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Life Cycle Assessment of MBMA Primary and Secondary Structural Steel and Wall and Roof Panel Products

Final Report

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The Metal Buildings Manufacturers Association

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Executive Summary

The Metal Buildings Manufacturers Association (MBMA) engaged the Athena Sustainable Materials Institute to conduct a life cycle assessment to benchmark the average environmental impacts of its structural and panel products used in metal building systems as manufactured by its member companies. The study focused on both MBMA member company manufacturing processes (gate-to-gate) as well as four key product profiles (cradle-to-gate): namely, primary and secondary structural frame components and metal wall and roof cladding. The respective gate-to-gate (G2G) process and cradle-to-gate (C2G) product environmental profiles will be used by MBMA for environmental benchmarking purposes and may be shared externally with targeted building community audiences.

In support of the project, annual primary life cycle inventory (LCI) data was collected from 10 geographically representative MBMA member companies producing all four of the products of interest for the reference production year 2008. Primary data on raw materials and energy use and emissions to air, water and land, scrap recycling as well as production output were provided by the MBMA member companies. In addition, secondary sourced LCI data were utilized to model upstream raw and ancillary material inputs, in-bound and out-bound transportation and energy use.

This LCA study is conducted in accordance with ISO 14040:2006 and ISO 14044:2006. The study data, methods, results and report underwent an external critical review by a panel of interested parties as per Clause 6, ISO 14044:2006 and was deemed compliant with ISO14040/44 standards. The study supports a comprehensive set of life cycle impact assessment (LCIA) indicator categories based on ISO 21930:2007 and the US EPA TRACI 2.1, 2012 impact assessment characterization model. TRACI was used as a basis for calculating the impact category indicator results. The study's representative sample, considerable process data transparency and its comprehensive set of supported environmental life cycle impact category indicators provides a credible industry benchmark and a high degree of study reproducibility by others.

Table ES1 summarizes the gate-to-gate LCA results for the manufacturing of one ton (2,000 lbs) of each metal building product. The manufacture of primary frames, secondary frames and wall and roof panels require in the order of 3,000 MJ, 2000 MJ and 1,350 MJ of energy respectively to produce, almost all of which is derived from non-renewable sources. The results for the majority LCIA indicators across these four product processes are generally scalable to these respective energy intensities of the product process (e.g., secondary frames are two-thirds as energy intensive as primary frames and secondary frames manufacture emits about two-thirds of the greenhouse gases of that of primary frames.) Both welding and painting are key secondary contributors to the primary and secondary frame process LCIA results, while final product packaging is a significant material input in the process of roll-formed cladding panels.

The addition of mastics and sealants to roof cladding panels explains the majority of the LCIA result differences between wall and roof cladding panels.

Table ES1. Summary of G2G LCA Results – Absolute Basis– per 1 Ton of MBMA Selected Manufacturing Processes - Primary Frames, Secondary Frames, and Roof and Wall Panels

Impact category	Unit	MBMA Selected Manufacturing Processes			
		Primary frames	Secondary frames	Roof panels	Wall panels
Global warming	kg CO2 eq	166.2	112.0	72.6	71.6
Abiotic depletion (elements)	kg Sb eq	1.0E-05	1.4E-06	3.0E-05	8.2E-08
Total primary energy	MJ	2,984	1,984	1,357	1,330
Non-renewable, energy	MJ	2,933	1,956	1,338	1,313
Acidification	kg SO2 eq	1.343	0.944	0.622	0.632
Eutrophication	kg N eq	0.071	0.038	0.022	0.019
Respiratory effects	kg PM2.5 eq	0.105	0.063	0.046	0.046
Smog formation	kg O3 eq	13.8	9.0	7.3	6.2
Ozone depletion	kg CFC-11 eq	4.5E-06	2.2E-06	8.7E-07	4.6E-07
Ecotoxicity	CTUe	139.2	82.9	60.4	60.5
Human health cancer	CTUh	3.4E-06	7.9E-07	4.3E-07	3.3E-07
Human health noncancer	CTUh	1.2E-05	6.6E-06	3.6E-06	3.7E-06

Table ES2 summarizes the cradle-to-gate LCA results for four MBMA selected metal building products. These C2G product profiles represent the environmental impacts associated with the extraction of raw materials and energy sources from the earth (cradle) through to the manufacture of one ton of each product ready for shipment at the plant (gate).

A contribution analysis revealed that the G2G processing generally accounted for 4% to 16% of the total primary energy use and 3% to 12% of the global warming potential (GWP) of the total C2G product system. Upstream steel production is the single and most significant input driving the environmental burden of all four products.

Generally, the upstream production and delivery of steel inputs was more significant for wall and roof panels (due to the inclusion of high performance coatings and paints) than the semi-finished steel inputs used in the production of primary and secondary frame components.
On a unit of output basis, wall and roof cladding embodies more energy and results in more emissions than either primary or secondary frame components. Electricity use, especially in the production of primary and secondary frame materials, was the main energy input used in MBMA plants and varied by as much as 20% across plants producing the same component. Curbing in-plant electricity use would yield the greatest improvement in plant operations.

Table ES2. Summary of C2G LCA Results – Absolute Basis – per Ton of MBMA Products - Primary Frames, Secondary Frames, and Roof and Wall Panels

Impact category	Unit	MBMA Selected Products			
		Primary frames	Secondary frames	Roof panels	Wall panels
Global warming	kg CO2 eq	1350.8	2177.5	2486.4	2486.2
Abiotic depletion (elements)	kg Sb eq	1.0E-05	6.4E-06	8.3E-02	6.5E-02
Total primary energy	MJ	18,929	27,938	32,203	32,563
Non-renewable, energy	MJ	18,878	27,901	32,026	32,410
Acidification	kg SO2 eq	5.236	8.962	10.717	11.311
Eutrophication	kg N eq	0.235	0.418	0.526	0.536
Respiratory effects	kg PM2.5 eq	0.945	0.731	0.830	0.879
Smog formation	kg O3 eq	74.2	146.9	156.1	167.1
Ozone depletion	kg CFC-11 eq	4.5E-06	3.1E-06	1.2E-05	1.0E-05
Ecotoxicity	CTUe	304.9	326.6	622.4	607.2
Human health cancer	CTUh	5.5E-06	7.4E-06	1.2E-05	1.2E-05
Human health noncancer	CTUh	8.3E-05	6.1E-05	8.4E-05	8.5E-05

Neither of the two tables is meant to convey a comparative assertion as none of the processes produce functionally equivalent products and therefore are not directly comparable.

The study goal was to conduct a “cradle-to-gate” LCA of the products of interest and their respective processes and did not consider the installation, use or end-of-life phases of these products. As a result, the in-service benefits of these products has not been captured and service life is likely a defining “use” consideration for any of these metal products. The majority of the credit benefit ascribed to the avoided burden approach resides with the end-of-life (EOL) recycling as opposed to intermediate fabrication scrap recycling as captured in this study. Consequently, the “cradle-to-gate” LCIA results, without end-of-life recycling as portrayed in this study are very likely conservative.

The upstream production, packaging and transport of semi-finished steel dominate the LCIA results calculated for MBMA products. These underlying North American steel data were issued by World Steel Association in April 2013 and properly reflect steel production and scrap steel recycling in the US.

For purposes of comparative LCA studies, the “cradle-to-gate” shall be expanded to “cradle-to-grave” LCA study to account for installation, use, and EOL disposal phase including EOL recycling of the MBMA selected products as per WSA’s “avoided burden” methodology (see Section 2.2.4).

Readers of this LCA report are cautioned not compare the four products of interest as they vary considerably in their properties, application within a building system and service life.

Acknowledgements

The Athena Sustainable Materials Institute completed this study with sponsorship from the Metal Building Manufacturers Association (MBMA) and its member companies. The Institute gratefully acknowledges MBMA's LCA Working Task Group members and plant data providers for their valuable comments and support during the study and preparation of this report. In particular, we would like to acknowledge Charles E. Praeger, Assistant General Manager, MBMA, and Jay Johnson, Director of Architectural Services, MBMA, for their continuous support during the study and their timely interventions guiding this project.

The report content reflects the views of the authors, who are responsible for the facts and accuracy of the information presented. The contents do not necessarily reflect the views of the sponsors.

Glossary of Terms

Based on ISO 14040/44:2006 – Terms and Definition Section [1].

Allocation: Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems.

Completeness check: Process of verifying whether information from the phases of a life cycle assessment is sufficient for reaching conclusions in accordance with the goal and scope definition.

Consistency check: Process of verifying that the assumptions, methods and data are consistently applied throughout the study and are in accordance with the goal and scope definition performed before conclusions are reached.

Cradle-to-gate: A cradle-to-gate assessment considers impacts starting with extracting raw materials from the earth (the “cradle”) and ending at the plant exit “gate” where the product is to be shipped to the user. In-bound transportation of input fuels and materials to the plant is included. Out-bound transportation of the product to the user is not included. The use phase, maintenance and disposal phase of the product are also not included within the scope of this study. Disposal of on-site waste at the plant and outside, and transportation within the plant (if applicable) are included.

Functional Unit: Quantified performance of a product system for use as a reference unit.

Life Cycle: Consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal.

Life Cycle Assessment (LCA): Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.

Life Cycle Impact Assessment (LCIA): Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product.

Life Cycle Interpretation: Phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations.

Life Cycle Inventory (LCI): Phase of Life Cycle Assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle.

Product system: Collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product.

Reference flow: Measure of the outputs from processes in a given product system required to fulfill the function expressed by the functional unit.

Sensitivity analysis: Systematic procedures for estimating the effects of the choices made regarding methods and data on the outcome of a study.

Sensitivity check: Process of verifying that the information obtained from a sensitivity analysis is relevant for reaching the conclusions and giving recommendations.

System boundary: Set of criteria specifying which unit processes are part of a product system. Note: the term system boundary is not used in this International Standard in relation to LCIA.

System expansion: Expanding the product system to include the additional functions related to the co-products, taking into account the requirements of 4.2.3.3.

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Acronyms and Abbreviations

ADP	Abiotic Depletion Potential
BF	Blast Furnace
BOF	Basic Oxygen Furnace
C2G	Cradle-to-Gate
CED	Cumulative Energy Demand
CF	Characterization Factor
CFCs	Chlorofluorocarbons
CFC-11	Trichlorofluoromethane
CML	Institute of Environmental Sciences of the University of Leiden, The Netherlands
CRC	Cold Rolled Coil
CTUe	Comparative Toxic Unit – ecotoxicity
CTUh	Comparative Toxic Unit - human toxicity
EAF	Electric Arc Furnace
EOL	End-of-Life
EPDs	Environmental Product Declarations
G2G	Gate-to-Gate
GWP	Global Warming Potential
H+	Hydrogen ion
HDG	Hot Dipped Galvanized
HHV	Higher Heating Value
HFCs	Hydrochlorofluorocarbons
HRB	Hot Rolled Bar
HRC	Hot Rolled Coil
HRP	Hot Rolled Plate
IAI	International Aluminum Institute
IC	Impact Categories
IPCC	International Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LEED	Leadership in Energy & Environmental Design
LDPE	Low Density Polyethylene Film
MBMA	Metal Building Manufacturers Association
MCA	Metal Construction Association
MJ	Mega joule
N	Nitrogen
NA	North America
NCCA	National Coil Coating Association
NO_x	Nitrogen Oxides
O_3	Ozone

P	Phosphorous
PAF	Potentially Affected Fraction of species
PM10	Particulate Matter less than 10 micrometers in diameter
POCP	Photochemical Ozone Creation Potential
PP	Polypropylene
PVDF	Polyvinylidene Fluoride
RR	Recycling Rate
Sb	Antimony
SETAC	The Society of Environmental Toxicology and Chemistry
SO2	Sulfur dioxide
SRI	Steel Recycling Institute
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
UNEP	United Nations Environment Program
US EPA	United States Environmental Protection Agency
VOCs	Volatile Organic Compounds
WMA	World Meteorological Organization
WRI	World Resource Institute
WSA	World Steel Association

Introduction

To accurately benchmark and assess the potential environmental impact of metal building components and key manufacturing processes, the Metal Building Manufacturers Association (MBMA) and its member companies engaged the Athena Sustainable Materials Institute to conduct a Life Cycle Assessment (LCA) of their primary processes and products according to the ISO 14040/44:2006 and ISO 21930:2007 standards.

The objective of this study was to develop a transparent ISO 14040/44:2006 conforming, weighted average, benchmark cradle-to-gate life cycle assessment of 1 ton of four main metal building products produced by the MBMA member companies, namely, primary and secondary structural components and metal roof and wall cladding panels. This study is based on primary LCI data collected from MBMA plants (10 sites) for the reference year 2008.

The results of the LCA study will be incorporated into MBMA's "Go-to-Market" product literature, and the cradle-to gate LCI results will be made available for inclusion in the US LCI Database and LCA software and calculation tools to support the needs of MBMA member companies, their suppliers, architectural, engineering, and specifying professionals, LCA practitioners and tool developers, academia, governmental organizations, policy makers and other interested value chain parties who require reliable information on sustainable building products and processes.

The Metal Building Manufacturers Association (http://www.mbma.com/) is a trade association established in 1956. The mission of the MBMA is to promote the design and construction of metal building systems in the low-rise, non-residential building marketplace. A metal building system is defined as an integrated set of components and assemblies, including but not limited to, frames that are built-up structural steel members, secondary members that are cold-formed steel or steel joists, and cladding components, specifically designed to support and transfer loads and provide a complete or partial building shell. MBMA members include manufacturers of metal buildings, and component products such as roof and wall panel systems.

1 ISO Conforming Life Cycle Assessment

Life cycle assessment (LCA) is an analytical tool used to comprehensively quantify and interpret the energy and material flows to and from the environment over the entire life cycle of a product, process, or service[1]. Environmental flows include emissions to air, water, and land, as well as the consumption of energy and material resources. By including the impacts throughout the product life cycle, LCA provides a comprehensive view of the environmental aspects of the product and a more accurate picture of the true environmental trade-offs in product selection. Two international standards, ISO 14040:2006 and ISO 14044:20061, describe an iterative four-stage or phased methodology framework for completing an LCA, as shown in Figure 1: (1) goal and scope definition, (2) life cycle inventory, (3) life cycle impact assessment, and (4) interpretation.

An LCA starts with an explicit statement of the goal and scope of the study, the functional unit, the system boundaries, the assumptions and limitations, the allocation methods used, and the impact categories chosen. The goal and scope includes a definition of the context of the study, which explains how and to whom the results are to be communicated. The ISO standards require that the goal and scope of an LCA be clearly defined and consistent with the intended application. The functional unit defines what is being studied. The purpose of the functional unit is to quantify the service delivered by the product system and provide a reference to which the inputs and outputs can be related. Allocation is the method used to partition the environmental load of a process when several products or functions share the same process.

In inventory analysis, a flow model of the technical system is constructed using data on inputs and outputs. The flow model is often illustrated with a flow chart that includes the activities that are going to be assessed and gives a clear picture of the technical system boundary. The input and output data needed for the construction of the model (such as materials and energy flows, emissions to air and water, and waste generation) are collected for all activities within the system boundary. Then the environmental loads of the defined system are calculated and related back to the functional unit, and the flow model is finished.

[1]ISO 14040:2006. Environmental Management – Life Cycle Assessment – Principles and Framework. ISO 14044:2006. Environmental Management – Life Cycle Assessment – Requirements and guidelines.

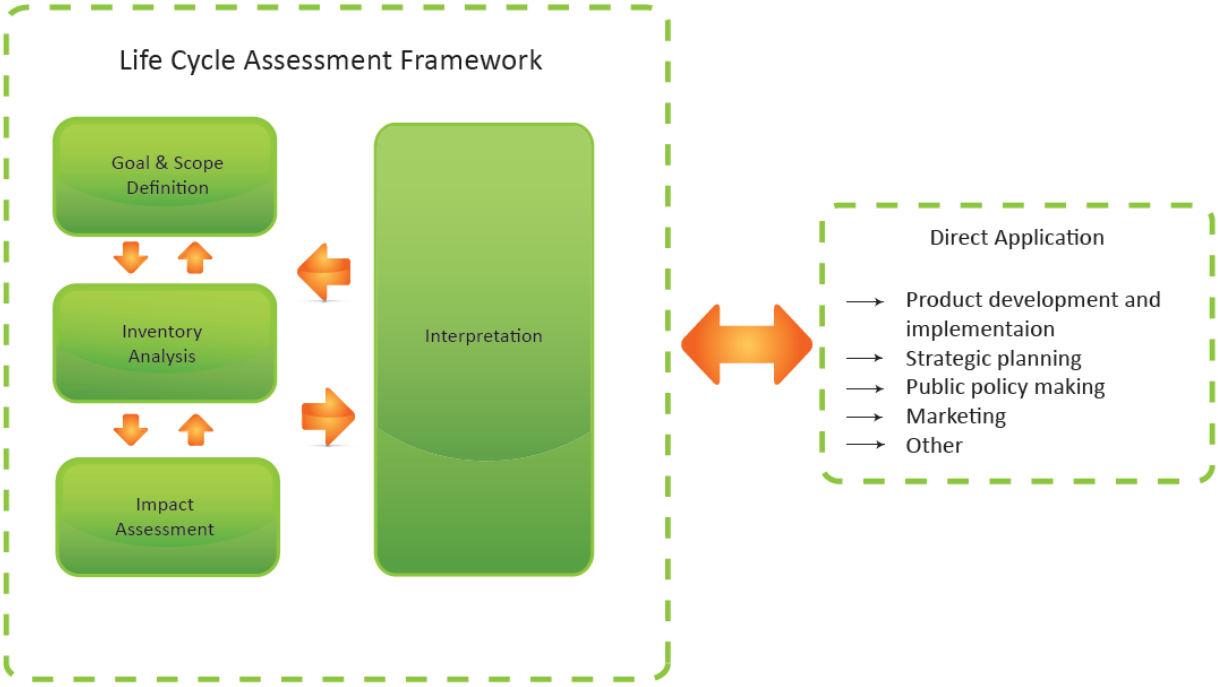


Figure 1 Stages of an LCA as per ISO 14044:2006

Inventory analysis is followed by impact assessment, in which the life cycle inventory data are characterized in terms of their potential environmental impacts; for example, resulting in acidification, ozone depletion, and global warming. The impact assessment phase of LCA is aimed at evaluating the significance of potential environmental impacts based on the LCI flow results. Classical life cycle impact assessment (LCIA) consists of the following mandatory elements – selection of impact categories, category indicators, and characterization models – and continues with the classification stage, where the inventory parameters are sorted and assigned to specific impact categories.

The categorized LCI flows are then characterized using one of many possible LCIA methodologies into common equivalence units and summed to provide an overall impact category total. This equivalency conversion is based on characterization factors as prescribed by the selected LCIA methodology. In many LCAs, characterization concludes the LCIA analysis; this is also the last compulsory stage according to ISO 14044:2006. However, in addition to the mandatory LCIA elements (selection, classification, and characterization), other optional LCIA elements (normalization, grouping, and weighting) may be conducted depending on the goal and scope of the LCA study. In normalization, the results of the impact categories from the study are usually compared with the total impact in the region of interest. Grouping consists of sorting and possibly ranking the impact categories. During weighting, the different environmental impacts are weighted against each other to get a single number for the total environmental impact. According to ISO 14044:2006, “Weighting shall not be used in LCA

studies intended to be used in comparative assertions intended to be disclosed to the public." While this study does not make explicit comparative assertions, readers and users of this study mayinfer a comparison, and therefore weighting and other optional LCIA elements are excluded to be consistent with the goal and scope of the LCA study and the ISO 14044:2006 protocol.

The results from the inventory analysis and impact assessment are summarized during the interpretation phase. The outcome of the interpretation phase is a set of conclusions and recommendations for the study. According to ISO 14040:2006 the interpretation should include the following:

- identification of significant issues based on the results of the LCI and LCIA phases of LCA;
- evaluation of the study considering completeness, sensitivity, and consistency checks; and
- conclusions, limitations and recommendations.

The working procedure of LCA is iterative, as illustrated by the back-and-forth arrows in Figure 1. The iteration means that information gathered in a latter stage can cause effects in a former stage. When this occurs, the former stage and the following stages have to be reworked taking into account the new information.

At the end, the results and conclusions of the LCA will be completely and accurately reported to the intended audience. The data, methods, assumptions, limitations, and results will be transparent and presented in sufficient detail to allow the interested parties to comprehend the complexities and trade-offs inherent in the LCA. The resulting report will allow the results and interpretation to be used in a manner consistent with the goals of the study.

2 Study Goals and Scope

2.1 General

2.1.1 Goals of the study

This is a sector-driven initiative by the MBMA and its members to conduct an LCA study of the industry's main processes and products as manufactured within the continental United States.

The primary goals and objectives for the study included the following.

1. To better understand the overall environmental performance of the four primary industry products and their respective production processes. These products include:
   - primary structural components (also known as primary frames, e.g., beams, columns);
   - secondary structural components (also known as secondary frames, e.g., girts, purlins);
   - metal roof panels (also known as roof claddings, e.g., pre-painted and unpainted metal roof panels in various gauges); and
   - metal wall panels – (known also as wall claddings, e.g., pre-painted and unpainted metal wall panels in various gauges).
2. To respond to customer and public requests for accurate environmental information on MBMA member products and systems.
3. To better understand the average contribution of the MBMA gate-to-gate processes relative to the full cradle-to-gate profile of the metal building products of interest.
4. To assist other organizations in understanding and communicating the environmental performance associated with using MBMA metal building products within a metal building system.

More specifically, the goals of this study were –

1. To determine the "gate-to-gate" process environmental profiles, on a production weighted average (representative) basis, of 1 short ton[2] of processed metal output and identify key environmental inputs and outputs for the four MBMA primary selected metal processes.

2. To determine the "cradle-to-gate" product environmental profiles, on a production weighted average (representative) basis, of 1 short ton of metal product output and identify key environmental inputs and outputs for the following four primary selected products:

- primary structural components;
- secondary structural components;
- metal roof panels; and
- metal wall panels.

[2] 1 short ton (U.S. ton) equals 2000 lbs.

2.1.2 Intended applications

1. To create an industry environmental performance baseline or benchmark associated with the primary product processes which will support future projects such as –
   - promoting and tracking the continuous improvement of the environmental performance of metal building component products as technology improves over time;
   - allowing member companies to benchmark their plant-specific product footprint against a valid industry average;
   - supporting the development of derivative works such as industry-average carbon footprint reporting and/or sector level environmental product declarations.
2. To populate the US LCI Database and have data incorporated into North American LCA software tools such as the Athena Institute's Impact Estimator for Buildings software.
3. On-going Market Support. The LCA provides detailed "gate-to-gate" process and selected "cradle-to-gate" product profiles, with key indicators of environmental performance. These product and process environmental profiles may be used in education and marketing efforts with environmentally conscious customers or organizations to properly position metal building components and systems within the building construction industry (e.g., LEED green building certification system and Green Globes rating systems, government procurement programs, etc.).
4. This report may also serve as the basis for possible derivative works such as carbon footprint efforts and environmental product declarations (EPDs).

2.1.3 Intended audience

The primary audience for this LCA report is MBMA's membership. The goal and scope of the project was purposely focused on the information needs of MBMA's membership including the development of a benchmarking tool such that MBMA and its members could continue to track their environmental performance; hence a number of key study production metrics are geared specifically to the industry and the manufacture of various building components which do not necessarily easily translate to finished products as employed in a building.

MBMA may make the study results available externally to their suppliers, architectural, engineering, and specifying professionals, LCA practitioners and tool developers, academia, governmental organizations, policy makers and other interested parties who require reliable information on metal building products and processes.

2.1.4 Comparative assertions

This LCA does not include comparative assertions and has not been assembled or reviewed to include the necessary elements to support such assertions.. However, it may lead to future comparative studies intended to be disclosed to the public. As a result, a critical review panel of interested parties was convened to verify that the completion of this LCA study is consistent with the ISO 14040/44:2006 guidelines and principles- see Appendix B: Third Party Critical Review Attestation.

The members of the peer review panel include:

1. Mr. Tom Gloria (Chair), Managing Director, Industrial Ecology Consultants
2. Mr. Jon Dettling, Quantis International, US Managing Director
3. Mr. Bill Savitz, Director, Business Development, Garco Construction, Inc. (former MBMA Chair)

2.2 Scope of the study

The scope of the study entailed developing both a “gate-to-gate” and “cradle-to-gate” life cycle assessment for the four primary component products of the US metal buildings industry on a production weighted average basis for the reference production year 2008. The production of each product is scaled to one ton of final product output.

2.2.1 System boundaries

Figures 2 to 5 depict the four “gate-to-gate” system boundaries for the selected product component manufacturing systems: primary structural, secondary structural, roof and wall panels. For the purposes of this study a “black box” approach was applied, meaning that input/output data were rolled-up and not reported for every single constituent process operation in the production of a product. For example, the primary structural component manufacturing process involves a discrete set of operations, such as plate shearing, punching, splicing, tacking, flange/web welding, finish welding, grinding, painting and warehousing; these processes were aggregated for “gate-to-gate” reporting purposes.

The “cradle-to-gate” boundary considers impacts starting with extracting raw materials from the earth (the “cradle”) and ending at the plant exit “gate”, where the product is ready to be shipped to the user. In-bound transportation of input fuels and materials to the plant are included. Tabulated weighted average out-bound final product transportation to the user is also reported as a separate information flow; however, it is outside the system boundary. The on-site construction, use phase, maintenance/periodic replacement and end-of-life disposition phases of the product’s life cycle are also excluded from the system boundary. Treatment and disposal of on-site generated waste from the plant and its respective transportation (where applicable) is included. “Fabrication” metal scrap recycling (also known as “prompt” scrap) is considered to be within the “cradle-to-gate” system boundary.

Figure 6 illustrates the “cradle-to-gate” system boundaries for the four primary selected product systems: primary and secondary structural, roll formed roof panels, and exterior metal wall claddings.

Figure 2 "Gate-to-Gate" System Boundaries for Finished Primary Structural (Frame) Steel Process

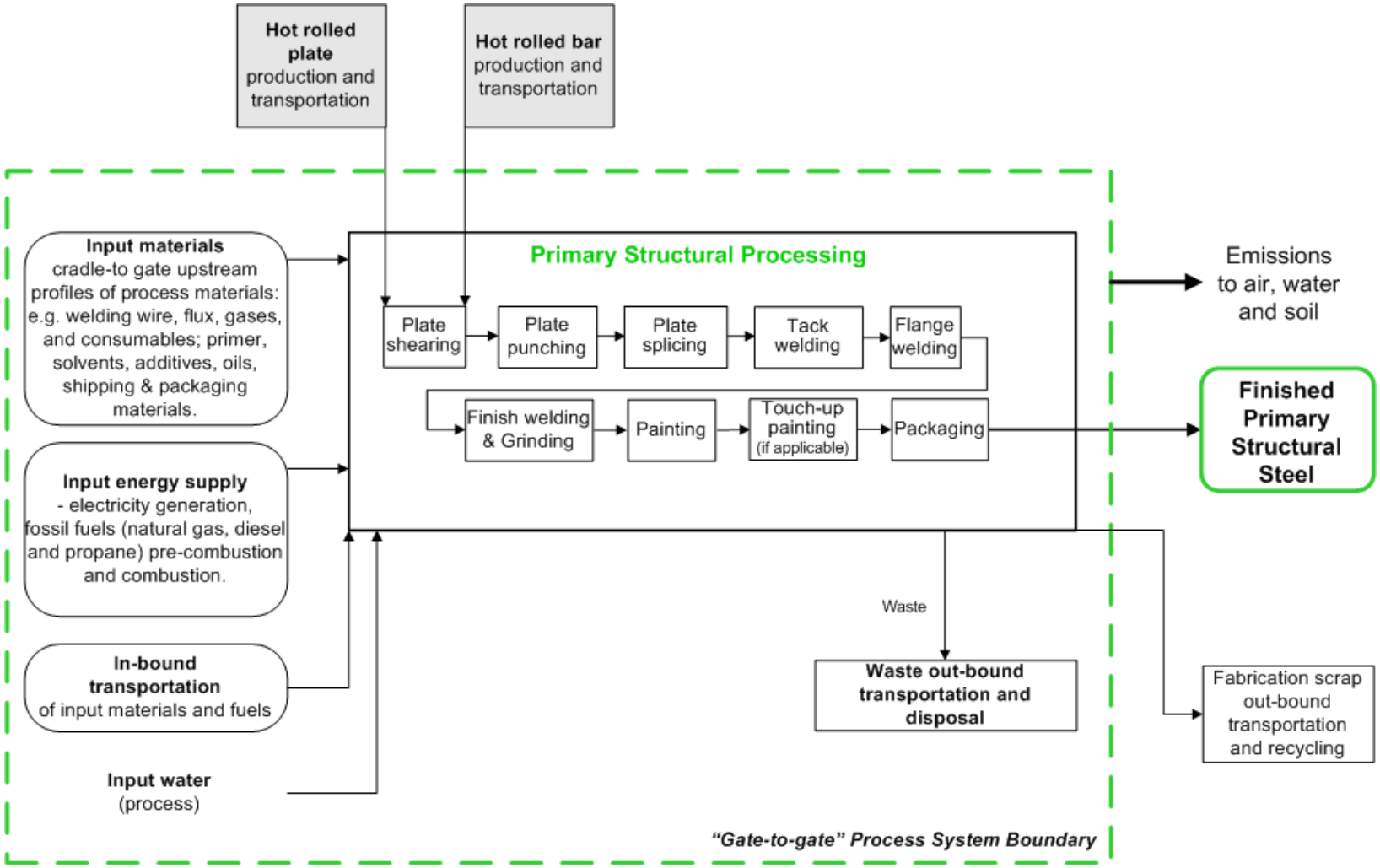


Figure 3 "Gate-to-Gate" System Boundaries for Finished Secondary Structural (Frame) Steel Process

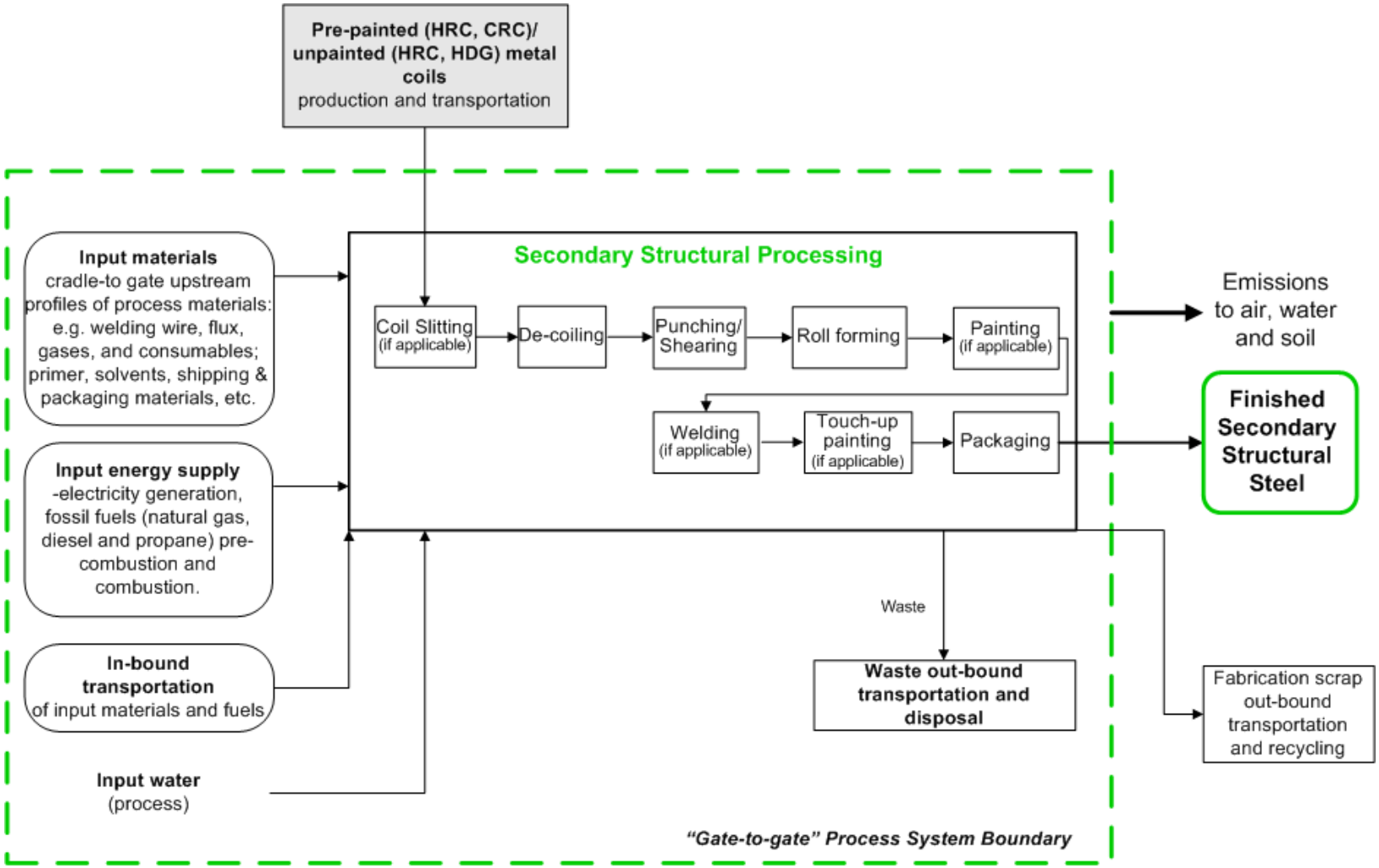


Figure 4 "Gate-to-Gate" System Boundaries for Roll Formed Metal Wall Cladding Process

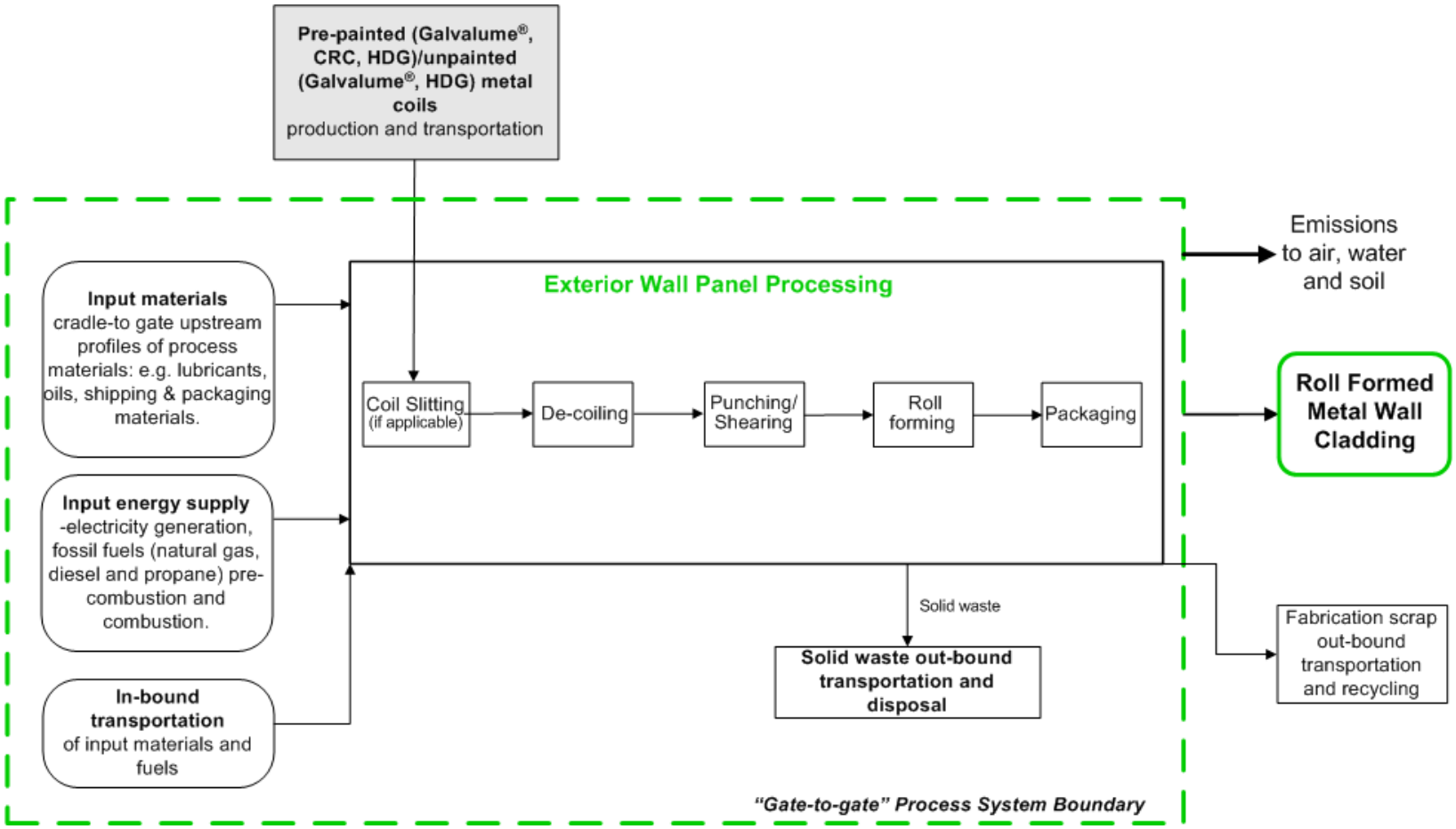


Figure 5 "Gate-to-Gate" System Boundaries for Roll Formed Metal Roof Panel Process

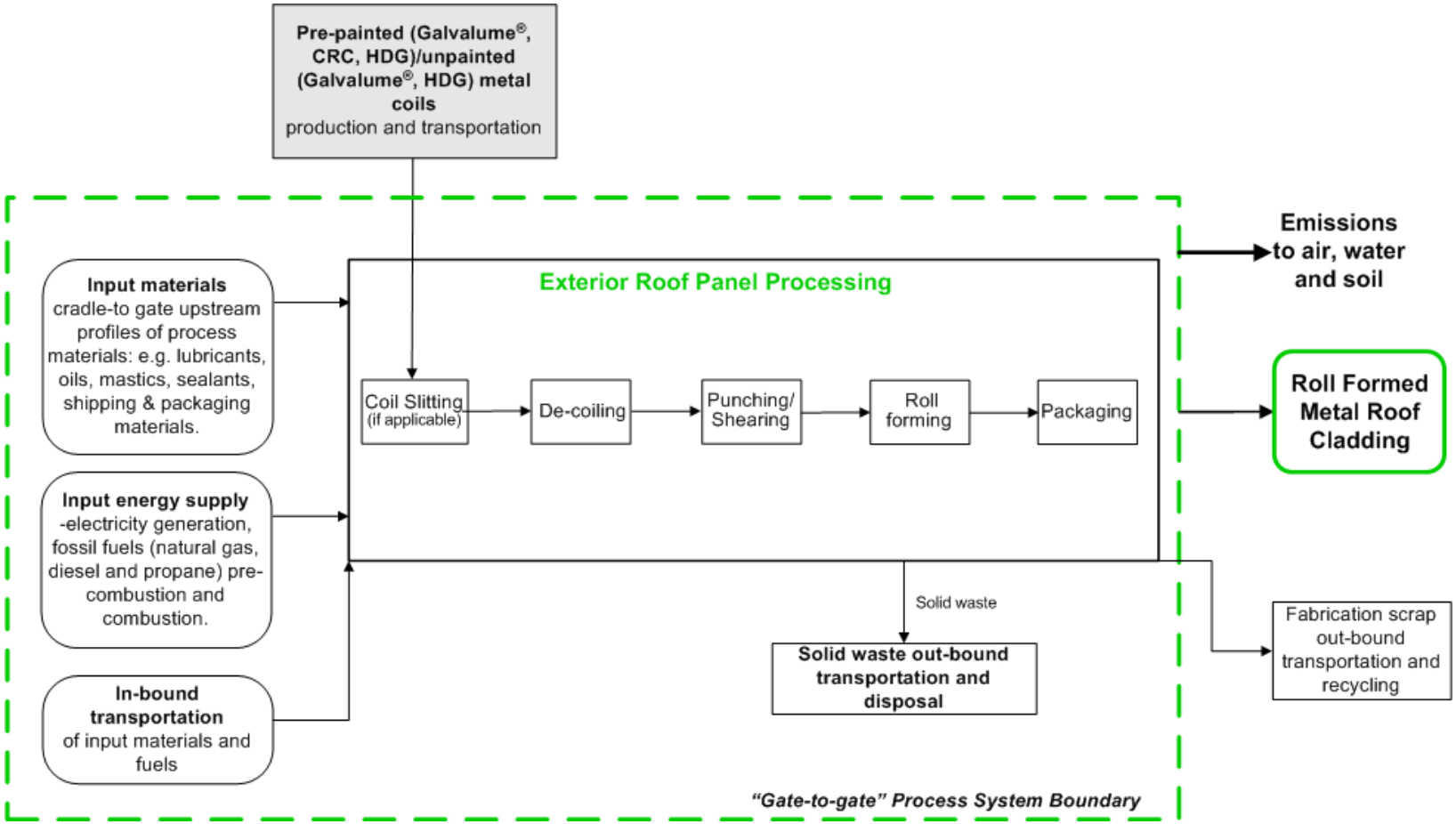
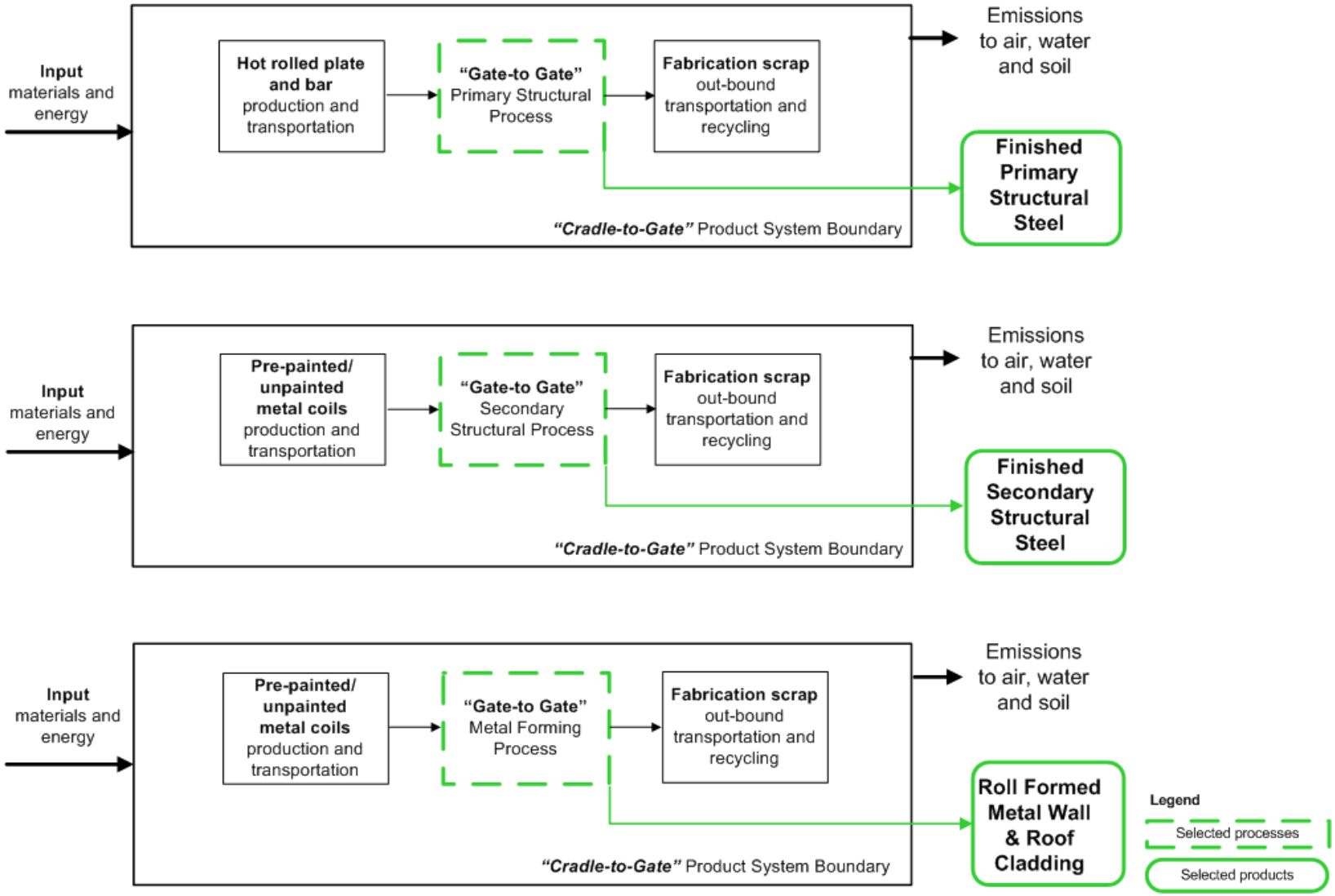
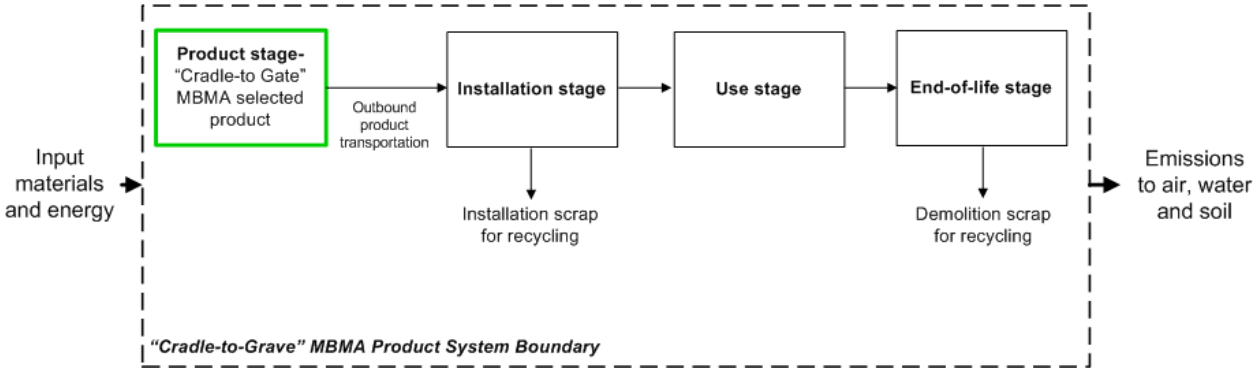


Figure 6 "Cradle-to-Gate" System Boundaries of the Four Primary Products



The “cradle-to-gate” environmental profiles for the four MBMA primary products can be used at a later stage to evaluate the full “cradle-to-grave” profile for these products. Figure 7 illustrates a general “cradle-to-grave” system boundary for MBMA products.

Figure 7 ”Cradle-to-Grave” System Boundaries of the MBMA Primary Products



A "cradle-to-grave" assessment of building products typically considers impacts at each stage of a product's life cycle, from the time natural resources are extracted from the ground and processed, through each subsequent stage of production, installation, use and end-of life, including transportation occuring during the life cycle of the building product. These “cradle-to-grave” profiles can be used to develop environmental product declarations (EPDs) for these products and support the MBMA education and marketing efforts in the future.

Table 1 presents a summary of the elements included and excluded from the “gate-to-gate” and “cradle-to-gate” system boundaries.

Table 1. General Overview of the System Boundaries for this LCA Study

Included	Excluded
“Gate-to-Gate” system boundaries	
• Process ancillary materials input • Energy input • Operation of primary production equipment • Operation of mobile support equipment • Input water (for process and cooling) • Waste and on-site waste-treatment • Packaging of products • In-bound transportation of all materials, intermediate products, packaging and fuels • Overhead (heating, lighting) of manufacturing facilities	• Production of intermediate or semi-finished metal material inputs • Recycling of metal scrap • Manufacture of fixed capital equipment • Manufacture of mobile support equipment • Hygiene related water use • Employee labor and commuting

Included	Excluded
• Internal transportation of materials • Process related waste and emissions	
"Cradle-to-Gate" system boundaries	
All above elements as well as: • Extraction, production and transportation of all input raw materials • Transportation and recycling of metal scrap	All above elements except: • The production of metal input materials and recycling of metal scrap and their respective transportation are now included

Raw material is defined as primary or secondary material that is used to produce a product (secondary material includes recycled materials); *ancillary* material is defined as material input that is used by the unit process producing the product, but which does not constitute part of the product, e.g., welding flux (ISO 14044:2006).

2.2.2 Functional unit

A *functional unit* is defined in ISO 14040:2006 as the quantified performance of a product system for use as a reference unit.

The functional unit used in the "gate-to-gate" analysis is:

- metal processing to fabricate 1 short ton of primary structural elements;
- metal processing to fabricate 1 short ton of secondary structural elements;
- metal processing to fabricate 1 short ton of metal exterior wall cladding; and
- metal processing to fabricate 1 short ton of metal roof cladding.

The functional unit used in the "cradle-to-gate" analysis is:

- production of 1 short ton of primary structural elements;
- production of 1 short ton of secondary structural elements;
- production of 1 short ton of metal exterior wall cladding; and
- production of 1 short ton of metal roof cladding.

Input metal substrates (e.g., hot rolled plate, hot rolled bar and pre-painted/unpainted metal coils) are key semi-finished steel product inputs for which the reference flow for each selected "metal processing" is determined, e.g., on average:

- the production of 1 short ton of *primary structural elements* requires the input of 1.079 short tons of hot rolled plate or bar;
- the production of 1 short ton of *secondary structural elements* requires the input of 1.051 short tons of pre-painted and unpainted metal coils;
- the production of 1 short ton of *metal exterior wall cladding* requires the input of 1.062 short tons of pre-painted and unpainted metal coils; and

- the production of 1 short ton of *metal roof cladding* requires the input of 1.050 short tons of pre-painted and unpainted metal coils.

In contrast to the "gate-to-gate" analysis, which is only focused on the environmental profile of the metal processing itself, the "cradle-to-gate" analysis includes both the upstream profile of metal substrate production, including metal scrap recycling and transportation, and the environmental profile of the metal processing.

Both primary (beams, columns) and secondary (girts, purlins) structural products work together to support the mass of the building for a specified dead, live, wind and auxiliary (crane) loads-see Appendix A. Metal building structural frames typically have column heights of 20 feet at the eave and may incorporate modular and clear spans any where from 20 to 100 feet along the main beam. Exterior wall and roof cladding provide the exterior envelope weathering surfaces for a building. Metal roof and wall cladding produced by MBMA members typically have thicknesses ranging from 24 to 26 ga. As calculated for this study, one ton of wall and roof cladding yields approximately 2,125 sq. ft. and 1,975 sq. ft. of finished product, respectively.

Table 2 below lists the key MBMA primary products with their primary substrate and the primary processes for which LCI data was collected from MBMA member facilities.

Table 2. Primary and Secondary Structural, Exterior Wall and Roof Panel Products, Key Metal Substrates and "Gate-to-Gate" Processing

MBMA Selected Products	Input Metal Substrate	MBMA Primary Processes
Primary Structural	Hot rolled plate, hot rolled bar and hot rolled sections of varying thicknesses	Plate shearing, punching, splicing, tack welding, flange welding, finish welding & grinding, painting, touch-up painting (if applicable) and packaging.
Secondary Structural	Pre-painted (HRC, CRC)/unpainted (HRC, HDG) metal coils of varying thicknesses	Coil slitting (if applicable), de-coiling, punching/shearing, roll forming, painting (if applicable), welding (if applicable), touch-up painting (if applicable) and packaging.
Roll Formed Metal Exterior Wall and Roof Panel (Cladding)	Pre-painted (Galvalume®[3], CRC, HDG)/unpainted (Galvalume®, HDG) metal coils of varying thicknesses	Coil slitting (if applicable), de-coiling, punching/shearing, roll forming, and packaging

[3] Galvalume® is the registered trademark of BIEC International, Inc, USA. for a patented sheet steel product having a coating of corrosion-resistant aluminum-zinc alloy applied by a continuous hot dipping process. The composition of the Galvalume® sheet coating is typically 55% aluminum, 1.6% silicon and 43.4% zinc, nominal percentages by weight.

It is recommended that no attempt be made to compare the four products of interest as they vary considerably in their application within a building. It is also recommended that, where the study provides additional summary profiles for various products by semi-finished steel substrate, these profiles also not be compared due to their differing properties, possible applications and varying service lives.

2.2.3 Cut-off criteria

Cut-off criteria for the inclusion of input flows were determined during the goal and scope of the study in an effort to reduce the effective cost of the LCA. Negligible inventory input flows may be excluded from a system boundary according to the following criteria.

- Mass – if a flow is less than 1% of the total mass input of the product system being modeled it may be excluded, providing its environmental relevance is minor.
- Energy – if a flow is less than 1% of the total product system's energy inputs it may be excluded, providing its environmental relevance is minor.
- Environmental relevance – if an input flow meets the above two criteria, but is determined (via secondary or proxy data analysis) to contribute 2% or more to any product life cycle impact category, it is included within the system boundary.

The sum of the neglected input flows was not to exceed 5% of the total mass, energy or environmental relevance. Similar cut-off criteria can also be used to identify which outputs should be traced to the environment; for example, by including waste treatment processes.

All flow data reported by the participating MBMA facilities were included in the selected process and product models. None of these reported flow data were excluded based on the above cut-off criteria.

2.2.4 Allocation Methods

The multi-functionality of many processes has been identified as a significant methodological LCA issue. The general situation is that most manufacturing processes that constitute part of a product system are multi-functional: (1) they produce more than one product (co-production); (2) they treat two or more waste inputs (combined waste treatment); (3) they treat one waste input and produce one valuable output (open- or close-loop recycling); or (4) they serve three or more valuable functions from both input and output perspective [13]. In such cases the materials and energy flows, as well as associated environmental releases, are to be allocated to the different products according to clearly stated procedures (ISO 14044:2006, Clause 4.3.4).

According to ISO 14044:2006, allocation means partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems. Under the heading "Allocation", ISO 14044:2006 presents a hierarchy of different approaches to this multi-functionality problem. As the hierarchy addresses approaches

other than allocation and also identifies the first two approaches as "avoiding allocation", it is argued that a clearer and more appropriate approach would be the encompassing title “Solving multi-functionality of processes“ [22].

ISO suggests a generic step-wise framework in LCA. The following three steps are required.

Step 1 Wherever possible, allocation should be avoided by –

(a) *Dividing* the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes, or

(b) *Expanding* the product system to include additional functions related to the co-products, taking into account the requirements of ISO 14044.

Step 2 Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products and functions in a way that reflects the underlying physical relationships between them; that is, in a way that reflects the fact that inputs and outputs are changed by quantitative changes in the products or functions delivered by the system.

Step 3 Where physical relationships alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and functions in a way that reflects other relationships between them. For example, input and output data might be allocated between co-products in relation to the economic value of the products.

ISO requirements and recommendations were followed in this LCA study for allocation procedures in general (Clause 4.3.4.2) and allocation procedures for reuse and recycling specifically (Clause 4.3.4.3).

“MBMA” plant production system – “Mass” was deemed as the most appropriate physical parameter for allocation of the total inputs/outputs of the plant production system between primary frames, secondary frames, and roof and wall panel manufacturing lines. Data collection participants provided input and output data specific to each of four selected manufacturing processes. Then inputs/outputs were allocated over the total outputs of panel or framing on a mass basis.

Semi-finished steel products are integral commodities used in the production of upstream and the primary MBMA metal building products. As a result, current peer-reviewed LCI data according to the ISO 14040 series for these metal products generated by the World Steel Association (WSA) were applied in this LCA study [8]. With regard to allocation rules applied for the upstream semi-finished steel products, WSA allocation rules as described in section 4.6, Methodological details, “WSA 2011: Methodology report, Life cycle inventory study for steel products”, were deemed appropriate [8, 20].The WSA states,*“System expansion method (ISO Step 1.b) is the preferred method of the steel industry as it provides the most consistent solution*

to avoiding many of the problems of other approaches." [8] System expansion/substitution are also called "system enlargement" and "crediting"/"avoided burden approach", respectively.

Steel scrap is a vital input to the steel making process, and the WSA recommends that this input of steel scrap should be considered in LCA studies [8]. "A closed loop approach" is applied by WSA for recycling of steel. This approach is certainly in line with the "Declaration by the Metals Industry on Recycling Principles", endorsed by 17 international industry associations in 2007 and published in the International Journal of LCA, which states, "*For purposes of environmental modeling, decision-making, and policy discussions involving recycling of metals, the metals industry strongly supports the end-of-life recycling approach over the recycled content approach*" [9].

This project uses the most recent North American (NA) peer-reviewed *"cradle-to-gate" LCI data excluding EOL recycling*, issued by WSA on April 2013, of semi-finished steel products such as plate, hot rolled coil, cold rolled coil and hot-dip galvanized steel[4]. As scrap is globally traded, WSA recommends to use 2010 WSA global scrap LCI data. No NA regional scrap LCI data is or will be available.

As the study is a "cradle-to-gate" product system, the study utilizes the WSA's "value of scrap" model to credit only "fabrication", also known as "prompt" scrap, which is known by MBMA facilities to be recycled, but applies no "credit" to the product system for the possible post consumer "end-of-life" scrap recycling of MBMA products.

The "value of scrap" LCI profile is provided by WSA and calculated as the difference between producing a given amount of material from 100% primary (virgin) material and producing the same amount of material through secondary (recycled scrap metal) production means.

It is also noted that the WSA method for "cradle-to gate" LCI profiles *with EOL recycling* are less a function of the "input scrap content" than a function of the *total recycling rate (RR)*, also known as total recovery rate, where *fabrication, installation and demolition scrap* are accounted for. Steel Recycling Institute (SRI) 2013 statistics for the 2011 reference year show a 98% recycling rate for structural steel products.

[4] For WSA definition of semi-finished steel products, please check Appendix 1: Description of steel products covered by the study; World Steel Association, 2011: Methodology report, Life cycle inventory study for steel products, ISBN 978-2-930069-66-1 [8].

Figure 8. 2011 US Structural Steel Recycling Rates [SRI 2013]

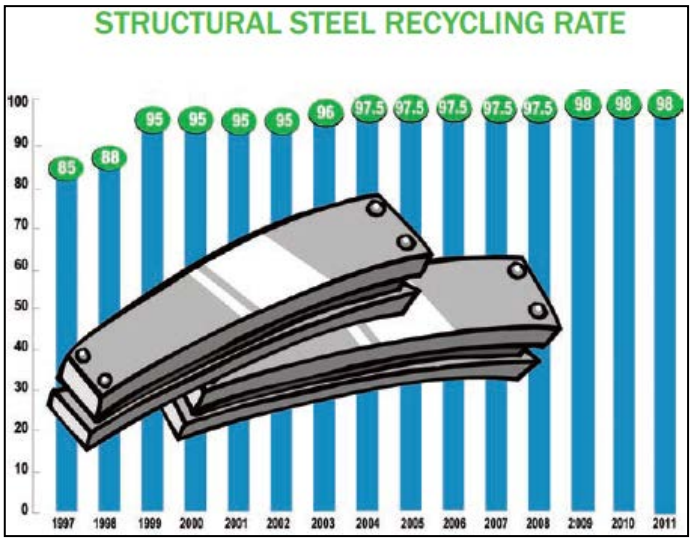
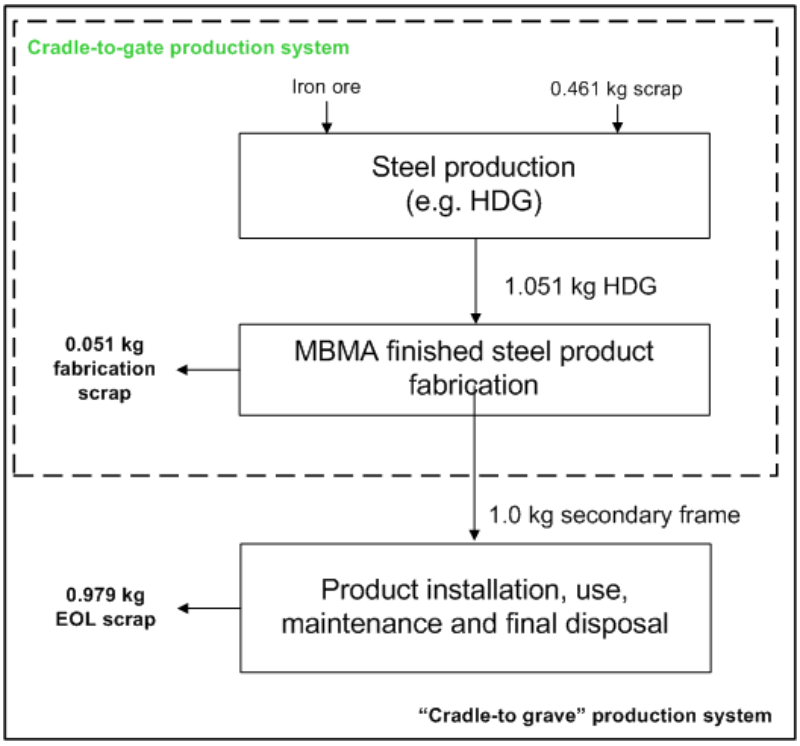


Figure 9 below (adaptation of WSA Figure 10-9 [8]) presents the approach applied to "credit/debit" the "cradle-to-gate" and "cradle-to-grave" production system of secondary frame made of HDG metal substrate, for the "fabrication" and "total recycled" scrap, respectively.

Figure 9 Example of "Cradle-to-Gate" and "Cradle-to-Grave" System



To calculate the cradle-to-gate (C2G) LCI of an MBMA secondary frame product, including fabrication scrap recycling, an example for CO_2 emissions is shown below, for NA secondary frame made of HDG metal substrate.

$LCI_{\text{C2G with fabrication scrap}} = 2.159 – 0.051 \times 1.409$
$LCI_{\text{C2G with fabrication scrap}} = \mathbf{2.087\ kg\ CO_2}$

Where,

2.159	is the amount of CO_2 emissions (in kg) per 1.051 kg NA HDG steel; 2.159 is calculated by multiplying 1.051 kg by the factor of 2.054 kg CO_2 per kg NA HDG steel [20]
1.051	is the amount of NA HDG steel (in kg) used to manufacture 1 kg of MBMA secondary frames;
0.051	is the amount of fabrication scrap (in kg) for MBMA secondary frames production
1.409	is the amount of CO_2 emissions (in kg) per 1 kg of “secondary steel”- the “value of scrap” [20]

SRI 2013 statistics indicate a 98 % total recycling rate of structural steel products in the US. This means for each kg of NA semi-finished steel product used for structural finished steel products, 0.98 kg of steel scrap is recovered and recycled during the life cycle (including both “fabrication” and “EOL” scrap”). In this example, the total amount of recycled scrap is 1.030 kg, which includes 0.051 kg fabrication scrap and 0.979 kg EOL recycled scrap.

Similarly, to calculate the cradle-to-gate (C2G) LCI of the MBMA secondary frame product, including EOL scrap recycling, an example for CO_2 emissions is shown below, for NA secondary frame made of HDG metal substrate.

$LCI_{\text{C2G with EOL recycling}} = 2.087 – (0.979 - 0.461) \times 1.409$
$LCI_{\text{C2G with EOL recycling}} = \mathbf{1.357\ kg\ CO_2}$

Where,

1.030	is the total amount of scrap (in kg) recovered from the life cycle system for recycling; 1.030 is calculated by multiplying 1.051 kg by the RR value of 98%,
0.979	is the EOL recycled scrap (in kg) including installation and demolition stage scrap; 0.979 is calculated by subtracting 0.051 kg fabrication scrap from 1.030 kg total recycled scrap,
0.461	is the amount of input scrap (in kg) in 1.051 kg NA HDG steel; 0.461 is calculated by multiplying 1.051 kg by the factor of 0.4386 kg scrap per kg NA HDG steel [20],

The carbon dioxide is used as illustration flow in this example. The same calculation method applies to all inputs and outputs of the LCI.

As can be seen from the formula above, the **RR value** is the defining parameter, and the *"cradle-to-gate" LCI profile of structural steel product, with EOL recycling,* is less a function of the "input scrap" than the net recovered scrap for the system.

For example,

- if the input amount of scrap is *low* (e.g., 0.10 kg), then at the end-of-life the structural finished steel product will be credited/debited for the net of amount of scrap 0.879 kg (=0.979 - 0.10); and
- if the input amount of scrap is *high* (e.g., 0.50 kg) then at the end-of-life the structural finished steel product will be credited/debited for the net of amount of scrap 0.479 kg (=0.979 - 0.50).

Table 3 presents the average input scrap for the selected NA steel products used for the manufacturing of MBMA primary frames, secondary frames and roof and wall panels.

Table 3. Input amount of ferrous scrap for the selected "cradle-to-gate" NA LCI steel products [20]

Input ferrous scrap (in kg/kg steel product)	**Plate**	**CRC**	**HDG**	**HRC**
North American steel products [WSA 2013]	0.838	0.177	0.439	0.223
World average steel products [WSA 2010]	0.039	0.114	0.103	0.121

More information on the treatment of recovered scrap can be found in Section 10.6, World Steel Methodology, of the WSA 2011 final report [8].

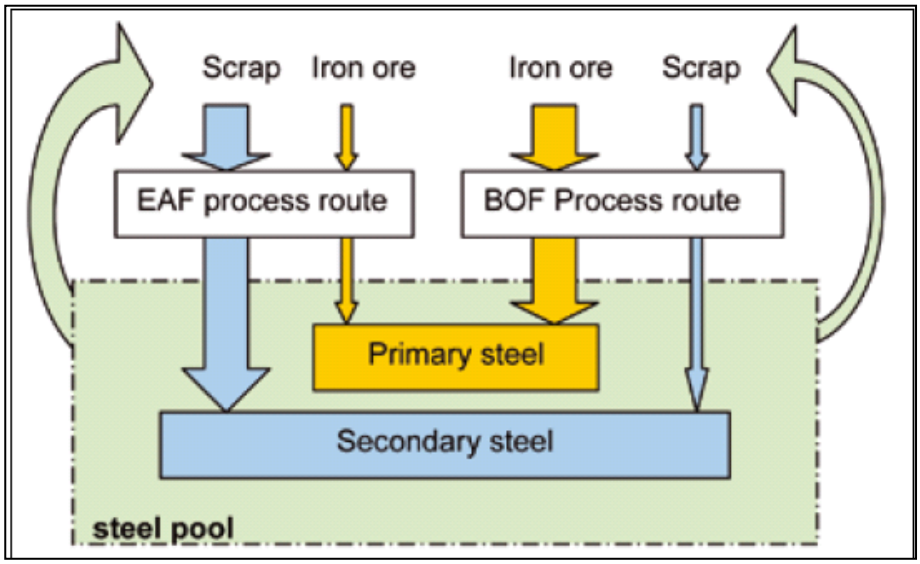
2.2.5 Primary and secondary steel production

In the manufacture of steel the term *'primary production'* generally refers to the manufacture of iron (hot metal) from iron ore in a blast furnace (BF), which is subsequently processed in the basic oxygen furnace (BOF) to make steel. *'Secondary production'* refers to the 'recycling' route, and is typically the electric arc furnace (EAF) process, which converts scrap into new steel by re-melting old steel [8].

However, primary steel production is not unique to the BOF route and similarly secondary steel production is not unique to the EAF. For example, it is common practice to use 10-30% scrap as iron input in the BOF route. Primary steel production occurs in the EAF route also, when pre-reduced iron is used as a feedstock to the EAF process[8].

Figure 10 shows that both EAF and BOF processes produce primary and secondary steel.

Figure 10 Conection between primary and secondary steel production [8]



More information on steel recycling practices can be found in Section 10.4, World Steel Methodology, of the WSA 2011 final report [8].

2.2.6 Selection of Impact Categories and Assessment Methodologies

Life cycle impact assessment (LCIA) is the phase in which the set of results of the inventory analysis – the inventory flow table – is further processed and interpreted in terms of environmental impacts. According to LCA-based ISO 14040/44:2006 [1,2], the mandatory elements of LCIA are:

- selection of impact categories, category indicators, and characterization models;
- assignment of LCI results (classification) to the impact categories; and
- calculation of category indicator results (characterization)[5].

For this study, ISO 21930:2007 "Sustainability in Building Construction – Environmental Declaration of Building Products"[3] provides internationally accepted guidance and a comprehensive list of impact categories to be addressed for an LCIA of building products. In addition, the US EPA Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI 2.0 published in 2011- last update TRACI 2.1, 2012) provides a North American context for the actual category indicators to be supported [5], [7]. ISO 21930 stipulates a number of mid-point LCIA characterization measures to be supported, and while not opposing end-point measures, discourages their use until they are more internationally accepted.

The mid-point measures advocated by ISO 21930:2007 include the following:

1. Use of resources and energy
   - Depletion of non-renewable material resources
   - Use of renewable resources
   - Depletion of non-renewable primary energy
   - Use of renewable primary energy
2. Climate change
3. Depletion of the stratospheric ozone layer
4. Formation of photochemical oxidants
5. Acidification of land and water sources
6. Eutrophication

[5]Category indicators present possible or potential impacts and are based on environmental impacts that may be realized if the emitted chemical compound(s) actually follows the designated impact pathway and reacts accordingly in the receiving environment. Each potential impact pathway is calculated in isolation, and while a number of compounds may contribute to two or more pathways, no effort is made to partition individual chemical compound flows between impact pathways. As a result, LCIA results are only relative expressions of potentials and do not predict actual impacts, the exceeding of thresholds, safety margins or risks [2].

Optional end-point LCIA measures listed in ISO 21930:2007 include human toxicity and ecotoxicity. US EPA TRACI 2.1, 2012 methodology supports the characterization factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment based on the UNEP-SETAC toxicity model "USEtox™" [6]. USEtox™ calculates both global and continental characterization factors for human toxicity and freshwater ecotoxicity. The characterization factor for human toxicity (human toxicity potential) is expressed in comparative toxic units (CTUh), providing the estimated increase in morbidity in the total human population per unit mass of a chemical emitted (cases per kilogram).

The CTUh for cancer and CTUh for non-cancer should not be summed without making an evaluation of the relative severity of the diseases whose incidence is predicted by each indicator. The characterization factor for aquatic ecotoxicity (ecotoxicity potential) is also expressed in comparative toxic units (CTUe) and provides an estimate of the potentially affected fraction of species (PAF) integrated over time and volume per unit mass of a chemical emitted (PAF m3 day kg−1) [6].

TRACI does not yet support abiotic depletion (elements). To fill this indicator gap, the study draws on Institute of Environmental Sciences (CML), Leiden University's CML-IA v.3.9, 2010 LCIA method [12]. The ecoinvent cumulative energy demand (CED) LCIA method (last update August 2010), was adopted to calculate and report total primary energy use and non-renewable energy sources as a subset of total primary energy use [11]. Higher heating value (HHV) of primary energy carriers was used to calculate the primary energy values used in the study. Higher heating value, gross heating value, or total heating value includes the latent heat of vaporization and is the reporting convention most used by US government agencies.

The impact method and characterization factors applicable to North American land use are still in development. Although it can have a significant impact, most North American LCI data do not include measures of land use (nor do WSA LCI profiles); land use has therefore been excluded as an impact category.

Table 4 summarizes the selected impact categories, their unit equivalence basis, source of the characterization method and geographic specificity to be supported and used for the study. Characterization factors are available for the "environmental media" listed in the last column of Table 4.

Table 4. Selected LCIA Indicators

LCIA category	Unit equivalence (equiv.) basis (indicator result)	Source of the characterization method	Level of site specificity selected	Environmental media
Global warming	kg CO_2 – equiv.	SP TRACI 2.1, 2012/ IPCC 2007	Global	Air
Abiotic depletion, (elements)	kg Sb/ yr equiv.	CML-IA v.3.9- last update Nov 2010	Global	Natural resources
Total primary energy- *gross calorific value*	MJ	SP CED- last update Aug 2010, adjusted for 2013 NA WSA steel LCI data	Global	Natural resources
Non-renewable energy (fossil & nuclear) †	MJ			
Acidification	kg SO_2 equiv.	SP TRACI 2.1, 2012	North America	Air, Water
Eutrophication	kg N equiv.	SP TRACI 2.1, 2012	North America	Air, Water
Human health: respiratory effects	kg $PM_{2.5}$ equiv.	SP TRACI 2.1, 2012	North America	Air
Photochemical smog	kg O_3 equiv.	SP TRACI 2.1, 2012	North America	Air
Ozone depletion	kg CFC-11 equiv.	SP TRACI 2.1, 2012 /WMO:2003	Global	Air
Eco-toxicity*	CTUe	SP TRACI 2.1, 2012/ USEtox	North America	Urban air, non-urban air, freshwater, seawater, natural soil, agricultural soil
Human health cancer*	CTUh	SP TRACI 2.1, 2012/ USEtox	North America	
Human health non-cancer*	CTUh	SP TRACI 2.1, 2012/ USEtox	North America	

* Indicate end-point impact indicators with higher degree of uncertainty

† Subset of primary energy. Renewable energy = total primary energy – non-renewable energy

A short description of TRACI 2.1 and CML impact categories (IC) and characterization factors (CF) is provided below. A characterization factor is a factor derived from a characterization model, which is applied to convert an assigned life cycle inventory analysis result to the common unit for the category indicator. The common unit allows calculation of the category indicator result.

a. **Global warming (IC)** – TRACI calculates global warming potential (GWP), a midpoint CF metric proposed by the International Panel on Climate Change (IPCC), for the calculation of the potency of greenhouse gases relative to carbon dioxide (CO_2). The 100-year time horizons recommended by the IPCC and used by the US for policy making and reporting are adopted within TRACI. The methodology and science behind the global warming potential calculation is considered one of the most accepted LCIA categories. Within TRACI 2.1, the most current GWPs published by IPCC (2007) were used for each substance. GWP_{100} is expressed on equivalency basis relative to CO_2, that is, equivalent CO_2 mass basis.
b. **Abiotic depletion (elements) IC** – As per Leiden University's CML-IA v.3.9 method (last updated in November 2010), the abiotic depletion potential (ADP) –chemical elements-baseline factors for characterizing abiotic elements are based on ultimate reserves and extraction rates. According to Guinee & Heijungs (1995) a method based on ultimate reserves and rates of extraction is the best option, as these parameters best indicate the seriousness of abiotic depletion. As the notion of economic reserves involves a variety of economic considerations not directly related to the environmental problem of element depletion, the measure of ultimate reserves appears to be a more appropriate yardstick. The indicator is expressed in kg of the reference resource antimony (Sb). Fossil fuels are excluded because they will be reported under a separate category (total primary energy). Abiotic depletion (elements) is expressed on an Antimony (Sb) equivalent mass basis.
c. **Total primary energy (IC)** – Total primary energy is the sum of all energy sources that are drawn directly from the earth, such as natural gas, oil, coal, and biomass or hydropower energy. Total primary energy contains further categories, namely non-renewable and renewable energy, and fuel and feedstock energy. Non-renewable energy includes all fossil and mineral energy resources, such as natural gas, oil, coal and nuclear energy. Renewable energy includes all other primary energy sources, such as hydropower, solar, geothermal and biomass. Total primary energy is expressed in mega joules (MJ).
d. **Acidification (IC)** – According to TRACI 2.1, acidification comprises processes that increase the acidity (hydrogen ion concentration, [H+]) within a local environment. This can be the result of the addition of acids (e.g., nitric acid and sulfuric acid) into the environment, or by the addition of other substances (e.g., ammonia) which increase the acidity of the environment due to various chemical reactions and/or biological activity, or by natural circumstances such as the change in soil concentrations because of the growth of local plant species [7]. Acidification is a more regional rather than global impact affecting water and soil. Consistent with the focus on providing midpoint assessments, TRACI 2.1 uses an acidification model which incorporates the increasing hydrogen ion potential within the environment without incorporation of site-specific

characteristics such as the ability for certain environments to provide buffering capability [7]. Acidification is expressed in kg SO_2 equivalent.

e. **Eutrophication (IC)** – In TRACI 2.1, eutrophication is defined as the fertilization of surface waters by nutrients that were previously scarce. This measure encompasses the release of mineral salts and their nutrient enrichment effects on waters – typically made up of nitrogen (N) and phosphorous (P) compounds and organic matter flowing into waterways. The result is expressed on an equivalent mass of nitrogen basis. The characterization factors estimate the eutrophication potential of a release of chemicals containing N or P to air or water, per kilogram of chemical released, relative to 1 kg N discharged directly to surface freshwater.

f. **Human health: criteria air pollutants, respiratory effects (IC)** – Particulate matter is a collection of small particles in ambient air, which has the ability to cause negative human health effects including respiratory illness and death [5]. Emissions of SO2 and NOx lead to formation of the secondary particulates (sulphates and nitrates). Particles can be suspended in the air for long periods of time. Some particles are large or dark enough to be seen as soot or smoke. Others are so small that individually they can only be detected with an electron microscope. Many man-made and natural sources emit PM directly or emit other pollutants that react in the atmosphere to form PM. These solid and liquid particles come in a wide range of sizes. Particles less than 10 micrometers in diameter (PM10) pose a health concern because they can be inhaled into and accumulate in the respiratory system. Particles less than 2.5 micrometers in diameter (PM2.5) are referred to as "fine" particles and are believed to pose the greatest health risks. Because of their small size (approximately 1/30th the average width of a human hair), fine particles can lodge deep within the lungs. Respiratory effects are expressed as a microDALY normalized to PM2.5 equivalent mass basis.

g. **Photochemical smog (IC)** – Photochemical ozone formation potential (CF) – Under certain climatic conditions, air emissions from industry and transportation can be trapped at ground level where, in the presence of sunlight, they produce photochemical smog, a symptom of photochemical ozone creation potential (POCP). While ozone is not emitted directly, it is a product of interactions of volatile organic compounds (VOCs) and nitrogen oxides (NOx). The “smog” indicator is expressed on a mass of equivalent ozone (O_3) basis.

h. **Ozone depletion (IC)** – Stratospheric ozone depletion is the reduction of the protective ozone within the stratosphere caused by emissions of ozone-depleting substances. International consensus exists on the use of ozone depletion potentials-ODPs (CF), a metric proposed by the World Meteorological Organization (WMO) for calculating the relative importance of chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HFCs), and halons expected to contribute significantly to the breakdown of the ozone layer. Within TRACI 2.1, the most recent sources of ODPs (WMO 2003) were used for each substance, where chemicals are characterized relative to trichlorofluoromethane (CFC-11).

i. **Human health cancer, non-cancer, and ecotoxicity (ICs)**
Under the UNEP/SETAC Life Cycle Initiative, the various international multimedia model developers of CalTOX, IMPACT 2002, USES-LCA, BETR, EDIP, WATSON, and EcoSense created a global consensus model—USEtox^{TM}—to address an expanded list of substances which might have potential impacts in human health cancer, non-cancer, and ecotoxicity [5,6]. The USEtox^{TM} model adopted many of the best features of the above-named models and was used to develop human health cancer and non-cancer toxicity potentials and freshwater ecotoxicity potentials for over 3,000 substances including organic and inorganic substances [5, 6]. USEtox was developed with two spatial scales: continental and global. The environmental compartments within the continental scale include urban air, rural air, agricultural soil, industrial soil, freshwater, and coastal marine water. USEtox also includes most of the pathways found in the EPA Risk Assessment Guidelines, including inhalation, ingestion of drinking water, produce, meat, milk and freshwater and marine fish [5].

TRACI 2.1 reports both human and ecotoxicity on a comparative toxic unit basis (CTUh and CTUe). USEtox also recognizes that the underlying models are better suited for some substances (i.e., organics) than other substances (i.e., in-organics). It should be noted that some of the characterization factors included within the USEtox model are “recommended” while others are listed as “interim”. The “interim” factors should be used, because in their absence, these substances would appear to have no impacts, but these interim factors should be recognized as having increased uncertainty and should be used ‘‘with caution’’ [5]. The total number of USEtox “recommended” substances for “Human toxicity, cancer”, “Human toxicity, non-cancer” and “Ecotoxicity” are respectively 423, 335 and 877 [18]. The number of USEtox “interim” substances for “Human toxicity, cancer”, “Human toxicity, non-cancer” and “Ecotoxicity” are respectively 603, 435 and 2505 [18].

The characterisation factors for '*metals*', 'dissociating substances' and 'amphiphilics' (e.g. detergents) were all classified as “interim” due to the relatively high uncertainty of addressing fate and human exposure for all chemicals within these substance groups. [18]

In this LCA study, both “recommended” and “interim” characterisation factors are included. It should be noted that “metals”, which all obtained “interim” factors, tend to dominate all the organic substances by several orders of magnitude in most LCAs [18]. For purposes of transparency and possible future use, both human toxicity and ecotoxicity indicators have been calculated and reported; however, as uncertainty is high around “interim” factors which dominate the project results (see Section 7.3- Substance Dominace Analysis), the study provides no substantive interpretive guidance about these three potential end-point impact indicators.

3 Data Quality

A primary deliverable of the project is the submission of the weighted average LCI data for each of the four component products to the US LCI Database. Publishing these four product profiles will ensure the availability of transparent and consistent LCI data, which will facilitate their use by North American LCA practitioners and software tool developers. Inherent data quality is an integral aspect for the submission of data to a recognized database. This section describes the achieved data quality relative to the ISO 14044:2006 requirements. Data quality is judged on the basis of its precision (measured, calculated or estimated), completeness (e.g., unreported emissions), consistency (degree of uniformity of the methodology applied within a study serving as a data source) and representativeness (geographical, temporal, and technological).

3.1 Precision and Completeness

Precision: The MBMA participating companies through measurement and calculation collected primary data on the production of primary and secondary structural products and roof and wall panel cladding products. For accuracy the LCA team individually validated these plant gate-to-gate input and output data.

Completeness: All relevant, specific processes, including inputs (raw materials, energy and ancillary materials) and outputs (emission and production volume) were considered and modeled to represent the four processes and products of interest. Primary data were also collected and validated for the "Galvalume®" coating process from a North American plant for the reference year 2011. Primary data for the "painting" process of metal coils were based on the Metal Construction Association (MCA) 2011 report. The relevant background materials and processes were taken from the US LCI Database (adjusted for known data placeholders), US adjusted ecoinvent v 2.2 LCI database and the World Steel Association global LCI data (2010), and modeled in SimaPro software v.7.3.3, 2012.

3.2 Consistency and Reproducibility

Consistency: To ensure consistency, the LCI modeling of the production weighted input and output LCI data for the four products used the same modeling structure across the respective product systems, which consisted of input raw and ancillary material, energy flows, water resource inputs, product and co-products outputs, emissions to air, water and soil, and scrap recycling and waste treatment. The same background LCI data from the MBMA SimaPro LCI database were used for the four product systems. Crosschecks concerning the plausibility of mass and energy flows were continuously conducted. The LCA team conducted mass and energy balances at the plant and selected process level to maintain a high level of consistency.

Reproducibility: Internal reproducibility is possible since the data and the models are stored and available in a database (MBMA SimaPro LCI database, 2012). A high level of transparency is provided throughout the report as the weighted average LCI profiles are presented for the reference products of interest (see Section 5) and key primary and secondary LCI data sources

are summarized in Table 5. The provision of more detailed data to allow full external reproducibility was not possible due to reasons of confidentiality.

3.3 Representativeness

The representativeness of the data is summarized as follows.

- Time related coverage of the MBMA *primary* collected data: 2008.
- Time related coverage of the "Galvalume®" coating process *primary* collected data: 2011.
- *Secondary* data: the most appropriate LCI datasets were used as found in the US LCI (adjusted) Database, US adjusted ecoinvent v.2.2 database, 2011, and the World Steel Association global LCI database (2010).
- Geographical coverage: the geographical coverage is the US.
- Technological coverage: typical or average.

The use of the World Steel Association global LCI database (2010) is a recognized limitation of the upstream data. The representativeness of the remaining data has been deemed "good to fair" as the best available data were used and these data adequately reflect North American geographic representativeness and prevailing technologies.

3.4 Primary and Secondary Data Sources

The study encompasses the processes necessary to manufacture four component metal building products, which when combined are able to represent the structure and exterior shell of a complete metal building. Typically all components are produced at each facility. The MBMA's LCA Working Task Group members confirmed that the technology differences across facility primary production processes were minimal.

Primary gate-to-gate LCI manufacturing and input transportation data were collected for each of the four component products for the reference year 2008, which was deemed a representative production year for the industry.

Primary LCI data were collected from 10 MBMA member companies from three discrete regions (East, Midwest and Western US), to represent the US industry average technology mix. These 10 plants produce all four products of interest and were deemed representative of the specific processes and the MBMA's membership. The MBMA represents 41 different production facilities; as a result, the plant sample represents about 25% of all establishments. For each of the four product processes, the 10 plants were combined on a production weighted basis to provide a weighted average profile for the US production of the four products of interest.

Table 5 below describes the LCI data sources drawn on in the completion of the study. Based on 2010 World Resource Institute (WRI) statistical data, the US electricity grid mix for the reference year 2008 was modeled using the US LCI Database and ecoinvent upstream LCI datasets. The cradle-to-gate production of steel semi-finished steel inputs as well as the "value of scrap" was sourced from the World Steel Association global LCI profiles for the reference

year 2010. For other input materials, energy flows and processes such as the production of paints, welding inputs, packaging materials, fossil fuels pre-combustion and combustion, waste disposal processes, data from commercially available databases were deemed acceptable for use (e.g., US LCI Database, North American adjusted Ecoinvent, etc.). In the course of employing various secondary datasets it was sometimes necessary to “adjust” various technosphere inputs by replacing them with appropriate US inputs (e.g., electricity grid or transportation data) and in some instances the US LCI Database were missing key upstream pre-combustion data (e.g., natural gas pipeline transport), which were filled using, adjusted ecoinvent data.

Table 5. Key Primary and Secondary LCI Data Sources

LCI data sets	Source of LCI Database*)	Comments
Semi-finished steel metal products and metal processes		
Hot Rolled Plate	World Steel Association	NA average profile 2013
Hot Rolled Coil	World Steel Association	NA average profile 2013
Cold Rolled Coil	World Steel Association	NA average profile 2013
Hot-Dip Galvanized	World Steel Association	NA average profile 2013
Galvalume® coil	Primary data collected from one North American plant	NA average profile 2013 Primary data collected for the Galvalume® coating process, 2011 – one North American plant
Value of scrap	World Steel Association	
Galvalume® coating process	Primary data collected from one North American plant	Primary data collected for the Galvalume® coating process, 2011 – one North American plant
"Painting" of metal coil	Metal Construction Association	Metal Construction Association Report, 2011 [17]
Fossil fuels and electricity grid		
Natural gas pre-combustion, combustion data	US LCI Database	
Diesel pre-combustion, combustion data	US LCI Database	
Propane pre-combustion, combustion data	US LCI Database	

LCI data sets	Source of LCI Database*)	Comments
US electricity grid (2008)	1. World Bank Indicators, 2008 [19] 2. US LCI Database, U.S electricity grid mix LCI dataset, 2000 3. ecoinvent database, U.S electricity grid mix LCI dataset, 2004	

Energy flows	Amount - (in kWh)- no losses	Amount - (in kWh)- 6.2% losses
Electricity, bituminous coal	0.465	0.494
Electricity, lignite coal	0.025	0.026
Electricity, residual fuel oil	0.018	0.019
Electricity, natural gas	0.212	0.225
Electricity, nuclear	0.194	0.206
Electricity, hydropower	0.058	0.062
Electricity, biomass	0.020	0.021
Electricity, wind	0.0062	0.007
Electricity, photovoltaic	0.0003	0.0003
Electricity, geothermal		
Electricity, industrial gas (COG)	0.002	0.002
Total	**1.000**	**1.062**

General materials and processes		
Hydraulic oil; gear and motor oils	US adjusted ecoinvent v 2.2 LCI database	
Packaging material		
Dunnage (wood)	US LCI Database	Surfaced dry lumber
Corrugated paper	US adjusted ecoinvent v 2.2 LCI database	Corrugated board, recycling fibre, single wall
Steel banding & nails	World Steel Association	Hot Rolled Coil- NA average profile 2013
Slip sheets	US LCI Database US adjusted ecoinvent v 2.2 LCI database	Stretch Wrap- Polypropylene (PP) film
Strippable film	US LCI Database US adjusted ecoinvent v 2.2 LCI database	Low Density Polyethylene Film (LDPE) Film
Waterproof packing paper	US adjusted ecoinvent v 2.2 LCI database	Packaging paper (80%), PP film (20%)
Rail, road and ocean freighter transportation	US LCI Database	
Waste disposal	US adjusted ecoinvent v 2.2 LCI database	

<table>
<tr><th>LCI data sets</th><th>Source of LCI Database*)</th><th>Comments</th></tr>
<tr><td colspan="2">MBMA Manufacturing System</td><td></td></tr>
<tr><td>“Gate-to gate” LCI data- primary frames</td><td>MBMA</td><td>Primary data collected from 10 MBMA plants, reference year 2008</td></tr>
<tr><td>“Gate-to gate” LCI data- secondary frames</td><td>MBMA</td><td>Primary data collected from 10 MBMA plants, reference year 2008</td></tr>
<tr><td>“Gate-to gate” LCI data- wall panels</td><td>MBMA</td><td>Primary data collected from 10 MBMA plants, reference year 2008</td></tr>
<tr><td>“Gate-to gate” LCI data- roof panels</td><td>MBMA</td><td>Primary data collected from 10 MBMA plants, reference year 2008</td></tr>
<tr><td>Inbound/outbound transportation mode and distance data- primary frames, secondary frames, wall and roof panels</td><td>MBMA</td><td>Primary data collected from 10 MBMA plants, reference year 2008</td></tr>
<tr><td colspan="3">MBMA process specific chemicals & welding gases</td></tr>
<tr><td>Welding Wire</td><td colspan="2">US adjusted ecoinvent v 2.2 LCI database
All available MSDS were collected and analyzed from 10 MBMA plants;
The following MSDS was used as reference:
<table>
<tr><th>Ingredients:</th><th>CAS No.</th><th>Wt.%</th></tr>
<tr><td>Carbon steel wire</td><td></td><td>100</td></tr>
<tr><td>Nominal wire composition:</td><td></td><td></td></tr>
<tr><td>Total manganese *****</td><td>7439-96-5</td><td>1</td></tr>
<tr><td>Total copper including plated coating *****</td><td>7440-50-8</td><td>< 0.5</td></tr>
<tr><td>Iron</td><td>7439-89-6</td><td>bal.</td></tr>
</table>
- WSA global average LCI data were used for carbon steel wire;
- Steel wire drawing process- US adjusted ecoinvent v 2.2 LCI database</td></tr>
<tr><td>Welding gases</td><td>US adjusted ecoinvent v 2.2 LCI database</td><td>Argon, oxygen, carbon dioxide, nitrogen, and acetylene.</td></tr>
<tr><td>Welding flux</td><td colspan="2">US adjusted ecoinvent v 2.2 LCI database</td></tr>
</table>

<table>
<tr><th>LCI data sets</th><th>Source of LCI Database*)</th><th>Comments</th></tr>
<tr><td></td><td colspan="2">All available MSDS were collected and analyzed from 10 MBMA plants; the following MSDS was used as reference (Linkolnweld 781):
<table>
<tr><th>Ingredients:</th><th>CAS No.</th><th>Wt.%</th></tr>
<tr><td>Zirconium alloys and compounds (as Zr)</td><td>12004-83-0</td><td>15</td></tr>
<tr><td>Magnesite</td><td>1309-48-4</td><td>15</td></tr>
<tr><td>Manganese and/or manganese alloys and compounds (as Mn)*****</td><td>7439-96-5</td><td>10</td></tr>
<tr><td>Titanium dioxides</td><td>13463-67-7</td><td>10</td></tr>
<tr><td>Mineral silicates</td><td>1332-58-7</td><td>10</td></tr>
<tr><td>Silicates and other binders</td><td>1344-09-8</td><td>5</td></tr>
<tr><td>Quartz</td><td>14808-60-7</td><td>< 5</td></tr>
<tr><td>Silicon and/or silicon alloys and compounds (as Si)</td><td>7440-21-3</td><td>< 5</td></tr>
<tr><td>Iron</td><td>7439-89-6</td><td>< 5</td></tr>
<tr><td>Aluminum oxide and/or Bauxite</td><td>1344-28-1</td><td>< 5</td></tr>
<tr><td>Fluorides (as F)</td><td>7789-75-5</td><td>< 5</td></tr>
<tr><td>Iron oxides</td><td>65996-74-9</td><td>< 0.5</td></tr>
<tr><td>Crystalline-Silica (cristobalite)</td><td>14464-46-1</td><td>< 0.5</td></tr>
</table></td></tr>
<tr><td>Primer (water based)</td><td colspan="2">US adjusted ecoinvent v 2.2 LCI database
All available MSDS were collected and analyzed from 10 MBMA plants
Both water and solvent-based primer were used at 78% and 22%, respectively

The following MSDS was used as reference for water based primer:
<table>
<tr><th>Ingredients:</th><th>CAS No.</th><th>Wt. %</th></tr>
<tr><td>Aliphatic petroleum distillates</td><td>60742-89-8</td><td>39.5</td></tr>
<tr><td>Carbon black</td><td>1333-86-6</td><td>0.1</td></tr>
<tr><td>Xylenes</td><td>1330-20-7</td><td>0.5</td></tr>
<tr><td>Ethyl benzene</td><td>100-41-4</td><td>0.2</td></tr>
<tr><td>Zinc Phos</td><td>7779-9-90</td><td>0.9</td></tr>
<tr><td>Water, de-ionized</td><td></td><td>balance</td></tr>
</table></td></tr>
</table>

<table>
<tr><th>LCI data sets</th><th>Source of LCI Database*)</th><th>Comments</th></tr>
<tr><td>Primer (solvent based)</td><td colspan="2">The following MSDS was used as reference for solvent based primer:
<table>
<tr><th>Ingredients:</th><th>CAS No.</th><th>Wt. %</th></tr>
<tr><td>Crystalline silica</td><td>14808-60-7</td><td>35.0%</td></tr>
<tr><td>Aliphatic Naphtha</td><td>64742-59-8</td><td>20.0%</td></tr>
<tr><td>Mineral spirits</td><td>8052-41-3</td><td>15.0%</td></tr>
<tr><td>Synthetic resin solution</td><td>N/A</td><td>10.0%</td></tr>
<tr><td>Chemicals, organic</td><td>N/A</td><td>balance</td></tr>
</table></td></tr>
<tr><td>Solvents</td><td>US adjusted ecoinvent v 2.2 LCI database</td><td>All available MSDS were collected and analyzed from MBMA plants that use solvent
Ethylene glycol monobutyl ether - >99.9%</td></tr>
<tr><td>Additives</td><td>US adjusted ecoinvent v 2.2 LCI database</td><td>Hydrogen Peroxide (100%)</td></tr>
<tr><td>Touch up paint</td><td colspan="2">US adjusted ecoinvent v 2.2 LCI database
All available MSDS were collected and analyzed from MBMA plants that use touch up paint;
The following MSDS was used as reference for touch up paint:
<table>
<tr><th>Ingredient Name
CAS-No.</th><th>Approx.
Weight %</th><th>Chemical Name</th></tr>
<tr><td>PROPRIETARY INERT</td><td>20 - 25</td><td>PROPRIETARY INERT</td></tr>
<tr><td>BUTYL ACETATE
123-86-4</td><td>15 - 20</td><td>n-Butyl acetate</td></tr>
<tr><td>TITANIUM DIOXIDE
13463-67-7</td><td>5 - 10</td><td>Titanium dioxide</td></tr>
<tr><td>METHYL N-AMYL KETONE
110-43-0</td><td>5 - 10</td><td>Heptan-2-one</td></tr>
<tr><td>AROMATIC NAPHTHA, LIGHT
64742-95-6</td><td>1 - 5</td><td>Petroleum naphtha, light aromatic</td></tr>
<tr><td>DIISOBUTYL KETONE
108-83-8</td><td>1 - 5</td><td>Diisobutylketone</td></tr>
<tr><td>ZINC OXIDE
1314-13-2</td><td>1 - 5</td><td>ZINC OXIDE</td></tr>
<tr><td>METHYL ETHYL KETONE
78-93-3</td><td>1 - 5</td><td>Methyl ethyl ketone</td></tr>
<tr><td>1,2,4-TRIMETHYLBENZENE
95-63-6</td><td>1 - 5</td><td>1,2,4-Trimethylbenzene</td></tr>
<tr><td>C.I. PIGMENT BLACK 7
1333-86-4</td><td>.1 - 1</td><td>Carbon black</td></tr>
</table></td></tr>
</table>

LCI data sets	Source of LCI Database*)	Comments
Lubricant	US LCI database	Aliphatic hydrocarbons- 325 Thinner
Mastics	US adjusted ecoinvent v 2.2 LCI database	100% petroleum based- 50% polyurethane (polymer base); 50% polyisobutylene (polymer base)
Sealants	US adjusted ecoinvent v 2.2 LCI database	Chemical family: mixed elastomers (Q41-20 series)

4 Gate-to-Gate Life Cycle Inventory

This section presents an overview of the "gate-to-gate" input material and energy flows and outputs (on a weighted average basis) for the four MBMA selected processes – primary structural, secondary structural, and roof and wall cladding panels – scaled to a ton of output for each product for the reference year 2008. While all flows as reported by the participating plants have been captured in the model, not all facilities use all reported inputs. To respect the confidentiality agreement with the participating plants, input and output data are rolled up to the level that assures confidentially of each individual plant and provides optimal data transparency for the interested parties.

4.1 Primary Frames

For the production of primary frames, the primary semi-finished steel inputs are hot-rolled plate (80%), bar (10%) and sections (10%) – see Table 6 below. The semi-finished steel input is sourced from both the EAF (73%) and BOF (27%) process routes (see Section 2.2.5) and varies in thickness from 0.071" to 1.5". For every ton of primary frame produced, a total of 1.079 tons of steel is required; this yields a 7.9 % scrap rate for the processes leading to the production of primary frames.

The major processes in the production of primary frames include cutting, welding and painting (application of protective primer). Welding wire and flux are key ancillary materials as are the inputs of welding gases – primarily shielding gases of argon and oxygen. Paint inputs are generally 80%/20% water and solvent based, including those used in the electro-coating process. The major process energy input is electricity (158 kWh) followed by natural gas (264 cu. ft.) used for space conditioning and in the paint process with lesser amounts of diesel and propane fuels used by plant mobile equipment.

Process air emissions are the result of fugitive releases of gas inputs as well as some more compound gas products associated with welding and painting. Water use and the consequent effluents are directly related to the painting process. Relative to steel scrap, which is recycled, the solid wastes are relatively minor in their total mass – a majority of the solid wastes are landfilled; others are recycled or sent to waste-to-energy facilities.

The packaging inputs also represent a small portion of the total input per unit of production, but are dominated by one-way pallet use.

Table 6. Primary Frames –Gate-to-Gate (G2G) inventory for 1 Ton of Production (Reference Flow)

Inputs/Outputs	Units	Quantity	Comments
Material Inputs			
Hot Rolled Plate[6], EAF	tons	0.635	0.071- 1.5 inch
Hot Rolled Plate, BOF	tons	0.225	0.071 – 1.250 inch
Hot Rolled Bar, EAF	tons	0.049	0.1875 – 1 inch
Hot Rolled Bar, BOF	tons	0.062	0.1875 – 1 inch
Hot Rolled Section, EAF	tons	0.109	0.25 - 1.0 inch
Total (input)	**tons**	**1.079**	Metal substrate
Welding Wire (carbon steel wire)	lb	15.8	
Welding Consumables	lb	0.047	Diffusers, grinders etc.
Welding Flux	lb	3.809	
Primer	gal	1.276	Both water and solvent based; avg. density= 10.72 lb/gallons
Solvents	gal	0.017	avg. density= 7.504 lb/gallons
Additives	gal	0.006	avg. density= 9.43 lb/gallons
Touch up paint	gal	0.0050	avg. density=11.54 lb/gallons
Hydraulic, gear and motor oils	gal	0.007	Machinery Maintenance; avg. density=7.237 lb/gallons
Argon	lb	7.307	Shielding gas
Oxygen	lb	2.141	Shielding gas
Carbon Dioxide	lb	0.222	Shielding gas
Nitrogen	lb	0.021	Cutting gas
Acetylene	lb	0.061	Cutting gas
Water Use			
Water use	gal	0.849	Process water for painting/E-coating
Energy Input			
Electricity (grid)	kWh	157.7	Process operations, lighting/space conditioning

[6] WSA hot rolled plate LCI profile includes both plates made of slabs and sheets made of thin slabs. Sections are obtained by further processing of hot rolled flat products. For more information on hot rolled flat products and sections, please check the steeluniversity.org website http://steeluniversity.org/content/html/eng/default.asp?catid=199&pageid=2081272065.

Inputs/Outputs	Units	Quantity	Comments
Natural Gas	cu ft.	263.7	Space conditioning; painting
Diesel	gal	0.206	On-site transportation
Propane	gal	0.487	Warehouse, loading, painting
Product Output			
Primary Beams	tons	0.598	
Primary Columns	tons	0.329	
Bracing	tons	0.057	
Misc. beams and columns	tons	0.016	Includes pipe columns, crane columns, crane beams, mezz beams and mezz columns
Total (output)	**tons**	**1.000**	Primary frames
Emissions to air - process only			
VOCs	lb	1.722	Painting /E-coating
PM10	lb	0.136	Painting/E-coating
Argon	lb	7.307	Shielding gas
Oxygen	lb	2.141	Shielding gas
Carbon dioxide	lb	0.428	Shielding gas; CO2 from acetylene combustion
Nitrogen	lb	0.021	Cutting gas
Acetylene	lb	0	Cutting gas; combusted to CO2
Hazardous air pollutant (HAP)	lb	0.004	Painting/E-coating
Wastewater effluents- process only			
Total Suspended Solids (TSS)	lb	4.8E-04	Painting /E-coating
Biochemical Oxygen Demand (B.O.D)	lb	0.188	Painting /E-coating
Solid Waste- process only			
Process wastes	lb	9.415	Landfill
Steel Scrap-recycling	lb	158.3	Recycling
	tons	**0.079**	

Inputs/Outputs	Units	Quantity	Comments
Slag from flux	lb	0.630	Recycled
Slag from flux	lb	1.941	Landfill
Plasma/Paint wastes	lb	2.224	Landfill
Paint wastes	lb	0.086	Burned
Paint wastes	lb	0.007	Recycled
Hazardous wastes	lb	0.048	Recycled
Hazardous wastes	lb	0.007	Waste-to-energy
Mixed Packaging	lb	0.418	Recycled
Wastewater- process only			
Wastewater	gal	0.227	Painting /E-coating
Packaging of finished product			
Dunnage (wood)	lb	41.7	
Corrugated paper	lb	0.419	
Steel Banding	lb	0.244	

Table 7 shows the transportation mode and distances for all inputs into the process and outputs. Trucking was the primary mode of transport for metal substrate (416 ton-miles), other input materials (2.4 ton-miles), metal scrap (25 ton-miles) and waste flows (0.4 ton-miles). Rail was the secondary mode of transportation used for metal substrate (109 ton-miles) followed by ocean freighter used for outbound transportation of primary frames (10 ton-miles).

Table 7. Inbound and Outbound Transportation Mode and Distances - Primary Frames- 1 Ton of Production (Reference Flow)

Inbound transportation (one-way)	**Units**	**Quantity**	**Comments**
Input Materials			
Hot Rolled Plate, EAF	ton-miles	217.8	Truck
Hot Rolled Bar, EAF	ton-miles	35.9	
Hot Rolled Plate, BOF	ton-miles	97.7	
Hot Rolled Bar, BOF	ton-miles	23.0	
Hot Rolled Section, EAF	ton-miles	44.1	
Welding Wire	ton-miles	0.335	
Welding Consumables	ton-miles	0.0012	
Welding Flux	ton-miles	0.137	

Inbound transportation (one-way)	**Units**	**Quantity**	**Comments**
Primer	ton-miles	1.529	
Solvent	ton-miles	0.048	
Additive	ton-miles	0.0214	
Touch up paint	ton-miles	0.0226	
Oils (machinery maintenance)	ton-miles	1.3E-03	
Argon (Shielding gases)	ton-miles	0.236	Truck
Oxygen (Shielding gases)	ton-miles	0.061	
Carbon Dioxide (Shielding gases)	ton-miles	0.008	
Nitrogen (Cutting gas)	ton-miles	3.8E-04	
Acetylene (Cutting gas)	ton-miles	1.1E-03	
Packaging materials	ton-miles	0.033	
Hot Rolled Plate, EAF	ton-miles	54.4	Rail
Hot Rolled Bar, EAF	ton-miles	54.4	
Outbound transportation (one-way)	**Units**	**Quantity**	**Comments**
Primary Frames	ton-miles	406.2	Truck
	ton-miles	10.42	Ocean Freighter
Solid Waste			
Process wastes-landfill	ton-miles	0.147	Truck
Steel Scrap-recycled	ton-miles	24.9	
Slag from flux-recycled	ton-miles	0.072	
Slag from flux-landfill	ton-miles	0.036	
Plasma/Paint wastes-landfill	ton-miles	0.036	
Paint wastes-burned	ton-miles	0.052	
Paint wastes-recycled	ton-miles	0.001	
Wastewater-city sewer	ton-miles	0.009	
Hazardous wastes-recycled	ton-miles	0.005	
Hazardous wastes-waste-to-energy	ton-miles	0.001	
Mixed Packaging-recycled	ton-miles	0.007	

4.2 Secondary Frames

For the production of secondary frames, the semi-finished steel inputs are hot-dipped galvanized (bare), cold-rolled pre-painted coil and hot rolled coil (both bare and pre-painted)- see Figure 11. Steel substrate input used in the production of secondary frames is sourced from both the BOF (57%) and EAF (43%) process routes (see Section 2.2.5) and varies in thickness from 0.054" to 0.12" (see Table 8). For every ton of secondary frame produced, a total of 1.051 tons of steel is required, which yields a 5.1 % scrap rate for the processes leading to the production of secondary frames.

Figure 11 Secondary Frames – Steel Substrate Use (%) US Average

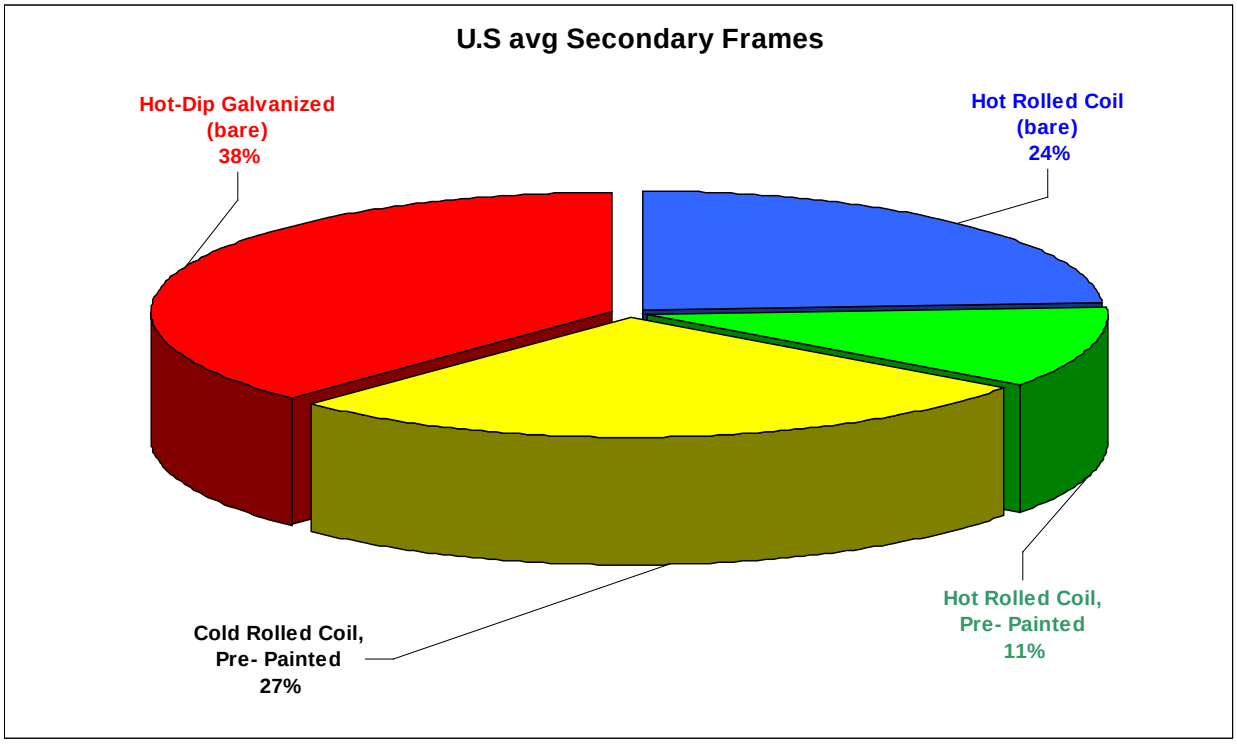


Table 8 summarizes the other production and packaging material inputs, energy and water used within the gate-to-gate process, product output (girts, purlins and bracing elements), and process air and water emissions. Solid waste quantities are also indicated with their downstream disposition (recycled, combustion (waste-to-energy) and landfilled).

Like primary frames, the major processes in the production of secondary frames include cutting, welding and painting. Welding wire and flux are the key ancillary materials as are the inputs of welding gases – primarily shielding gases of argon and oxygen. Paint inputs are generally 80%/20% water and solvent based, including those used in the electro-coating process. The major process energy input is electricity (110 kwh) followed by natural gas (246 cu. ft.) used for

space conditioning and in the paint process with lesser amounts of diesel and propane fuels used by plant mobile equipment.

Major process air emissions are the result of fugitive releases of gas inputs as well as some more compound gas products associated with welding and painting. Water use and the consequent effluents are directly related to the painting process. Relative to steel scrap, which is recycled, the sold wastes are relatively minor in their total mass – a majority of the solid wastes are landfilled; others are recycled or sent to waste-to-energy facilities.

The packaging inputs also represent a small portion of the total input per unit of production, but are dominated by one-way pallet use.

Table 8. Secondary Frames–Gate-to-Gate (G2G) inventory for 1 Ton of Production (Reference Flow)

Inputs/Outputs	Units	Quantity	Comments
Material Inputs			
Hot Rolled Coil (bare), EAF	tons	0.152	17 to 11 ga (0.054 to 0.120 inch)
Hot Rolled Coil (bare), BOF	tons	0.101	17 to 12 ga (0.057 to 0.108 inch)
Hot Rolled Coil, Pre-Painted, EAF	tons	0.105	17 to 11 ga (0.054 to 0.120 inch)
Hot Rolled Coil, Pre-Painted, BOF	tons	0.011	17 to 12 ga (0.056 to 0.099 inch)
Cold Rolled Coil, Pre-Painted, EAF	tons	0.088	16 to 12 ga (0.060 to 0.099 inch)
Cold Rolled Coil, Pre-Painted, BOF	tons	0.201	16 to 12 ga (0.060 to 0.099 inch)
Hot-Dip Galvanized (bare), BOF	tons	0.289	17 to 11 ga (0.054 to 0.120 inch)
Hot-Dip Galvanized (bare), EAF	tons	0.104	17 to 12 ga (0.054 to 0.120 inch)
Total (input)	**tons**	**1.051**	Metal substrate
Welding Wire	lb	2.160	
Welding Consumables	lb	0.007	Diffusers, grinders etc.
Welding Flux	lb	0.362	
Primer	gal	0.388	Both water and solvent based; avg. density= 10.72 lb/gallons
Solvents	gal	0.033	avg. density= 7.504 lb/gallons

Inputs/Outputs	Units	Quantity	Comments
Additives	gal	0.012	avg. density= 9.43 lb/gallons
Touch up paint	gal	0.0099	avg. density=11.54 lb/gallons;
Hydraulic, gear and motor oils	gal	0.007	Machinery Maintenance; avg. density=7.237 lb/gallons
Argon	lb	1.841	Shielding gas
Oxygen	lb	0.682	Shielding gas
Carbon Dioxide	lb	0.033	Shielding gas
Nitrogen	lb	0.006	Cutting gas
Acetylene	lb	0.017	Cutting gas
Water Use			
Water use	gal	0.737	Process water for painting/ E-coating
Energy Input			
Electricity (grid)	kWh	110.2	Process operations, lighting/space conditioning
Natural Gas	cu ft.	245.7	Space conditioning; painting
Diesel	gal	0.207	On-site transportation
Propane	gal	0.185	Warehouse, loading
Product Output			
Girts	tons	0.322	
Purlins	tons	0.591	
Bracing	tons	0.029	
Other Secondary	tons	0.058	Eave struts, posts, boxed C-section, cold-formed columns and beams etc.
Total (output)	**tons**	**1.000**	Secondary frames
Emissions to air- process only			
VOCs	lb	0.748	Painting/E-coating
PM10	lb	0.016	Painting/E-coating
Argon	lb	1.841	Shielding gas
Oxygen	lb	0.682	Shielding gas
Carbon dioxide	lb	0.091	Shielding gas
Nitrogen	lb	0.006	Cutting gas

Inputs/Outputs	Units	Quantity	Comments
Acetylene	lb	0	Cutting gas; combusted to CO2
Wastewater Effluents - process only			
Total Suspended Solids (TSS)	lb	4.3E-04	Painting/E-coating
Biochemical Oxygen Demand (B.O.D)	lb	0.168	Painting/E-coating
Solid Waste- process only			
Process wastes	lb	9.125	Landfill
Steel Scrap-recycling	lb	102.4	Recycled
	tons	**0.051**	
Slag from flux	lb	1.228	Landfill
Plasma/Paint wastes	lb	1.893	Landfill
Hazardous wastes	lb	0.040	Recycled
Hazardous wastes	lb	0.006	Waste-to-energy
Mixed Packaging	lb	0.669	Recycled
Wastewater- process only			
Wastewater	gal	0.202	Painting/E-coating
Packaging of finished product			
Dunnage (wood)	lb	42.7	
Steel Banding	lb	1.08	

Table 9 shows the transportation mode and distances for all inputs into the process and outputs. Trucking was the primary mode of transport for metal substrate (474 ton-miles), other input materials (2.0 ton-miles), metal scrap (13 ton-miles) and waste flows (0.2 ton-miles). Rail was the secondary mode of transportation used for metal substrate (138 ton-miles) followed by ocean freighter used for outbound transportation of secondary frames (9 ton-miles).

Table 9. Inbound and Outbound Transportation Mode and Distances - Secondary Frames- 1 Ton of Production (Reference Flow)

Inbound transportation (one-way)	**Units**	**Quantity**	**Comments**
Hot Rolled Coil (bare), EAF	ton-miles	26.6	Truck
Hot Rolled Coil (bare), BOF	ton-miles	46.1	
Hot Rolled Coil, Pre- Painted, EAF	ton-miles	6.03	
Hot Rolled Coil, Pre- Painted, BOF	ton-miles	0.52	
Cold Rolled Coil, Pre- Painted, EAF	ton-miles	47.6	
Cold Rolled Coil, Pre- Painted, BOF	ton-miles	128.9	
Hot-Dip Galvanized (bare), BOF	ton-miles	159.0	
Hot-Dip Galvanized (bare), EAF	ton-miles	59.4	
Welding Wire	ton-miles	0.016	
Welding Consumables	ton-miles	0.0002	
Welding Flux	ton-miles	0.001	
Primer	ton-miles	1.701	
Solvent	ton-miles	0.095	
Additive	ton-miles	0.042	
Touch up paint	ton-miles	0.045	
Oils (machinery maintenance)	ton-miles	1.3E-03	
Argon (Shielding gases)	ton-miles	0.040	
Oxygen (Shielding gases)	ton-miles	0.016	
Carbon Dioxide (Shielding gases)	ton-miles	0.002	
Nitrogen (Cutting gas)	ton-miles	5.7E-05	
Acetylene (Cutting gas)	ton-miles	1.7E-04	
Packaging materials	ton-miles	0.054	
Cold Rolled Coil, Pre- Painted, EAF	ton-miles	17.510	Rail
Hot-Dip Galvanized (bare), BOF	ton-miles	120.7	
Outbound transportation (one-way)	**Units**	**Quantity**	**Comments**
Secondary Frames	ton-miles	401.1	Truck
	ton-miles	8.60	Ocean Freighter

Outbound transportation (one-way)	**Units**	**Quantity**	**Comments**
Solid Waste			
Process wastes- landfill	ton-miles	0.143	Truck
Steel Scrap- recycled	ton-miles	13.1	
Slag from flux- landfill	ton-miles	0.014	
Paint wastes- landfill	ton-miles	0.030	
Hazardous wastes- recycled	ton-miles	0.004	
Hazardous wastes- waste-to-energy	ton-miles	0.001	
Mixed Packaging-recycled	ton-miles	0.013	
Wastewater- city sewer	ton-miles	0.008	

4.3 Wall Panels

The production of wall panels (cladding) uses five different semi-finished steel inputs (see Figure 12) with bare and pre-painted Galvalume® coated coil accounting for 58% of the input. Steel substrate inputs used to produce wall panels were sourced from both the BOF (62%) and EAF (38%) process routes (see Section 2.2.5) and varied in thickness from 29 to 18 gauge (see Table 10). The most common thicknesses for wall panel production are 26 and 24 gauge steel. For every ton of wall panel produced, a total of 1.062 tons of steel input is required, which yields a 6.2% scrap rate for the processes leading to the production of wall panels.

Figure 12 Wall Panels– Steel Substrate Use (%) US Average

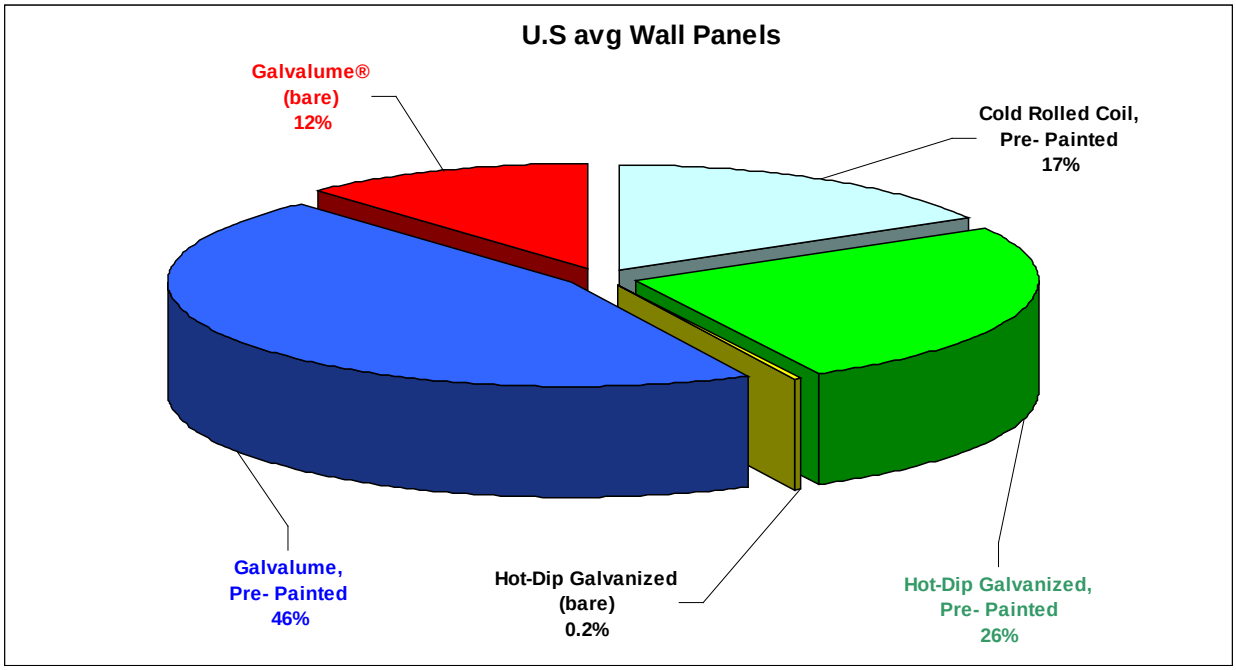


Table 10 summarizes the other production and packaging material inputs, energy and water used within the gate-to-gate process, cladding output, process air and water emissions. Solid waste quantities are also indicated with their downstream disposition (recycled, combustion (waste-to-energy) and landfilled).

The roll-forming process is not particularly ancillary material intensive – a small amount of lubricant is applied to the coils to aid roll-forming of the metal substrate. In fact, packaging inputs are higher than any ancillary input. One-way pallets are the single largest packaging input, followed by steel banding and protective slip-sheets. Electricity is used throughout the process (68 kWh), both directly (roll-forming machinery) and indirectly (lighting and space conditioning), while natural gas usage (62 cu ft.) is ascribed to space conditioning only. The process results in no water effluents and a small amount of volatile organic compound releases

due to evaporative losses from lubricant use. All scrap steel is recycled, with the majority of other process solid waste going to landfill.

Table 10. Wall Panels (Cladding) –Gate-to-Gate (G2G) inventory for 1 Ton of Production (Reference Flow)

Inputs/Outputs	Units	Quantity	Comments
Material Input			
Cold Roll Coil, Pre-Painted, EAF	tons	0.067	28 and 26 ga
Cold Roll Coil, Pre-Painted, BOF	tons	0.108	26 and 24 ga
Hot-Dip Galvanized, Pre-Painted, EAF	tons	0.275	26, 24 and 22 ga
Hot-Dip Galvanized (bare), EAF	tons	0.002	26 to 24 ga
Galvalume®, Pre-Painted, BOF	tons	0.446	29, 26, 24 and 18 ga
Galvalume®, Pre-Painted, EAF	tons	0.039	18 ga
Galvalume® (bare), EAF	tons	0.018	26, 24 and 22
Galvalume® (bare), BOF	tons	0.106	26, 24 and 22
Total (input)	**tons**	**1.0618**	Metal substrate
Hydraulic, gear and motor oils	gal	0.0070	Equipment maintenance avg. density=7.237 lb/gallons
Machining lubricants	gal	0.030	Lubricants are applied to the panel coils to aid in the roll forming process. avg. density=6.580 lb/gallons
Mastics	gal	0	Not applicable
Sealants	gal	0	Not applicable
Water Use			
Water use (process water)	gal	0	Not applicable
Energy Input			
Electricity (grid)	kWh	67.64	Process operations, lighting/space conditioning
Natural Gas	cu ft.	61.28	Space conditioning only
Diesel	gal	0.215	On-site transportation
Propane	gal	0.183	Warehouse, loading

Inputs/Outputs	Units	Quantity	Comments
Product Output			
Unpainted Wall Panel	tons	0.296	
Pre-painted Wall Panel	tons	0.704	
Total (output)	**tons**	**1.000**	Wall panel
Emissions to air- process only			
VOCs (evaporative lubricant)	lb	0.189	
Solid Waste- process only			
Process wastes	lb	9.130	Landfill
Steel Scrap-recycling	lb	123.7	Recycling
	tons	**0.0618**	
Hazardous wastes	lb	0.022	Recycling
Hazardous wastes	lb	0.004	Waste-to-energy
Mixed Packaging	lb	0.663	Recycling
Packaging of finished product			
Dunnage (wood)	lb	93.755	
Steel Banding	lb	3.983	
Slip Sheets	lb	3.898	
Waterproof packing paper	lb	0.319	
Nails	lb	0.150	
Strippable film	lb	0.477	

Table 11 shows the transportation mode and distances for all inputs into the process and outputs. Trucking was the primary mode of transport for metal substrate (636 ton-miles), other input materials (0.4 ton-miles), metal scrap (15 ton-miles) and waste flows (0.2 ton-miles). Ocean freighter was the secondary mode of transportation used in outbound transportation of wall panels (5 ton-miles).

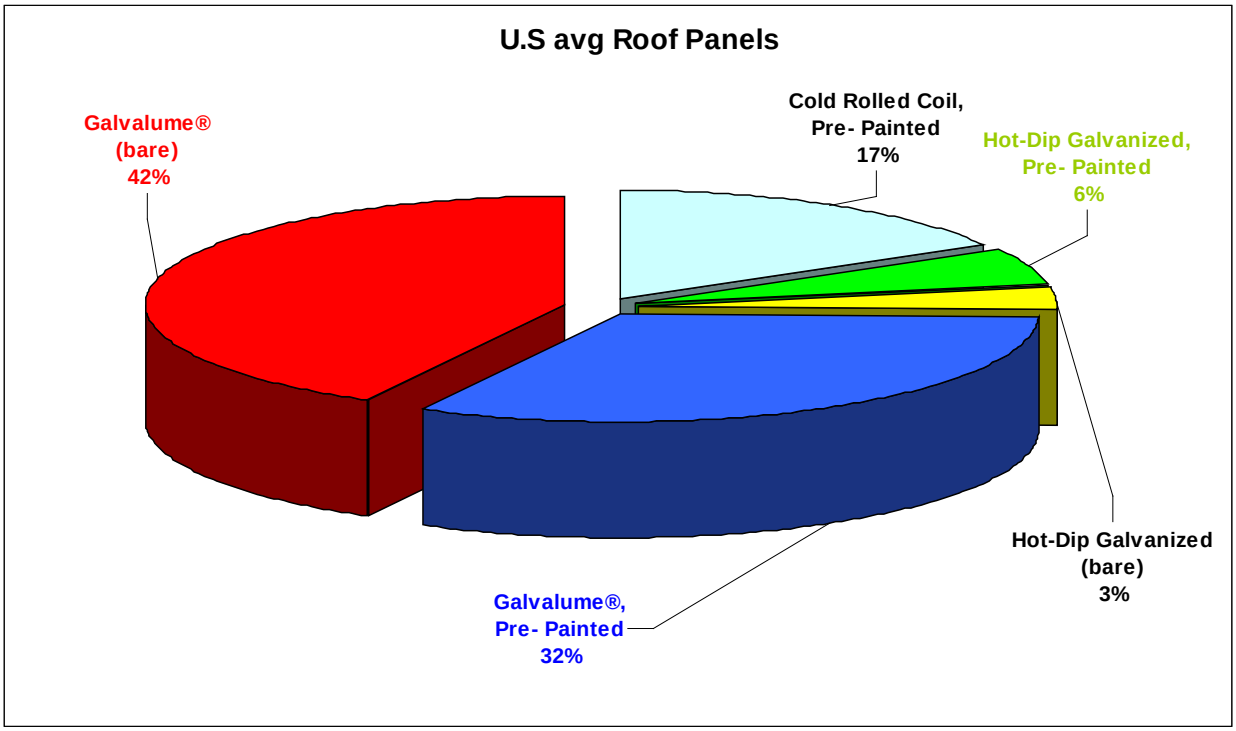
Table 11. Inbound and Outbound Transportation Mode and Distances - Wall Panels- 1 Ton of Production (Reference Flow)

Inbound transportation (one-way)	**Units**	**Quantity**	**Comments**
Cold Roll Coil, Pre-Painted, EAF	ton-miles	41.613	Truck
Cold Roll Coil, Pre-Painted, BOF	ton-miles	71.202	
Hot-Dip Galvanized, Pre-Painted, EAF	ton-miles	142.167	
Hot-Dip Galvanized (bare), EAF	ton-miles	2.345	
Galvalume®, Pre-Painted, BOF	ton-miles	273.460	
Galvalume®, Pre-Painted, EAF	ton-miles	38.344	
Galvalume® (bare), EAF	ton-miles	8.921	
Galvalume® (bare), BOF	ton-miles	57.504	
Oils (machinery maintenance)	ton-miles	1.3E-03	
Lubricants	ton-miles	0.005	
Mastics	ton-miles	0.000	
Sealants	ton-miles	0.000	
Packaging materials	ton-miles	0.441	
Outbound transportation (one-way)	**Units**	**Quantity**	**Comments**
Wall Panels	ton-miles	378.692	Truck
	ton-miles	4.989	Ocean Freighter
Solid Waste			
Process wastes-Landfill	ton-miles	0.146	Truck
Steel Scrap-recycling	ton-miles	14.608	
Hazardous wastes-recycling	ton-miles	0.002	
Hazardous wastes-waste-to-energy	ton-miles	0.001	
Mixed Packaging-recycling	ton-miles	0.014	

4.4 Roof Panels

The production of roof panels (cladding) uses five different semi-finished steel inputs (see Figure 13) with bare and pre-painted Galvalume® coated coil accounting for 74% of the input. Steel substrate used in the production of roof cladding is sourced from both the BOF (62%) and EAF (38%) process routes (see Section 2.2.5) and varies in thickness from 26 to 22 gauge (see Table 12). For every ton of roof panel produced, a total of 1.05 tons of steel input is required, which yields a 5% scrap rate for the processes leading to the production of wall panels.

Figure 13 Roof Panels – Steel Substrate Use (%) US Average



The roof roll-forming process is not particularly ancillary material intensive – a small amount of lubricant is applied to the coils to aid roll-forming of the metal substrate. Additional mastics and sealants are applied to roof panels to improve water tightness. In fact, packaging inputs are higher than any ancillary input. One-way pallets are the single largest packaging input, followed by steel banding and protective slip-sheets. Electricity is used throughout the process (66 kWh), both directly (roll-forming machinery) and indirectly (lighting and space conditioning), while natural gas usage (71 cu. ft.) is ascribed to space conditioning only (see Table 12). The process uses no water; as a result, no effluent is ascribed to the process. A small amount of volatile organic compound releases to air is noted due to evaporative losses from lubricant use. All scrap steel is recycled, with the majority of other process solid waste going to landfill. Some packaging material losses are also recycled.

Table 12. Roof Panels (Cladding)–Gate-to-Gate (G2G) Inventory for 1 Ton of Production (Reference Flow)

Inputs/Outputs	Units	Quantity	Comments
Material Input			
Cold Roll Coil, Pre-Painted, BOF	tons	0.129	26, 24 and 22 ga
Cold Roll Coil, Pre-Painted, EAF	tons	0.046	26 and 24 ga
Hot-Dip Galvanized, Pre-Painted, EAF	tons	0.058	26, 24 and 22 ga
Hot-Dip Galvanized (bare), EAF	tons	0.031	26, 24 and 22 ga
Hot-Dip Galvanized (bare), BOF	tons	0.005	26 ga
Galvalume®, Pre-Painted, BOF	tons	0.289	26, 24 and 22 ga
Galvalume®, Pre-Painted, EAF	tons	0.050	26 and 22 ga
Galvalume® (bare), EAF	tons	0.200	26, 24 and 22 ga
Galvalume® (bare), BOF	tons	0.243	26, 24 and 22 ga
Total (input)	**tons**	**1.0496**	Metal substrate
Hydraulic, gear and motor oils	gal	0.007	Equipment maintenance avg. density=7.237 lb/gallons
Machining lubricants	gal	0.085	Lubricants are applied to the coils to aid in the roll forming process. avg. density=6.580 lb/gallons
Mastics	gal	0.185	avg. density=8.920 lb/gallons
Sealants	gal	0.138	avg density=7.508 lb/gallons
Water Use			
Water use (process water):	gal	0	Not applicable
Energy Input			
Electricity (grid)	kWh	66.22	Process operations, lighting/space conditioning
Natural Gas	cu ft.	71.07	Space conditioning only
Diesel	gal	0.226	On-site transportation
Propane	gal	0.156	Warehouse, loading

Inputs/Outputs	Units	Quantity	Comments
Product Output			
Unpainted Roof Panel	tons	0.455	
Pre-Painted Roof Panel	tons	0.545	
Total (output)	**tons**	**1.000**	Roof panel
Emissions to air- process only			
VOCs (evaporative lubricant)	lb	0.530	
VOCs from mastics	lb	0.330	
Solid Waste- process only			
Process wastes	lb	9.61	Landfill
Steel Scrap-recycling	lb	99.1	Recycling
	tons	**0.0496**	
Hazardous wastes	lb	0.021	Recycling
Hazardous wastes	lb	0.003	Waste-to-energy
Mixed Packaging	lb	0.762	Recycling
Packaging of finished product			
Dunnage (wood)	lb	88.8	
Steel Banding	lb	2.73	
Plastic slip sheets (stretch wrap)	lb	1.70	
Waterproof packing paper	lb	0.147	
Nails	lb	0.216	
Plastic strip film	lb	0.629	

Table 13 shows the transportation mode and distances for all inputs into the process and outputs. Trucking was the primary mode of transport for metal substrate (553 ton-miles), other input materials (1.3 ton-miles), metal scrap (20 ton-miles) and waste flows (0.2 ton-miles). Ocean freighter was the secondary mode of transport used for outbound transportation of roof panels (4 ton-miles).

Table 13. Inbound and Outbound Transportation Mode and Distances – Roof Panels- 1 Ton of Production (Reference Flow)

Inbound transportation (one-way)	**Units**	**Quantity**	**Comments**
Cold Roll Coil, Pre-Painted, BOF	ton-miles	85.1	Truck
Cold Roll Coil, Pre-Painted, EAF	ton-miles	28.3	
Hot-Dip Galvanized, Pre-Painted, EAF	ton-miles	29.8	
Hot-Dip Galvanized (bare), EAF	ton-miles	19.0	
Hot-Dip Galvanized (bare), BOF	ton-miles	110.3	
Galvalume®, Pre-Painted, BOF	ton-miles	67.2	
Galvalume®, Pre-Painted, EAF	ton-miles	1.9	
Galvalume® (bare), EAF	ton-miles	88.1	
Galvalume® (bare), BOF	ton-miles	123.5	
Oils (machinery maintenance)	ton-miles	1.3E-03	
Lubricants	ton-miles	0.008	
Mastics	ton-miles	0.538	
Sealants	ton-miles	0.483	
Packaging materials	ton-miles	0.271	
Outbound transportation (one-way)	**Units**	**Quantity**	**Comments**
Roof Panels (Cladding)	ton-miles	393	Truck
	ton-miles	4.03	Ocean Freighter
Solid Waste			
Process wastes-landfill	ton-miles	0.148	Truck
Steel Scrap-recycling	ton-miles	20.1	
Hazardous wastes-recycling	ton-miles	0.002	
Hazardous wastes-waste-to-energy	ton-miles	0.0005	
Mixed Packaging-recycling	ton-miles	0.016	

5 Gate-to-Gate Life Cycle Assessment Results

This section summarizes the gate-to-gate (G2G) life cycle assessment results for the respective manufacturing processes for each of the four products of interest. Results are presented for each product on a reference flow basis of one ton of manufactured product. The gate-to-gate assessment includes all cradle-to-gate upstream ancillary material inputs as well as their transportation to the facility (excluding steel substrate inputs). All on-site energy use is included as are any process emissions. Except for the recycling and transportation of steel scrap, all wastes are included and are tracked, inclusive of their treatment process or final disposal.

5.1 Primary Frames Manufacturing Process

Table 14 summarizes the life cycle impact assessment (LCIA) results for the manufacturing process of one ton of primary frames. It takes a total of 2,984 MJ of primary energy to produce one ton of primary frame elements at the facility. Over 84% of the energy is attributed to on-site demand as opposed to background energy used to produce auxiliary and ancillary materials. Further, all but 51 MJ of the primary energy use is in the form of non-renewable sources (fossil and nuclear). The production of each ton of primary frame results in the emission of 166 kg of greenhouse gases on a CO_2 equivalent basis.

On-site energy was also the primary source of the greenhouse gas emissions, accounting for 86% of the total GWP. In fact, on-site energy use was the major contributor to all impact burdens except for abiotic depletion (elements), ozone depletion and eutrophication.

Welding, including welding consumables, and then the paint process, were the next most significant contributors to the burdens exhibited in the production of primary frames (see Table 15). On-site process emissions had a minor effect generally, but contributed between 13% and 20% of the G2G process respiratory effects and smog. Packaging materials use accounted for less than 4% of the burdens across all LCIA indicators, while maintenance consumables and inbound transportation contributed less than 1% to the set of selected indicators.

Table 14. Weighted Average Primary Frames G2G LCIA Results for 1 Ton of Production (Reference Flow) –Absolute Basis

Impact category	Unit	Total	On-site process emissions	Welding (wire, consumables, flux, gases)	Painting (primer, solvents, additives, touch up paint)	Hydraulic, gear and motor oils	On-site energy consumption	Inbound/ Outbound transportation	Packaging material	Waste disposal
Global warming	kg CO2 eq	**166.2**	0.2	14.9	4.9	2.2E-02	143.1	0.7	2.5	-0.1
Abiotic depletion (elements)	kg Sb eq	**1.0E-05**	0	1.0E-05	4.1E-07	1.3E-10	4.7E-11	0	1.3E-09	-5.2E-07
Total primary energy	MJ	**2,984**	0	190	253	1.8	2,499	11	40	-10
Non-renewable, energy	MJ	**2,933**	0	185	246	1.8	2,458	11	40	-8
Acidification	kg SO2 eq	**1.3**	0	0.1	0.0	2.1E-04	1.2	0.0	0.0	0.0
Eutrophication	kg N eq	**0.071**	0.006	0.016	0.019	6.1E-05	0.019	2.4E-04	0.002	0.011
Respiratory effects	kg PM2.5 eq	**0.105**	0.014	0.009	0.002	1.6E-05	0.075	8.9E-05	0.005	-0.001
Smog formation	kg O3 eq	**13.8**	2.8	0.7	0.3	1.5E-03	9.6	0.1	0.4	0.0
Ozone depletion	kg CFC-11 eq	**4.5E-06**	0	1.1E-06	2.0E-06	1.9E-08	1.5E-06	2.9E-11	2.2E-08	-1.1E-07
Ecotoxicity	CTUe	**139.2**	0	33.1	5.8	8.1E-03	89.7	2.0	2.8	5.8
Human health cancer	CTUh	**3.4E-06**	0	2.8E-06	1.2E-07	1.4E-10	3.9E-07	1.1E-08	1.7E-08	3.8E-08
Human health noncancer	CTUh	**1.2E-05**	0	3.4E-06	6.6E-07	9.7E-10	5.6E-06	1.0E-07	2.0E-07	1.8E-06

Table 15. Weighted Average Primary Frames G2G LCIA Results for 1 Ton of Production (Reference Flow) –% basis

Impact category	Total	On-site process emissions	Welding (wire, consumables, flux, gases)	Painting (primer, solvents, additives, touch up paint)	Hydraulic, gear and motor oils	On-site energy consumption	Inbound/ Outbound transportation	Packaging material	Waste disposal
Global warming	**100%**	0%	9%	3%	0%	86%	0%	2%	0%
Abiotic depletion (elements)	**100%**	0%	101%	4%	0%	0%	0%	0%	-5%
Total primary energy	**100%**	0%	6%	8%	0%	84%	0%	1%	0%
Non-renewable, energy	**100%**	0%	6%	8%	0%	84%	0%	1%	0%
Acidification	**100%**	0%	5%	2%	0%	91%	0%	1%	0%
Eutrophication	**100%**	8%	22%	26%	0%	26%	0%	2%	15%
Respiratory effects	**100%**	13%	9%	2%	0%	72%	0%	4%	-1%
Smog formation	**100%**	20%	5%	2%	0%	69%	1%	3%	0%
Ozone depletion	**100%**	0%	25%	43%	0%	34%	0%	0%	-2%
Ecotoxicity	**100%**	0%	24%	4%	0%	64%	1%	2%	4%
Human health cancer	**100%**	0%	83%	3%	0%	12%	0%	1%	1%
Human health noncancer	**100%**	0%	29%	6%	0%	48%	1%	2%	16%

Table 16 provides an absolute breakdown of the on-site energy consumption by energy type and Figure 14 displays the contribution of each fuel type on a percent basis. Electricity is the dominant energy form and is responsible for 83% of the total GWP effect arising from on-site energy consumption. With the exception of ozone depletion potential, electricity use is responsible for 55% to 87% of the effects observed within each impact category.

Table 16. Contribution by Fuel Type to "On-site Energy Consumption" Impact Categories –Absolute Basis– per 1 Ton of Primary Frame

Impact category	Unit	Total-On-site energy consumption	Electricity	Natural gas	Diesel	Propane
Global warming	kg CO2 eq	**143.1**	118.4	18.5	2.5	3.8
Abiotic depletion (elements)	kg Sb eq	**4.7E-11**	3.5E-11	8.7E-12	1.1E-12	2.6E-12
Total primary energy	MJ	**2,499**	2,083	325	37	54
Non-renewable, energy	MJ	**2,458**	2,042	325	37	54
Acidification	kg SO2 eq	**1.2**	1.0	0.2	0.0	0.0
Eutrophication	kg N eq	**0.019**	0.014	0.002	0.002	0.001
Respiratory effects	kg PM2.5 eq	**0.075**	0.065	0.009	0.001	0.000
Smog formation	kg O3 eq	**9.6**	7.8	0.4	1.1	0.2
Ozone depletion	kg CFC-11 eq	**1.5E-06**	7.6E-09	1.5E-06	1.2E-10	2.0E-10
Ecotoxicity	CTUe	**89.7**	49.2	23.8	6.7	9.9
Human health cancer	CTUh	**3.9E-07**	2.2E-07	7.5E-08	3.7E-08	5.4E-08
Human health noncancer	CTUh	**5.6E-06**	3.8E-06	9.8E-07	3.5E-07	5.2E-07

Tables 17 and 18 provide an absolute and percent breakdown of how the various welding materials and gases contribute to the impact of welding primary frames. Welding wire followed by welding flux use are the major sources of the "welding" impacts. The use of Argon is by far the most significant gas input contributing to the impact of welding, but it is a distant third relative to wire and flux.

The effects ascribed to the painting of primary frames are summarized in Table 19 on an absolute basis and Figure 15 on a percent basis. Over 90% of the burdens associated with paint inputs – primer, solvents, additives and touch-up paint use – can be traced to the primer.

Figure 14 Contribution by Fuel Type to "On-site Energy Consumption" Impact Categories – % Basis - per 1 Ton of Primary Frame

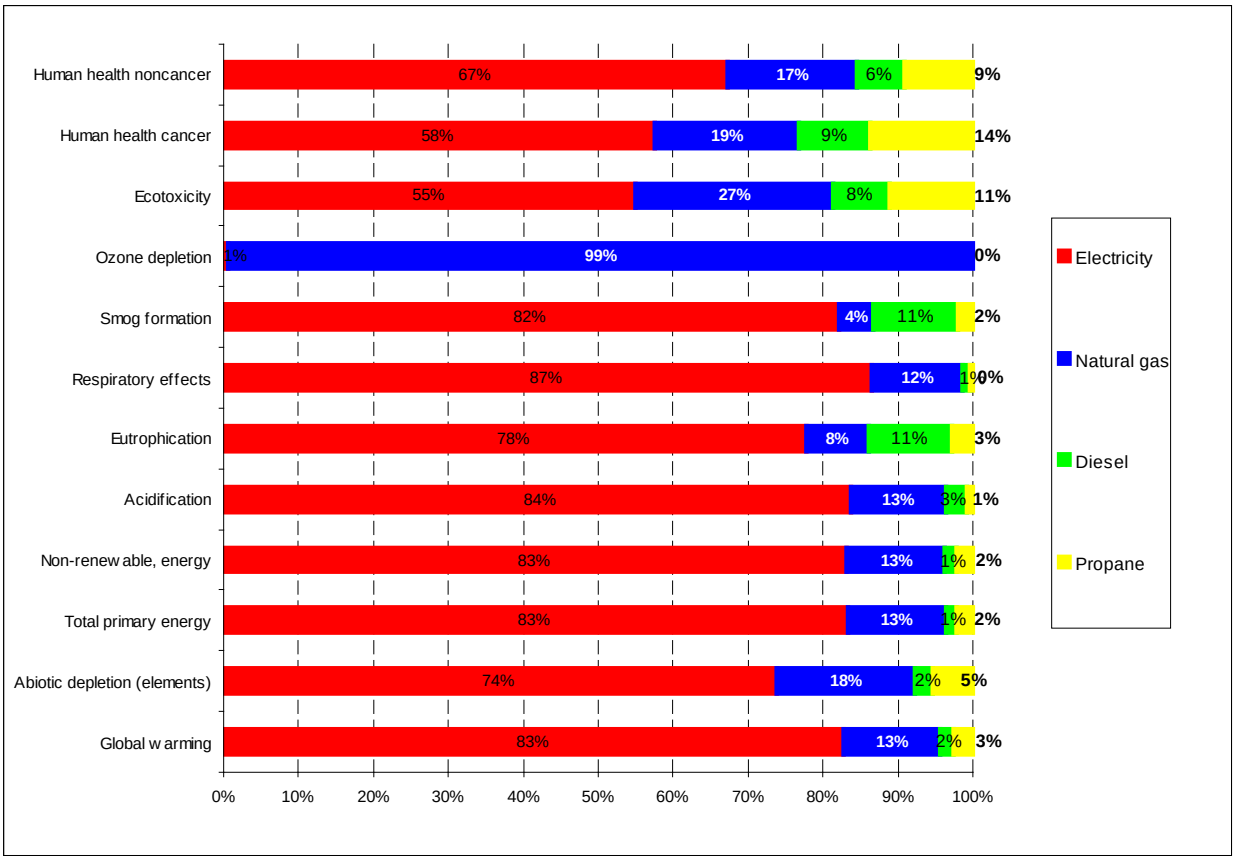


Table 17. Contribution by Material Type to "Welding" Impact Categories – Absolute Basis – per 1 Ton of Primary Frame

Impact category	Unit	Total-Welding	Welding wire	Welding consumables	Welding flux	Argon	Oxygen	Carbon dioxide	Nitrogen	Acetylene
Global warming	kg CO2 eq	**14.9**	10.4	0.0	2.5	1.3	0.6	0.1	0.01	0.1
Abiotic depletion (elements)	kg Sb eq	**1.0E-05**	5.7E-06	-3.0E-08	4.5E-06	3.8E-13	1.6E-13	4.7E-11	1.7E-15	4.2E-14
Total primary energy	MJ	**190**	106	2.3E-01	48	23	10	1	0.1	1
Non-renewable, energy	MJ	**185**	104	2.3E-01	46	22	10	1	0.1	1
Acidification	kg SO2 eq	**0.1**	0.0	6.5E-05	0.0	0.0	0.0	3.2E-04	5.0E-05	7.3E-04
Eutrophication	kg N eq	**0.016**	0.007	3.5E-06	0.008	1.6E-04	6.8E-05	2.3E-05	7.1E-07	1.0E-05
Respiratory effects	kg PM2.5 eq	**0.009**	0.004	6.6E-06	0.004	0.001	0.000	2.3E-05	3.2E-06	4.7E-05
Smog formation	kg O3 eq	**0.7**	0.3	6.5E-04	0.2	0.1	0.04	1.2E-02	3.9E-04	5.9E-03
Ozone depletion	kg CFC-11 eq	**1.1E-06**	2.0E-07	0.0E+00	9.1E-07	8.2E-11	3.6E-11	4.8E-09	3.8E-13	7.3E-11
Ecotoxicity	CTUe	**33.1**	29.0	6.6E-03	3.2	0.5	0.2	2.9E-02	2.4E-03	3.5E-02
Human health cancer	CTUh	**2.8E-06**	2.7E-06	7.5E-11	1.6E-07	2.4E-09	1.1E-09	1.6E-10	1.1E-11	1.6E-10
Human health noncancer	CTUh	**3.4E-06**	3.0E-06	7.7E-09	3.3E-07	4.1E-08	1.8E-08	1.4E-09	1.9E-10	2.7E-09

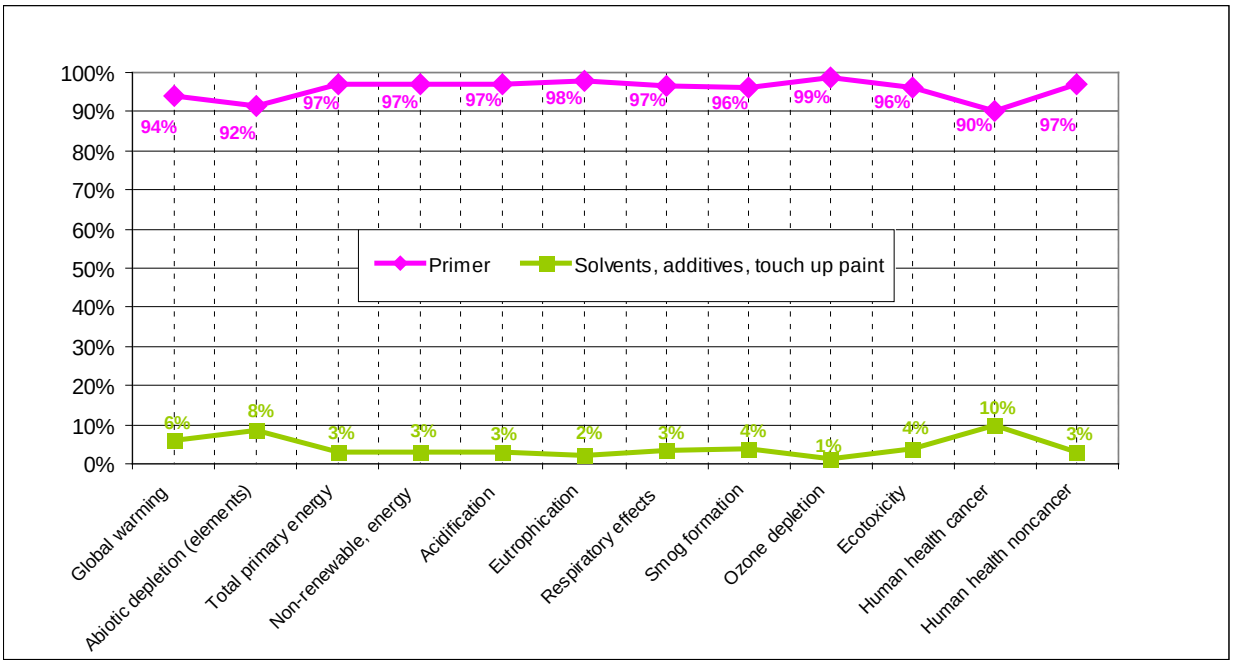
Table 18. Contribution by Material Type to "Welding" Impact Categories – % Basis – per 1 Ton of Primary Frame

Impact category	Total	Welding wire	Welding consumables	Welding flux	Argon	Oxygen	Carbon dioxide	Nitrogen	Acetylene
Global warming	**100%**	69.6%	0.1%	16.7%	8.6%	3.8%	0.6%	0.0%	0.6%
Abiotic depletion (elements)	**100%**	56.1%	-0.3%	44.2%	0.00%	0.00%	0.00%	0.00%	0.00%
Total primary energy	**100%**	55.8%	0.1%	25.6%	11.9%	5.2%	0.6%	0.1%	0.8%
Non-renewable, energy	**100%**	56.6%	0.1%	24.7%	11.9%	5.2%	0.6%	0.1%	0.8%
Acidification	**100%**	47.7%	0.1%	27.4%	16.1%	7.1%	0.5%	0.1%	1.1%
Eutrophication	**100%**	47.6%	0.0%	50.7%	1.0%	0.4%	0.2%	0.0%	0.1%
Respiratory effects	**100%**	43.4%	0.1%	44.5%	7.8%	3.4%	0.3%	0.0%	0.5%
Smog formation	**100%**	48.1%	0.1%	30.6%	12.9%	5.6%	1.7%	0.1%	0.9%
Ozone depletion	**100%**	17.7%	0.0%	81.8%	0.0%	0.0%	0.4%	0.0%	0.0%
Ecotoxicity	**100%**	87.8%	0.0%	9.7%	1.6%	0.7%	0.1%	0.0%	0.1%
Human health cancer	**100%**	94.1%	0.0%	5.8%	0.1%	0.0%	0.0%	0.0%	0.0%
Human health noncancer	**100%**	88.2%	0.2%	9.7%	1.2%	0.5%	0.0%	0.0%	0.1%
	1st highest	2nd highest	3rd highest						

Table 19. Contribution by Material Type to "Painting" Impact Categories – Absolute Basis- per 1 Ton of Primary Frame

Impact category	Unit	Total- Painting	Primer	Solvents	Additives	Touch up paint
Global warming	kg CO2 eq	**4.9**	4.6	0.2	0.0	0.0
Abiotic depletion (elements)	kg Sb eq	**4.1E-07**	3.7E-07	7.0E-10	9.4E-09	2.5E-08
Total primary energy	MJ	**253**	246	5	1	1
Non-renewable, energy	MJ	**246**	238	5	1	1
Acidification	kg SO2 eq	**0.0**	0.0	0.0	0.0	0.0
Eutrophication	kg N eq	**0.019**	0.018	0.000	0.000	0.000
Respiratory effects	kg PM2.5 eq	**0.002**	0.002	0.000	0.000	0.000
Smog formation	kg O3 eq	**0.3**	0.3	0.0	0.0	0.0
Ozone depletion	kg CFC-11 eq	**2.0E-06**	1.9E-06	1.4E-08	3.1E-09	6.9E-09
Ecotoxicity	CTUe	**5.8**	5.6	0.1	0.1	0.0
Human health cancer	CTUh	**1.2E-07**	1.1E-07	2.9E-09	7.9E-09	9.8E-10
Human health noncancer	CTUh	**6.6E-07**	6.4E-07	8.0E-09	1.2E-09	1.1E-08

Figure 15 Contribution by Material Type to "Painting" Impact Categories – % Basis – per 1 Ton of Primary Frame



5.2 Secondary Frames Manufacturing Process

Table 20 summarizes the life cycle impact assessment (LCIA) results for the G2G manufacturing of one ton of secondary frames. It takes a total of 1,984 MJ of primary energy to manufacture one ton of secondary frame components. Over 92% of the energy is a function of on-site demand as opposed to the background energy used to produce auxiliary and ancillary materials. Further, all but 28 MJ of the primary energy use is from non-renewable sources (fossil and nuclear).

On-site energy was also the primary source of the greenhouse gas emissions, accounting for 93% of the total. The production of each ton of primary frame results in the emission of 112 kg of greenhouse gases on a CO_2 equivalent basis. In fact, on-site energy use was the major contributor to all impact burdens except for abiotic depletion (elements) and eutrophication. Welding, including welding consumables, and then the painting process inputs were the next most significant contributors to the burdens exhibited in the production of secondary frames (see Table 21). On-site process emissions contributed between 11 and 14% to the eutrophication and smog potential indicators, but otherwise were a minor factor. Packaging material use contributed as much as 8% to the respiratory effects, but typically was responsible for 2% to 5% of the G2G effects. Both equipment maintenance fluid inputs and transportation of inputs and waste outputs proved to be minor contributors (<1% invidually) to the impact measures. Waste disposal was responsible for 26% of the eutrophication result.

Table 22 provides an absolute breakdown of the on-site energy consumption by energy type and Figure 16 displays the contribution of each fuel type on a percent basis. Electricity is the dominant energy form and is responsible for 80% of the total GWP effect arising from on-site energy demand. With the exception of ozone depletion potential, electricity use is responsible for 70% to 80% of the effects observed within each impact category.

Tables 23 and 24 provide an absolute and percent breakdown of how the various welding materials and gases contribute to the impact of welding primary frames. Welding wire and then welding flux use are the major sources of the “welding” impacts. The use of Argon is by far the most significant gas input contributing to the impact of welding and often is more important than welding flux as a contributor to the welding of secondary frames.

The impacts ascribed to the painting of secondary frames are summarized in Table 25 on an absolute basis and Figure 17 on a percent basis. Between 62% and 93% of the burdens associated with paint inputs – primer, solvents, additives and touch-up paint use – can be traced to the use of primer.

Table 20. Weighted Average Secondary Frames G2G LCIA Results for 1 Ton of Production (Reference Flow) –Absolute Basis

Impact category	Unit	Total	On-site process emissions	Welding (wire, consumables, flux, gases)	Painting (primer, solvents, additives, touch up paint)	Hydraulic, gear and motor oils	On-site energy consumption	Inbound/ Outbound transportation	Packaging material	Waste disposal
Global warming	kg CO2 eq	**112.0**	0.04	2.2	2.0	2.2E-02	103.9	0.6	3.2	0.1
Abiotic depletion (elements)	kg Sb eq	**1.4E-06**	0	1.2E-06	1.8E-07	1.3E-10	3.4E-11	0	0.0E+00	8.1E-11
Total primary energy	MJ	**1,984**	0	29	89	1.8	1,816	8	47	-7
Non-renewable, energy	MJ	**1,956**	0	28	86	1.8	1,787	8	47	-3
Acidification	kg SO2 eq	**0.944**	0	1.09E-02	1.06E-02	2.08E-04	8.97E-01	3.46E-03	2.22E-02	-7.64E-04
Eutrophication	kg N eq	**0.038**	0.004	1.83E-03	6.37E-03	6.05E-05	1.38E-02	1.91E-04	1.39E-03	9.75E-03
Respiratory effects	kg PM2.5 eq	**0.063**	0.002	1.21E-03	8.51E-04	1.55E-05	5.49E-02	7.11E-05	4.87E-03	-1.18E-04
Smog formation	kg O3 eq	**9.0**	1.2	0.1	0.1	1.5E-03	7.0	0.1	0.4	4.0E-03
Ozone depletion	kg CFC-11 eq	**2.2E-06**	0	1.1E-07	6.3E-07	1.9E-08	1.4E-06	2.3E-11	7.6E-11	-7.9E-10
Ecotoxicity	CTUe	**82.9**	0	4.5	2.2	8.1E-03	67.2	1.5	2.4	5.0
Human health cancer	CTUh	**7.9E-07**	0	3.8E-07	5.5E-08	1.4E-10	2.8E-07	8.4E-09	1.5E-08	4.7E-08
Human health noncancer	CTUh	**6.6E-06**	0	4.6E-07	2.3E-07	9.7E-10	4.1E-06	8.1E-08	1.7E-07	1.6E-06

Table 21. Weighted Average Secondary Frames G2G LCIA Results for 1 Ton of Production (Reference Flow) –% Basis

Impact category	Total	On-site process emissions	Welding (wire, consumables, flux, gases)	Painting (primer, solvents, additives, touch up paint)	Hydraulic, gear and motor oils	On-site energy consumption	Inbound/ Outbound transportation	Packaging material	Waste disposal
Global warming	**100%**	0%	2%	2%	0%	93%	1%	3%	0%
Abiotic depletion (elements)	**100%**	0%	87%	13%	0%	0%	0%	0%	0%
Total primary energy	**100%**	0%	1%	4%	0%	92%	0%	2%	0%
Non-renewable, energy	**100%**	0%	1%	4%	0%	91%	0%	2%	0%
Acidification	**100%**	0%	1%	1%	0%	95%	0%	2%	0%
Eutrophication	**100%**	11%	5%	17%	0%	37%	1%	4%	26%
Respiratory effects	**100%**	3%	2%	1%	0%	87%	0%	8%	0%
Smog formation	**100%**	14%	1%	1%	0%	79%	1%	5%	0%
Ozone depletion	**100%**	0%	5%	29%	1%	65%	0%	0%	0%
Ecotoxicity	**100%**	0%	5%	3%	0%	81%	2%	3%	6%
Human health cancer	**100%**	0%	48%	7%	0%	36%	1%	2%	6%
Human health noncancer	**100%**	0%	7%	4%	0%	62%	1%	3%	24%

Table 22. Contribution by Fuel Type to "On-site Energy Consumption"Impact Categories – Absolute Basis per Ton of Secondary Frame

Impact category	Unit	Total-On-site energy consumption	Electricity	Natural gas	Diesel	Propane
Global warming	kg CO2 eq	**103.9**	82.7	17.2	2.5	1.4
Abiotic depletion (elements)	kg Sb eq	**3.4E-11**	2.4E-11	8.1E-12	1.1E-12	9.7E-13
Total primary energy	MJ	**1,816**	1,456	303	37	21
Non-renewable, energy	MJ	**1,787**	1,427	303	37	21
Acidification	kg SO2 eq	**0.897**	0.7	0.1	3.4E-02	3.9E-03
Eutrophication	kg N eq	**0.014**	0.010	0.001	2.0E-03	2.0E-04
Respiratory effects	kg PM2.5 eq	**0.055**	0.046	0.009	7.6E-04	1.1E-04
Smog formation	kg O3 eq	**7.0**	5.5	0.4	1.1	0.1
Ozone depletion	kg CFC-11 eq	**1.4E-06**	5.3E-09	1.4E-06	1.2E-10	7.4E-11
Ecotoxicity	CTUe	**67.2**	34.4	22.2	6.8	3.8
Human health cancer	CTUh	**2.8E-07**	1.6E-07	7.0E-08	3.7E-08	2.0E-08
Human health noncancer	CTUh	**4.1E-06**	2.7E-06	9.1E-07	3.5E-07	2.0E-07

Figure 16 Contribution by Fuel Type to "On-site Energy Consumption" Impact Categories – % Basis – per 1 Ton of Secondary Frame

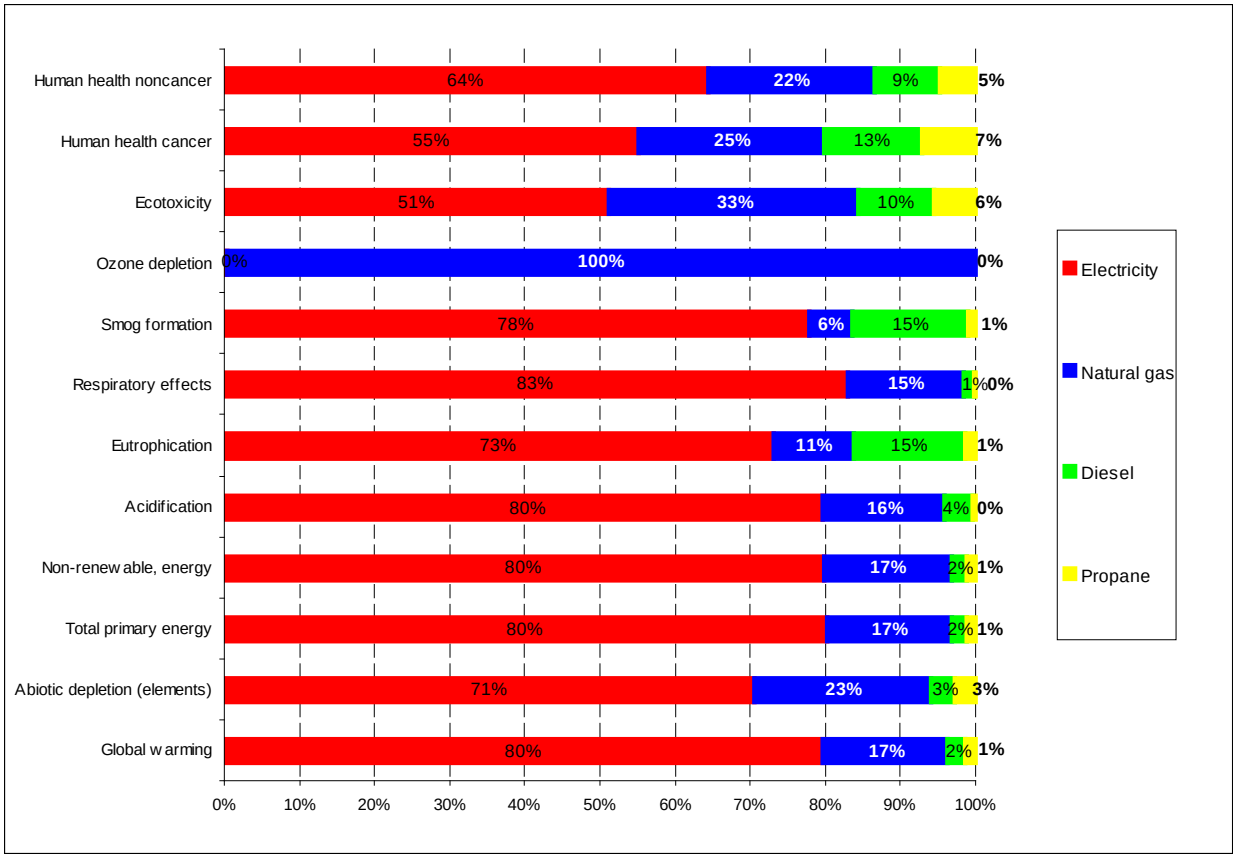


Table 23. Contribution by Material Type to "Welding" Impact Categories – Absolute Basis – per 1 Ton of Secondary Frame

Impact category	Unit	Total - Welding	Welding wire	Welding consumables	Welding flux	Argon	Oxygen	Carbon dioxide	Nitrogen	Acetylene
Global warming	kg CO2 eq	**2.2**	1.4	0.0	0.2	0.3	0.2	0.0	0.00	0.0
Abiotic depletion (elements)	kg Sb eq	**1.2E-06**	7.7E-07	-4.5E-09	4.2E-07	9.5E-14	5.2E-14	7.0E-12	4.9E-16	1.2E-14
Total primary energy	MJ	**29**	14	3.4E-02	5	6	3	0	0.0	0
Non-renewable, energy	MJ	**28**	14	3.4E-02	4	6	3	0	0.0	0
Acidification	kg SO2 eq	**0.011**	4.5E-03	9.7E-06	1.8E-03	2.8E-03	1.5E-03	4.8E-05	1.4E-05	2.0E-04
Eutrophication	kg N eq	**0.002**	0.001	5.2E-07	0.001	3.9E-05	2.2E-05	3.5E-06	2.0E-07	2.9E-06
Respiratory effects	kg PM2.5 eq	**0.001**	5.3E-04	9.9E-07	3.8E-04	1.8E-04	9.8E-05	3.4E-06	9.2E-07	1.3E-05
Smog formation	kg O3 eq	**0.099**	4.3E-02	9.6E-05	1.9E-02	2.1E-02	1.2E-02	1.7E-03	1.1E-04	1.6E-03
Ozone depletion	kg CFC-11 eq	**1.1E-07**	2.7E-08	0.0E+00	8.7E-08	2.1E-11	1.1E-11	7.1E-10	1.1E-13	2.0E-11
Ecotoxicity	CTUe	**4.5**	4.0	9.8E-04	0.3	0.1	0.1	4.2E-03	6.9E-04	9.8E-03
Human health cancer	CTUh	**3.8E-07**	3.6E-07	1.1E-11	1.5E-08	6.1E-10	3.4E-10	2.4E-11	3.2E-12	4.5E-11
Human health noncancer	CTUh	**4.6E-07**	4.1E-07	1.2E-09	3.1E-08	1.0E-08	5.7E-09	2.1E-10	5.3E-11	7.6E-10

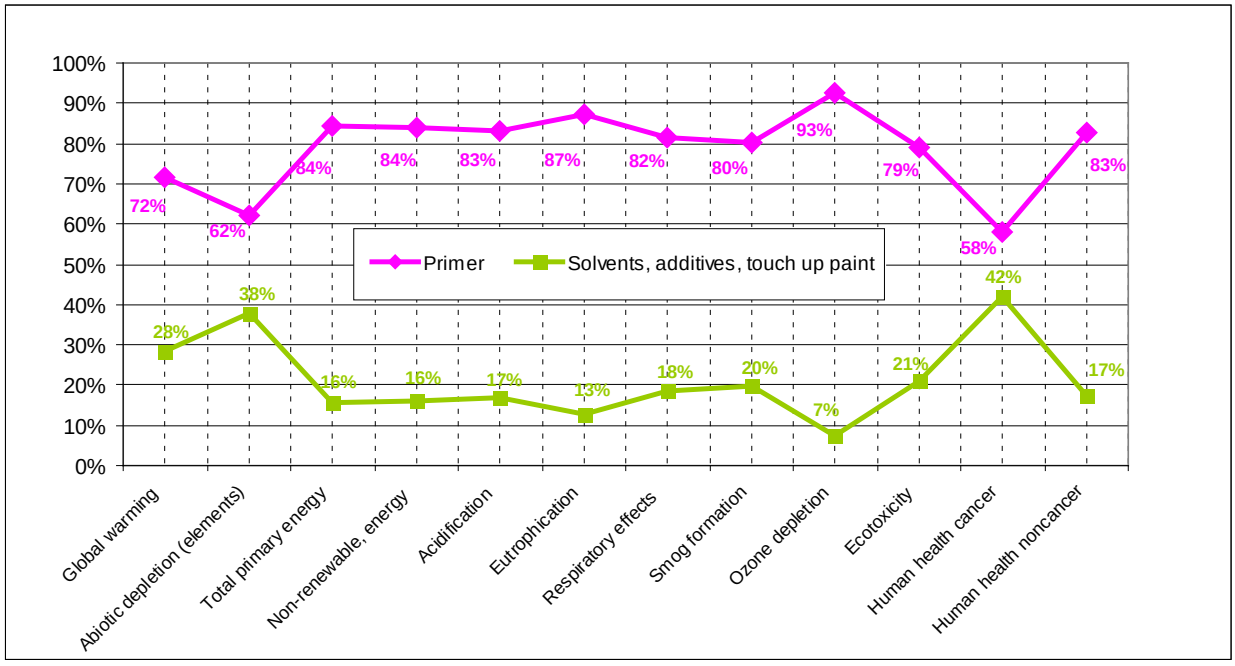
Table 24. Contribution by Material Type to "Welding" Impact Categories – % basis – per 1 Ton of Secondary Frame

Impact category	Total	Welding wire	Welding consumables	Welding flux	Argon	Oxygen	Carbon dioxide	Nitrogen	Acetylene
Global warming	**100%**	64.6%	0.1%	10.7%	14.7%	8.1%	0.6%	0.1%	1.1%
Abiotic depletion (elements)	**100%**	64.8%	-0.4%	35.5%	0.00%	0.00%	0.00%	0.00%	0.00%
Total primary energy	**100%**	50.7%	0.1%	16.1%	19.9%	11.0%	0.6%	0.1%	1.5%
Non-renewable, energy	**100%**	51.2%	0.1%	15.6%	19.9%	11.0%	0.6%	0.1%	1.5%
Acidification	**100%**	41.1%	0.1%	16.5%	25.7%	14.2%	0.4%	0.1%	1.9%
Eutrophication	**100%**	55.3%	0.0%	40.9%	2.2%	1.2%	0.2%	0.0%	0.2%
Respiratory effects	**100%**	44.2%	0.1%	31.5%	14.7%	8.1%	0.3%	0.1%	1.1%
Smog formation	**100%**	43.7%	0.1%	19.3%	21.5%	11.9%	1.7%	0.1%	1.7%
Ozone depletion	**100%**	23.6%	0.0%	75.7%	0.0%	0.0%	0.6%	0.0%	0.0%
Ecotoxicity	**100%**	88.2%	0.0%	6.8%	3.0%	1.7%	0.1%	0.0%	0.2%
Human health cancer	**100%**	95.6%	0.0%	4.1%	0.2%	0.1%	0.0%	0.0%	0.0%
Human health noncancer	**100%**	89.2%	0.3%	6.8%	2.3%	1.3%	0.0%	0.0%	0.2%
	1st highest	2nd highest	3rd highest						

Table 25. Contribution by Material Type to "Painting" Impact Categories – Absolute Basis – per 1 Ton of Secondary Frame

Impact category	Unit	Total-Painting	Primer	Solvents	Additives	Touch up paint
Global warming	kg CO2 eq	**2.0**	1.4	0.4	0.1	0.1
Abiotic depletion (elements)	kg Sb eq	**1.8E-07**	1.1E-07	1.4E-09	1.9E-08	4.9E-08
Total primary energy	MJ	**89**	75	10	1	3
Non-renewable, energy	MJ	**86**	73	10	1	3
Acidification	kg SO2 eq	**0.011**	0.009	0.001	2.8E-04	3.8E-04
Eutrophication	kg N eq	**0.006**	0.006	0.001	4.4E-05	2.0E-04
Respiratory effects	kg PM2.5 eq	**0.001**	0.001	0.000	2.2E-05	3.5E-05
Smog formation	kg O3 eq	**0.1**	0.1	0.0	0.0	0.0
Ozone depletion	kg CFC-11 eq	**6.3E-07**	5.9E-07	2.7E-08	6.1E-09	1.4E-08
Ecotoxicity	CTUe	**2.2**	1.7	0.2	0.2	0.1
Human health cancer	CTUh	**5.5E-08**	3.2E-08	5.6E-09	1.6E-08	1.9E-09
Human health noncancer	CTUh	**2.3E-07**	1.9E-07	1.5E-08	2.3E-09	2.2E-08

Figure 17 Contribution by Material Type to "Painting" Impact Categories – % Basis – per 1 Ton of Secondary Frame



5.3 Wall Panels Manufacturing Process

Table 26 summarizes the life cycle impact assessment (LCIA) results for the G2G manufacturing of one ton of wall cladding panels. A total of 1,330 MJ of primary energy is used to manufacture one ton of wall cladding panels and all but 17 MJ of this energy is derived from non-renewable fossil and nuclear energy sources. Over 77% of the energy is a function of on-site demand as opposed to being used in the background to produce auxiliary and ancillary materials.

On-site energy was also the primary source of the greenhouse gas emissions, accounting for 82% of the total 72 kg emitted on a CO_2 equivalent basis per ton of wall cladding panels. In fact, on-site energy use was the major contributor to all impact burdens except for abiotic depletion (elements) and eutrophication. Packaging materials were the next most significant contributor to the burdens exhibited in the production of wall cladding panels – accounting for all abiotic depletion (elements), over 50% of the eutrophication potential and 33% of the respiratory effects (see Table 27). On-site process emissions, maintenance and roll-forming lubricants use and transportation created negligible impact burdens. Waste disposal was also a minor contributor, but due to downstream recycling or waste-to-energy conversion it often led to negative burdens.

Table 28 provides an absolute breakdown of the on-site energy consumption by energy type and Figure 18 displays the contribution of each fuel type on a percent basis. Electricity is the dominant energy form and is responsible for 86% of the total GWP effect arising from on-site energy consumption. With the exception of ozone depletion potential, electricity use is responsible for 70% to 90% of the effects observed within each impact category.

Tables 29 and 30 present the LCIA results for the wall panel packaging materials use on an absolute and percent basis, respectively. The majority of the packaging materials' impact for wall panels can be traced to dunnage wood and slip-sheets use.

Table 26. Weighted Average Wall Panels G2G LCIA Results for 1 Ton of Production (Reference Flow) –Absolute Basis

Impact category	Unit	Total	On-site process emissions	Hydraulic, gear and motor oils	Lubricant	On-site energy consumption	Inbound/ Outbound transportation	Packaging material	Waste disposal
Global warming	kg CO2 eq	**71.6**	0	0.02	0.05	59.1	0.2	12.3	0.016
Abiotic depletion (elements)	kg Sb eq	**8.2E-08**	0	1.3E-10	0.0E+00	1.9E-11	0.0E+00	8.3E-08	-1.5E-09
Total primary energy	MJ	**1,330**	0	2	5	1,028	2	309	-15
Non-renewable, energy	MJ	**1,313**	0	2	5	1,010	2	300	-6
Acidification	kg SO2 eq	**0.632**	0	2.1E-04	6.1E-04	0.514	0.001	1.2E-01	-2.0E-03
Eutrophication	kg N eq	**0.019**	0	6.1E-05	2.7E-05	0.009	0.000	9.8E-03	9.2E-05
Respiratory effects	kg PM2.5 eq	**0.046**	0	1.6E-05	2.0E-05	0.031	0.000	1.5E-02	-2.9E-04
Smog formation	kg O3 eq	**6.2**	0.3	1.5E-03	7.0E-03	4.7	0.0	1.2E+00	-3.7E-03
Ozone depletion	kg CFC-11 eq	**4.6E-07**	0	1.9E-08	1.3E-11	3.5E-07	6.4E-12	7.6E-08	1.1E-08
Ecotoxicity	CTUe	**60.5**	0	8.1E-03	8.8E-01	37.4	0.4	2.3E+01	-8.5E-01
Human health cancer	CTUh	**3.3E-07**	0	1.4E-10	4.7E-09	1.7E-07	2.3E-09	1.6E-07	-4.2E-09
Human health noncancer	CTUh	**3.7E-06**	0	9.7E-10	4.6E-08	2.4E-06	2.2E-08	1.3E-06	-1.1E-07

Table 27. Weighted Average Wall Panels G2G LCIA Results for 1 Ton of Production (Reference Flow) –% Basis

Impact category	Total	On-site process emissions	Hydraulic, gear and motor oils	Lubricant	On-site energy consumption	Inbound/ Outbound transportation	Packaging material	Waste disposal
Global warming	**100%**	0%	0%	0.1%	82%	0%	17%	0%
Abiotic depletion (elements)	**100%**	0%	0%	0%	0%	0%	102%	-2%
Total primary energy	**100%**	0%	0%	0.4%	77%	0%	23%	-1%
Non-renewable, energy	**100%**	0%	0%	0.4%	77%	0%	23%	0%
Acidification	**100%**	0%	0%	0.1%	81%	0%	19%	0%
Eutrophication	**100%**	0%	0%	0.1%	47%	0%	52%	0%
Respiratory effects	**100%**	0%	0%	0.04%	67%	0%	33%	-1%
Smog formation	**100%**	5%	0%	0.1%	76%	0%	19%	0%
Ozone depletion	**100%**	0%	4%	0%	77%	0%	16%	2%
Ecotoxicity	**100%**	0%	0%	1%	62%	1%	37%	-1%
Human health cancer	**100%**	0%	0%	1%	52%	1%	47%	-1%
Human health noncancer	**100%**	0%	0%	1%	66%	1%	35%	-3%

Table 28. Contribution by Fuel Type to "On-site Energy Consumption" Impact Categories – Absolute Basis – per Ton of Wall Panels

Impact category	Unit	Total on-site energy consumption	Electricity	Natural gas	Diesel	Propane
Global warming	kg CO2 eq	**59.1**	50.8	4.3	2.6	1.4
Abiotic depletion (elements)	kg Sb eq	**1.9E-11**	1.5E-11	2.0E-12	1.1E-12	9.6E-13
Total primary energy	MJ	**1,028**	894	76	38	20
Non-renewable, energy	MJ	**1,010**	876	76	38	20
Acidification	kg SO2 eq	**0.514**	0.4	3.6E-02	3.6E-02	3.9E-03
Eutrophication	kg N eq	**0.009**	0.006	3.7E-04	2.1E-03	2.0E-04
Respiratory effects	kg PM2.5 eq	**0.031**	0.028	0.002	7.8E-04	1.1E-04
Smog formation	kg O3 eq	**4.7**	3.4	0.1	1.1	0.1
Ozone depletion	kg CFC-11 eq	**3.5E-07**	3.3E-09	3.5E-07	1.3E-10	7.4E-11
Ecotoxicity	CTUe	**37.4**	21.1	5.5	7.0	3.7
Human health cancer	CTUh	**1.7E-07**	9.6E-08	1.8E-08	3.8E-08	2.0E-08
Human health noncancer	CTUh	**2.4E-06**	1.6E-06	2.3E-07	3.7E-07	1.9E-07

Figure 18 Contribution by Fuel Type to "On-site Energy Consumption" Impact Categories – % Basis per Ton of Wall Panels

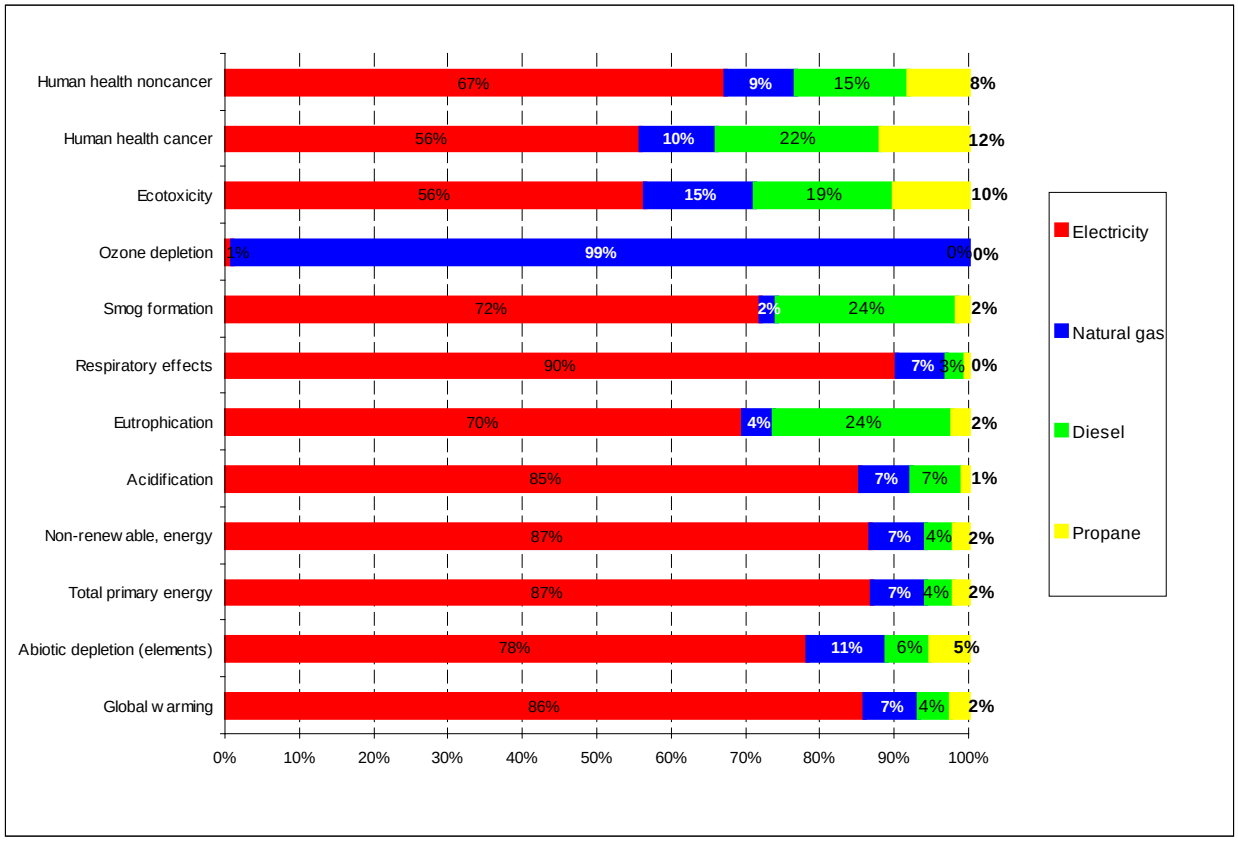


Table 29. Contribution by Material Type to "Packaging" Impact Categories – Absolute Basis – per 1 Ton of Wall Panels

Impact category	Unit	Total-Packaging material	Dunnage (wood)	Steel banding and nails	Slip Sheets	Waterproof packing paper	Strippable film
Global warming	kg CO2 eq	**12.3**	4.8	3.8	3.1	0.2	0.4
Abiotic depletion (elements)	kg Sb eq	**8.3E-08**	0.0E+00	0.0E+00	1.4E-08	6.8E-08	1.7E-09
Total primary energy	MJ	**309**	79	44	157	10	20
Non-renewable, energy	MJ	**300**	79	44	154	4	19
Acidification	kg SO2 eq	**0.118**	0.0	0.0	0.1	0.0	0.0
Eutrophication	kg N eq	**9.8E-03**	2.7E-03	5.5E-04	5.5E-03	3.4E-04	6.7E-04
Respiratory effects	kg PM2.5 eq	**1.5E-02**	1.0E-02	1.0E-03	3.5E-03	1.8E-04	4.7E-04
Smog formation	kg O3 eq	**1.2E+00**	7.9E-01	1.8E-01	1.5E-01	1.4E-02	1.7E-02
Ozone depletion	kg CFC-11 eq	**7.6E-08**	1.7E-10	0.0E+00	6.1E-08	6.4E-09	7.5E-09
Ecotoxicity	CTUe	**2.3E+01**	5.4E+00	1.7E-02	1.5E+01	3.6E-01	1.8E+00
Human health cancer	CTUh	**1.6E-07**	3.1E-08	2.1E-09	1.1E-07	3.1E-09	1.3E-08
Human health noncancer	CTUh	**1.3E-06**	3.3E-07	6.8E-08	7.6E-07	3.8E-08	8.7E-08

Table 30. Contribution by Material Type to "Packaging" Impact Categories – % Basis – per 1 Ton of Wall Panels

Impact category	Total-Packaging material	Dunnage (wood)	Steel banding and nails	Slip Sheets	Waterproof packing paper	Strippable film
Global warming	**100%**	39%	31%	25%	1%	3%
Abiotic depletion (elements)	**100%**	0%	0%	16%	82%	2%
Total primary energy	**100%**	25%	14%	51%	3%	6%
Non-renewable, energy	**100%**	26%	15%	51%	1%	6%
Acidification	**100%**	36%	9%	47%	2%	6%
Eutrophication	**100%**	28%	6%	56%	4%	7%
Respiratory effects	**100%**	66%	7%	23%	1%	3%
Smog formation	**100%**	69%	16%	13%	1%	1%
Ozone depletion	**100%**	0%	0%	81%	8%	10%
Ecotoxicity	**100%**	24%	0%	67%	2%	8%
Human health cancer	**100%**	20%	1%	69%	2%	8%
Human health noncancer	**100%**	26%	5%	59%	3%	7%
	1st highest	2nd highest	3rd highest			

5.4 Roof Panels Manufacturing Process

Table 31 summarizes the life cycle impact assessment (LCIA) results for the manufacturing process of one ton of roof cladding panels. A total of 1,357 MJ of primary energy is used to manufacture one ton of roof cladding panels and all but 19 MJ of this energy is derived from non-renewable fossil and nuclear energy sources. Over 75% of the energy is from on-site demand as opposed to being used in the background to produce auxiliary and ancillary materials. The production of each ton of roof cladding panels results in the emission of 73 kg of greenhouse gases on a CO_2 equivalent basis.

On-site energy was also the primary source of the greenhouse gas emissions, accounting for 81% of the total. In fact, on-site energy use was the major contributor to all impact burdens except for abiotic depletion (elements) and eutrophication. Packaging materials was consistently the next most significant contributor to the burdens exhibited in the production of roof cladding panels (see Table 32). Mastics and sealants combined accounted for 100% of the abiotic depletion (elements), 29% of the eutrophication potential and 46% of the ozone depletion potential. Process emissions, equipment and roll-forming lubricants, transportation and waste disposal were negligible contributors to the LCIA results for roof cladding panels.

Table 33 provides an absolute breakdown of the on-site energy comsumption by energy type in the production of roof panels. Figure 19 displays the contribution of each fuel type on a percent basis. Electricity is the dominant energy form and is responsible for 85% of the total GWP effect arising from on-site energy consumption. With the exception of ozone depletion potential, electricity use is responsible for 68% to 89% of the effects observed within each impact category.

Tables 34 and 35 present the LCIA results for the roof panel packaging materials use on an absolute and percent basis, respectively. The majority of the packaging materials impact for roof panels can be traced to dunnage wood and slip-sheets use.

Table 31. Weighted Average Roof Panels G2G LCIA Results for 1 Ton of Production (Reference Flow) – Absolute Basis

Impact category	Unit	Total	On-site process emissions	Hydraulic, gear and motor oils	Lubricant	Mastics	Sealants	On-site energy consumption	Inbound/ Outbound transportation	Packaging material	Waste disposal
Global warming	kg CO2 eq	**72.6**	0	0.02	0.13	2.3	2.0	58.6	0.38	9.24	0.01
Abiotic depletion (elements)	kg Sb eq	**3.0E-05**	0	1.3E-10	0.0E+00	2.5E-07	3.0E-05	1.9E-11	0.0E+00	3.9E-08	-8.1E-10
Total primary energy	MJ	**1,357**	0	2	13	63	57	1,020	6	205	-8
Non-renewable, energy	MJ	**1,338**	0	2	13	62	56	1,003	6	200	-4
Acidification	kg SO2 eq	**0.622**	0	2.1E-04	1.7E-03	0.009	0.015	0.512	2.3E-03	8.3E-02	-1.1E-03
Eutrophication	kg N eq	**0.022**	0	6.1E-05	7.7E-05	0.003	0.004	0.009	1.3E-04	6.4E-03	3.8E-05
Respiratory effects	kg PM2.5 eq	**0.046**	0	1.6E-05	5.8E-05	0.001	0.001	0.031	4.7E-05	1.3E-02	-1.5E-04
Smog formation	kg O3 eq	**7.3**	1.4	1.5E-03	2.0E-02	0.1	0.1	4.7	6.2E-02	9.7E-01	-7.2E-04
Ozone depletion	kg CFC-11 eq	**8.7E-07**	0	1.9E-08	3.7E-11	3.0E-09	4.0E-07	4.1E-07	1.5E-11	4.0E-08	1.6E-09
Ecotoxicity	CTUe	**60.4**	0	8.1E-03	2.5E+00	3.9	1.7	37.7	1.0E+00	1.4E+01	-4.4E-01
Human health cancer	CTUh	**4.3E-07**	0	1.4E-10	1.3E-08	1.0E-07	4.8E-08	1.7E-07	5.5E-09	9.6E-08	-2.2E-09
Human health noncancer	CTUh	**3.6E-06**	0	9.7E-10	1.3E-07	8.0E-08	1.2E-07	2.4E-06	5.3E-08	8.2E-07	-5.8E-08

Table 32. Weighted Average Roof Panels G2G LCIA Results for 1 Ton of Production (Reference Flow) – Percent Basis

Impact category	Total	On-site process emissions	Hydraulic, gear and motor oils	Lubricant	Mastics	Sealants	On-site energy consumption	Inbound/ Outbound transportation	Packaging material	Waste disposal
Global warming	**100%**	0%	0%	0.2%	3%	3%	81%	1%	13%	0%
Abiotic depletion (elements)	**100%**	0%	0%	0%	1%	99%	0%	0%	0%	0%
Total primary energy	**100%**	0%	0%	1%	5%	4%	75%	0%	15%	-1%
Non-renewable, energy	**100%**	0%	0%	1%	5%	4%	75%	0%	15%	0%
Acidification	**100%**	0%	0%	0%	1%	2%	82%	0%	13%	0%
Eutrophication	**100%**	0%	0%	0%	12%	17%	41%	1%	29%	0%
Respiratory effects	**100%**	0%	0%	0%	3%	3%	67%	0%	27%	0%
Smog formation	**100%**	19%	0%	0%	1%	1%	64%	1%	13%	0%
Ozone depletion	**100%**	0%	2%	0%	0%	46%	47%	0%	5%	0%
Ecotoxicity	**100%**	0%	0%	4%	6%	3%	62%	2%	23%	-1%
Human health cancer	**100%**	0%	0%	3%	23%	11%	40%	1%	22%	-1%
Human health noncancer	**100%**	0%	0%	4%	2%	3%	68%	1%	23%	-2%

Table 33. Contribution by Fuel Type to "On-site Energy Consumption" Impact Categories – Absolute Basis per Ton of Roof Panels

Impact category	Unit	Total-On-site energy consumption	Electricity	Natural gas	Diesel	Propane
Global warming	kg CO2 eq	**58.6**	49.7	5.0	2.7	1.2
Abiotic depletion (elements)	kg Sb eq	**1.9E-11**	1.5E-11	2.3E-12	1.2E-12	8.2E-13
Total primary energy	MJ	**1,020**	875	88	40	17
Non-renewable, energy	MJ	**1,003**	857	88	40	17
Acidification	kg SO2 eq	**0.5**	0.4	4.2E-02	0.037	3.3E-03
Eutrophication	kg N eq	**0.009**	0.006	4.2E-04	0.002	1.7E-04
Respiratory effects	kg PM2.5 eq	**0.031**	0.027	2.5E-03	0.001	9.6E-05
Smog formation	kg O3 eq	**4.7**	3.3	0.1	1.2	0.1
Ozone depletion	kg CFC-11 eq	**4.1E-07**	3.2E-09	4.1E-07	1.3E-10	6.3E-11
Ecotoxicity	CTUe	**37.7**	20.7	6.4	7.4	3.2
Human health cancer	CTUh	**1.7E-07**	9.4E-08	2.0E-08	4.0E-08	1.7E-08
Human health noncancer	CTUh	**2.4E-06**	1.6E-06	2.6E-07	3.9E-07	1.7E-07

Figure 19 Contribution by Fuel Type to "On-site Energy Consumption" by Impact Categories – Percent Basis per Ton of Roof Panels

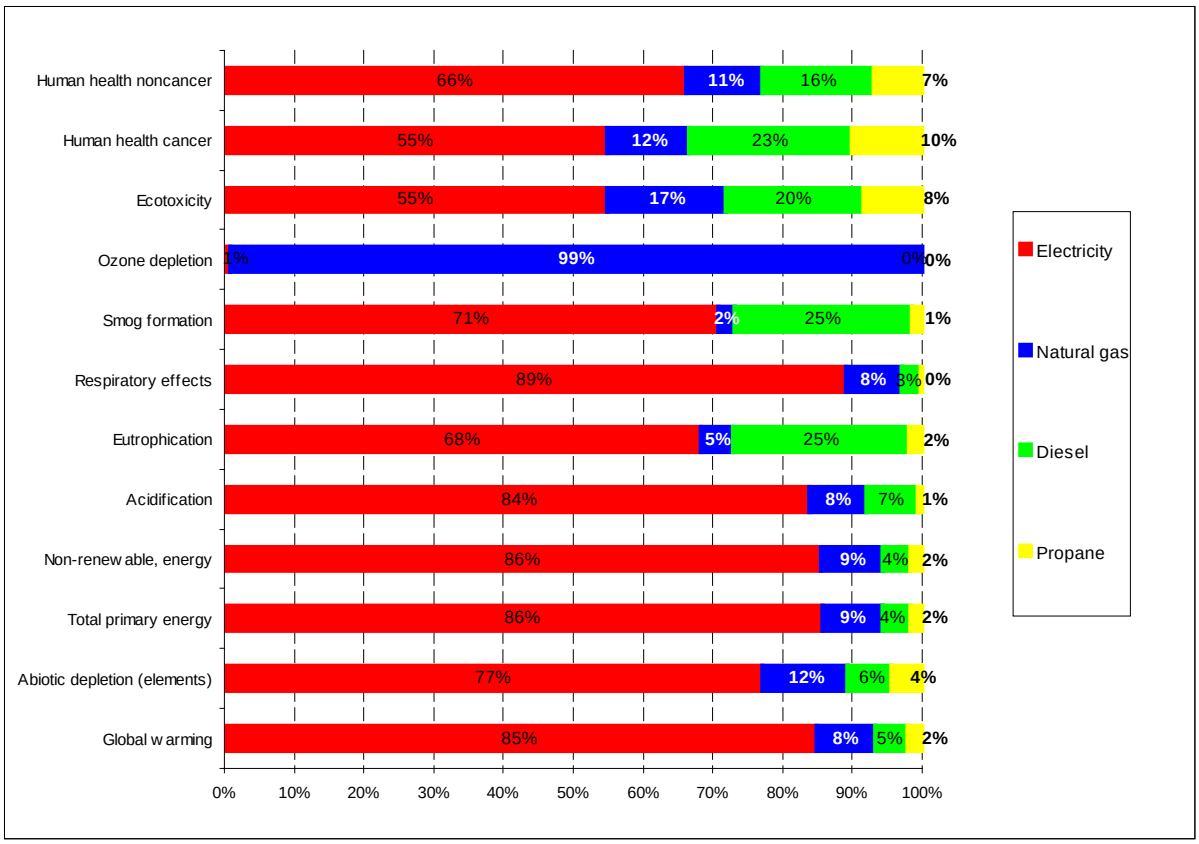


Table 34. Contribution by Material Type to "Packaging" Impact Categories – Absolute Basis – per 1 Ton of Roof Panels

Impact category	Unit	Total-Packaging material	Dunnage (wood)	Steel banding and nails	Slip Sheets	Waterproof packing paper	Strippable film
Global warming	kg CO2 eq	**9.2**	4.6	2.7	1.4	0.1	0.5
Abiotic depletion (elements)	kg Sb eq	**3.9E-08**	0.0E+00	0.0E+00	6.0E-09	3.1E-08	2.2E-09
Total primary energy	MJ	**205**	74	32	68	4	26
Non-renewable, energy	MJ	**200**	74	32	67	2	25
Acidification	kg SO2 eq	**8.3E-02**	4.0E-02	7.7E-03	2.4E-02	9.4E-04	9.7E-03
Eutrophication	kg N eq	**6.4E-03**	2.6E-03	3.9E-04	2.4E-03	1.6E-04	8.8E-04
Respiratory effects	kg PM2.5 eq	**1.3E-02**	9.6E-03	7.1E-04	1.5E-03	8.1E-05	6.2E-04
Smog formation	kg O3 eq	**9.7E-01**	7.5E-01	1.3E-01	6.4E-02	6.5E-03	2.2E-02
Ozone depletion	kg CFC-11 eq	**4.0E-08**	1.6E-10	0.0E+00	2.7E-08	3.0E-09	9.9E-09
Ecotoxicity	CTUe	**1.4E+01**	5.1E+00	1.2E-02	6.6E+00	1.6E-01	2.3E+00
Human health cancer	CTUh	**9.6E-08**	2.9E-08	1.5E-09	4.7E-08	1.4E-09	1.7E-08
Human health noncancer	CTUh	**8.2E-07**	3.1E-07	4.8E-08	3.3E-07	1.8E-08	1.1E-07

Table 35. Contribution by Material Type to "Packaging" Impact Categories – % Basis – per 1 Ton of Roof Panels

Impact category	Total-Packaging material	Dunnage (wood)	Steel banding and nails	Slip Sheets	Waterproof packing paper	Strippable film
Global warming	**100%**	50%	29%	15%	1%	6%
Abiotic depletion (elements)	**100%**	0%	0%	15%	79%	6%
Total primary energy	**100%**	36%	15%	33%	2%	13%
Non-renewable, energy	**100%**	37%	16%	33%	1%	13%
Acidification	**100%**	49%	9%	29%	1%	12%
Eutrophication	**100%**	40%	6%	37%	2%	14%
Respiratory effects	**100%**	77%	6%	12%	1%	5%
Smog formation	**100%**	77%	13%	7%	1%	2%
Ozone depletion	**100%**	0%	0%	67%	7%	25%
Ecotoxicity	**100%**	36%	0%	46%	1%	16%
Human health cancer	**100%**	30%	2%	49%	1%	17%
Human health noncancer	**100%**	38%	6%	40%	2%	14%
	1st highest	2nd highest	3rd highest			

6 Cradle-to-Gate Life Cycle Assessment Results

This section builds on the previous gate-to-gate analyses to provide a complete cradle-to-gate (C2G) life cycle assessment of the four products of interest. Results are presented for each product on a weighted average reference flow basis for one ton of manufactured product. However, for secondary frames, wall and roof panels, the cradle-to-gate results are also summarized on a steel substrate input basis, that is, the type of semi-finished steel processed, as the basis for the product. The cradle-to-gate assessment includes all gate-to-gate flows (see Section 6), but now the system boundary includes the upstream steel semi-finished product input manufacturing and transportation to the MBMA facility and steel fabrication scrap (pre-consumer) recycling and transportation impacts.

6.1 Primary Frames

Tables 36 and 37 summarize the cradle-to-gate LCIA results for the production of one ton of primary frame material on an absolute and percent basis, respectively. The cradle-to-gate manufacture of one ton of primary frame embodies about 18,930 MJ of primary energy use and emits in the order of 1,350 kg of greenhouse gas emissions. Over 99% of the total primary energy is derived from non-renewable fossil and nuclear fuels. On-site gate-to-gate effects contribute 16% of the total primary energy and 12% of the net global warming (greenhouse gas) effects with the “value of fabrication scrap” accounted for in the system. By far the single largest contributor to the cradle-to-gate environmental effects for primary frame elements was the semi-finished steel input - hot rolled plate[7], which generally accounted for 80% or more of the calculated category indicator effects.

The effect of packaging and inbound transportation of hot rolled plate/bar on the LCIA results was generally less than 5% for global warming, primary energy use and respiratory effect measures and between 9% and 13% for eutrophication and smog formation. The “value of scrap” as a credit to the product system varied between 1% and 8% across the LCIA category indicators. The outbound transportation of recycled scrap was found to be negligible.

Figure 20 graphically displays the cradle-to-gate percent contribution of materials and processes to the production of one ton of primary structural frame; highlighting the degree to which the primary frame profile is dominated by the semi-finished steel input and the minor influence of the fabrication scrap recycling (“value of scrap”) credit on the overall profile.

[7] Primary frame production also utilizes 10% hot rolled bar, but the WSA semi-finished steel database does not support this material as such, so the complete semi-finished input was modeled using hot rolled plate.

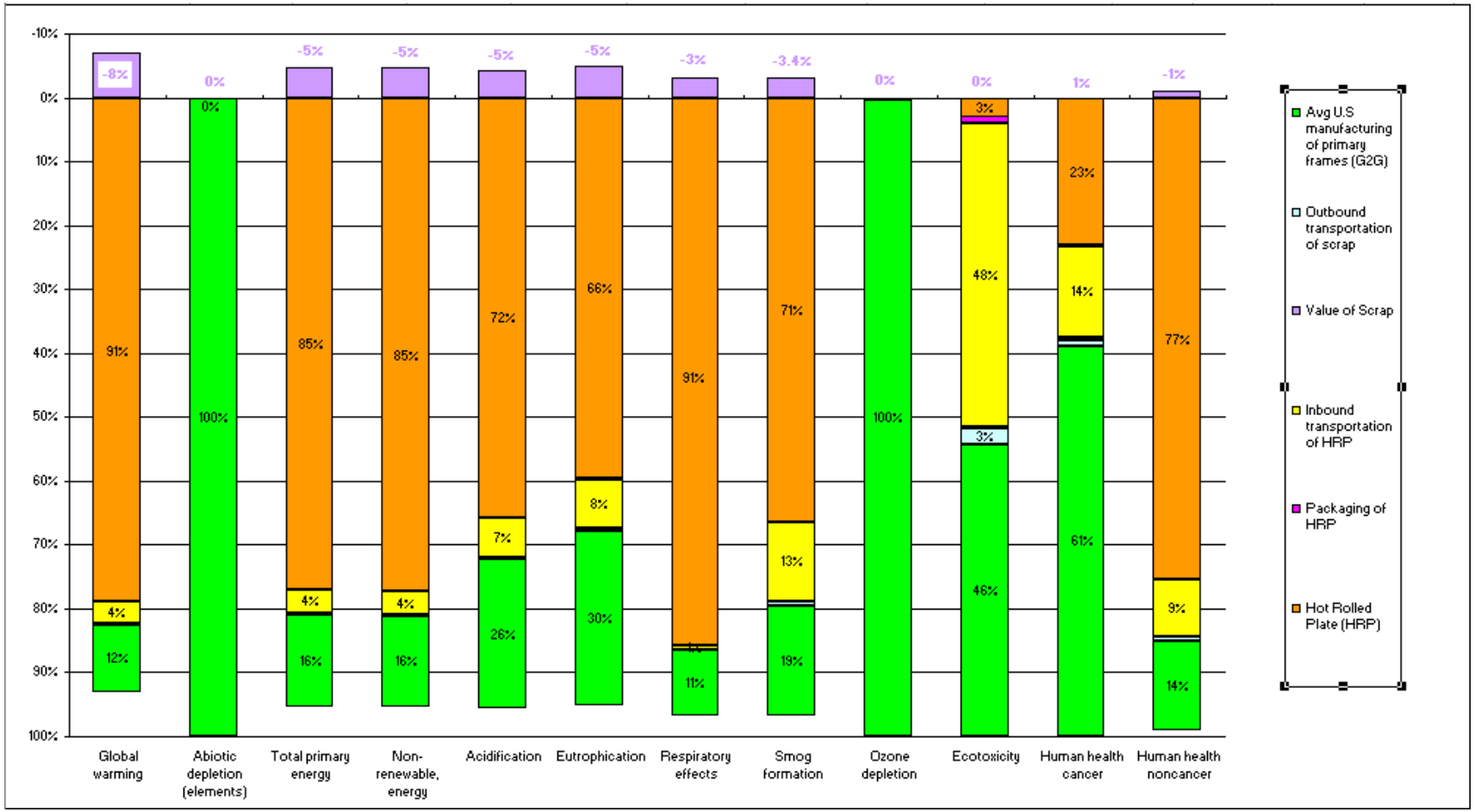
Table 36. Weighted Average Primary Frame C2G LCIA Results – Absolute Basis, per Ton of Primary Frame

Impact category	Unit	Total	Hot Rolled Plate (HRP)	Packaging of HRP	Inbound transportation of HRP	Value of Scrap	Outbound transportation of scrap	Avg U.S manufacturing of primary frames (G2G)
Global warming	kg CO2 eq	**1350.8**	1234.6	1.5	54.3	-108.9	3.0	166.2
Abiotic depletion (elements)	kg Sb eq	**1.0E-05**	0.0E+00	2.8E-09	0.0E+00	0.0E+00	0.0E+00	1.0E-05
Total primary energy	MJ	**18,929**	16,047	45	786	-976	44	2,984
Non-renewable, energy	MJ	**18,878**	16,047	44	786	-976	44	2,933
Acidification	kg SO2 eq	**5.2**	3.8	0.0	0.4	-0.2	0.0	1.3
Eutrophication	kg N eq	**0.235**	0.154	0.001	0.020	-0.013	0.001	0.071
Respiratory effects	kg PM2.5 eq	**0.945**	0.863	0.002	0.007	-0.032	0.000	0.105
Smog formation	kg O3 eq	**74.2**	52.6	0.1	9.8	-2.5	0.5	13.8
Ozone depletion	kg CFC-11 eq	**4.5E-06**	0.0E+00	1.2E-08	2.2E-09	0.0E+00	1.2E-10	4.5E-06
Ecotoxicity	CTUe	**304.9**	8.8	3.7	144.8	0.3	8.1	139.2
Human health cancer	CTUh	**5.5E-06**	1.3E-06	2.6E-08	7.8E-07	3.7E-08	4.4E-08	3.4E-06
Human health noncancer	CTUh	**8.3E-05**	6.3E-05	2.0E-07	7.5E-06	-8.0E-07	4.2E-07	1.2E-05

Table 37. Weighted Average Primary Frame C2G LCIA Results – % Basis, per Ton of Primary Frame

Impact category	Total	Hot Rolled Plate (HRP)	Packaging of HRP	Inbound transportation of HRP	Value of Scrap	Outbound transportation of scrap	Avg U.S manufacturing of primary frames (G2G)
Global warming	**100%**	91%	0%	4%	-8%	0%	12%
Abiotic depletion (elements)	**100%**	0%	0%	0%	0%	0%	100%
Total primary energy	**100%**	85%	0%	4%	-5%	0%	16%
Non-renewable, energy	**100%**	85%	0%	4%	-5%	0%	16%
Acidification	**100%**	72%	0%	7%	-5%	0%	26%
Eutrophication	**100%**	66%	1%	8%	-5%	0%	30%
Respiratory effects	**100%**	91%	0%	1%	-3%	0%	11%
Smog formation	**100%**	71%	0%	13%	-3%	1%	19%
Ozone depletion	**100%**	0%	0%	0%	0%	0%	100%
Ecotoxicity	**100%**	3%	1%	48%	0%	3%	46%
Human health cancer	**100%**	23%	0%	14%	1%	1%	61%
Human health noncancer	**100%**	77%	0%	9%	-1%	1%	14%

Figure 20 Cradle-to-Gate Contribution of Materials and Processes by Impact Categories – % Basis per Ton of Primary Frame



6.2 Secondary Frames

Tables 38 and 39 summarize the cradle-to-gate LCIA results for the production of one ton of secondary frame material on an absolute and percent basis. The cradle-to-gate manufacture of one ton of secondary frame embodies 27,938 MJ of primary energy use and emits in the order of 2,178 kg of greenhouse gas emissions. Similar to primary frames, 99% of the total primary energy used in the cradle-to-gate production of secondary frame elements is derived from non-renewable fossil and nuclear fuels. On-site gate-to-gate effects contribute 7% of the total primary energy and 5% of the net global warming (greenhouse gas) effects with the "value of fabrication scrap" accounted for in the system. The single largest contributor to the cradle-to-gate environmental effects for secondary frame elements was the semi-finished steel input – metal coil – which generally accounted for around 78% or more of the majority of the calculated category indicator impacts.

The effect of packaging and inbound transportation of the semi-finished steel inputs on the LCIA results was generally less than 5% for global warming, primary energy use, and respiratory effect measures, and between 5% and 8% for acidification, eutrophication and smog formation. The outbound transportation of recycled scrap was found to be negligible. The net avoided burden effect of fabrication scrap recycling (the value of scrap) was less than 3%. Figure 21 graphically displays the cradle-to-gate percent contribution of materials and processes to the production of one ton of secondarystructural frame elements.

On a percent input share basis, the steel substrates used in the production of secondary framing were 24% hot rolled coil (bare), 11% pre-painted hot rolled coil, 27% pre-painted cold rolled coil and 38% bare hot-dipped galvanized sheet. Table 40 provides a contribution analysis of the various substrates to and across the weighted average LCIA result, and Figure 22 graphically depicts the contribution by substrate type on a percent basis. Both HDG and prepainted CRC contribute 74% or less to the overall LCIA profile of the total input metal substrate for secondary frames.

Table 41 presents a similar but different profile. It depicts the absolute calculated cradle-to-gate LCIA results for secondary frame elements as though produced from each semi-finished steel input with the gate-to-gate processing effects held constant. Table 42 then contrasts the relative effects of each semi-finished substrate to the weighted average LCIA results. These results may be more appropriately used in future detailed analyses of various secondary frame elements where the upstream steel substrate input is known. Excluding abiotic depletion (elements) and ozone depletion, which are very small values figuratively, it is evident that the differences in various steel substrates varies from about +/- 5% to 15% with hot rolled coil tending to be on the low side of the weighted average value for the LCIA indicators and cold-rolled coil, pre-painted tending to be on the higher side. It is cautioned that no comparative assertion is implied in this analysis. Comparative assertions are only valid when the full "cradle-

to-grave" life cycle has been consistently assessed, including all life cycle stages from manufacturing to use, maintainance and end-of-life disposal, and the assessment has undergone the critical peer review process.

Table 38.Weighted Average Secondary Frame C2G LCIA Results – Absolute Basis, per Ton of Secondary Frame

Impact category	Unit	Total	Input metal coil	Packaging of input metal coil	Inbound transportation of metal coil	Value of Scrap	Outbound transportation of scrap	Avg U.S manufacturing of secondary frames (G2G)
Global warming	kg CO2 eq	**2177.5**	2071.0	1.5	62.0	-70.5	1.6	**112.0**
Abiotic depletion (elements)	kg Sb eq	**6.4E-06**	5.0E-06	2.7E-09	0.0E+00	0.0E+00	0.0E+00	**1.4E-06**
Total primary energy	MJ	**27,938**	25,622	44	897	-632	23	**1,984**
Non-renewable, energy	MJ	**27,901**	25,613	43	897	-632	23	**1,956**
Acidification	kg SO2 eq	**9.0**	7.7	0.0	0.4	-0.2	0.0	**0.9**
Eutrophication	kg N eq	**0.418**	0.363	0.001	0.023	-0.008	0.001	**0.038**
Respiratory effects	kg PM2.5 eq	**0.731**	0.678	0.002	0.008	-0.021	0.000	**0.063**
Smog formation	kg O3 eq	**146.9**	127.8	0.1	11.4	-1.6	0.2	**9.0**
Ozone depletion	kg CFC-11 eq	**3.1E-06**	8.6E-07	1.2E-08	2.5E-09	0.0E+00	6.4E-11	**2.2E-06**
Ecotoxicity	CTUe	**326.6**	70.4	3.6	165.3	0.2	4.3	**82.9**
Human health cancer	CTUh	**7.4E-06**	5.6E-06	2.5E-08	8.9E-07	2.4E-08	2.3E-08	**7.9E-07**
Human health noncancer	CTUh	**6.1E-05**	4.6E-05	1.9E-07	8.6E-06	-5.2E-07	2.2E-07	**6.6E-06**

Table 39.Weighted Average Secondary Frame C2G LCIA Results – % Basis, per Ton of Secondary Frame

Impact category	Unit	Total	Input metal coil	Packaging of input metal coil	Inbound transportation of metal coil	Value of Scrap	Outbound transportation of scrap	Avg U.S manufacturing of secondary frames (G2G)
Global warming	kg CO2 eq	**2177.5**	2071.0	1.5	62.0	-70.5	1.6	**112.0**
Abiotic depletion (elements)	kg Sb eq	**6.4E-06**	5.0E-06	2.7E-09	0.0E+00	0.0E+00	0.0E+00	**1.4E-06**
Total primary energy	MJ	**27,938**	25,622	44	897	-632	23	**1,984**
Non-renewable, energy	MJ	**27,901**	25,613	43	897	-632	23	**1,956**
Acidification	kg SO2 eq	**9.0**	7.7	0.0	0.4	-0.2	0.0	**0.9**
Eutrophication	kg N eq	**0.418**	0.363	0.001	0.023	-0.008	0.001	**0.038**
Respiratory effects	kg PM2.5 eq	**0.731**	0.678	0.002	0.008	-0.021	0.000	**0.063**
Smog formation	kg O3 eq	**146.9**	127.8	0.1	11.4	-1.6	0.2	**9.0**
Ozone depletion	kg CFC-11 eq	**3.1E-06**	8.6E-07	1.2E-08	2.5E-09	0.0E+00	6.4E-11	**2.2E-06**
Ecotoxicity	CTUe	**326.6**	70.4	3.6	165.3	0.2	4.3	**82.9**
Human health cancer	CTUh	**7.4E-06**	5.6E-06	2.5E-08	8.9E-07	2.4E-08	2.3E-08	**7.9E-07**
Human health noncancer	CTUh	**6.1E-05**	4.6E-05	1.9E-07	8.6E-06	-5.2E-07	2.2E-07	**6.6E-06**

Figure 21 Cradle-to-Gate Contribution of Materials and Processes by Impact Categories – % Basis per Ton of Secondary Frame

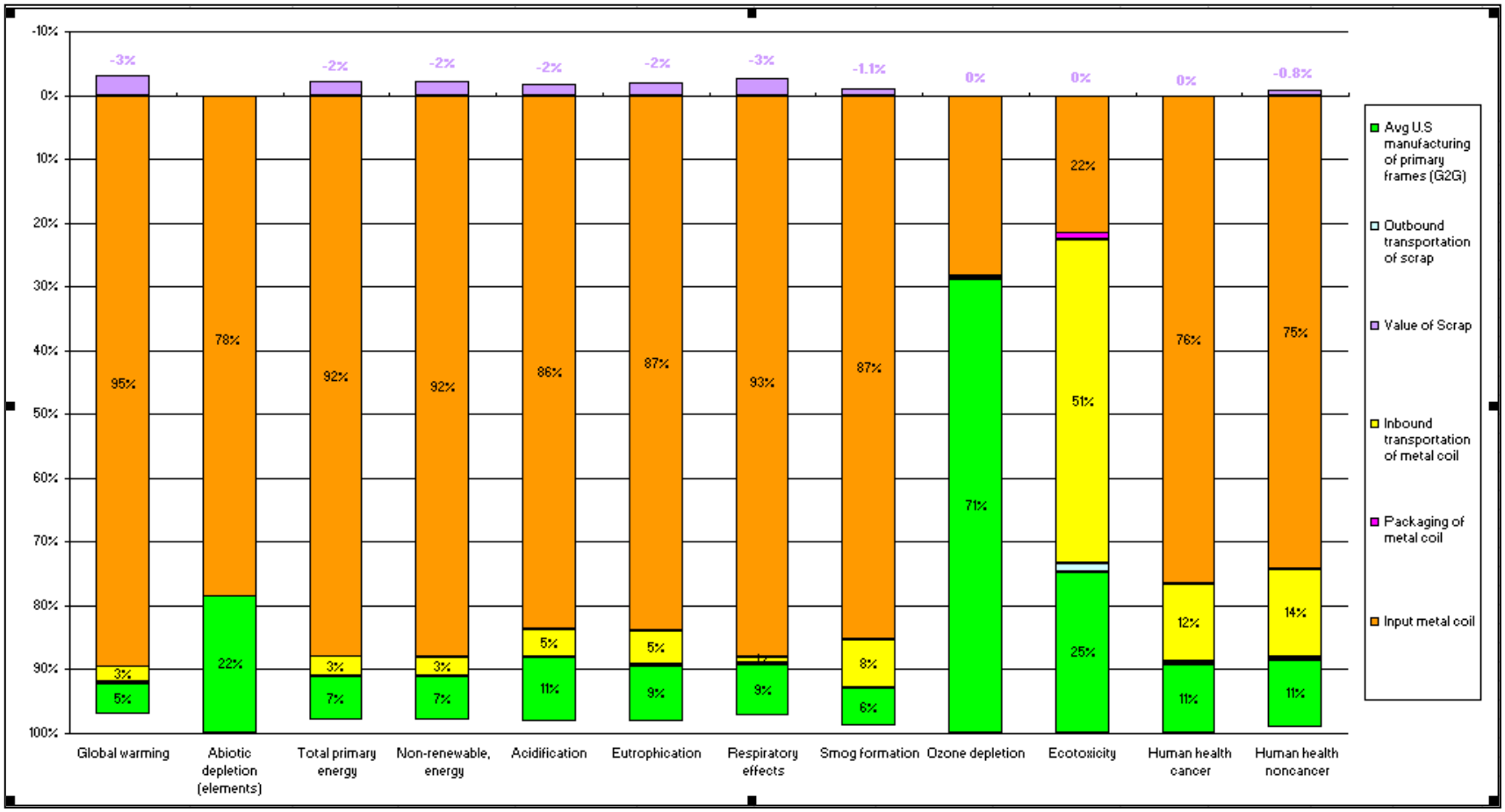


Table 40. Contribution by Steel Substrate Type to "Total Input Metal Substrate" by Impact Categories – Absolute Basis per Ton of Secondary Frames

Impact category	Unit	Total- Input metal coil	Hot Rolled Coil (bare)	Hot Rolled Coil, Pre-painted	Cold Rolled Coil, Pre-painted	Hot Dipped Galvanized (bare)
Global warming	kg CO2 eq	**2071.0**	461.4	224.9	608.9	775.9
Abiotic depletion (elements)	kg Sb eq	**5.0E-06**	0.0E+00	1.4E-06	3.6E-06	0.0E+00
Total primary energy	MJ	**25,622**	5,424	2,697	7,445	10,057
Non-renewable, energy	MJ	**25,613**	5,424	2,695	7,438	10,057
Acidification	kg SO2 eq	**7.7**	1.3	0.8	2.1	3.5
Eutrophication	kg N eq	**0.363**	0.067	0.037	0.104	0.155
Respiratory effects	kg PM2.5 eq	**0.678**	0.122	0.066	0.176	0.314
Smog formation	kg O3 eq	**127.8**	22.1	11.4	33.2	61.1
Ozone depletion	kg CFC-11 eq	**8.6E-07**	0.0E+00	2.5E-07	6.1E-07	0.0E+00
Ecotoxicity	CTUe	**70.4**	2.1	6.2	35.4	26.7
Human health cancer	CTUh	**5.6E-06**	2.5E-07	1.7E-07	2.4E-06	2.8E-06
Human health noncancer	CTUh	**4.6E-05**	8.3E-06	4.4E-06	1.2E-05	2.2E-05

Figure 22 Contribution by Steel Substrate Type to "Total Input Metal Substrate" by Impact Categories – % Basis per Ton of Secondary Frames

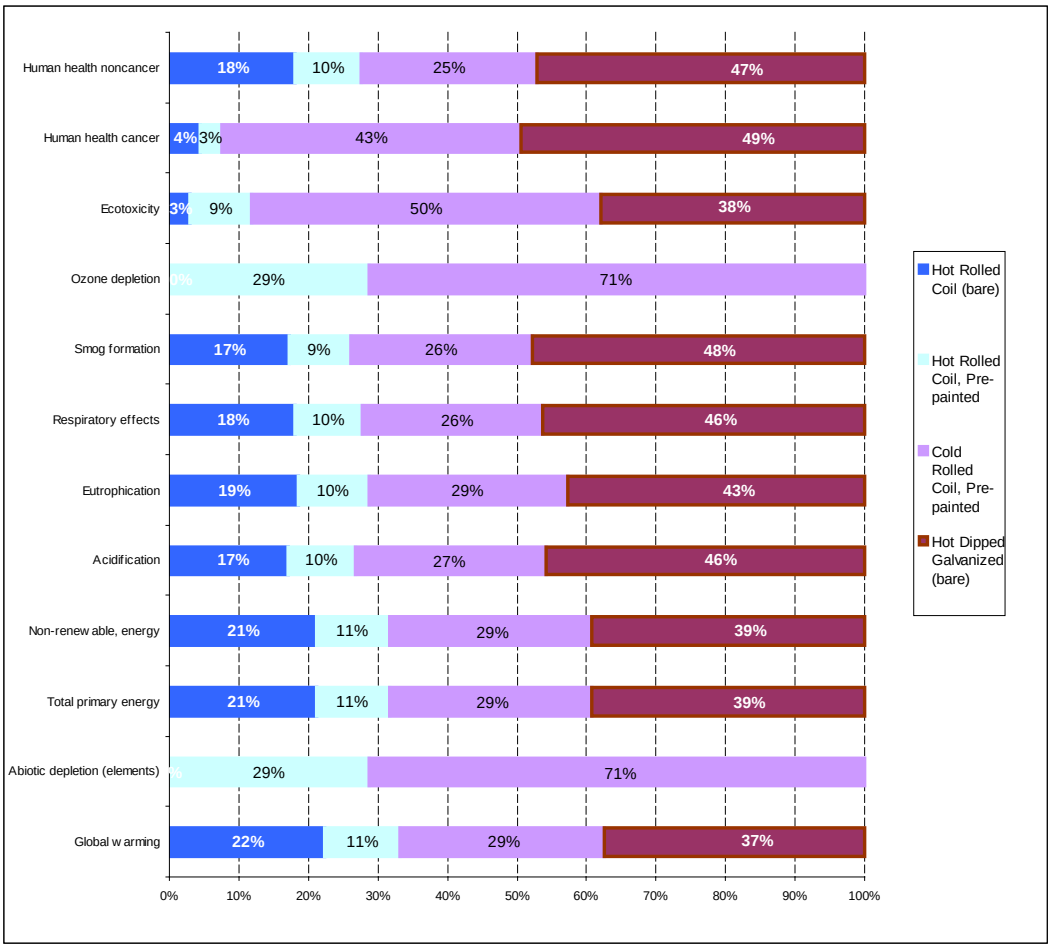


Table 41. Relative C2G LCIA Results by Steel Input Substrate – Absolute Basis, per Ton of Secondary Frame

Impact category	Unit	Avg U.S secondary frames	Secondary frames, CRC Pre-Painted	Secondary frames, HDG (bare)	Secondary frames, HRC Pre-Painted	Secondary frames, HRC (bare)
Global warming	kg CO2 eq	**2177.5**	2326.5	2178.1	2141.2	2023.5
Abiotic depletion (elements)	kg Sb eq	**6.4E-06**	1.4E-05	1.4E-06	1.4E-05	1.4E-06
Total primary energy	MJ	**27,938**	29,461	29,168	26,716	24,850
Non-renewable, energy	MJ	**27,901**	29,409	29,139	26,665	24,822
Acidification	kg SO2 eq	**9.0**	9.0	10.7	8.0	6.7
Eutrophication	kg N eq	**0.418**	0.433	0.468	0.389	0.335
Respiratory effects	kg PM2.5 eq	**0.731**	0.695	0.892	0.647	0.561
Smog formation	kg O3 eq	**146.9**	140.3	182.3	122.3	110.7
Ozone depletion	kg CFC-11 eq	**3.1E-06**	4.4E-06	2.2E-06	4.4E-06	2.2E-06
Ecotoxicity	CTUe	**326.6**	385.1	327.5	312.6	265.1
Human health cancer	CTUh	**7.38E-06**	1.06E-05	9.17E-06	3.31E-06	2.81E-06
Human health noncancer	CTUh	**6.13E-05**	5.76E-05	7.32E-05	5.53E-05	4.96E-05

Table 42. Relative C2G LCIA Results by Steel Input Substrate – % Basis, per Ton of Secondary Frame

Impact category	Avg U.S secondary frames	Secondary frames, CRC Pre-Painted	Secondary frames, HDG (bare)	Secondary frames, HRC Pre-Painted	Secondary frames, HRC (bare)
Global warming	**100%**	107%	100%	98%	93%
Abiotic depletion (elements)	**100%**	225%	22%	225%	22%
Total primary energy	**100%**	105%	104%	96%	89%
Non-renewable, energy	**100%**	105%	104%	96%	89%
Acidification	**100%**	100%	119%	89%	75%
Eutrophication	**100%**	104%	112%	93%	80%
Respiratory effects	**100%**	95%	122%	88%	77%
Smog formation	**100%**	95%	124%	83%	75%
Ozone depletion	**100%**	145%	72%	145%	72%
Ecotoxicity	**100%**	118%	100%	96%	81%
Human health cancer	**100%**	144%	124%	45%	38%
Human health noncancer	**100%**	94%	119%	90%	81%

6.3 Wall Panels

Tables 43 and 44 summarize the cradle-to-gate weighted average LCIA results for the production of one ton of wall cladding panel on an absolute and percent basis. The cradle-to-gate manufacture of one ton of wall cladding panel embodies about 32,563 MJ of primary energy use and emits in the order of 2,486 kg of greenhouse gas emissions. Similar to the production of primary and secondary frames, 99% of the total primary energy used in the cradle-to-gate production of wall cladding panels is derived from non-renewable fossil and nuclear fuels. On-site gate-to-gate effects contribute 4% of the total primary energy and 3% of the net global warming (greenhouse gas) effects with the "value of fabrication scrap" accounted for in the system. Generally gate-to-gate processing contributes 6% or less to the overall LCIA profile for wall cladding panels. The single largest contributor to the cradle-to-gate environmental effects for wall cladding panel was the semi-finished steel input – painted and coated coil – which generally accounted for 90% or more of the supported category indicators.

The effect of packaging and inbound transportation of the semi-finished steel coil inputs on the overall wall panel LCIA results was generally less than 7%. The outbound transportation of recycled scrap was found to be negligible. The net avoided burden effect of fabrication scrap recycling (the value of scrap) was generally less than 3%. Figure 23 graphically displays the cradle-to-gate percent contribution of materials and processes to the production of one ton of wall cladding panels.

On a percent input share basis, the steel substrates used in the production of wall cladding were 12% bare Galvalume®, 46% pre-painted Galvalume®, 26% pre-painted HDG, 0.2% bare HDG and 17% pre-painted CRC. Table 45 provides a contribution analysis of the various substrates to and across the weighted average LCIA result and Figure 24 graphically depicts the contribution by substrate type on a percent basis. Both pre-painted Galvalume® and HDG contribute 80% or less to the overall LCIA profile of the total input metal substrate for wall cladding panels.
The contribution results are pretty much in line with the percent share of mass inputs.

Table 46 presents a similar but different profile. It depicts the absolute calculated cradle-to-gate LCIA results for wall cladding panels as though produced from each semi-finished steel input with the gate-to-gate processing effects held constant. Table 47 then contrasts the relative effects of each semi-finished substrate against the weighted average LCIA results. These results may be more appropriately used in future detailed analyses of various wall cladding panels where the upstream steel substrate input is known. Excluding abiotic depletion (elements) and ozone depletion, which are very small values figuratively, it is evident that the differences in types of possible steel substrates varies from +/- 5% to 15% with pre-painted cold rolled coil and hot dip galvanized tending to be on the low side of the weighted average value for the LCIA indicators and pre-painted Galvalume® based wall panels tending to be on the

higher side. Again, it is cautioned that no comparative assertion is implied in this analysis. Comparative assertions are only valid when the full “cradle-to-grave” life cycle has been consistently assessed, including all life cycle stages from manufacturing to use, maintainance and end-of-life disposal, and the assessment has undergone critical peer review process.

Table 43.Weighted Average Wall Panels C2G LCIA Results – Absolute Basis, per Ton of Wall Panel

Impact category	Unit	Total	Input metal coil	Packaging of input metal coil	Inbound transportation of metal coil	Value of Scrap	Outbound transportation of scrap	Avg U.S manufacturing of wall panels (G2G)
Global warming	kg CO2 eq	**2486.2**	2419.3	1.5	77.1	-85.1	1.8	**71.6**
Abiotic depletion (elements)	kg Sb eq	**6.5E-02**	6.5E-02	2.7E-09	0.0E+00	0.0E+00	0.0E+00	**8.2E-08**
Total primary energy	MJ	**32,562.6**	30,805	44	1,120	-763	26	**1,330**
Non-renewable, energy	MJ	**32,410**	30,670	44	1,120	-763	26	**1,313**
Acidification	kg SO2 eq	**11.3**	10.4	0.0	0.4	-0.2	0.0	**0.6**
Eutrophication	kg N eq	**0.536**	0.501	0.001	0.024	-0.010	0.001	**0.019**
Respiratory effects	kg PM2.5 eq	**0.879**	0.847	0.002	0.009	-0.025	0.000	**0.046**
Smog formation	kg O3 eq	**167.1**	150.8	0.1	11.8	-2.0	0.3	**6.2**
Ozone depletion	kg CFC-11 eq	**1.0E-05**	9.5E-06	1.2E-08	3.1E-09	0.0E+00	7.1E-11	**4.6E-07**
Ecotoxicity	CTUe	**607.2**	331.7	3.6	206.4	0.2	4.7	**60.5**
Human health cancer	CTUh	**1.2E-05**	1.0E-05	2.5E-08	1.1E-06	2.9E-08	2.6E-08	**3.3E-07**
Human health noncancer	CTUh	**8.5E-05**	7.1E-05	1.9E-07	1.1E-05	-6.3E-07	2.5E-07	**3.7E-06**

Table 44.Weighted Average Wall Panels C2G LCIA Results – % Basis, per Ton of Wall Panel

Impact category	Total	Input metal coil	Packaging of input metal coil	Inbound transportation of metal coil	Value of Scrap	Outbound transportation of scrap	Avg U.S manufacturing of wall panels (G2G)
Global warming	**100%**	97%	0%	3%	-3%	0%	3%
Abiotic depletion (elements)	**100%**	100%	0%	0%	0%	0%	0%
Total primary energy	**100%**	95%	0%	3%	-2%	0%	4%
Non-renewable, energy	**100%**	95%	0%	3%	-2%	0%	4%
Acidification	**100%**	92%	0%	4%	-2%	0%	6%
Eutrophication	**100%**	93%	0%	5%	-2%	0%	4%
Respiratory effects	**100%**	96%	0%	1%	-3%	0%	5%
Smog formation	**100%**	90%	0%	7%	-1%	0%	4%
Ozone depletion	**100%**	95%	0%	0%	0%	0%	5%
Ecotoxicity	**100%**	55%	1%	34%	0%	1%	10%
Human health cancer	**100%**	87%	0%	10%	0%	0%	3%
Human health noncancer	**100%**	83%	0%	13%	-1%	0%	4%

Figure 23 Cradle-to-Gate Contribution of Materials and Processes by Impact Categories – % Basis per Ton of Wall Cladding

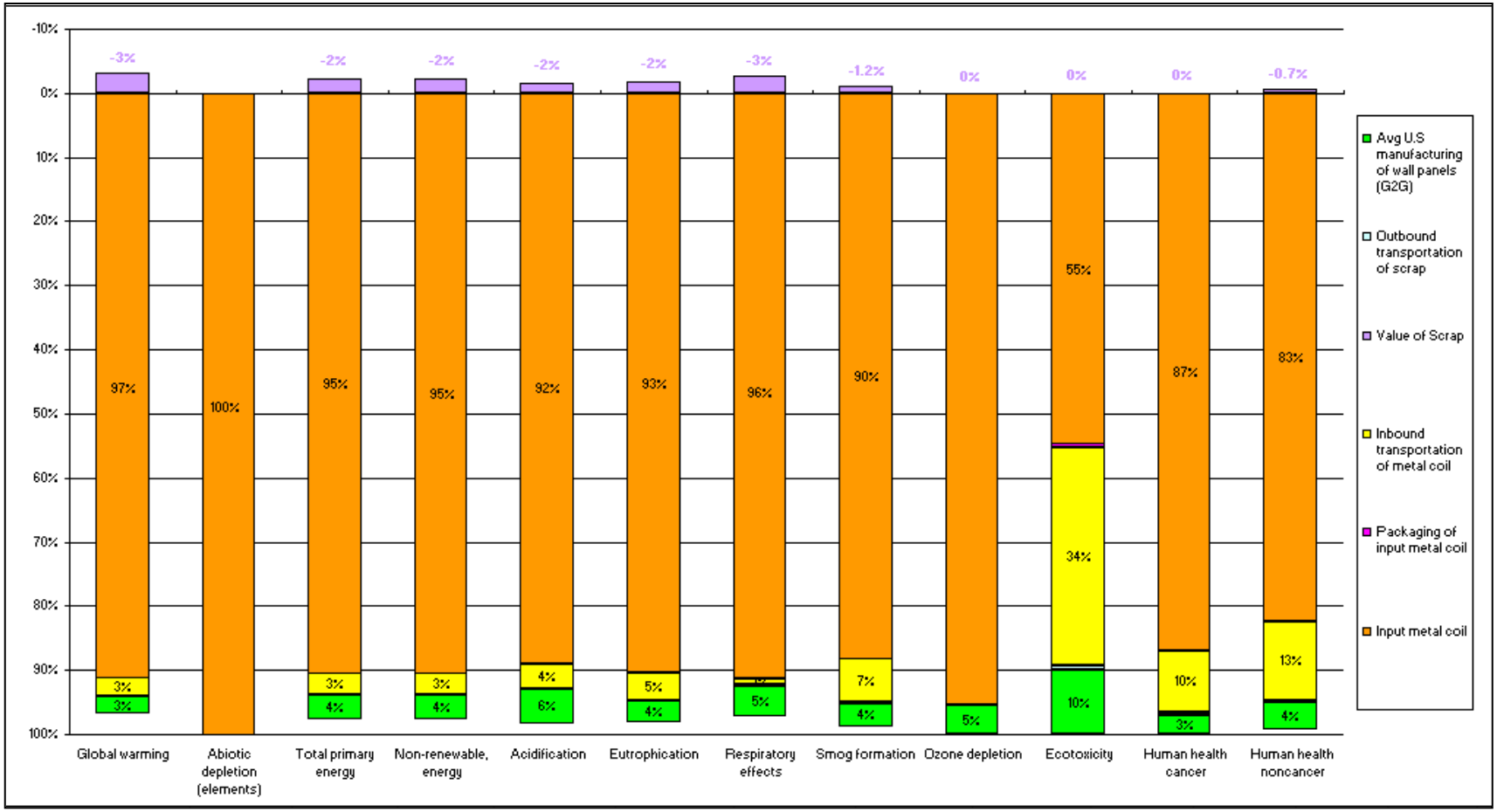


Table 45. Contribution by Steel Substrate Type to "Total Input Metal Substrate" by Impact Categories – Absolute Basis per Ton of Wall Panels

Impact category	Unit	Total- Input metal coil	Cold Rolled Coil, Pre-painted	Hot Dipped Galvanized, Pre-painted	Hot Dipped Galvanized (bare)	Galvalume®, Pre-painted	Galvalume® (bare)
Global warming	kg CO2 eq	**2419.3**	371.3	573.9	4.1	1182.6	287.4
Abiotic depletion (elements)	kg Sb eq	**6.5E-02**	2.2E-06	3.4E-06	0.0E+00	5.2E-02	1.3E-02
Total primary energy	MJ	**30,805**	4,540	7,544	54	15,056	3,611
Non-renewable, energy	MJ	**30,670**	4,536	7,538	54	14,954	3,589
Acidification	kg SO2 eq	**10.4**	1.3	2.8	0.0	5.1	1.1
Eutrophication	kg N eq	**0.501**	0.063	0.123	0.001	0.255	0.058
Respiratory effects	kg PM2.5 eq	**0.847**	0.107	0.244	0.002	0.402	0.092
Smog formation	kg O3 eq	**150.8**	20.3	46.2	0.3	68.0	15.9
Ozone depletion	kg CFC-11 eq	**9.5E-06**	3.7E-07	5.9E-07	0.0E+00	7.0E-06	1.5E-06
Ecotoxicity	CTUe	**331.7**	21.6	31.5	0.1	227.3	51.2
Human health cancer	CTUh	**1.0E-05**	1.5E-06	2.1E-06	1.5E-08	5.2E-06	1.3E-06
Human health noncancer	CTUh	**7.1E-05**	7.1E-06	1.7E-05	1.2E-07	3.8E-05	9.0E-06

Figure 24 Contribution by Steel Substrate Type to "Total Input Metal Substrate" by Impact Categories –% Basis per Ton of Wall Panels

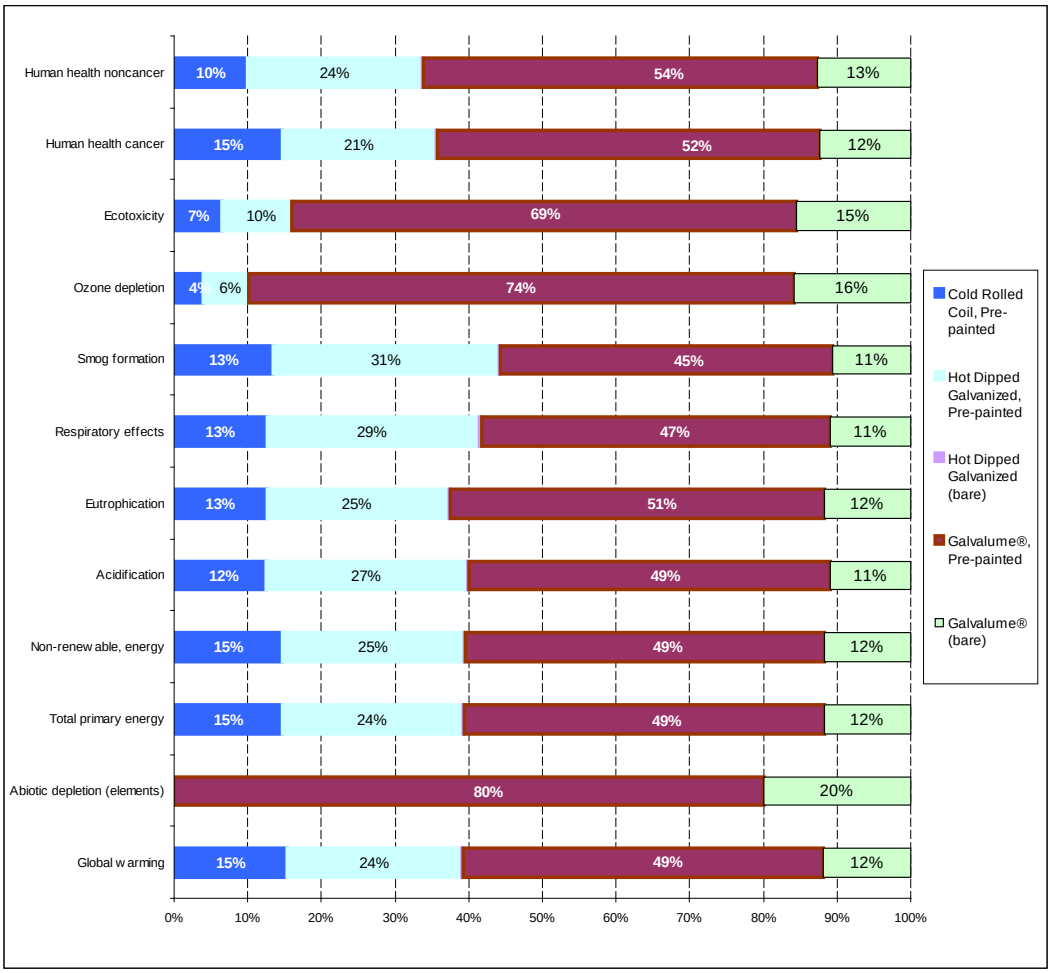


Table 46. Relative C2G LCIA Results by Steel Input Substrate – Absolute Basis, per Ton of Wall Panel

Impact category	Unit	Avg U.S wall panels	Wall panels, CRC Pre-Painted	Wall panels, Galvalume® (bare)	Wall panels, Galvalume® Pre-Painted	Wall panels, HDG (bare)	Wall panels, HDG Pre-Painted
Global warming	kg CO2 eq	**2486.2**	2309.3	2524.2	2657.6	2159.4	2282.7
Abiotic depletion (elements)	kg Sb eq	**6.5E-02**	1.3E-05	1.1E-01	1.1E-01	8.5E-08	1.3E-05
Total primary energy	MJ	**32,563**	29,176	32,631	34,741	28,880	30,886
Non-renewable, energy	MJ	**32,410**	29,135	32,418	34,499	28,862	30,844
Acidification	kg SO2 eq	**11.3**	8.7	10.6	12.1	10.5	11.9
Eutrophication	kg N eq	**0.536**	0.418	0.534	0.595	0.453	0.512
Respiratory effects	kg PM2.5 eq	**0.879**	0.680	0.818	0.912	0.879	0.975
Smog formation	kg O3 eq	**167.1**	138.8	152.4	165.4	181.2	195.0
Ozone depletion	kg CFC-11 eq	**1.0E-05**	2.7E-06	1.3E-05	1.6E-05	4.7E-07	2.7E-06
Ecotoxicity	CTUe	**607.2**	405.7	713.5	773.3	347.5	397.3
Human health cancer	CTUh	**1.16E-05**	1.05E-05	1.22E-05	1.30E-05	9.02E-06	9.71E-06
Human health noncancer	CTUh	**8.53E-05**	5.71E-05	9.08E-05	9.77E-05	7.29E-05	7.92E-05

Table 47. Relative C2G LCIA Results by Steel Input Substrate – % Basis, per Ton of Wall Panel

Impact category	Avg U.S wall panels	Wall panels, CRC Pre-Painted	Wall panels, Galvalume® (bare)	Wall panels, Galvalume® Pre-Painted	Wall panels, HDG (bare)	Wall panels, HDG Pre-Painted
Global warming	**100%**	93%	102%	107%	87%	92%
Abiotic depletion (elements)	**100%**	0%	171%	175%	0%	0%
Total primary energy	**100%**	90%	100%	107%	89%	95%
Non-renewable, energy	**100%**	90%	100%	106%	89%	95%
Acidification	**100%**	77%	94%	107%	92%	105%
Eutrophication	**100%**	78%	99%	111%	84%	95%
Respiratory effects	**100%**	77%	93%	104%	100%	111%
Smog formation	**100%**	83%	91%	99%	108%	117%
Ozone depletion	**100%**	27%	133%	159%	5%	27%
Ecotoxicity	**100%**	67%	117%	127%	57%	65%
Human health cancer	**100%**	90%	105%	112%	78%	84%
Human health noncancer	**100%**	67%	106%	114%	85%	93%

6.4 Roof Panels

Tables 48 and 49 summarize the cradle-to-gate weighted average LCIA results for the production of one ton of roof cladding panels on an absolute and percent basis. The cradle-to-gate manufacture of one ton of roof cladding panels embodies about 32,203 MJ of primary energy use and emits in the order of 2,486 kg of greenhouse gas emissions. Similar to the production of wall cladding panels, 99% of the total primary energy used in the cradle-to-gate production of roof cladding panels is derived from non-renewable fossil and nuclear fuels. On-site gate-to-gate effects contribute 4% of the total primary energy and 3% of the net global warming (greenhouse gas) effects with the "value of fabrication scrap" accounted for in the system. Generally gate-to-gate processing contributes 7% or less to the overall LCIA profile for roof cladding panels. The single largest contributor to the cradle-to-gate environmental effects for roof cladding panels was the semi-finished steel input – painted and coated coil – which generally accounted for 89% or more of the supported category indicators.

The effect of packaging and inbound transportation of the semi-finished steel coil inputs on the overall roof panel LCIA results was generally less than 5% for global warming, primary energy use, abiotic depletion (elements), acidification, eutrophication and respiratory effect measures, and 7% for smog formation. The outbound transportation of recycled scrap was found to be negligible. The net avoided burden effect of fabrication scrap recycling (the value of scrap) was 3% or less. Figure 25 graphically displays the cradle-to-gate percent contribution of materials and processes to the production of one ton of roof cladding panels.

On a percent input share basis, the steel substrates used in the production of roof cladding were 42% bare Galvalume®, 32% pre-painted Galvalume®, 6% pre-painted HDG, 3% bare HDG and 17% pre-painted CRC. Table 50 provides a contribution analysis of the various substrates to and across the weighted average LCIA results for roof panels and Figure 26 graphically depicts the contribution by substrate type on a percent basis. Both bare and pre-painted Galvalume® contribute 75% or more to the overall LCIA profile of the total input metal substrate for roof cladding panels.

Table 51 depicts the absolute calculated cradle-to-gate LCIA results for roof cladding panels as though produced from each semi-finished steel input with the gate-to-gate processing effects held constant. Table 52 then contrasts the relative effects of each semi-finished substrate against the weighted average roof panel LCIA results on a percent basis. These results may be more appropriately used in future detailed analyses of various roof cladding panels where the upstream steel substrate input is known. Excluding abiotic depletion (elements) and ozone depletion, which are very small values figuratively, it is evident that the differences in roof panels made with different steel substrates varies from +/- 5% to 15%, with pre-painted cold rolled coil and hot dip galvanized tending to be on the low side of the weighted average value for the LCIA indicators and pre-painted Galvalume® based roof panels tending to be on the higher side.

Again, it is cautioned that no comparative assertion is implied in this analysis. Comparative assertions are only valid when the full “cradle-to-grave” life cycle has been consistently assessed, including all life cycle stages from manufacturing to use, maintainance and end-of-life disposal and the assessment has undergone critical peer review process.

Table 48.Weighted Average Roof Panels C2G LCIA Results – Absolute Basis, per Ton of Roof Panel

Impact category	Unit	Total	Input metal coil	Packaging of input metal coil	Inbound transportation of metal coil	Value of Scrap	Outbound transportation of scrap	Avg U.S manufacturing of roof panels (G2G)
Global warming	kg CO2 eq	**2486.4**	2411.0	1.5	67.1	-68.3	2.4	**72.6**
Abiotic depletion (elements)	kg Sb eq	**8.3E-02**	8.3E-02	2.7E-09	0.0E+00	0.0E+00	0.0E+00	**3.0E-05**
Total primary energy	MJ	**32,203**	30,404	44	975	-612	36	**1,357**
Non-renewable, energy	MJ	**32,026**	30,246	43	975	-612	36	**1,338**
Acidification	kg SO2 eq	**10.7**	9.8	0.0	0.4	-0.2	0.0	**0.6**
Eutrophication	kg N eq	**0.526**	0.489	0.001	0.021	-0.008	0.001	**0.022**
Respiratory effects	kg PM2.5 eq	**0.830**	0.795	0.002	0.008	-0.020	0.000	**0.046**
Smog formation	kg O3 eq	**156.1**	139.6	0.1	10.3	-1.6	0.4	**7.3**
Ozone depletion	kg CFC-11 eq	**1.2E-05**	1.1E-05	1.2E-08	2.7E-09	0.0E+00	9.9E-11	**8.7E-07**
Ecotoxicity	CTUe	**622.4**	372.0	3.6	179.7	0.2	6.5	**60.4**
Human health cancer	CTUh	**1.2E-05**	1.0E-05	2.5E-08	9.7E-07	2.3E-08	3.5E-08	**4.3E-07**
Human health noncancer	CTUh	**8.4E-05**	7.1E-05	1.9E-07	9.4E-06	-5.0E-07	3.4E-07	**3.6E-06**

Table 49.Weighted Average Roof Panels C2G LCIA Results – % Basis, per Ton of Roof Panel

Impact category	Total	Input metal coil	Packaging of input metal coil	Inbound transportation of metal coil	Value of Scrap	Outbound transportation of scrap	Avg U.S manufacturing of roof panels (G2G)
Global warming	**100%**	97%	0%	3%	-3%	0%	3%
Abiotic depletion (elements)	**100%**	100%	0%	0%	0%	0%	0%
Total primary energy	**100%**	94%	0%	3%	-2%	0%	4%
Non-renewable, energy	**100%**	94%	0%	3%	-2%	0%	4%
Acidification	**100%**	92%	0%	4%	-1%	0%	6%
Eutrophication	**100%**	93%	0%	4%	-2%	0%	4%
Respiratory effects	**100%**	96%	0%	1%	-2%	0%	6%
Smog formation	**100%**	89%	0%	7%	-1%	0%	5%
Ozone depletion	**100%**	92%	0%	0%	0%	0%	7%
Ecotoxicity	**100%**	60%	1%	29%	0%	1%	10%
Human health cancer	**100%**	87%	0%	8%	0%	0%	4%
Human health noncancer	**100%**	85%	0%	11%	-1%	0%	4%

Figure 25 Cradle-to-Gate Contribution of Materials and Processes by Impact Categories – % Basis per Ton of Roof Cladding

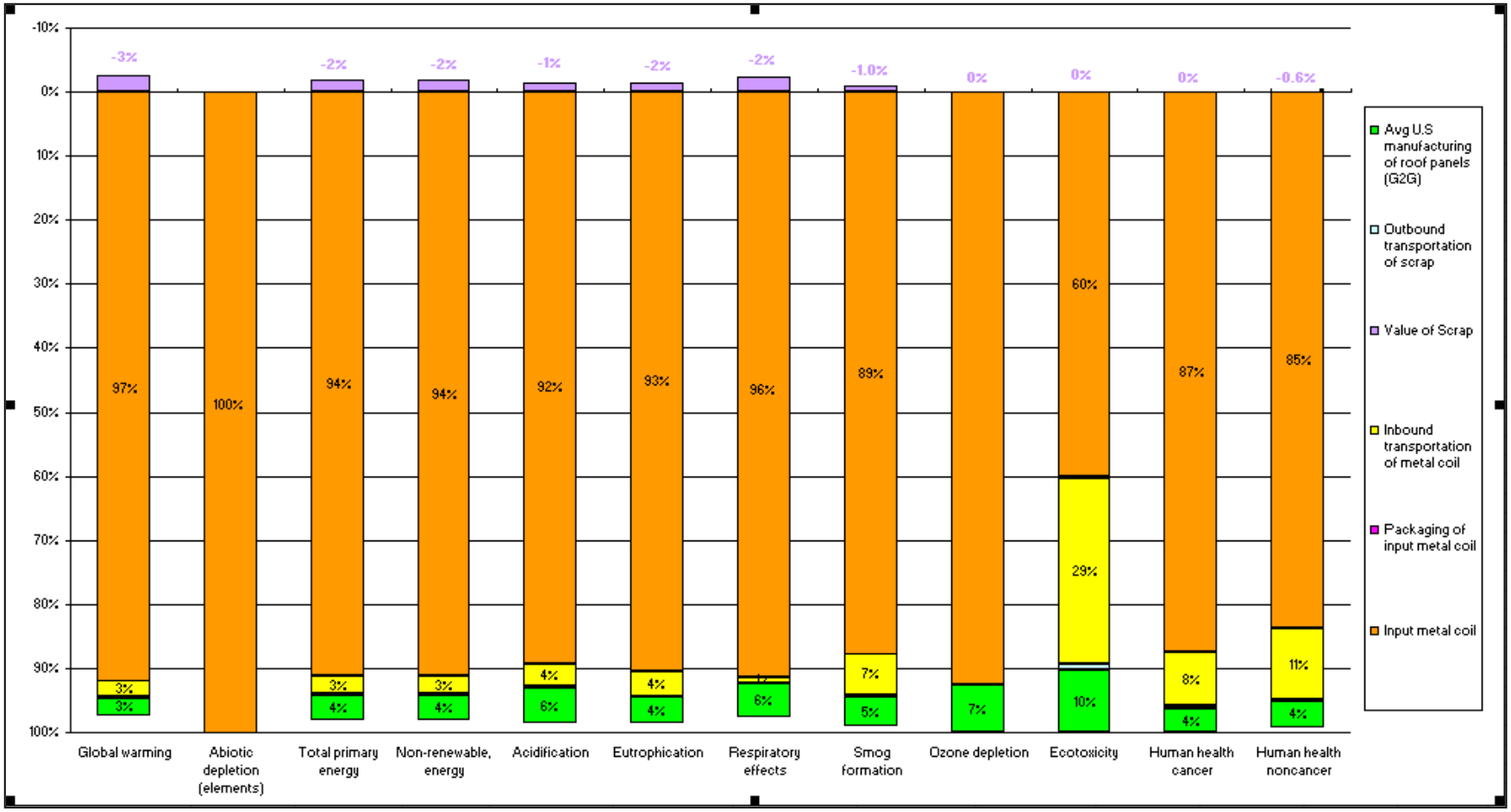


Table 50. Contribution by Steel Substrate Type to "Total Input Metal Substrate" by Impact Categories – Absolute Basis per Ton of Roof Panels

Impact category	Unit	Total- Input metal coil	Cold Rolled Coil, Pre-	Hot Dipped Galvanized, Pre-painted	Hot Dipped Galvanized (bare)	Galvalume®, Pre-painted	Galvalume® (bare)
Global warming	kg CO2 eq	**2411.0**	369.4	120.6	69.4	827.4	1024.3
Abiotic depletion (elements)	kg Sb eq	**8.3E-02**	2.2E-06	7.1E-07	0.0E+00	3.6E-02	4.6E-02
Total primary energy	MJ	**30,404**	4,516	1,586	899	10,533	12,869
Non-renewable, energy	MJ	**30,246**	4,513	1,584	899	10,462	12,788
Acidification	kg SO2 eq	**9.8**	1.3	0.6	0.3	3.6	4.1
Eutrophication	kg N eq	**0.489**	0.063	0.026	0.014	0.179	0.208
Respiratory effects	kg PM2.5 eq	**0.795**	0.107	0.051	0.028	0.281	0.327
Smog formation	kg O3 eq	**139.6**	20.2	9.7	5.5	47.6	56.7
Ozone depletion	kg CFC-11 eq	**1.1E-05**	3.7E-07	1.2E-07	0.0E+00	4.9E-06	5.3E-06
Ecotoxicity	CTUe	**372.0**	21.5	6.6	2.4	159.0	182.6
Human health cancer	CTUh	**1.0E-05**	1.5E-06	4.5E-07	2.5E-07	3.7E-06	4.5E-06
Human health noncancer	CTUh	**7.1E-05**	7.1E-06	3.5E-06	1.9E-06	2.7E-05	3.2E-05

Figure 26 Contribution by Steel Substrate Type to "Total Input Metal Substrate" by Impact Categories – % Basis per Ton of Roof Panels

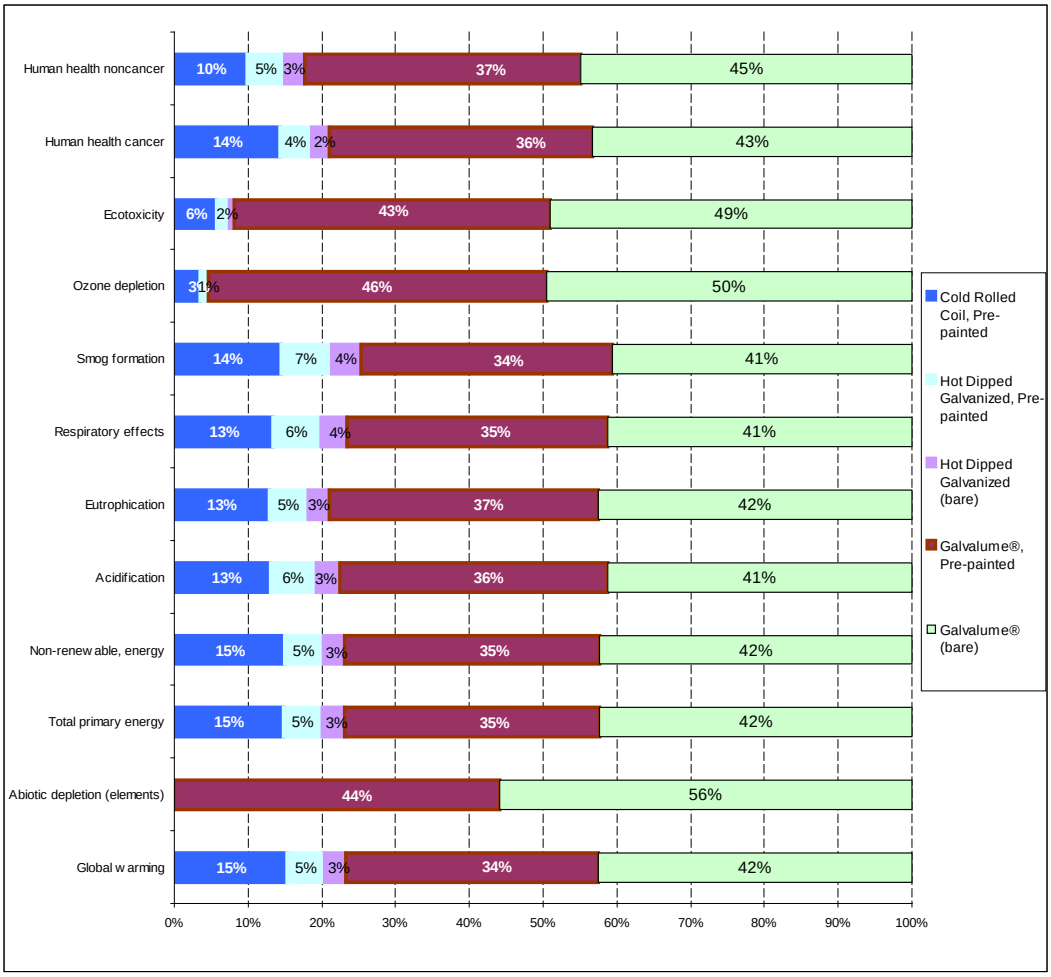


Table 51. Relative C2G LCIA Results by Steel Input Substrate – Absolute Basis, per Ton of Roof Panel

Impact category	Unit	Avg U.S roof panels	Roof panels, CRC Pre-Painted	Roof panels, Galvalume® (bare)	Roof panels, Galvalume® Pre-Painted	Roof panels, HDG (bare)	Roof panels, HDG Pre-Painted
Global warming	kg CO2 eq	**2486.4**	2292.0	2504.5	2636.3	2143.8	2265.7
Abiotic depletion (elements)	kg Sb eq	**8.3E-02**	4.3E-05	1.1E-01	1.1E-01	3.0E-05	4.3E-05
Total primary energy	MJ	**32,203**	28,903	32,318	34,403	28,610	30,592
Non-renewable, energy	MJ	**32,026**	28,860	32,106	34,163	28,590	30,550
Acidification	kg SO2 eq	**10.7**	8.6	10.5	11.9	10.3	11.7
Eutrophication	kg N eq	**0.526**	0.416	0.530	0.590	0.450	0.508
Respiratory effects	kg PM2.5 eq	**0.830**	0.676	0.812	0.906	0.873	0.968
Smog formation	kg O3 eq	**156.1**	137.5	151.0	163.8	179.5	193.0
Ozone depletion	kg CFC-11 eq	**1.2E-05**	3.1E-06	1.4E-05	1.6E-05	8.9E-07	3.1E-06
Ecotoxicity	CTUe	**622.4**	379.2	683.3	742.5	321.6	370.8
Human health cancer	CTUh	**1.18E-05**	1.03E-05	1.21E-05	1.28E-05	8.90E-06	9.58E-06
Human health noncancer	CTUh	**8.41E-05**	5.54E-05	8.87E-05	9.54E-05	7.09E-05	7.72E-05

Table 52. Relative C2G LCIA Results by Steel Input Substrate – % Basis, per Ton of Roof Panel

Impact category	Avg U.S roof panels	Roof panels, CRC Pre-Painted	Roof panels, Galvalume® (bare)	Roof panels, Galvalume® Pre-Painted	Roof panels, HDG (bare)	Roof panels, HDG Pre-Painted
Global warming	**100%**	92%	101%	106%	86%	91%
Abiotic depletion (elements)	**100%**	0%	133%	136%	0%	0%
Total primary energy	**100%**	90%	100%	107%	89%	95%
Non-renewable, energy	**100%**	90%	100%	107%	89%	95%
Acidification	**100%**	81%	98%	111%	96%	110%
Eutrophication	**100%**	79%	101%	112%	86%	97%
Respiratory effects	**100%**	81%	98%	109%	105%	117%
Smog formation	**100%**	88%	97%	105%	115%	124%
Ozone depletion	**100%**	27%	116%	139%	8%	27%
Ecotoxicity	**100%**	61%	110%	119%	52%	60%
Human health cancer	**100%**	88%	102%	109%	76%	81%
Human health noncancer	**100%**	66%	105%	114%	84%	92%

6.5 Project Summary MS Excel Spreadsheet

The cradle-to-gate Life Cycle Inventories for the four (4) selected MBMA products (Tables S1 to S4) and North American semi-finished steel LCI data (Tables S5) are summarized in the *"MBMA LCA Study- Summary of LCI Profiles"* MS Excel spreadsheet as follows:

Table S1 **Cradle-to-gate LCI Results for 1 short ton of *primary frames* - US weighted average profile**

Table S2 **Cradle-to-gate LCI Results for 1 short ton of secondary frames- US weighted average profile;**

Table S2.1 Cradle-to-gate LCI Results for 1 short ton of secondary frames - CRC Pre-Painted (metal substrate)

Table S2.2 Cradle-to-gate LCI Results for 1 short ton of secondary frames - HDG (metal substrate)

Table S2.3 Cradle-to-gate LCI Results for 1 short ton of secondary frames - HRC Pre-Painted (metal substrate)

Table S2.4 Cradle-to-gate LCI Results for 1 short ton of secondary frames - HRC (metal substrate)

Table S3 **Cradle-to-gate LCI Results for 1 short ton of wall panels- US weighted average profile;**

Table S3.1 Cradle-to-gate LCI Results for 1 short ton of wall panels - CRC Pre-Painted (metal substrate)

Table S3.2 Cradle-to-gate LCI Results for 1 short ton of wall panels – Galvalume® (metal substrate)

Table S3.3 Cradle-to-gate LCI Results for 1 short ton of wall panels – Galvalume® Pre-Painted (metal substrate)

Table S3.4 Cradle-to-gate LCI Results for 1 short ton of wall panels – HDG (metal substrate)

Table S3.5 Cradle-to-gate LCI Results for 1 short ton of wall panels – HDG Pre-Painted (metal substrate)

Table S4 Cradle-to-gate LCI Results for 1 short ton of roof panels - US weighted average profile

Table S4.1 Cradle-to-gate LCI Results for 1 short ton of roof panels - CRC Pre-Painted (metal substrate)

Table S4.2 Cradle-to-gate LCI Results for 1 short ton of roof panels – Galvalume® (metal substrate)

Table S4.3 Cradle-to-gate LCI Results for 1 short ton of roof panels – Galvalume® Pre-Painted (metal substrate)

Table S4.4 Cradle-to-gate LCI Results for 1 short ton of roof panels – HDG (metal substrate)

Table S4.5 Cradle-to-gate LCI Results for 1 short ton of roof panels – HDG Pre-Painted (metal substrate)

Table S5 2013 North American WSA LCI profiles of semi-finished steel products used in this LCA study: hot rolled plate, hot rolled coil, hot dipped galvanized steel, cold rolled coil and “value of scrap”

These profiles are generated with SimaPro LCA Software v.7.3.3, 2013 and consist of input resources and output emissions to air, water and land and are available upon request at:

Metal Building Manufacturers Association (MBMA)
1300 Sumner Avenue
Cleveland, OH 44115-2851
Phone: (216) 241-7333
Fax: (216) 241-0105
Internet: www.mbma.com
Email: mbma@mbma.com

7 LCIA Interpretation

Interpretation is the phase of LCA in which the findings from the inventory analysis and the impact assessment are brought together and significant issues are identified and considered in the context of the study goal and scope. In addition, the study's completeness, consistency of all applied information, and sensitivity to key assumptions or parameters as they relate to the goal and scope of the study, are evaluated. Lastly, the interpretation phase ends by drawing conclusions, stating the study's limitations and making recommendations for further study (as per Clause 4.5.1.1, ISO 14044:2006).

7.1 Identification of the significant issues

ISO recommends several possible methods to identify significant issues such as dominance, influence, and contribution analysis. Based on established LCA practices, the following analytical techniques were applied for the interpretation phase of this study:

- *Dominance Analysis:* in which remarkable or significant contributions are examined [2].
- *Influence Analysis*: in which the possibility of influencing the environmental issues is examined for the product system of interest [2].
- *Contribution Analysis*: in which the contribution of life cycle stages, groups of processes or specific substances to the total results are examined [2].

  The previous section of this report detailed the key contributing life cycle stages, processes, materials, energy inputs and transportation modes for each product system. In this section, the contribution analysis was limited to the examination of the three major contributing flows for each of the selected impact indicators categories. The overall findings of the contribution analysis are highlighted in the conclusion section.
- *Sensitivity analysis: which determines the influence of assumptions, methods and data on the results [2].*

7.1.1 Dominance Analysis- Primary and Secondary Frames

Tables 53 and 54 present the three most significant inputs that dominate the overall LCIA category indicators for the cradle-to-gate production of primary structural elements on an absolute and percent basis. Similarly, Tables 55 and 56 show that the same three inputs (upstream semi-finished steel, on-site electricity use and inbound transportation of semi-finished steel inputs) also dominate the overall LCIA category indicator results for the cradle-to-gate production of secondary structural frame elements.

The use of semi-finished steel inputs dominates the LCIA indicator results for both primary and secondary structural frame elements varying from a low of 66% and 87% eutrophication to a high of 91% and 95% global warming, for primary and secondary frames, respectively.

Electricity use at the MBMA plant ranked a distant second in terms of dominance effect, typically accounting for 11% or less of any one category impact. Inbound transportation of the semi-finished steel input was the next most dominant process contributing to the overall cradle-to-gate LCIA results, but with few exceptions it accounted for less than 10% of the total impact. The impact of the remaining processes is shown in the last column (see tables 53 to 56) and generally was minimal (with the exception of abiotic depletion, elements and ozone depletion).

Table 53. Dominance Analysis: C2G Primary Structural Product System – Absolute Basis, per Ton

Impact category	Unit	Total	Hot Rolled Plate (HRP)	Electricity generation process-consumed at MBMA plants	Inbound transportation of HRP by truck	Rest
Global warming	kg CO2 eq	**1350.8**	1234.6	118.4	50.8	-53.1
Abiotic depletion (elements)	kg Sb eq	**1.0E-05**	0.0E+00	3.5E-11	0	1.0E-05
Total primary energy	MJ	**18,929**	16,047	2,083	738	61
Non-renewable, energy	MJ	**18,878**	16,047	2,042	738	51
Acidification	kg SO2 eq	**5.2**	3.8	1.0	0.3	0.2
Eutrophication	kg N eq	**0.235**	0.154	0.014	0.016	0.050
Respiratory effects	kg PM2.5 eq	**0.945**	0.863	0.065	0.006	0.011
Smog formation	kg O3 eq	**74.2**	52.6	7.8	7.8	6.0
Ozone depletion	kg CFC-11 eq	**4.5E-06**	0.0E+00	7.6E-09	2.0E-09	4.5E-06
Ecotoxicity	CTUe	**304.9**	8.8	49.2	136.0	110.9
Human health cancer	CTUh	**5.5E-06**	1.3E-06	2.2E-07	7.3E-07	3.3E-06
Human health noncancer	CTUh	**8.3E-05**	6.3E-05	3.8E-06	7.1E-06	8.3E-06

Table 54. Dominance Analysis: C2G Primary Structural Product System – Relative % Basis, per Ton

Impact category	Total	Hot Rolled Plate production	Electricity generation process-consumed at MBMA plants	Inbound transportation of HRP by truck	Rest
Global warming	**100%**	91%	9%	4%	-4%
Abiotic depletion (elements)	**100%**	0%	0%	0%	100%
Total primary energy	**100%**	85%	11%	4%	0%
Non-renewable, energy	**100%**	85%	11%	4%	0%
Acidification	**100%**	72%	20%	6%	3%
Eutrophication	**100%**	66%	6%	7%	21%
Respiratory effects	**100%**	91%	7%	1%	1%
Smog formation	**100%**	71%	11%	10%	8%
Ozone depletion	**100%**	0%	0%	0%	100%
Ecotoxicity	**100%**	3%	16%	45%	36%
Human health cancer	**100%**	23%	4%	13%	60%
Human health noncancer	**100%**	77%	5%	9%	10%

Table 55. Dominance Analysis: C2G Secondary Structural Product System – Absolute Basis, per Ton

Impact category	Unit	Total	Input metal coil	Electricity generation process-consumed at MBMA plants	Inbound transportation of metal coil by truck	Rest
Global warming	kg CO2 eq	**2177.5**	2071.0	82.7	57.5	-33.7
Abiotic depletion (elements)	kg Sb eq	**6.4E-06**	5.0E-06	2.4E-11	0.0E+00	1.4E-06
Total primary energy	MJ	**27,938**	25,622	1,456	836	24
Non-renewable, energy	MJ	**27,901**	25,613	1,427	836	25
Acidification	kg SO2 eq	**9.0**	7.7	0.7	0.3	0.2
Eutrophication	kg N eq	**0.418**	0.363	0.010	0.018	0.026
Respiratory effects	kg PM2.5 eq	**0.731**	0.678	0.046	0.007	0.001
Smog formation	kg O3 eq	**146.9**	127.8	5.5	8.8	4.8
Ozone depletion	kg CFC-11 eq	**3.1E-06**	8.6E-07	5.3E-09	2.3E-09	2.2E-06
Ecotoxicity	CTUe	**326.6**	70.4	34.4	154.0	67.8
Human health cancer	CTUh	**7.4E-06**	5.6E-06	1.6E-07	8.3E-07	7.7E-07
Human health noncancer	CTUh	**6.1E-05**	4.6E-05	2.7E-06	8.0E-06	4.5E-06

Table 56. Dominance Analysis: C2G Secondary Structural Product System – Relative % Basis, per Ton

Impact category	Total	Input metal coil	Electricity generation process-consumed at MBMA plants	Inbound transportation of metal coil by truck	Rest
Global warming	**100%**	95%	4%	3%	-2%
Abiotic depletion (elements)	**100%**	78%	0%	0%	22%
Total primary energy	**100%**	92%	5%	3%	0%
Non-renewable, energy	**100%**	92%	5%	3%	0%
Acidification	**100%**	86%	8%	4%	2%
Eutrophication	**100%**	87%	2%	4%	6%
Respiratory effects	**100%**	93%	6%	1%	0%
Smog formation	**100%**	87%	4%	6%	3%
Ozone depletion	**100%**	28%	0%	0%	72%
Ecotoxicity	**100%**	22%	11%	47%	21%
Human health cancer	**100%**	76%	2%	11%	10%
Human health noncancer	**100%**	75%	4%	13%	7%

7.1.2 Dominance Analysis- Wall and Roof Panels

Tables 57 through 60 present the absolute and percent basis dominance analysis results for the wall and roof cladding panels, respectively. Both product profiles show a similar level of dominance, as the semi-finished steel coil input and its inbound transportation rank first (>89%) and second (<7%) across all impacts with on-site electricity use generally ranking third (<4%), but having a similar impact as inbound transportation of steel coil across a number of LCIA indicators. Relative to primary and secondary structural element production, wall and roof cladding manufacture was less electricity use intensive.

Table 57. Dominance Analysis: C2G Wall Panel Product System – Absolute Basis, per Ton

Impact category	Unit	Total	Input metal coil	Inbound transportation of metal coil by truck	Electricity generation process-consumed at MBMA plants	Rest
Global warming	kg CO2 eq	**2486.2**	2419.3	77.1	50.8	-61.0
Abiotic depletion (elements)	kg Sb eq	**6.5E-02**	6.5E-02	0.0E+00	1.5E-11	8.5E-08
Total primary energy	MJ	**32,563**	30,805	1,120	894	-256
Non-renewable, energy	MJ	**32,410**	30,670	1,120	876	-257
Acidification	kg SO2 eq	**11.3**	10.4	0.4	0.4	0.0
Eutrophication	kg N eq	**0.536**	0.501	0.024	0.006	0.005
Respiratory effects	kg PM2.5 eq	**0.879**	0.847	0.009	0.028	-0.005
Smog formation	kg O3 eq	**167.1**	150.8	11.8	3.4	1.2
Ozone depletion	kg CFC-11 eq	**1.0E-05**	9.5E-06	3.1E-09	3.3E-09	4.7E-07
Ecotoxicity	CTUe	**607.2**	331.7	206.4	21.1	48.0
Human health cancer	CTUh	**1.2E-05**	1.0E-05	1.1E-06	9.6E-08	3.2E-07
Human health noncancer	CTUh	**8.5E-05**	7.1E-05	1.1E-05	1.6E-06	1.8E-06

Table 58. Dominance Analysis: C2G Wall Panel Product System – Relative % Basis, per Ton

Impact category	Total	Input metal coil	Inbound transportation of metal coil by truck	Electricity generation process-consumed at MBMA plants	Rest
Global warming	**100%**	97%	3%	2%	-2%
Abiotic depletion (elements)	**100%**	100%	0%	0%	0%
Total primary energy	**100%**	95%	3%	3%	-1%
Non-renewable, energy	**100%**	95%	3%	3%	-1%
Acidification	**100%**	92%	4%	4%	0%
Eutrophication	**100%**	93%	5%	1%	1%
Respiratory effects	**100%**	96%	1%	3%	-1%
Smog formation	**100%**	90%	7%	2%	1%
Ozone depletion	**100%**	95%	0%	0%	5%
Ecotoxicity	**100%**	55%	34%	3%	8%
Human health cancer	**100%**	87%	10%	1%	3%
Human health noncancer	**100%**	83%	13%	2%	2%

Table 59. Dominance Analysis: C2G Roof Panel Product System – Absolute Basis, per Ton

Impact category	Unit	Total	Input metal coil	Inbound transportation of metal coil by truck	Electricity generation process-consumed at MBMA plants	Rest
Global warming	kg CO2 eq	**2486.4**	2411.0	67.1	49.7	-41.4
Abiotic depletion (elements)	kg Sb eq	**8.3E-02**	8.3E-02	0.0E+00	1.5E-11	3.0E-05
Total primary energy	MJ	**32,203**	30,404	975	875	-50
Non-renewable, energy	MJ	**32,026**	30,246	975	857	-53
Acidification	kg SO2 eq	**10.7**	9.8	0.4	0.4	0.1
Eutrophication	kg N eq	**0.526**	0.489	0.021	0.006	0.010
Respiratory effects	kg PM2.5 eq	**0.830**	0.795	0.008	0.027	0.001
Smog formation	kg O3 eq	**156.1**	139.6	10.3	3.3	3.0
Ozone depletion	kg CFC-11 eq	**1.2E-05**	1.1E-05	2.7E-09	3.2E-09	8.8E-07
Ecotoxicity	CTUe	**622.4**	372.0	179.7	20.7	50.1
Human health cancer	CTUh	**1.2E-05**	1.0E-05	9.7E-07	9.4E-08	4.2E-07
Human health noncancer	CTUh	**8.4E-05**	7.1E-05	9.4E-06	1.6E-06	2.0E-06

Table 60. Dominance Analysis: C2G Roof Panel Product System – Relative % Basis, per Ton

Impact category	Total	Input metal coil	Inbound transportation of metal coil by truck	Electricity generation process-consumed at MBMA plants	Rest
Global warming	**100%**	97%	3%	2%	-2%
Abiotic depletion (elements)	**100%**	100%	0%	0%	0%
Total primary energy	**100%**	94%	3%	3%	0%
Non-renewable, energy	**100%**	94%	3%	3%	0%
Acidification	**100%**	92%	4%	4%	1%
Eutrophication	**100%**	93%	4%	1%	2%
Respiratory effects	**100%**	96%	1%	3%	0%
Smog formation	**100%**	89%	7%	2%	2%
Ozone depletion	**100%**	92%	0%	0%	8%
Ecotoxicity	**100%**	60%	29%	3%	8%
Human health cancer	**100%**	87%	8%	1%	4%
Human health noncancer	**100%**	85%	11%	2%	2%

7.2 Influence Analysis

Tables 61, through 64 depict the results of the cradle-to-gate influence analysis by impact category for the four product systems of interest. The influence analysis shows the degree to which the various LCIA results are controlled by the MBMA plant as opposed to the suppliers of inputs to the plant (both materials and energy). The sphere of the MBMA plant's influence is greater for primary frames than for wall and roof panel production; this reflects the greater energy use and on-site emissions to air and water associated with primary frame production process as opposed to roll forming of wall and roof panels. Excluding ozone depletion, which is of a minor absolute value, the influence of primary frame gate-to-gate processing varies from a low of 0% (abiotic depletion) to a high of 23% (acidification potential). The influence of plant practices on the LCIA results was next highest for secondary structural component manufacturing, which varied between a low of 0% (abiotic depletion) to a high of 10% (acidification potential). Wall and roof cladding demonstrated the lowest results, albeit with similar influence, with plant practices influencing the LCIA outcomes by 0% to 5%; this again underscores the lower energy intensiveness of the roll forming process used to produce both wall and roof cladding panels. All four product process are largely influenced by upstream and downstream supplier inputs and energy use; as a result, few of the LCIA results are likely to change dramatically with in-plant improvements. That is, MBMA plants are as likely to see greater benefits from different material sourcing practices than from in-house process improvements.

Table 61. Influence Analysis: C2G Primary Structural Product System – Relative % Basis, per Ton

Impact category	Total	Upstream and downstream suppliers-impact (including transport)	MBMA plant - impact
Global warming	**100%**	89%	11%
Abiotic depletion (elements)	**100%**	100%	0%
Total primary energy	**100%**	87%	13%
Non-renewable, energy	**100%**	87%	13%
Acidification	**100%**	77%	23%
Eutrophication	**100%**	90%	10%
Respiratory effects	**100%**	91%	9%
Smog formation	**100%**	83%	17%
Ozone depletion	**100%**	67%	33%
Ecotoxicity	**100%**	71%	29%
Human health cancer	**100%**	93%	7%
Human health noncancer	**100%**	93%	7%

Table 62. Influence Analysis: C2G Secondary Structural Product System – Relative % Basis, per Ton

Impact category	Total	Upstream and downstream suppliers-impact (including transport)	MBMA plant - impact
Global warming	**100%**	95%	5%
Abiotic depletion (elements)	**100%**	100%	0%
Total primary energy	**100%**	93%	7%
Non-renewable, energy	**100%**	94%	6%
Acidification	**100%**	90%	10%
Eutrophication	**100%**	96%	4%
Respiratory effects	**100%**	92%	8%
Smog formation	**100%**	94%	6%
Ozone depletion	**100%**	54%	46%
Ecotoxicity	**100%**	79%	21%
Human health cancer	**100%**	96%	4%
Human health noncancer	**100%**	93%	7%

Table 63. Influence Analysis: C2G Wall Cladding Panel Product System – Relative % Basis, per Ton

Impact category	Total	Upstream and downstream suppliers-impact (including transport)	MBMA plant - impact
Global warming	**100%**	98%	2%
Abiotic depletion (elements)	**100%**	100%	0%
Total primary energy	**100%**	97%	3%
Non-renewable, energy	**100%**	97%	3%
Acidification	**100%**	95%	5%
Eutrophication	**100%**	98%	2%
Respiratory effects	**100%**	96%	4%
Smog formation	**100%**	97%	3%
Ozone depletion	**100%**	96%	4%
Ecotoxicity	**100%**	94%	6%
Human health cancer	**100%**	99%	1%
Human health noncancer	**100%**	97%	3%

Table 64. Influence Analysis: C2G Roof Cladding Panel Product System – Relative % Basis, per Ton

Impact category	Total	Upstream and downstream suppliers-impact (including transport)	MBMA plant - impact
Global warming	**100%**	98%	2%
Abiotic depletion (elements)	**100%**	100%	0%
Total primary energy	**100%**	97%	3%
Non-renewable, energy	**100%**	97%	3%
Acidification	**100%**	95%	5%
Eutrophication	**100%**	98%	2%
Respiratory effects	**100%**	96%	4%
Smog formation	**100%**	96%	4%
Ozone depletion	**100%**	96%	4%
Ecotoxicity	**100%**	94%	6%
Human health cancer	**100%**	99%	1%
Human health noncancer	**100%**	97%	3%

7.3 Substance Contribution Analysis

Tables 65 to 68 report the contribution of the major substance flows to the LCIA indicators for the four gate-to-gate product systems. By identifying the important LCI flows contributing to each LCIA indicator outcome, we can better anticipate which flows matter when considering future improvements. Given the results of dominance and influence analysis, however, it is acknowledged that many of these reported flows are beyond the purview of the MBMA plant. Overall, the substances driving the LCIA indicator results were generally similar across all four product systems – e.g., over 90% of the global warming potential outcome was driven by carbon dioxide emissions to air; sulfur dioxide emissions to air were largely responsible for the acidification potential and respiratory effects results;and nitrogen oxide emissions drove the eutrophication and smog potential results. The demand for coal, followed by natural gas, largely drove the total primary energy result, and various metal releases to the environment were responsible for the human and eco-toxicity results.

Table 65. Substance Contribution Analysis: G2G Primary Structural Product System – Absolute and Relative % Basis, per Ton

No	LCIA impact categories	Substance	Compartment	Unit	Total	%
1	**Global Warming**	Total of all compartments			**166.24**	
		Carbon dioxide, fossil	Air	kg CO2 eq	155.12	**93.3%**
		Methane, fossil	Air	kg CO2 eq	10.32	**6.2%**
		Dinitrogen monoxide	Air	kg CO2 eq	0.69	**0.4%**
2	**Acidification**	Total of all compartments			**1.34**	
		Sulfur dioxide	Air	kg SO2 eq	0.99	**74.0%**
		Nitrogen oxides	Air	kg SO2 eq	0.28	**21.1%**
		Sulfur oxides	Air	kg SO2 eq	0.04	**2.7%**
		Hydrogen chloride	Air	kg SO2 eq	0.02	**1.6%**
3	**Respiratory effects**	Total of all compartments			**0.105**	
		Sulfur dioxide	Air	kg PM2.5 eq	0.06	**57.9%**
		Particulates, unspecified	Air	kg PM2.5 eq	0.02	**18.2%**
		Particulates, < 10 um	Air	kg PM2.5 eq	0.01	**13.4%**
		Particulates, > 2.5 um, and < 10um	Air	kg PM2.5 eq	0.004	**3.8%**
		Particulates, < 2.5 um	Air	kg PM2.5 eq	0.003	**2.9%**
		Nitrogen oxides	Air	kg PM2.5 eq	0.003	**2.8%**
4	**Eutrophication**	Total of all compartments			**0.071**	
		Nitrogen oxides	Air	kg N eq	1.8E-02	**25.2%**
		Phosphate	Water	kg N eq	1.6E-02	**21.8%**
		COD, Chemical Oxygen Demand	Water	kg N eq	1.5E-02	**20.7%**
		BOD5, Biological Oxygen Demand	Water	kg N eq	1.0E-02	**14.6%**
		Nitrate	Water	kg N eq	9.1E-03	**12.7%**
		Nitrogen	Air	kg N eq	1.4E-03	**2.0%**
5	**Ozone depletion**	Total of all compartments			**4.51E-06**	
		Methane, bromochlorodifluoro-, Halon 1211	Air	kg CFC-11 eq	1.86E-06	**41.2%**
		Methane, bromotrifluoro-, Halon 1301	Air	kg CFC-11 eq	1.85E-06	**41.0%**
		Methane, monochloro-, R-40	Air	kg CFC-11 eq	3.60E-07	**8.0%**
		Methane, tetrachloro-, CFC-10	Air	kg CFC-11 eq	2.43E-07	**5.4%**
		Methane, dichlorodifluoro-, CFC-12	Air	kg CFC-11 eq	1.36E-07	**3.0%**

No	LCIA impact categories	Substance	Compartment	Unit	Total	%
6	**Smog**	Total of all compartments			**13.8**	
		Nitrogen oxides	Air	kg O3 eq	10.0	**72.8%**
		VOC, volatile organic compounds	Air	kg O3 eq	2.9	**21.3%**
		Isoprene	Air	kg O3 eq	0.8	**5.7%**
7	**Total Primary Energy**	Total of all compartments			**2984**	
		Coal, 26.4 MJ per kg, in ground	Raw	MJ	1212	**40.6%**
		Gas, natural, in ground	Raw	MJ	860	**28.8%**
		Uranium oxide, 332 GJ per kg, in ore	Raw	MJ	381	**12.8%**
		Oil, crude, in ground	Raw	MJ	371	**12.4%**
		Energy, from coal	Raw	MJ	51	**1.7%**
8	**Abiotic depletion (elements)**	Total of all compartments			**9.97E-06**	
		Lead, in ground	Raw	kg Sb eq	1.57E-05	**157.8%**
		Manganese, in ground	Raw	kg Sb eq	9.05E-07	**9.1%**
		Copper, in ground	Raw	kg Sb eq	3.39E-07	**3.4%**
		Zinc, in ground	Raw	kg Sb eq	-1.04E-05	**-104.3%**
9	**Eco-toxicity**	Total of all compartments			**139.2**	
		Barium	Water	CTUe	54.96	**39.5%**
		Silver	Water	CTUe	31.98	**23.0%**
		Chromium VI	Water	CTUe	28.46	**20.4%**
		Lead	Water	CTUe	5.77	**4.1%**
		Zinc	Water	CTUe	3.26	**2.3%**
10	**Human health-cancer**	Total of all compartments			**3.39E-06**	
		Chromium VI	Water	CTUh	2.9E-06	**84.7%**
		Chromium, ion	Water	CTUh	2.3E-07	**6.8%**
		Chromium	Water	CTUh	1.9E-07	**5.5%**
		Chromium	Air	CTUh	3.5E-08	**1.0%**
		Mercury	Air	CTUh	2.1E-08	**0.6%**
11	**Human health-noncancer**	Total of all compartments			**1.2E-05**	
		Barium	Water	CTUh	3.5E-06	**29.8%**
		Mercury	Air	CTUh	2.4E-06	**20.5%**
		Zinc	Air	CTUh	1.9E-06	**16.1%**
		Lead	Water	CTUh	1.8E-06	**15.6%**
		Arsenic, ion	Water	CTUh	1.0E-06	**8.5%**
		Lead	Air	CTUh	2.6E-07	**2.2%**
		Zinc	Soil	CTUh	2.5E-07	**2.1%**

Table 66. Substance Contribution Analysis: G2G Secondary Structural Product System – Absolute and Relative % Basis, per Ton

No	LCIA impact categories	Substance	Compartment	Unit	Total	%
1	**Global Warming**	Total of all compartments			**111.97**	
		Carbon dioxide, fossil	Air	kg CO2 eq	104.27	**93.1%**
		Methane, fossil	Air	kg CO2 eq	7.35	**6.6%**
		Dinitrogen monoxide	Air	kg CO2 eq	0.27	**0.2%**
2	**Acidification**	Total of all compartments			**0.94**	
		Sulfur dioxide	Air	kg SO2 eq	0.70	**74.1%**
		Nitrogen oxides	Air	kg SO2 eq	0.20	**21.2%**
		Sulfur oxides	Air	kg SO2 eq	0.03	**2.7%**
		Hydrogen chloride	Air	kg SO2 eq	0.01	**1.6%**
3	**Respiratory effects**	Total of all compartments			**0.063**	
		Sulfur dioxide	Air	kg PM2.5 eq	0.043	**67.3%**
		Particulates, unspecified	Air	kg PM2.5 eq	0.014	**22.8%**
		Nitrogen oxides	Air	kg PM2.5 eq	0.002	**3.2%**
		Particulates, > 2.5 um, and < 10um	Air	kg PM2.5 eq	0.002	**2.8%**
		Particulates, < 10 um	Air	kg PM2.5 eq	0.002	**2.6%**
		Particulates, < 2.5 um	Air	kg PM2.5 eq	0.001	**0.8%**
4	**Eutrophication**	Total of all compartments			**0.038**	
		Nitrogen oxides	Air	kg N eq	1.3E-02	**33.5%**
		COD, Chemical Oxygen Demand	Water	kg N eq	9.9E-03	**26.3%**
		BOD5, Biological Oxygen Demand	Water	kg N eq	7.1E-03	**19.0%**
		Phosphate	Water	kg N eq	3.9E-03	**10.3%**
		Nitrate	Water	kg N eq	2.6E-03	**7.0%**
		Ammonia	Air	kg N eq	7.2E-04	**1.9%**
5	**Ozone depletion**	Total of all compartments			**2.18E-06**	
		Methane, bromochlorodifluoro-, Halon 1211	Air	kg CFC-11 eq	1.49E-06	**68.3%**
		Methane, bromotrifluoro-, Halon 1301	Air	kg CFC-11 eq	5.53E-07	**25.4%**
		Methane, tetrachloro-, CFC-10	Air	kg CFC-11 eq	4.24E-08	**1.9%**
		Methane, monochloro-, R-40	Air	kg CFC-11 eq	3.93E-08	**1.8%**
		Methane, chlorodifluoro-, HCFC-22	Air	kg CFC-11 eq	3.65E-08	**1.7%**

No	LCIA impact categories	Substance	Compartment	Unit	Total	%
6	**Smog**	Total of all compartments			**9.0**	
		Nitrogen oxides	Air	kg O3 eq	7.1	**79.0%**
		VOC, volatile organic compounds	Air	kg O3 eq	1.3	**14.9%**
		Isoprene	Air	kg O3 eq	0.5	**6.0%**
7	**Total Primary Energy**	Total of all compartments			**1984**	
		Coal, 26.4 MJ per kg, in ground	Raw	MJ	837	**42.2%**
		Gas, natural, in ground	Raw	MJ	642	**32.3%**
		Uranium oxide, 332 GJ per kg, in ore	Raw	MJ	263	**13.3%**
		Oil, crude, in ground	Raw	MJ	185	**9.3%**
		Energy, hydropower	Raw	MJ	26	**1.3%**
8	**Abiotic depletion (elements)**	Total of all compartments			**1.37E-06**	
		Lead, in ground	Raw	kg Sb eq	2.15E-06	**156.5%**
		Manganese, in ground	Raw	kg Sb eq	9.72E-08	**7.1%**
		Copper, in ground	Raw	kg Sb eq	4.32E-08	**3.1%**
		Zinc, in ground	Raw	kg Sb eq	-1.42E-06	**-103.6%**
9	**Eco-toxicity**	Total of all compartments			**82.9**	
		Barium	Water	CTUe	40.3	**48.7%**
		Silver	Water	CTUe	24.5	**29.6%**
		Lead	Water	CTUe	4.9	**5.9%**
		Chromium VI	Water	CTUe	4.5	**5.5%**
		Zinc	Water	CTUe	2.3	**2.8%**
10	**Human health-cancer**	Total of all compartments			**7.89E-07**	
		Chromium VI	Water	CTUh	4.6E-07	**57.8%**
		Chromium, ion	Water	CTUh	1.6E-07	**20.1%**
		Chromium	Water	CTUh	1.3E-07	**15.9%**
		Chromium	Air	CTUh	1.3E-08	**1.6%**
		Mercury	Air	CTUh	1.0E-08	**1.3%**
11	**Human health-noncancer**	Total of all compartments			**6.6E-06**	
		Barium	Water	CTUh	2.6E-06	**39.0%**
		Lead	Water	CTUh	1.6E-06	**23.6%**
		Mercury	Air	CTUh	1.2E-06	**18.0%**
		Arsenic, ion	Water	CTUh	5.3E-07	**7.9%**
		Zinc	Air	CTUh	2.9E-07	**4.4%**
		Arsenic	Air	CTUh	1.0E-07	**1.5%**
		Lead	Air	CTUh	8.6E-08	**1.3%**

Table 67. Substance Contribution Analysis: G2G Wall Cladding Panel Product System – Absolute and Relative % Basis, per Ton

No	LCIA impact categories	Substance	Compartment	Unit	Total	%
1	**Global Warming**	Total of all compartments			**71.6**	
		Carbon dioxide, fossil	Air	kg CO2 eq	66.60	**93.0%**
		Methane, fossil	Air	kg CO2 eq	4.82	**6.7%**
		Dinitrogen monoxide	Air	kg CO2 eq	0.16	**0.2%**
2	**Acidification**	Total of all compartments			**0.63**	
		Sulfur dioxide	Air	kg SO2 eq	0.45	**71.1%**
		Nitrogen oxides	Air	kg SO2 eq	0.15	**23.8%**
		Sulfur oxides	Air	kg SO2 eq	0.02	**3.3%**
		Hydrogen chloride	Air	kg SO2 eq	0.01	**1.5%**
3	**Respiratory effects**	Total of all compartments			**0.046**	
		Sulfur dioxide	Air	kg PM2.5 eq	2.7E-02	**59.5%**
		Particulates, unspecified	Air	kg PM2.5 eq	1.6E-02	**33.9%**
		Nitrogen oxides	Air	kg PM2.5 eq	1.6E-03	**3.4%**
		Particulates, > 2.5 um, and < 10um	Air	kg PM2.5 eq	1.1E-03	**2.5%**
		Particulates, > 10 um	Air	kg PM2.5 eq	1.5E-04	**0.3%**
4	**Eutrophication**	Total of all compartments			**0.019**	
		Nitrogen oxides	Air	kg N eq	9.5E-03	**50.3%**
		Phosphate	Water	kg N eq	7.2E-03	**38.4%**
		COD, Chemical Oxygen Demand	Water	kg N eq	8.0E-04	**4.2%**
		Ammonia	Water	kg N eq	5.4E-04	**2.9%**
		BOD5, Biological Oxygen Demand	Water	kg N eq	4.3E-04	**2.3%**
		Nitrogen, total	Water	kg N eq	1.7E-04	**0.9%**
5	**Ozone depletion**	Total of all compartments			**4.59E-07**	
		Methane, bromochlorodifluoro-, Halon 1211	Air	kg CFC-11 eq	4.15E-07	**90.4%**
		Methane, bromotrifluoro-, Halon 1301	Air	kg CFC-11 eq	2.57E-08	**5.6%**
		Methane, chlorodifluoro-, HCFC-22	Air	kg CFC-11 eq	1.17E-08	**2.5%**
		Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	Air	kg CFC-11 eq	6.24E-09	**1.4%**

No	LCIA impact categories	Substance	Compartment	Unit	Total	%
6	**Smog**	Total of all compartments			**6.2**	
		Nitrogen oxides	Air	kg O3 eq	5.3	**86.4%**
		VOC, volatile organic compounds	Air	kg O3 eq	0.5	**7.9%**
		Isoprene	Air	kg O3 eq	0.3	**5.6%**
7	**Total Primary Energy**	Total of all compartments			**1330**	
		Coal, 26.4 MJ per kg, in ground	Raw	MJ	575	**43.2%**
		Gas, natural, in ground	Raw	MJ	393	**29.5%**
		Uranium oxide, 332 GJ per kg, in ore	Raw	MJ	170	**12.8%**
		Oil, crude, in ground	Raw	MJ	153	**11.5%**
		Energy, hydropower	Raw	MJ	16	**1.2%**
8	**Abiotic depletion (elements)**	Total of all compartments			**8.18E-08**	
		Zinc, in ground	Raw	kg Sb eq	6.84E-08	**83.6%**
		Chromium, in ground	Raw	kg Sb eq	6.47E-09	**7.9%**
		Molybdenum, in ground	Raw	kg Sb eq	4.49E-09	**5.5%**
		Nickel, in ground	Raw	kg Sb eq	2.05E-09	**2.5%**
9	**Eco-toxicity**	Total of all compartments			**60.5**	
		Barium	Water	CTUe	36.1	**59.7%**
		Silver	Water	CTUe	17.7	**29.3%**
		Zinc	Water	CTUe	1.9	**3.1%**
		Chromium	Water	CTUe	1.5	**2.5%**
		Chromium, ion	Water	CTUe	0.9	**1.6%**
10	**Human health-cancer**	Total of all compartments			**3.32E-07**	
		Chromium	Water	CTUh	1.5E-07	**46.2%**
		Chromium, ion	Water	CTUh	9.5E-08	**28.6%**
		Chromium VI	Water	CTUh	5.8E-08	**17.4%**
		Mercury	Air	CTUh	6.3E-09	**1.9%**
		Chromium	Air	CTUh	6.3E-09	**1.9%**
11	**Human health-noncancer**	Total of all compartments			**3.7E-06**	
		Barium	Water	CTUh	2.3E-06	**63.3%**
		Mercury	Air	CTUh	7.4E-07	**20.2%**
		Arsenic, ion	Water	CTUh	3.8E-07	**10.5%**
		Arsenic	Air	CTUh	6.5E-08	**1.8%**
		Zinc	Water	CTUh	6.3E-08	**1.7%**
		Lead	Air	CTUh	5.2E-08	**1.4%**

Table 68. Substance Contribution Analysis: G2G Roof Cladding Panel Product System – Absolute and Relative % Basis, per Ton

No	LCIA impact categories	Substance	Compartment	Unit	Total	%
1	**Global Warming**	Total of all compartments			**72.65**	
		Carbon dioxide, fossil	Air	kg CO2 eq	67.48	**92.9%**
		Methane, fossil	Air	kg CO2 eq	4.99	**6.9%**
		Dinitrogen monoxide	Air	kg CO2 eq	0.16	**0.2%**
2	**Acidification**	Total of all compartments			**0.62**	
		Sulfur dioxide	Air	kg SO2 eq	0.44	**70.2%**
		Nitrogen oxides	Air	kg SO2 eq	0.15	**24.5%**
		Sulfur oxides	Air	kg SO2 eq	0.02	**3.2%**
		Hydrogen chloride	Air	kg SO2 eq	0.01	**1.5%**
3	**Respiratory effects**	Total of all compartments			**0.046**	
		Sulfur dioxide	Air	kg PM2.5 eq	0.027	**58.0%**
		Particulates, unspecified	Air	kg PM2.5 eq	0.015	**32.4%**
		Nitrogen oxides	Air	kg PM2.5 eq	0.002	**3.4%**
		Particulates, > 2.5 um, and < 10um	Air	kg PM2.5 eq	0.001	**3.0%**
		Particulates, < 2.5 um	Air	kg PM2.5 eq	0.001	**2.1%**
		Particulates, > 10 um	Air	kg PM2.5 eq	0.0003	**0.7%**
4	**Eutrophication**	Total of all compartments			**0.022**	
		Nitrogen oxides	Air	kg N eq	9.7E-03	**44.4%**
		Phosphate	Water	kg N eq	7.4E-03	**34.1%**
		COD, Chemical Oxygen Demand	Water	kg N eq	1.3E-03	**6.1%**
		Phosphorus	Water	kg N eq	7.0E-04	**3.2%**
		Nitrate	Water	kg N eq	6.2E-04	**2.9%**
		BOD5, Biological Oxygen Demand	Air	kg N eq	6.2E-04	**2.8%**
5	**Ozone depletion**	Total of all compartments			**8.72E-07**	
		Methane, bromochlorodifluoro-, Halon 1211	Air	kg CFC-11 eq	4.81E-07	**55.2%**
		Methane, bromotrifluoro-, Halon 1301	Air	kg CFC-11 eq	3.67E-07	**42.1%**
		Methane, chlorodifluoro-, HCFC-22	Air	kg CFC-11 eq	1.31E-08	**1.5%**
		Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	Air	kg CFC-11 eq	6.79E-09	**0.8%**
		Methane, tetrachloro-, CFC-10	Air	kg CFC-11 eq	3.15E-09	**0.4%**

No	LCIA impact categories	Substance	Compartment	Unit	Total	%
6	**Smog**	Total of all compartments			**7.3**	
		Nitrogen oxides	Air	kg O3 eq	5.4	**73.8%**
		VOC, volatile organic compounds	Air	kg O3 eq	1.6	**21.5%**
		Isoprene	Air	kg O3 eq	0.3	**4.6%**
7	**Total Primary Energy**	Total of all compartments			**1357**	
		Coal, 26.4 MJ per kg, in ground	Raw	MJ	556	**40.9%**
		Gas, natural, in ground	Raw	MJ	386	**28.5%**
		Oil, crude, in ground	Raw	MJ	200	**14.8%**
		Uranium oxide, 332 GJ per kg, in ore	Raw	MJ	167	**12.3%**
		Energy, hydropower	Raw	MJ	17	**1.2%**
8	**Abiotic depletion (elements)**	Total of all compartments			**3.04E-05**	
		Cadmium, in ground	Raw	kg Sb eq	2.72E-05	**89.6%**
		Zinc, in ground	Raw	kg Sb eq	2.83E-06	**9.3%**
		Sulfur, in ground	Raw	kg Sb eq	2.57E-07	**0.8%**
		Indium, in ground	Raw	kg Sb eq	1.99E-08	**0.1%**
9	**Eco-toxicity**	Total of all compartments			**60.4**	
		Barium	Water	CTUe	33.3	**55.2%**
		Silver	Water	CTUe	16.1	**26.6%**
		Antimony	Water	CTUe	3.9	**6.5%**
		Zinc	Water	CTUe	1.8	**2.9%**
		Chromium VI	Water	CTUe	1.6	**2.7%**
10	**Human health-cancer**	Total of all compartments			**4.35E-07**	
		Chromium VI	Water	CTUh	1.7E-07	**38.2%**
		Chromium	Water	CTUh	1.4E-07	**33.1%**
		Chromium, ion	Water	CTUh	9.8E-08	**22.5%**
		Chromium	Air	CTUh	6.8E-09	**1.6%**
		Mercury	Air	CTUh	6.6E-09	**1.5%**
11	**Human health-noncancer**	Total of all compartments			**3.6E-06**	
		Barium	Water	CTUh	2.1E-06	**60.1%**
		Mercury	Air	CTUh	7.9E-07	**22.0%**
		Arsenic, ion	Water	CTUh	3.8E-07	**10.7%**
		Arsenic	Air	CTUh	6.4E-08	**1.8%**
		Zinc	Water	CTUh	5.9E-08	**1.6%**
		Lead	Air	CTUh	5.0E-08	**1.4%**
		Cadmium	Air	CTUh	3.2E-08	**0.9%**

7.4 Sensitivity Analysis

It was noted previously that electricity was the main energy input used within the MBMA plants for the production of all four products.

The weighted average electricity use for primary frames, secondary frames, wall and roof panels manufacturing processes were 158, 110, 68 and 66 kWh, respectively, at the MBMA plant. A statistical analysis of the 10 MBMA plants that participated in the study indicated a +/- 10% coefficient of variation[8] of the electricity data sample for primary frames and +/- 20% for secondary frames, wall and roof panels. A sensitivity analysis of gate-to-gate electricity use was then conducted to determine the sensitivity of the gate-to-gate global warming potential and total primary energy use to a reduction or increase in the weighted average electricity use.

Table 69 shows the sensitivity of global warming potential and total primary energy use to a 10% variation in electricity use in the production of a ton of primary frame. Global warming potential and total primary energy were found to be equally sensitive to a change in electricity. A 10% change in electricity demand led to a 7% change in global warming potential and total primary energy use.

Tables 70, 71 and 72 provide a similar sensitivity analysis of electricity use for secondary frames, wall and roof cladding panels, but the variation is +/- 20%. Like primary frames, all three products show a similar linear correlation of global warming potential to total primary energy use. A 20% change in electricity demand led to a 13 to 15% change in global warming potential and total primary energy use.

[8] The coefficient of variation (COV) is the ratio of the standard deviation to the arithmetic mean, and represents a normalized measure of the dispersion of the sample data.

Table 69. Sensitivity Analysis: G2G Primary Frame Production – 10% Variation in Electricity Use, Absolute and Relative % Basis, per Ton

Impact category	**Unit**	**Base case - manufacturing of primary frames**	**Altered assumption** - 10% ***reduction*** of electricity	**Deviation- in absolute basis**	**Deviation- in %**
Global warming	kg CO2 eq	166	154	-12	-7%
Total Primary Energy	MJ	2,984	2,776	-208	-7%
Impact category	**Unit**	**Base case - manufacturing of primary frames**	**Altered assumption** - 10% ***increase*** of electricity	**Deviation- in absolute basis**	**Deviation- in %**
Global warming	kg CO2 eq	166	178	12	7%
Total Primary Energy	MJ	2,984	3,192	208	7%

Table 70. Sensitivity Analysis: G2G Secondary Frame Production – 20% Variation in Electricity Use, Absolute and Relative % Basis, per Ton

Impact category	**Unit**	**Base case - manufacturing of secondary frames**	**Altered assumption** - 20% ***reduction*** of electricity	**Deviation- in absolute basis**	**Deviation- in %**
Global warming	kg CO2 eq	112	95	-17	-15%
Total Primary Energy	MJ	1,984	1,693	-291	-15%
Impact category	**Unit**	**Base case - manufacturing of secondary frames**	**Altered assumption** - 20% ***increase*** of electricity	**Deviation- in absolute basis**	**Deviation- in %**
Global warming	kg CO2 eq	112	129	17	15%
Total Primary Energy	MJ	1,984	2,275	291	15%

Table 71. Sensitivity Analysis: G2G Wall Cladding Panel Production – 20% Variation in Electricity Use, Absolute and Relative % Basis, per Ton

Impact category	**Unit**	**Base case - manufacturing of wall panels**	**Altered assumption** - 20% ***reduction*** of electricity	**Deviation- in absolute basis**	**Deviation- in %**
Global warming	kg CO2 eq	72	61	-10	-14%
Total Primary Energy	MJ	1,330	1,152	-179	-13%
Impact category	**Unit**	**Base case - manufacturing of wall panels**	**Altered assumption** - 20% ***increase*** of electricity	**Deviation- in absolute basis**	**Deviation- in %**
Global warming	kg CO2 eq	72	82	10	14%
Total Primary Energy	MJ	1,330	1,509	179	13%

Table 72. Sensitivity Analysis: G2G Roof Cladding Panel Production – 20% Variation in Electricity Use, Absolute and Relative % Basis, per Ton

Impact category	**Unit**	**Base case - manufacturing of roof panels**	**Altered assumption** - 20% ***reduction*** of electricity	**Deviation- in absolute basis**	**Deviation- in %**
Global warming	kg CO2 eq	73	63	-10	-14%
Total Primary Energy	MJ	1,357	1,182	-175	-13%
Impact category	**Unit**	**Base case - manufacturing of roof panels**	**Altered assumption** - 20% ***increase*** of electricity	**Deviation- in absolute basis**	**Deviation- in %**
Global warming	kg CO2 eq	73	83	10	14%
Total Primary Energy	MJ	1,357	1,532	175	13%

8 Conclusions, Limitations and Recommendations

Life cycle inventory data collected from a total of 10 MBMA plant facilities (approximately 25% of MBMA's membership) were collected, verified, and process-chained to the best representative and available background LCI datasets to provide a complete "cradle-to-gate" LCA of primary and secondary structural frame components and wall and roof cladding production for the reference years 2008-2010. This section summarizes the major study findings as well as the general conclusions, limitations and recommendations for future work related to using and advancing these benchmark product LCA profiles.

Primary Frames (gate-to-gate and cradle-to-gate)

- The manufacture of one short ton of primary frames requires the input of 1.079 tons of semi-finished hot rolled plate and bar. The implied 7.9% steel scrap rate was treated as fabrication scrap and debited/credited to the system using the WSA "system expansion" methodology for steel scrap. One ton of primary frames embodies about 18.9 GJ of primary energy use. Over 99% of this energy was derived from non-renewable energy sources (fossil and nuclear fuels). The 16% of the cradle-to-gate primary energy use was due to the "on-site" consumption of energy at the manufacturing plant. Delivered electricity dominated on-site G2G energy use, accounting for 83% of the G2G primary energy. Natural gas use (used for both space conditioning (65%) and painting (35%) was the next most significant on-site energy source, accounting for 13% of the G2G energy use. By far, the most significant contributor to the C2G primary energy use was the upstream manufacture, packaging and transport of the semi-finished steel input – accounting for 84% of the total primary energy use.
- The C2G manufacture of one short ton of primary frames emitted 1,351 kg (CO2 equivalent) of greenhouse gases. Gate-to-gate manufacturing contributed 166 kg (12%) of the total C2G greenhouse gas emissions. The 88% of the C2G greenhouse gas emissions were again traced to the delivered semi-finished steel used in the process of manufacturing primary frame components (beams and columns).
- Except for ozone depletion potential and abiotic depletion (elements), the C2G LCIA results were largely attributable to the upstream manufacture, packaging and transport of the semi-finished steel input, accounting for 74% to 89% of the individual category indicator values.
- After "on-site" manufacturing energy consumption, the welding and painting processes, inclusive of their ancillary materials, were the next most significant contributors to the G2G LCIA results for primary frames. Both packaging materials and waste treatment were less significant than welding and painting, but more significant than inbound transportation of ancillary materials and outbound transport of wastes to treatment.

Secondary Frames (gate-to-gate and cradle-to-gate)

- The manufacture of one short ton of secondary frame components requires the input of 1.051 tons of semi-finished steel; however, the type of steel used to produce these components was considerably more varied than those used to produce primary frames. Besides hot rolled coil bare (24% of the input), MBMA facilities also used HDG (38%) and pre-painted hot (11%) and cold-rolled (27%) coil in the production of secondary framing components. The 5.1% steel scrap rate was treated as recycled fabrication scrap and was also debited/credited to the system using the WSA "system expansion" methodology. One ton of secondary frames embody about 27.9 GJ of primary energy use. Over 99% of this energy was derived from non-renewable energy sources (fossil and nuclear fuels). The 7% of the cradle-to-gate primary energy use was due to the "on-site" consumption of energy at the manufacturing plant. Delivered electricity dominated on-site G2G energy use, accounting for 80% of the G2G primary energy. Natural gas use (used for both space conditioning (65%) and painting (35%)) was the next most significant on-site energy source, accounting for 17% of the G2G energy use. Diesel and propane use combined accounted for the remaining 3% of primary energy use. By far, the most significant contributor to the C2G secondary frames' primary energy use was the upstream manufacture, packaging and transport of semi-finished steel input – accounting for 93% of the total primary energy use.
- The C2G manufacture of one short ton of primary frames emitted 2,178 kg (CO_2 equivalent) of greenhouse gases (GWP). Gate-to-gate manufacturing contributed 112 kg (5%) of the total C2G greenhouse gas emissions. The 95% of the C2G greenhouse gas emissions were traced to the delivered semi-finished steel used in the process of manufacturing secondary frame components (purlins, girts and bracing components).
- Except for ozone depletion potential, the C2G LCIA results were largely attributable to the upstream manufacture, packaging and transport of the semi-finished steel input, accounting for 78% to 95% of the reported category indicator values.
- After "on-site" manufacturing energy consumption, the welding and painting processes, inclusive of their ancillary materials, were the next most significant contributors to the G2G LCIA results for secondary frames. Both packaging materials and waste treatment were both less significant than welding and painting, but more significant than inbound transportation of ancillary materials and outbound transport of wastes to treatment.

Wall Panels (gate-to-gate and cradle-to-gate)

- The manufacture of one short ton of wall cladding panels requires the input of 1.062 tons of semi-finished steel inputs; again, all recovered fabrication scrap was recycled. Of the five semi-finished steel inputs, bare and pre-painted Galvalume® coil was the predominate input (58%) used in the manufacture of wall cladding panels.The steel input used in the production of wall panels varied in thickness from 29 to 18 gauge. The most common finished thicknesses for wall panel production were 26 and 24 gauge steel.

- One ton of wall cladding panels embodies about 32.5 GJ of primary energy use. Again, over 99% of this energy was derived from non-renewable energy sources (fossil and nuclear fuels). The 4% of the cradle-to-gate primary energy use was due to the "on-site" consumption of energy at the manufacturing plant. Delivered electricity dominated on-site G2G energy use, accounting for 87% of the G2G primary energy. Natural gas (used for space conditioning only) was the next most significant on-site energy source, accounting for 7% of the G2G energy use. By far, the most significant contributor to the C2G primary energy use was the upstream manufacture, packaging and transport of the semi-finished steel inputs – accounting for 96% of the total primary energy use.
- The C2G manufacture of one short ton of wall cladding panels emitted 2,486 kg (CO2 equivalent) of greenhouse gases. Gate-to-gate manufacturing contributed 72 kg or 3% of the total C2G greenhouse gas emissions. The 97% of the C2G greenhouse gas emissions were again traced to the delivered semi-finished steel used in the process of manufacturing wall cladding panels.
- Except for ozone depletion potential, the remaining C2G LCIA results were also largely attributable to the upstream manufacture, packaging and transport of the semi-finished steel inputs, accounting for between 94% and 100% of the individual category indicator values.
- Relative to the weighted average LCIA results, the C2G profile by steel input substrate revealed considerable variation across the LCIA indicators – generally wall panels based on a pre-painted cold rolled coil substrate and HDG source had lower burdens while those based on pre-painted Galvalume® coil had a higher impact profile.
- After "on-site" manufacturing energy consumption, packaging materials were the next most significant contributor to the G2G burdens exhibited in the production of wall cladding panels.

Roof Panels (gate-to-gate and cradle-to-gate)

- The manufacture of one short ton of roof cladding panels requires the input of 1.05 tons of semi-finished steel inputs – all recovered fabrication scrap was recycled. Of the five semi-finished steel inputs, bare and pre-painted Galvalume® coil was the predominate input (74%) used in the manufacture of roof cladding panels. The steel input used in the production of roof panels varied in thickness from 26 to 22 gauge. The most common finished thicknesses for roof panel production were 26 and 24 gauge steel.
- One ton of roof cladding panels embodies about 32.2 GJ of primary energy use. Again, over 99% of this energy was derived from non-renewable energy sources. The 4% of the cradle-to-gate primary energy use was due to the "on-site" consumption of energy at the manufacturing plant. Delivered electricity demand dominated on-site, G2G energy use accounting for 86% of the G2G primary energy. Natural gas (used for space conditioning only) was a distant second – on-site energy input accounting for 9% of the G2G energy use. By far, the most significant contributor to the C2G primary energy use

was the upstream manufacture, packaging and transport of the semi-finished steel inputs – accounting for 96% of the total primary energy use.

- The C2G manufacture of one short ton of roof cladding panels emitted 2,486 kg (CO2 equivalent) of greenhouse gases. Gate-to-gate manufacturing contributed 72 kg, accounting for 3% of the total C2G greenhouse gas emissions. Over 97% of the C2G greenhouse gas emissions were again traced to the delivered semi-finished steel used in the process of manufacturing roof cladding panels.
- The remaining C2G LCIA results were also largely attributable to the upstream manufacture, packaging and transport of the semi-finished steel inputs, accounting for 94% to 100% of the individual category indicator values. The G2G manufacture of roof panels accounted for less than 6% of the burdens recorded for each indicator.
- Relative to the weighted average LCIA results for roof panels, the C2G profile by steel input substrate revealed considerable variation across the LCIA indicators – generally roof panels based on a pre-painted cold rolled coil substrate and HDG source had lower burdens while those based on pre-painted Galvalume® coil had a higher impact profile.
- After "on-site" manufacturing energy consumption, packaging materials were the next most significant contributor to the G2G burdens exhibited in the production of wall cladding panels.

8.1 Conclusions

The following conclusions were drawn from the results of the study:

- The influence analysis revealed that MBMA product processes account for between 16% (primary frames) and 4% (wall cladding panels) of the total cradle-to-gate primary energy use attributed to each product.
- Within MBMA manufacturing facilities, electricity use is the dominant source of the environmental burden for of all four products of interest. On a unit of output basis, primary frame production was the most electricity intensive product category with wall and roof panel production requiring the least amount of electricity use. A G2G sensitivity analysis of electricity use indicated a significant but less than proportional sensitivity to "on-site" electricity use.
- After "on-site" electricity use, welding and painting processes (including related ancillary materials) were the next most significant on-site activities for primary and secondary frame production, while product packaging was the most significant process for wall and roof cladding production after on-site electricity use.
- In-plant steel scrap rates varied from 8% to 5%, depending on the output product. The recycling of this scrap typically resulted in a debit/credit to the C2G products system, but its effect was typically less than 5% across the supported LCIA indicators. Generally, the avoided burden effect or "value of scrap" was in the same order of magnitude as the inbound transportation of steel inputs to the product system, which was minor.

- Upstream steel production is the single and most significant input driving the environmental burden of all four products. Generally, the upstream production and delivery of steel inputs was more significant for wall and roof cladding panels (due to the inclusion of high performance coatings and paints) than the semi-finished steel inputs used in the production of primary and secondary frame components. On a unit of output basis, wall and roof cladding embodies more energy and results in more emissions than either primary or secondary frame components.

8.2 Limitations

The study is limited to a "cradle-to-gate" LCA of the products of interest and their respective processes and does not consider the installation, use or end-of-life stages of these products. As a result, the in-service benefits of these products have not been captured and service life is likely a defining "use" consideration for any of these products. By not considering the end-of-life recovery rate of these products, the scope of the avoided burden credit applied to modeling of these highly recyclable products is also limited. The majority of the credit benefit ascribed to the avoided burden approach resides with the end-of-life recycling as opposed to intermediate fabrication scrap recycling as captured in this study. Consequently, the "cradle-to-gate" LCIA results, without end-of-life recycling as portrayed in this study are very likely.

While the study reports human and eco-toxicity indicators, it offers no interpretation of these category indicators. These end-point indicators are rather new and have an inherent high degree of uncertainty. It is likely that these results will be advanced in the near future as they undergo further categorization and assessment within toxicology circles.

8.3 Recommendations

While the current study met its initial goals – to develop a representative benchmark "cradle-to-gate" profile for MBMA processes and major product outputs and to provide a contribution analysis to understand the degree to which MBMA facilities influence the environmental outcome of these products – a number of recommendations are evident given some of the limitations of the study.

MBMA should recommend that the North American Steel LCI database be expanded to include coated coil products: high performance paint and Galvalume®.

In the future, the MBMA should consider undertaking a *"cradle-to-gate", with end-of-life recycling* (excluding the use phase) study to better capture the recovery rate of its products as modeled within WSA "avoided burden" methodology.

The MBMA is encouraged to expand the study to determine how the products included within this report are installed in a building. This may prove beneficial from a life cycle perspective.

Lastly, the study team recommends that no attempt be made to compare the four products of interest as they vary considerably in their application within a building. Moreover, the study team recommends that, where the study provided additional summary profiles for various products by semi-finished steel substrate, these profiles also not be compared due to their differing properties, possible applications and varying service lives.

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Appendix A. Metal Building Systems Industry - General Overview of Building Elements

[Source: MBMA 2010]

Metal building systems are used in a wide variety of applications, such as manufacturing plants, industrial and commercial warehouses, shopping centers and retail stores, auto dealerships, educational, transportation and health care facilities, office structures, hangars, churches, community centers, and governmental and recreational buildings.

Structural

One of the inherent advantages of a metal building system, and one of the key reasons that allows it to be perhaps the best value in construction today, is the industry's ability to utilize "welded up" frames as opposed to mill sections. In this way, the engineer using sophisticated computer programs can design the most efficient shape for a frame. The industry can put the steel material where it is needed and eliminate it where it is not needed, thus effecting economy without compromising design. Another point of interest is that welded shapes are only welded on one side. There is technically no reason for welding to be on both sides unless shear force requires it, and shear force in rigid frames is usually relatively low.

The entire building system consists of an integrated set of components and assemblies, including but not limited, to frames that are structural steel members, secondary members that are made with cold-formed steel and steel joists, and roof and wall cladding components systems specifically designed to support and transfer loads and provide a complete or partial building shell. Figure A.1 provides a sectional view of a building system including terminology used by the industry for each element of the building.

Metal building systems can span great widths and lengths with or without additional interior supports. Where very large areas are required, and interior columns are not a problem, the modular rigid frame is an ideal solution. With a roof slope of 1/4 inches to 12 inches, even a 1000-foot building can be designed without excessive height.

The roof secondary structural or purlin normally utilizes the lap method for economy and ease of installation. Lapping over the frame allows the purlins to act as a continuous beam with attendant efficiency and greatly reduced deflections compared to simple span purlins. Bay spacing of up to 33 feet is possible when using purlins. The open web joists allow designers to specify bay sizes up to 60' and even longer.

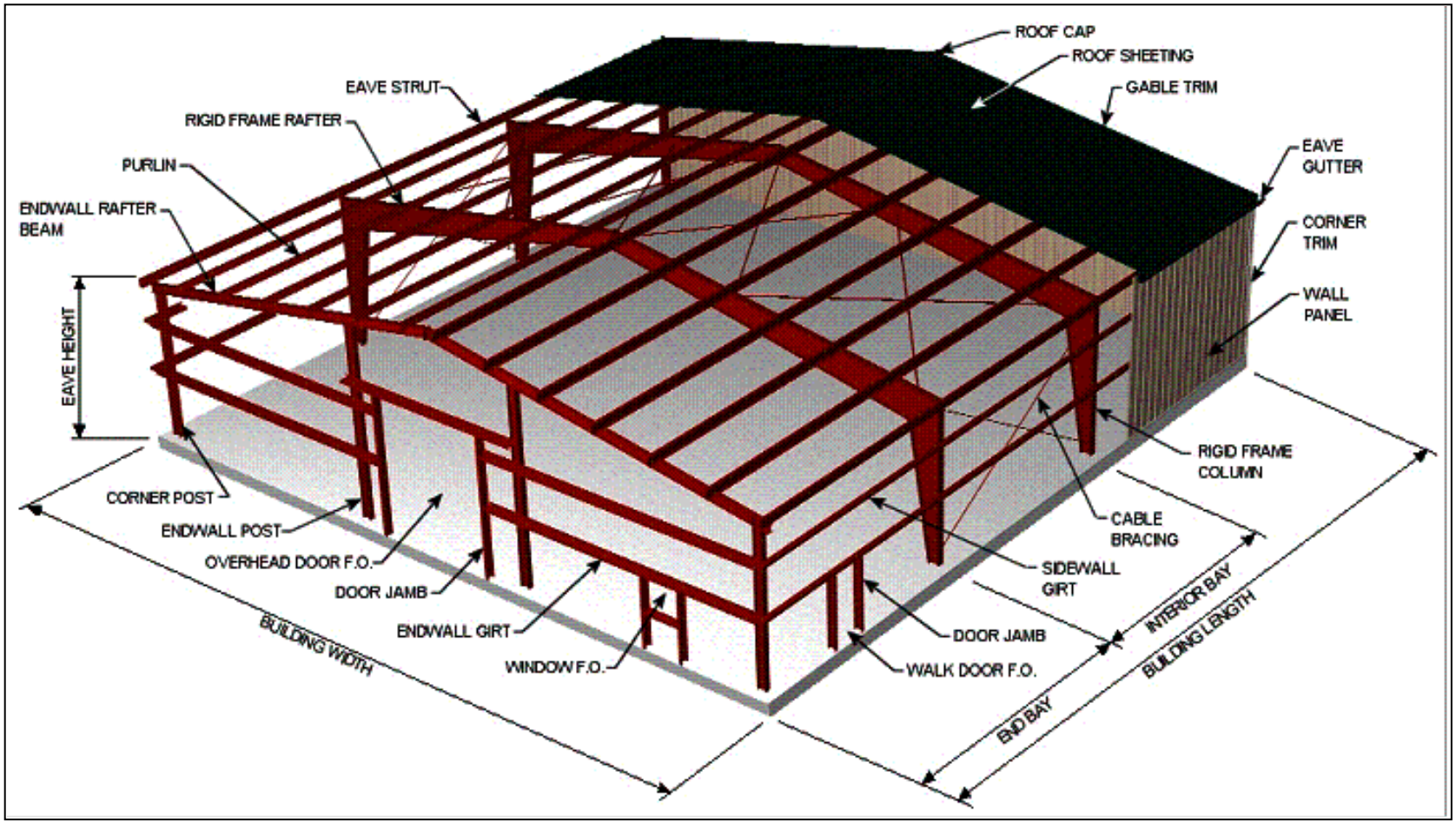

Figure A.1: A sectional view of a building system including terminology used by the industry for each element of the building [Photo courtesy: MBMA 2010]

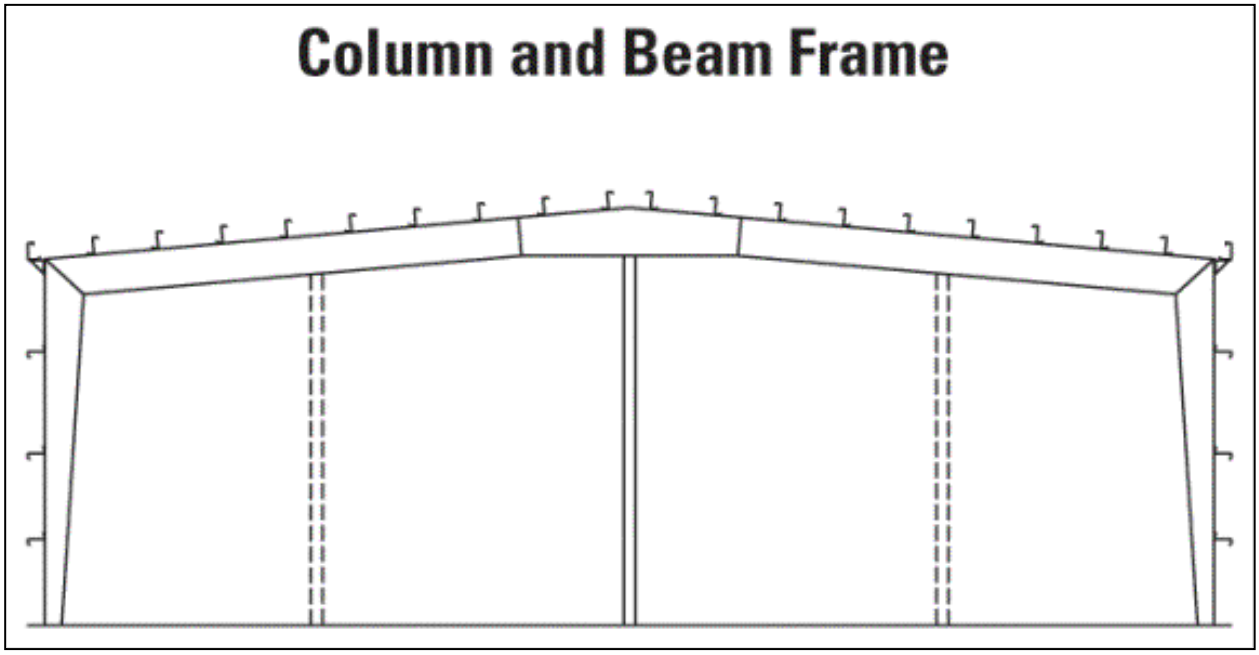

Figure A.2: Column and Beam Frame [Photo courtesy: MBMA 2010]

Metal Roof Systems

Metal roofs are the other major component of metal buildings. Metal roofs are cost efficient and versatile and can be constructed on most building types. It is even possible to retrofit older, non-metal roofs with a metal roof. The roofs can be standing seam (where the panels overlap and are attached by a concealed fastener system to the purlins below) or they can be thru-fastened. A thru-fastened roof is often a good, economical choice for smaller projects.

With steeper pitched roofs, the color and look will be more important and must often conform to local standards and codes. The metal building system manufacturer can offer a wide variety of options in coatings and colors. For low slope buildings, Galvalume® material coated with a mixture of zinc and aluminum is primarily used.

Wall Systems

For warehouse and distribution facilities, which are common and traditional uses for metal buildings, metal wall systems offer a wide range of profiles, coatings and colors.
Insulating the building with fiberglass or rigid board insulation enables the building to achieve considerable energy efficiency, thus lowering energy cost and consumption.

Concrete, masonry, and tilt walls are often used as the wall materials for metal buildings. Tilt walls can incorporate sandwich walls, where two walls are combined with an insulating layer in

between to increase insulation. Masonry and concrete walls are often designed with exterior treatments that coordinate into a neighborhood, business park or community.

Windows, walk doors, overhead doors and a wide variety of other accessories can go just about anywhere you want them and help facilitate the occupancy need. For retail and commercial facilities, store front glass systems are commonly used to facilitate merchandising practices. Even concrete tilt walls that are load bearing can be constructed with windows, so you can get natural light inside the building.

Appendix B. Third Party Critical Review Attestation

Industrial Ecology Consultants
35 Bracebridge Road
Newton, Massachusetts 02459

Critical Review by Panel of LCA Experts
In the capacity as the *original study commissioner*, the Metal Building Manufacturers Association (MBMA) commissioned a panel of life cycle assessment (LCA) experts to conduct a critical review the *Life Cycle Assessment of MBMA Primary and Secondary Structural Steel and Wall and Roof Panel Products* study performed by the Athena Sustainable Materials Institute. The following is a report of the review results of the *Updated Final Report*, April, 2013 version by the external review panel.

Panel Members
The panel comprised of the following members:

Chair
Thomas P. Gloria, Ph.D., LCACP
Managing Director, Industrial Ecology Consultants

Jonathan Dettling
US Managing Director, Quantis International

William Savitz
Garco Construction, former MBMA Chair

Critical Review Objectives
Per International Organization of Standardization (ISO) 14044:2006(E) *Environmental management – Life cycle assessment – Requirements and guidelines*, the critical review process included the following criteria to ensure conformance with applicable standards:

- Are methods used to carry out the LCA were consistent with ISO 14040/14044 standards?
- Are methods used to carry out the LCA were scientifically and technically valid?
- Are data used were appropriate and reasonable in relation to the goal of the study?
- Do interpretations reflected the limitations identified and the goal of the study?
- The study report was transparent and consistent?

Review Results
On the basis of the goals set forth to review this study, **the review panel concludes that the study conforms to the applicable ISO standards as a comprehensive study that may be disclosed to the public.**

Respectfully,

Thomas P. Gloria, Critical Review Panel Chair

16 May 2013
Newton, Massachusetts