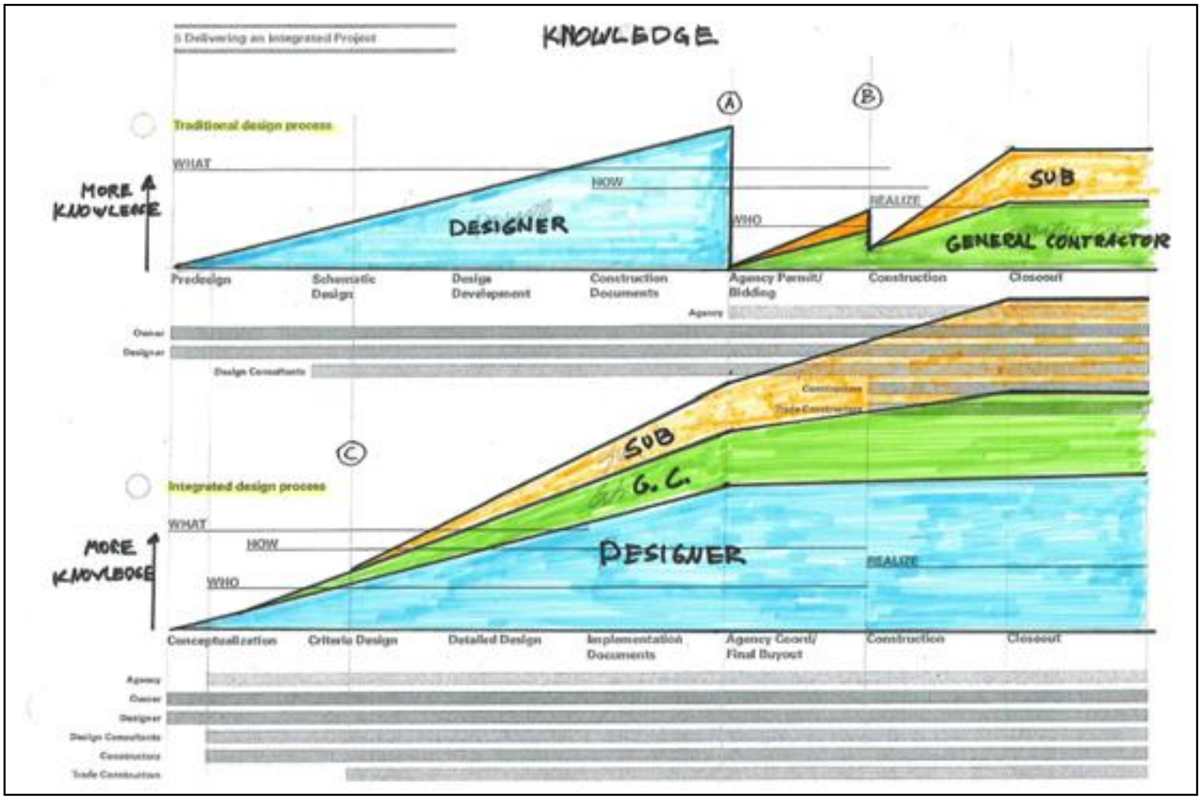

Figure 3. Early Involvement Diagram. (AIA National & AIA California Council, 2007; Rutledge, 2009).

The top graph plots the level and path of knowledge for a traditional design process. The project begins with a design team building knowledge of a particular project from predesign to the construction documents phase. Then, traditionally, the project will go out to bid. At that point, the general contractor (if they were not involved early) and the subcontractors will work extremely hard for a short amount of time in order to learn the project so that they may produce a competitive bid. Once awarded, the project then gets handed off to the construction team who then has to relearn the project yet again. Each drop in the line of knowledge represents the drop in energy and understanding of the entity that is dedicated to the project.

Conversely, the second illustration depicts the level and path of knowledge for an integrated delivery process. The graph shows that if the team members (i.e. primary stakeholders as well as subcontractors such as the fabricator and erector) are brought onto a project sooner, the team will acquire a higher level of knowledge about the project congruously. This eliminates a drop in knowledge at the transition between project phases that can result in inefficiencies as a result of multiple knowledge transfers.

The group agreed that early involvement would be beneficial, but an integrated effort would be null if the exchange of information between phases are not smooth. Haselden echoed this concern, noting that a smooth handoff between the preconstruction team (of which PVS was a member) and the field crew (of which LPR was a member) is sometimes overlooked (personal communication, December 22, 2009). Early involvement of both parties is extremely important to ensure that a loss of knowledge does not occur when the preconstruction team hands off the project to the field crew. Once again, early involvement of the fabricator and erector might have narrowed the gap in knowledge between the two parties.

The group discussed implementing a more integrated delivery model for future projects and concluded that the biggest impediment to the integrated model is trust (personal communication, December 22, 2009). Often times, the owners and general contractors feel that they can get the best price by competitively bidding a project, which automatically excludes certain delivery methods. Furthermore, the established practices of the construction industry can often make an integrated process much more difficult, since including a wide range of project team members early in the process is not standard industry practice. Such a practice will take time to establish credibility in the eyes of a conservative industry.

Process Recommendation #3: Utilize Appropriate Technology

Utilizing appropriate technology, such as Building Information Modeling (BIM), can greatly enhance the sustainability of a project. Building information modeling has the ability to track several project components including scheduling, sequencing, deliveries, and the erection progress. Utilizing a 3D model also allows for initial problem detection virtually rather than on site. Corrections can be made before construction begins allowing savings in time, money, and resources (AIA National & AIA California Council, 2007). Furthermore, 3D modeling allows the erectors to visualize connections better and understand the project more quickly. It was brought up in the focus group session that steel detailers can also benefit from a 3D building model because they can model a detailed component including the weld or even a washer (personal communication, December 22, 2009).

The NREL project team utilized several different software applications. Although almost every entity produced a 3D model of the building, they were all created using different software programs. RNL built their model in Revit, Haselden used NavisWorks, and KL&A used SDS/2 by Design Data. The project team experienced interoperability issues that prevented them from sharing files and developing a comprehensive building model. Interoperability issues are not always linked to the software applications, however. Often, it is the inability of the translator that exists between the two applications.

No one denied that better use of technology could have been applied; however, the way in which to do that was a main point of discussion. Short term, the team found that the simplest interoperability fix would be to take advantage of the model that the steel detailer creates in order to approve electronic drawings instead of relying on hard copies. KL&A did have some success utilizing electronic documents, thus reducing the amount of resources used to create and transport paper documents.

One strong recommendation that came from KL&A and PVS was for the team to hold a technology planning meeting early in the project (personal communication, December 22, 2009). If the team chooses to use 3D modeling or BIM, the first thing to do is set modeling expectations within the team. The American Institute of Architects (AIA) and Associated General Contractors (AGC) have both written governing documents to help project teams determine what those expectations should be [see (Eastman, Liston, Sacks, and Teicholz, 2008; AGC of America, 2008)]. Second, the team will need to understand what each software program is capable of producing, and identify any interoperability issues for the different software applications. Finally, it is important to define the level of modeling that each party is interested in providing, and then assign specific components to project team members. A dedicated planning effort is the key to successful collaboration.

Long term, companies will need to invest in more appropriate technology that can house multiple software applications. The goal is to successfully transfer knowledge from one team member to another, thus reducing errors and waste as a result of interoperability barriers.

Life Cycle Inventory Assessment

In addition to improvements in the contractual arrangements, timing of stakeholder input, and appropriate use of technology, there are opportunities to reduce the environmental impacts of structural steel by careful examination of the inputs and outputs of the fabrication and erection phases. An inventory of five key air pollutants and embodied energy was conducted for the steel frame of the RSF facility. Environmental impacts from the material production, fabrication, and erection phases were all quantified for the beams, columns, joists, girders, stair assemblies, and decking. The building's operation and end-of-life phases were assumed to have similar impacts regardless of the structural steel design and were thus not included in the study.

For the sake of clarity and consistency, the different life cycle phases have been defined as follows throughout the Results section. *Material production* includes the extraction and refinement of raw materials into useable commodities, such as steel. *Fabrication* consists of transporting materials to all activities at the various fabrication plants that convert standard steel shapes into specific building components and includes the emissions produced by generating electricity for the plants. *Erection* includes transportation of materials from the fabricator to the jobsite, transportation of workers and equipment to the jobsite, onsite equipment usage for erection and detailing, and the indirect impacts of producing the electricity and fuel used during construction.

Table 2 aggregates the emissions produced during each life cycle phase, shows totals for all structural steel activities for the NREL RSF project and gives the relative contribution of each phase. As a portion of total impacts, the material production category dominates across all pollutants with the exception of NO_X. However, the contributions from fabrication and erection are still significant in absolute terms. For instance, the 342,000 kilograms of CO_2 emitted during erection is equivalent to the emissions from 30 average homes or 65 cars for one year.

Table 2. NREL RSF Project's Structural Steel Emissions by Life Cycle Phase.

	CO_2 (kg)	SO_x (kg)	CO (kg)	NO_x (kg)	PM_{10} (kg)	Energy (MJ)
Material production	894,000	2,170	12,800	1,360	1,080	11,500,000
(% of Total)	59%	57%	91%	32%	89%	58%
Fabrication	277,000	1,240	494	868	49.0	3,640,000
	18%	33%	3%	20%	4%	18%
Erection	342,000	388	823	2,060	83.5	4,740,000
	23%	10%	6%	48%	7%	24%
Total	**1,510,000**	**3,800**	**14,100**	**4,230**	**1,210**	**19,900,000**

Figure 4 presents CO_2 emissions by source. The transportation impacts have been subtracted out of each phase and are presented as their own category to highlight the significant contribution of CO_2 from shipping activities across all phases.

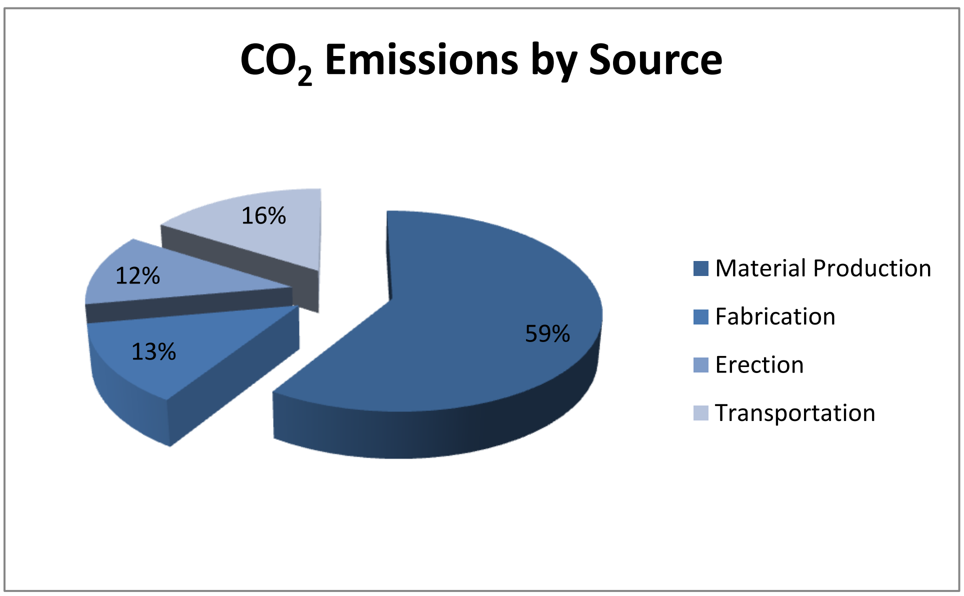

Figure 4. CO_2 Emissions for NREL RSF Project Structural Steel by Source.

With these results in mind, opportunities to improve environmental performance, or alternative scenarios, were identified across all three life cycle phases and then modeled to quantify their potential savings. Through discussions with the project team, these alternative scenarios were deemed to be hypothetically feasible from a cost and technological perspective. The following sections present the findings from the proposed alternatives.

Alternative Scenarios: Material Production

Analysis of the steel delivery process identified that the material production phase is responsible for approximately 58% of the total embodied energy and CO_2 emissions for installed structural steel material. In recent years, studies have shown that significant manufacturing efficiencies have been made in the steel production industry, reducing energy consumption by as much as 33% per ton in the period between 1990 and 2007 (AISI, 2008). These improvements are the result of the combined effort of steel industry associations, producers, and the government to eliminate waste and improve efficiency. Although additional improvements are possible, many of the primary technological advancements that result in lower energy and emissions have already been adopted by producers (Stubbles, 2000).

Fabricators and erectors downstream from production facilities have realized process efficiencies through technological advancements. Equipment such as computer-controlled cutting machines can extract the maximum number of usable shapes from a single plate, thereby minimizing waste. In contrast to the steel production industry, few studies have explored opportunities for energy and environmental emissions reductions by downstream players. That said, fabricators and designers may have opportunities to make significant contributions to energy and emissions reductions by simply reducing the amount of steel needed to be produced. This study found two possible ways that raw material production energy use and environmental emissions may be reduced for a given project: material salvage and reuse and waste reduction in fabrication.

Reused and Salvaged Materials

The salvaged oil and gas piping used for 124 columns (88% of all columns) on the NREL project were compared to a manufactured equivalent to identify energy and emissions impacts. This alternative design option (W-columns) was based on the structural engineer's determination of a newly manufactured alternative (See Table 3). A number of the 16" diameter pipe columns were filled with concrete in order to meet structural support requirements. Given that the concrete is a primary component of the structural member, the concrete material and placement impacts were included in the evaluation.

Table 3. Pipe Column Alternatives.

Salvaged column type	Manufactured alternative
16" x .375 pipe	W14 x 74
16" x .375 concrete filled pipe	W14 x 120
10" x .50 pipe	W12 x 53

The use of salvaged pipe columns was determined to be an environmentally superior alternative to a conventional structural steel column design. (See Table 4). When compared to equivalent manufactured W-columns, the use of salvaged columns reduced CO_2 emissions by 121,000 kg or 69%. Total embodied energy was reduced from 192,000 to 60,600 MJ, a reduction of over 68%. In addition, it was determined that there was actually a net decrease in transportation of the steel, because the baseline W-columns were significantly heavier than the pipe columns.

Table 4. CO2 Emissions and Energy Reduction for Salvaged Pipe Columns vs. Manufactured Alternative Columns.

	CO_2 (kg)	Energy (MJ)
Salvaged Pipe Column	55,000	606,000
Standard W-Column	176,000	1,920,000
Emissions Reduction	121,000	1,314,000
Percent Reduction	**69%**	**68%**

Material Waste Reduction

Demand for new steel may be reduced through reduction of waste in the fabrication phase. One example of a waste reduction strategy is optimizing material cut lengths. This was identified through a focus group interview in the initial phase of research. The effort would involve expanded coordination between fabricator and designer to evaluate steel sizing options early in the design phase. Early review by the fabricator of structural dimensions and connections may identify opportunities for member sizing to better align with the standard manufactured sizes. The result would be a lower waste factor in fabrication and potentially a lower overall cost. Analysis of the steel fabricated by PVS in 2008 showed that the typical waste factor for a given unit fabricated product is 8.4%. The production impacts associated with 8.4% of the steel on the NREL project are summarized in Table 5.

Table 5. PVS Steel Production Phase Impacts with Waste Factor Reduction for NREL RSF Project.

	CO_2 (kg)	Energy (MJ)
Total Project Steel Production Impacts	1,510,000	19,900,000
Total Project Fabrication Impacts	277,000	3,640,000
Waste in Fabrication (8.4%)	75,200	966,000

Alternative Scenarios: Fabrication

The structural steel elements of the RSF building are comprised of numerous and often unique components and subcomponents. In fabrication, these required varying equipment and process inputs in order to produce what are largely custom products. Despite this variation, the majority of significant energy-intensive steps throughout the fabrication process are constant from member to member (e.g. shot blasting, transferring, cutting, and welding). Due to the high level of variability in fabrication, the process-based analysis of the fabrication within the shop was limited to a representative structural column and a beam fabricated at PVS. This allowed for the fabrication process stages to be evaluated and prioritized within the plant without evaluating each unique component and over-complicating the evaluation. As these primary inputs are associated with all primary structural steel members, they help identify opportunities for the environmental improvement for all steel processed in the fabrication shop.

With a representative model established, improvement opportunities were tested and evaluated for energy, fuel, and emissions reductions. These variables included local factors such as equipment operation schedules and shop lighting efficiency, as well as external factors such as raw material selection and transportation alternatives. Structural steel fabricated for the project by contractors other than PVS have been excluded from the process-level research. However, for project-wide inventory for the NREL structure, the fabrication energy was based on annual electricity consumption per ton of steel fabricated by PVS in 2008. Because site-specific data was not available for the other fabricators on the project, energy consumption and emissions impacts were estimated using the EIO-LCA database.

Fabrication Process Energy

In any effort to identify energy conservation opportunities within a process, the starting point should be those areas with greatest potential reduction for the lowest cost and greatest ease of implementation. These “low-hanging fruit” strategies may require little investment while yielding significant reduction of energy and environmental impacts with a rapid payback.

The PVS fabrication shop is a large consumer of electricity for fabrication processes and operations. Electricity is a primary input to the steel delivery process. In exploring opportunities to reduce the environmental impacts within the control of PVS, on site electricity reduction is the obvious starting point.

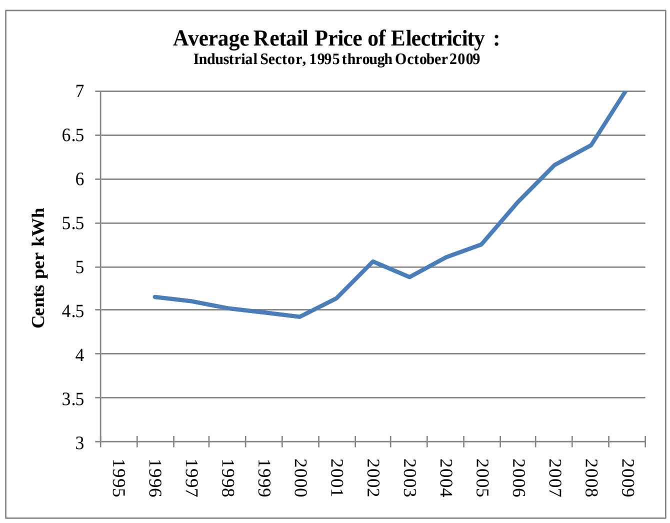

Figure 5. Average Retail Price of Electricity: Industrial Sector, 1995 - October 2009 (EIA, 2009a)

The reliance on electricity as a primary input to fabrication can be viewed as a risk. Over the past 10 years, electricity costs have increased consistently (See Figure 5) (EIA, 2010). There is little indication that the trend will reverse. By making a modest investment in the short term, and reducing the overall energy requirement for fabrication, the amount of risk associated with future electricity price fluctuations is reduced. Reducing electricity is also a primary means to reduce the carbon footprint for steel fabrication.

Shot Blaster Operation Schedule

Following analysis of the fabrication process and associated energy and emissions impacts, the steel shot blaster was identified as a primary consumer of energy. This is, in part, due to the numerous large electric motors used to propel rough steel pellets used to strip the surface of each fabricated member before coating. Unlike many other pieces of equipment used in the process, the blaster is in a state of operation at all times. It does have an idle mode for when the machine is not actively in use, which shuts off twelve 25-horsepower electric motors.

The blaster is in operation for a total of 16 hours per day, of which it was estimated to operate in idle mode for 6 hours per day and be in full operation for the remaining 10 hours. At the time of the visit to the fabrication shop, the blaster was operated in idle mode during breaks and between shift changes.

An opportunity for energy and cost reduction would be to evaluate the operating schedule for the blaster and identify opportunities for reducing the overall idle time. This analysis looked at the impact of a two-hour per day reduction in idle time relative to the overall electricity consumption per year by the blaster. The impact resulted in a net reduction of over 60,000 kWh in electricity consumption per year, which is detailed in **Error! Reference source not found.**. The blaster's full operating mode is much more energy-intensive and would yield much higher reductions if the operating time was decreased as well.

Table 6. Annual Impacts of Shot Blasting Idle Time Reduction for PVS.

	Annual kWh	CO_2 (kg)	Energy (MJ)	Cost ($US)
Existing Blastings	1,060,000	728,000	8,850,000	$99,900
Reduced Idle Schedule	1,000,000	687,000	8,350,000	$94,200
Reduction	**60,000**	**41,000**	**500,000**	**$5,700**

Fabrication Shop Lighting Retrofit

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

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

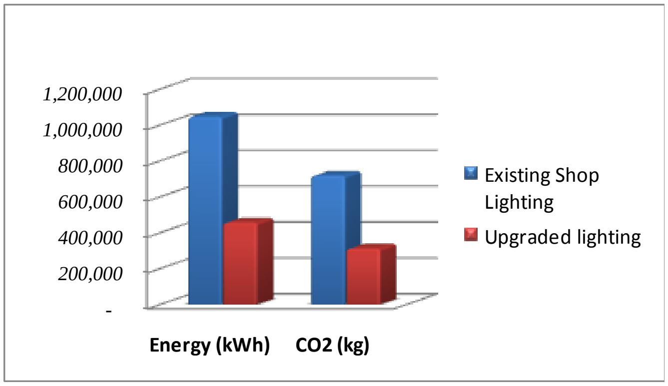

Figure 6. Fabrication Shop Lighting Upgrade.

A lighting upgrade would require the removal and replacement of all fixtures with 6- and 10-lamp F32T8 high lumen output, vapor tight, high bay fixtures at a cost of approximately US $178,000. The resulting estimated annual electricity savings would be over US $55,000, with a simple payback of 3.2 years and an annual net CO_2 reduction of over 405,000 kg (See Figure 6). Table 7 details the costs and impacts associated with a lighting upgrade.

Table 7. Annual Impacts for PVS Fabrication Shop Lighting Upgrade.

	Energy (kWh)	CO_2 (kg)	Energy (MJ)	Cost ($US)
Existing Shop Lighting	1,050,000	719,000	8,730,000	$98,400
Upgraded Lighting	459,000	314,000	3,820,000	$43,100
Reduction	**591,000**	**405,000**	**4,910,000**	**$55,300**
Percent Reduction	56%			
Upgrade Cost	$178,000			
Simple Payback (yrs.)	**3.22**			

Green Power

The effort to reduce the environmental footprint associated with steel delivery can be achieved by first reducing energy consumption and secondly by lowering the impacts from energy production. Once efficiency measures have been addressed, installing renewable energy on site would, after the initial material acquisition, lead to significant carbon and emissions reductions associated with the burning of common fossils fuels such as coal used in electricity production. A second option would be to purchase renewable energy certificates (RECs). RECs are renewable energy commodities equaling the production of 1 megawatt hour of electricity. The actual energy produced may be located in another state where renewable energy production is more efficient or cost effective. The energy produced is not directly supplied to the REC purchaser, rather, the renewable electricity production is subsidized and fed into the grid to be consumed in the market of origin. The idea is to use open markets to promote the production of renewable energy in areas where it is most efficient to produce. Once that 1 MWh of power is generated and a REC is sold, that renewable attribute is “used up” and applied to the purchaser of the REC.

The RECs should not be confused with carbon or emissions offset instruments. Offset instruments are possible alternatives to RECs, but their impact is less because they do not promote the long term development of renewable alternatives and lack credibility due to limited regulation (Gillenwater, 2008). Based on the total 2008 electricity consumption by PVS, the shop and offices could use RECs to effectively reduce CO_2 emissions by over 2.8 million kilograms. The additional cost of RECs for the associated power would be $2-3 dollars per megawatt hour of electricity per year for an annual cost to PVS of $9,000 – $12,000 dollars.

Material Transport from Fabrication to Jobsite

The LCIA for the NREL steel showed that transportation throughout the complete steel delivery process was responsible for approximately 16% of the total CO_2 emissions. Opportunities for reduction of transportation impacts are constrained by the limited availability of alternatives to truck transport. The issue of transportation is further compounded by the fact that steel for the NREL project fabricated by PVS was sourced from mills and wholesalers located in 19 states and Canada.

Rail can be a viable alternative to truck transport when the infrastructure is accessible to both the seller and buyer. In many cases, the cost and logistical efforts make rail transport unfeasible for delivery from supplier to fabricator. The transport of fabricated steel from rail yards to the jobsite is difficult because it requires unloading trucks at the nearest delivery point and transporting the material to the jobsite. The benefit of the fabrication-to-jobsite stage of transport is that all of the project’s steel moves through one of the fabrication shops. On the other hand, the transportation phase between mill and fabricator involves many suppliers in different locations.

In the case of the NREL project, rail transport from PVS to the jobsite may be a viable alternative to truck transport due to the proximity of the jobsite and PVS to rail infrastructure. An analysis compared the impacts of rail transport to truck transport for the PVS portion of steel for the NREL building. This hypothetical example serves to identify potential benefits of diesel rail transport compared to truck transport for the 544 mile trip between PVS and the jobsite. The ability of the team to successfully utilize the alternative method is contingent upon sufficient lay down area for the material between batch shipments. Table shows the emissions impacts for each alternative method.

Table 8. Truck vs. Train Transport from PVS to NREL RSF Jobsite.

	Trips	Fuel (gal)	CO_2 (kg)
Truck Transport	23.0	2,350	28,200
Train Transport	4.00	564	6,770
Reduction		**1,786**	**21,430**
Percent reduction		**76%**	**76%**

Alternative Scenarios: Erection

Table shows the contribution of individual activities to the total erection phase environmental emissions and energy use for the NREL project. Transportation impacts include the delivery of materials and equipment to the site, commuting by iron workers, and upstream impacts from diesel and gasoline production. Raising gang activities consist of unloading trucks, organizing materials, and placement and temporary connection of structural members. Detailing covers the welding and bolting of permanent connections and all associated equipment use.

Table 9. Erection Phase Emissions and Energy Use for NREL RSF Project.

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

Alternatives were modeled for all three activities with the results discussed in the following sections. Transportation was responsible for a large share of erection phase impacts due to the long distances covered by materials and workers coming to the site, thus the relative percentage of transportation impacts could vary greatly for different projects. Likewise, the potential emissions reductions from each alternative would vary depending on a project’s location, site constraints, commuting distance, etc.

Reduced Erection Schedule

Due to site constraints and crane-sizing issues, steel erection activities took approximately three weeks longer than the original schedule proposed by the erector. Had the erection crew been afforded a larger staging area and the preferred crane size, LPR felt that erection could have been compressed by fifteen working days, resulting in reduced impacts from worker transportation and site equipment. This alternative scenario quantifies these savings by eliminating 225 worker days (15 days at average manpower of 15 employees) worth of commuting and 17% of raising gang related emissions (14 week versus 17 week schedule). Table 8 presents the resulting savings in CO_2 emissions and energy, as well as the equivalent gallons of diesel fuel and approximate cost savings. Cost calculations throughout all alternative scenarios assume $2.66 per gallon of diesel and $0.94 per kilowatt hour of electricity (USEIA, 2009b, USEIA, 2009a).

Table 8. Emissions Reduction from Shortening Erection by 3 Weeks for NREL RSF Steel.

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

Use of Site Electricity Only & No Diesel Welders

The raising gang and 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 welders for smaller tasks or when site power could not be reached. An alternative scenario was modeled to demonstrate the impact of using site electricity exclusively and no 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 9 shows the impact on CO_2, electricity consumption, diesel usage, and approximate cost. The CO_2 values are representative of the entire erection phase, while the electricity, diesel, and cost columns represent only the welder operation. An 11.1% increase in electricity consumption resulted in a minor 1.7% savings in erection-wide CO_2 emissions but the 6.7% reduction in particulate matter generation could significantly improve jobsite air quality.

Table 9. Emissions Reductions from Using Site Electricity Only for NREL RSF Project.

	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%

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 CO_2 emissions and gasoline savings of 3,420 gallons when compared to every worker driving a separate vehicle. Table 10 shows the increase in emissions and costs if every worker were to drive their own vehicle. All cost calculations assumed $2.63 per gallon for gasoline (USEIA, 2009c).

Table 10. Increase in Emissions and Energy Consumption without Worker Carpooling for NREL RSF Project.

	CO_2 (kg)	Energy (MJ)	Gas (gal)	Cost ($US)
Current	342,000	4,740,000	5,130	$13,500
No carpooling	376,000	5,250,000	8,560	$22,500
Increase	**33,500**	**508,000**	**3,420**	**$9,000**
Percent increase	9.8%	10.7%	66.7%	66.7%

To encourage additional ridesharing, an employer-sponsored incentive was 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 erection phase CO_2 emissions and $2,250 in fuel savings for employees. Table 11 details the savings from the increased carpooling scenario.

Table 11. Additional Emissions and Energy Consumption Reductions with Carpooling Incentive for NREL RSF Project.

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

Ten Hour Work Days

Another suggestion for reducing emissions from worker transportation was switching to ten-hour work days. By working the same number of hours in only four days per week, worker transportation would be reduced by 20%. According to feedback from the erector's 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 trips for worker transportation. Results are shown in Table 12. 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 12. Emissions Reductions from 10 Hour Work Day on NREL RSF Project.

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

No Partial Loads of Materials

Site constraints, mid-construction design changes, and coordination issues between different parties led to a number of partial loads being delivered 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 semi-trucks (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 be cut by 8.7% even after accounting for the reduced fuel mileage of the heavier loads (See Table 13). Additionally, diesel consumption for materials transportation would decrease by 2,480 gallons, saving approximately $6,600. 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 erection to unloading tasks and back again.

Table 13. Emissions Reductions from Not Shipping Partial Loads to the NREL RSF Project.

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

Source Materials from Local Suppliers

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 can 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 emissions and $13,600 in fuel cost savings. Table 14 illustrates the results for this scenario.

Table 14. Erection Phase Emissions Reductions from Sourcing Materials within 500 Miles of NREL RSF Project.

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

Conclusion

Environmentally speaking, the NREL RSF project has had many successes. The building itself serves as a model of energy efficiency and sustainable design. The project is targeting a LEED™ Platinum certification level, constructing a net-zero building, and incorporating advanced building technologies developed at NREL.

The steel delivery team must also be credited for working to enhance the sustainability efforts on this project. Incorporating reused gas pipes for structural columns was a unique contribution by the team and proved to be a superior environmental decision compared to using a newly manufactured alternative. The reused pipes resulted in a reduction of more than 69% of the energy that would have been required to produce new comparable materials. It should be noted that the estimated savings account for typical recycled content that would have been in any newly manufactured materials. While there were challenges associated with incorporating the reused gas piping into the project, there were measureable environmental benefits from this decision.

Beyond recycled content and reused materials, there is significant room for improvement in the design, fabrication, and erection of structural steel. The recommendations chronicled in this report are based on the notion that inefficiencies result in increased physical waste, which negatively impact sustainability efforts. The underlying assumption is that by increasing efficiencies throughout the structural steel delivery process, not only are costs reduced, but also waste, time, energy, materials, and the overall environmental impact of the structural steel industry.

The individual interviews and focus group revealed several opportunities for improvement for the structural steel delivery process of future projects. Opportunities for improvement include: (1) establish direct lines of communication among the structural steel team members, (2) ensure early involvement of the erector and fabricator in the steel design process, and (3) utilize appropriate technology in the planning process. Adopting an integrated steel delivery model could positively impact the team's communication, improve overall design efficiency, reduce the need for RFIs and shorten response times for questions. As demonstrated in the LCIA portion of the study, reductions in waste and project schedule have measurable environmental benefits. It is important to note, however, that the integrated steel delivery model is highly dependent on the project team members. KL&A has been successful in using an integrated steel delivery model, but they recognize that their success is largely driven by their project team's experience, level of trust, and a willingness to communicate openly and frequently (personal communication, December 22, 2009).

In addition to conducting interviews, the research team performed life cycle inventory assessments (LCIA) on several scenarios to identify practical opportunities for energy and emissions reductions throughout the structural steel delivery process. The results of the LCIA revealed several opportunities for improvement related to the fabrication and erection phases of the project. Acknowledging that the largest component in the process is steel production, downstream players still have the potential to make significant improvements within their own operations. Modeled improvements include: retrofitting fabrication shop lighting, reducing idle time of the blasting equipment in the fabrication shop, using 100% electrical site power for erection, eliminating diesel welders, creating incentives for carpooling to the jobsite, and sourcing materials from local suppliers.

In total, the research team analyzed seventeen scenarios. Ultimately, it will be the responsibility of the project stakeholders to determine which scenarios to implement. Each scenario will have a varying level of cost, difficulty of implementation, and overall benefit to a project. The research team found that the following scenarios would likely have the lowest cost (relative to the other scenarios) with the highest impact (please refer to the Results section for a detailed analysis of each scenario):

- Ensure a smooth transition of information, and thus a minimal drop in knowledge, between project phases
- Conduct a Technology Planning Meeting at the start of every project to ensure interoperability
- Use salvaged gas pipe columns instead of new manufactured columns
- Upgrade the fabrication shop lighting
- Implement a carpooling program for the erection crew
- Source materials locally and/or within 500 miles

The structural steel industry has made progress towards the interrelated goals of sustainability and a more integrated delivery process, yet much work remains to develop and implement recommendations for all stages of the design, fabrication, and erection processes. During the group interview, the project team recognized that, as of now, the biggest constraints to employing the above suggestions are the slow changing construction industry and trust issues. The construction industry was built on adversarial relationships, after all, and it will take some time to experience a shift in mindsets (personal communication, December 22, 2009). Eventually the steel industry may move toward a green steel certification similar to those found in other industries (e.g. the Forest Stewardship Council certification for sustainable forestry practices). This report chronicles some of the efforts made towards these goals by the structural steel team on the NREL RSF project and offers opportunities for improvement on future projects.

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