Life Cycle Assessment of

Metal Construction Association (MCA)

Production Processes, Metal Roof and Wall Panel Products

Prepared by:

PE INTERNATIONAL, Inc.

For:

The Metal Construction Association

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GLOSSARY

Note: Many of these terms are excerpted from ISO 14040:2006, Environmental management - Life cycle assessment - Principles and framework, International Organization for Standardization (ISO), Geneva

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

Cradle-to-Gate

Addresses the environmental aspects and potential environmental impacts (e.g., use of resources and environmental consequences of releases) throughout a product's life cycle from raw material acquisition until the end of a production process ("gate of the factory"). It may also include distribution from manufacturing to use phase.

Functional Unit

Quantified performance of a product system for use as a reference unit

Life cycle

The life cycle is a unit operations view of consecutive and interlinked stages of a product system, from raw material acquisition or energy resources extraction to final disposal. This includes all materials and energy input as well as waste generated to air, land and water.

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 Inventory - LCI

Phase of Life Cycle Assessment process involving the compilation and quantification of inputs and outputs for a product 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.

MCA

The Metal Construction Association (MCA) is a trade organization representing manufacturers of metal products for use in the North American building construction industry.

NCAA

The National Coil Coating Association is a trade association of coil coaters and related manufacturers that provide components used in the manufacture of metal products.

Overhead

Overhead denotes materials, energy, and other inputs required to operate the production facility, but not directly involved in production processes (e.g., water, heating, lighting, etc.).

ABBREVIATIONS

AP	Acidification Potential
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CtG	Cradle-to-Gate process
CV	Coefficient of Variation
EP	Eutrophication Potential
EPA	Environmental Protection Agency
GaBi	Ganzheitliche Bilanzierung (German meaning Holistic Balancing)
GHG	Greenhouse gases
GtG	Gate-to-gate process
GVWR	Gross Vehicle Weight Rating
GWP	Global Warming Potential
H^+	Hydrogen ion
IEA	International Energy Agency
IMP	Insulated Metal Panel
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization of Standardization
kg	kilogram
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MCM	Metal Composite Material
MJ	Megajoule
N	Nitrogen
NA	North America
NO	Nitric monoxide
NO_2	Nitrogen dioxide
NO_x	Oxides of nitrogen
O_3	Ozone
ODP	Ozone Depletion Potential
P	Phosphorous
PED	Primary Energy Demand
POCP	Photochemical Ozone Creation Potential
SO_2	Sulfur dioxide
SO_x	Sulfur oxides
TRACI	Tool for the Reduction and Assessment of Chemical and other Environmental Impacts
US	United States of America
VOC	Volatile organic compound

EXECUTIVE SUMMARY

The Metal Construction Association (MCA) , in cooperation with the National Coil Coating Association (NCAA), commissioned PE INTERNATIONAL, Inc. to conduct a Life Cycle Assessment (LCA) in order to calculate the average environmental impacts of building envelope products manufactured by its member companies. Primary data were collected from MCA members on five manufacturing processes used in manufacturing three key products: steel Insulated Metal Panels (IMP), aluminum Metal Composite Material (MCM) Panels, and steel roll-formed claddings. The environmental profiles of the respective gate-to-gate (GtG) processes and cradle-to-gate (CtG) products are expected to be used for environmental benchmarking and decision-making by MCA member companies, architects, designers, and the buildings and construction community at large.

A fundamental component of LCA is the Life Cycle Inventory (LCI), a compilation of all relevant energy and material inputs and environmental release data associated with the processes related to production, manufacture and use. The LCI data in this project are expressed as averages where the data represents MCA production across the industry in the United States and Canada during the year 2010.

Primary data on raw materials, energy, and emissions were measured or calculated by the participating members based upon annual purchases, emission monitoring, and production output. Background data for upstream raw materials, energy, and transport were taken from PE INTERNATIONAL's GaBi database.

The calculated average environmental profile for each finished product is summarized in Table 1. These values represent the impacts associated with extraction of raw materials and energy from their deposits (Cradle) through the manufacture of 1,000 square feet of each product (Gate). The installation, use phase, and end of life treatment for each product are not included in this table. As a result, **these products should not be directly compared as they do not provide equivalent functions**.[1]

Table 1. Cradle-to-Gate Environmental Profile of MCA Products (1,000 square feet)

	Impact Methodology	Insulated Metal Panels	MCM Panels	Roll Formed Cladding
Global Warming Potential [kg CO_2-Equiv.]	IPCC	6,310	6,120	1,660
Primary energy (total) [MJ, net calorific]	LCI flow	62,200	99,100	19,200
Primary energy (non-renewable) [MJ, net calorific]	LCI flow	60,300	88,800	18,700
Primary energy (renewable) [MJ, net calorific]	LCI flow	1,810	10,300	534
Feedstock energy [MJ, net calorific]	LCI flow	10.2	0.531	5.31
Acidification Potential [mol H^+ Equiv.]	TRACI 2.0	844	1,850	257
Abiotic Depletion Potential (mineral) [kg Sb-Equiv.]	CML 2001	0.0282	0.00255	0.0140
Eutrophication Potential [kg N-Equiv.]	TRACI 2.0	0.648	0.852	0.134
Ozone Depletion Potential [kg CFC 11-Equiv.]	TRACI 2.0	0.000138	0.000145	0.0000473
Smog Potential [kg O_3-Equiv.]	TRACI 2.0	241	292	57.2
Human Health Criteria Air Pollution [kg PM_{10}-Equiv.]	TRACI 2.0	2.37	5.50	0.841
Water Usage [L]	LCI flow	11,900	25,300	3,930
Solid Waste [kg]	LCI flow	40	6.77	0.567

[1] For example, some products may require more or less insulation in order to provide an equivalent U value when installed in a building. When comparing products it is important that the products be compared according to their ability to provide equivalent services to the user.

1 Goals and Objectives

1.1 Background

The Metal Construction Association (MCA) engaged PE INTERNATIONAL, Inc. to evaluate the environmental profile of some of its key industry processes and primary products using the Life Cycle Assessment (LCA) methodology according to the ISO 14040/44 and 21930 standards. The decision to undertake this study was driven by both market interest and an internal desire to strengthen the position of MCA's products in the building and construction industry. MCA is also interested in understanding how the results of the LCA can be best positioned in go-to-market materials and claims, and what best practice tools and resources can be leveraged (e.g., using Federal Trade Commission (FTC) guidance documents and ISO requirements to generate Environmental Product Declarations). This study will be used to help MCA integrate sustainability into its support for members, and drive continuous improvement in the industry.

1.2 Goals of the Study

This study was carried out to evaluate the life cycle impacts of the member companies' five key manufacturing processes along with three main products, namely steel Insulated Metal Panels (IMP), aluminum MCM Panels, and steel rolled formed claddings. The primary goals and objectives of the LCA were to:

- Develop a better understanding of the environmental profile of MCA's primary products, and the relative contribution of MCA processes;
- Become more able to respond to stakeholder requests for information regarding the environmental impacts of MCA member products; and
- Assist other organizations in understanding and communicating the environmental performance of MCA member products.

1.3 Intended Audience and Applications

This LCA study provides detailed gate-to-gate process profiles and cradle-to-gate product profiles using key indicators of environmental performance. The information in this study is intended for use in the following applications:

- Population of the publicly available NREL LCI Database and incorporation of data into North American LCA software tools such as the GaBi database and the Athena EcoCalculator;
- Creation of an industry baseline to track continuous improvement in the industry and allow member companies to benchmark their plant-specific product footprint against a valid industry average; and

- Furthering education and marketing efforts to customers in the Building and Construction Industry (e.g., Leadership in Energy & Environmental Design (LEED) green building certifications, Green Globes rating systems, government procurement programs, etc.).

The results of the study are intended for public distribution. The intended audience for this information is the Building and Construction technical community (i.e., MCA member companies and their suppliers; architectural, engineering, and specifying professionals; LCA practitioners and tool developers; academia; governmental organizations; policy makers, etc.).It is expected that the majority of the audience interested in the results of this work will read Environmental Product Declarations or other business to business communication pieces derived from this report rather than this report in its entirety. This report is therefore constructed to serve as a reference document for such derivative works.

While comparative assertions are outside the scope of this study, the data in this report can be used by other interested parties for this purpose. To support these efforts, this LCA follows the ISO 14040 and 14044 guidelines, including a third-party critical review by a panel of relevant experts. Note that if any comparisons or benchmarks to this study are done, those parties should ensure that either the same or similar background datasets, reference year, assumptions, etc. are used to ensure an 'apples to apples' comparison.

2 Scope of the Study

2.1 Products and Processes Evaluated

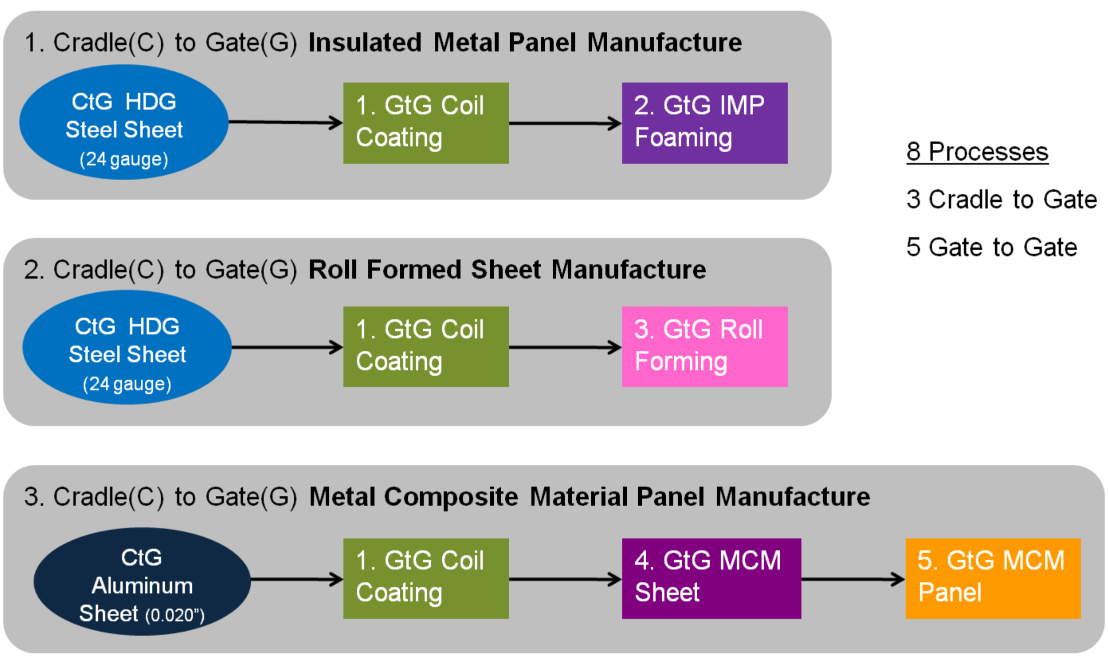
This LCA study evaluated the gate-to-gate (GtG) environmental impacts of the following five primary processes (each scaled to a production-weighted average of 1,000 square feet of the final product or process output):

1. Continuous Coil Coating Process
2. Insulated Metal Panel (IMP) Continuous Foaming Process
3. Metal Composite Material (MCM) Sheet Manufacturing Process
4. Metal Composite Material (MCM) Panel Fabrication Process
5. Metal Roll-Forming Process

In addition, a cradle-to-gate (CtG) LCA study was conducted on the following three MCA products (using a production-weighted average of 1,000 square feet of final product):

1. Insulated Steel Panels – steel coil based with high performance coating
2. Aluminum MCM Panels – aluminum coil based with high performance coating
3. Steel Roll Formed Claddings – steel coil based with high performance coating

The relationships between these gate-to-gate and cradle-to-gate processes are depicted graphically below.



2.2 FUNCTIONAL UNIT

Wall and roof panels can provide multiple functions; among these are covering a certain area, creating a barrier that controls noise, air, water, and thermal transmission between the external environment and the interior space of a building, as well as other functions such as load carrying capacity and aesthetics.

A functional unit is a quantified description of the performance of a product system for use as a reference. For non-comparative studies such as this one, the service provided by the product systems under study can simply be providing the product in a specified quantity. The functional unit for this study is **"coverage of 1,000 square feet with metal product"** for each process evaluated. The coverage area refers to the projected flat area covered by the product as output by the final manufacturing process step, and does not account losses due to overlap and scrap during installation.

To achieve the functional unit of 1000 ft^2 coverage, the reference flow for each of the five MCA "gate-to-gate" processes calculates to:

1. Continuous Coil Coating: 527 kg of pre-painted steel coils
2. IMP Continuous Foaming: 1371 kg of 2" IMP insulated steel panel made with high performance coated steel coil
3. MCM Sheet Manufacturing: 511 kg of cut-to-size, pre-painted MCM sheet
4. MCM Panel Fabrication: 768 kg of 4mm MCM insulated aluminum panels made with high performance coated aluminum coil
5. Metal Cladding Manufacture: 527 kg of Roll Formed Metal Claddings made of high performance coated steel coil

Reference flows 2, 4, and 5 likewise apply to the three "cradle-to-gate" product LCIs created in this study.

Table 2 summarizes the key MCA primary products, substrates, and processes for which LCI data was collected from MCA member facilities.

Table 2: Wall and Roof Panel Products, Key Metal Substrates and Processing

Primary Product	Metal Substrate of Interest	MCA Primary Processes
2" Insulated Metal Panel (IMP) with polyurethane/ polyisocyanurate foam core	High performance coated 0.028" (24 gauge) steel coil	• Continuous Coil Coating • IMP Continuous Foaming
Metal Composite Material (MCM) Panel	High performance coated 0.020" aluminum cladding skins with thermoplastic core	• Continuous Coil Coating • MCM Sheet Manufacturing • MCM Panel Fabrication
Roll Formed Metal Cladding	High performance coated 0.028" (24 gauge) steel coil	• Continuous Coil Coating • Metal Forming

2.3 PROCESS SYSTEM BOUNDARIES

A "gate-to-gate" assessment is an LCA that focuses on one process, production line, or manufacturing facility in the entire production chain. For this entity, all inputs and outputs that cross the system boundary are usually reported, while everything within the system boundaries follows a "black box" approach (wherein flows are not assigned to specific process steps, but are aggregated as if a single process step). Note that for confidentiality reasons, the "gate-to-gate" concept was broadened to encompass all upstream production processes of energy and material inputs - with the exception of the metal inputs themselves - as well as inbound transportation and downstream waste treatment/disposal of production wastes. Although this constitutes a hybrid between a "cradle-to-gate" and a "gate-to-gate" system boundary (sometimes called 'partially aggregated'), we will continue denominating the process LCIs as "gate-to-gate" and the product LCIs as "cradle-to-gate" to avoid any confusion between the two. Figures 1 to 5 below illustrate the system boundaries for each of the five selected gate-to-gate process systems. The gate-to-gate processes presented in this report refer to the sum of all components within the dotted lines below. The small individual manufacturing process within each diagram represent unit processes which were included in the gate-to-gate process for the facilities in which they are applicable. Most manufacturers do not measure energy and material usage across these individual steps. Therefore the overall process of transforming the incoming metal products above the dotted line of each figure, into the outgoing products to the right of dotted lines, was treated as a single unit process for the purposes of data collection and reporting in this study.

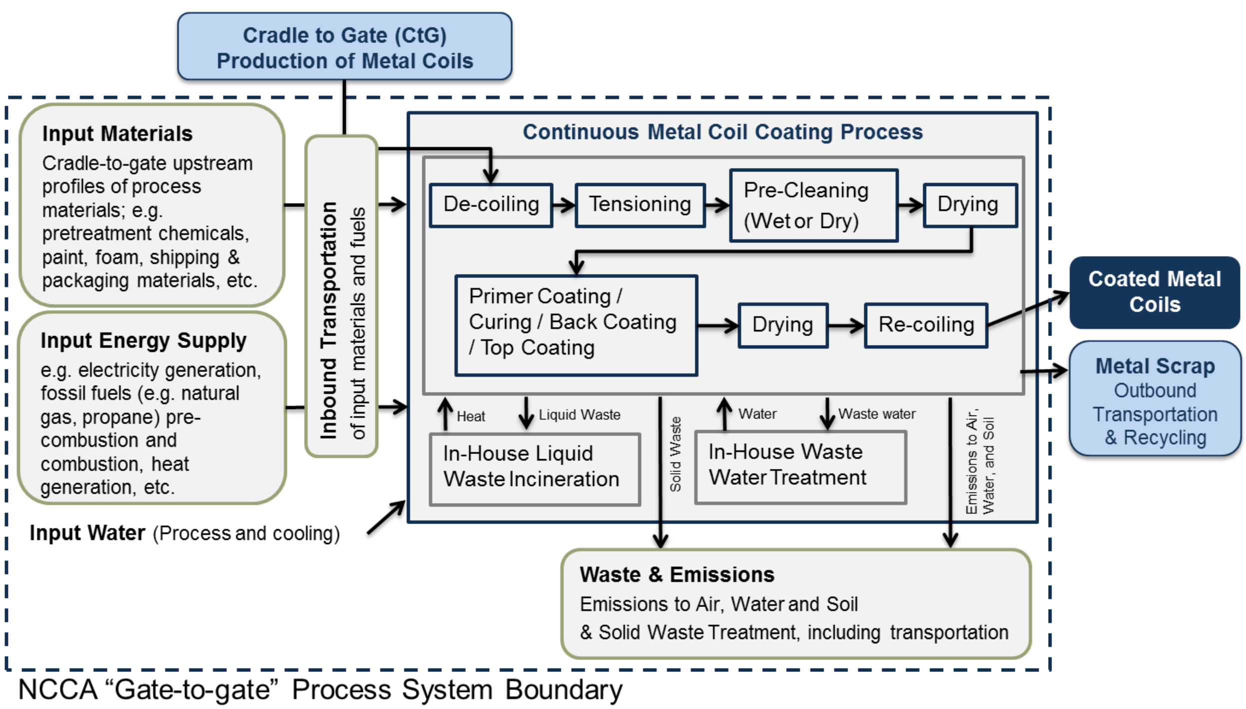


Figure 1: Gate-to-Gate System Boundary of the Continuous Coil Coating Process

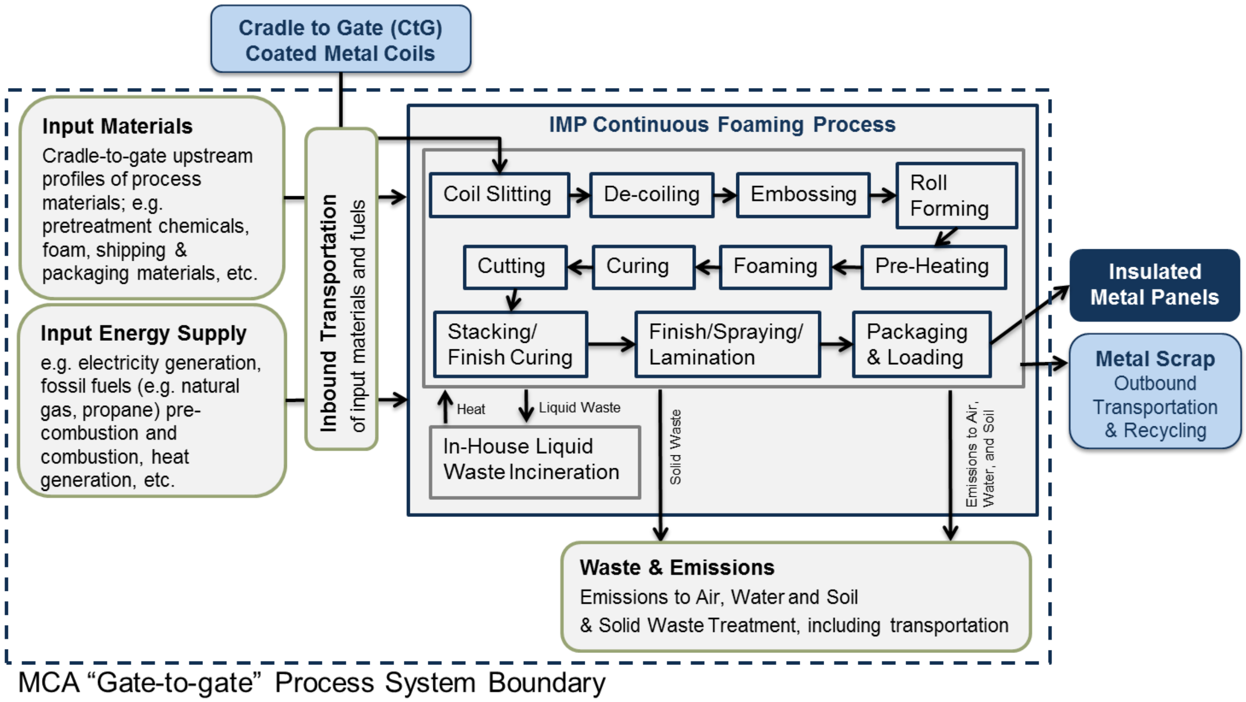


Figure 2: Gate-to-Gate System Boundary of the IMP Continuous Foaming Process

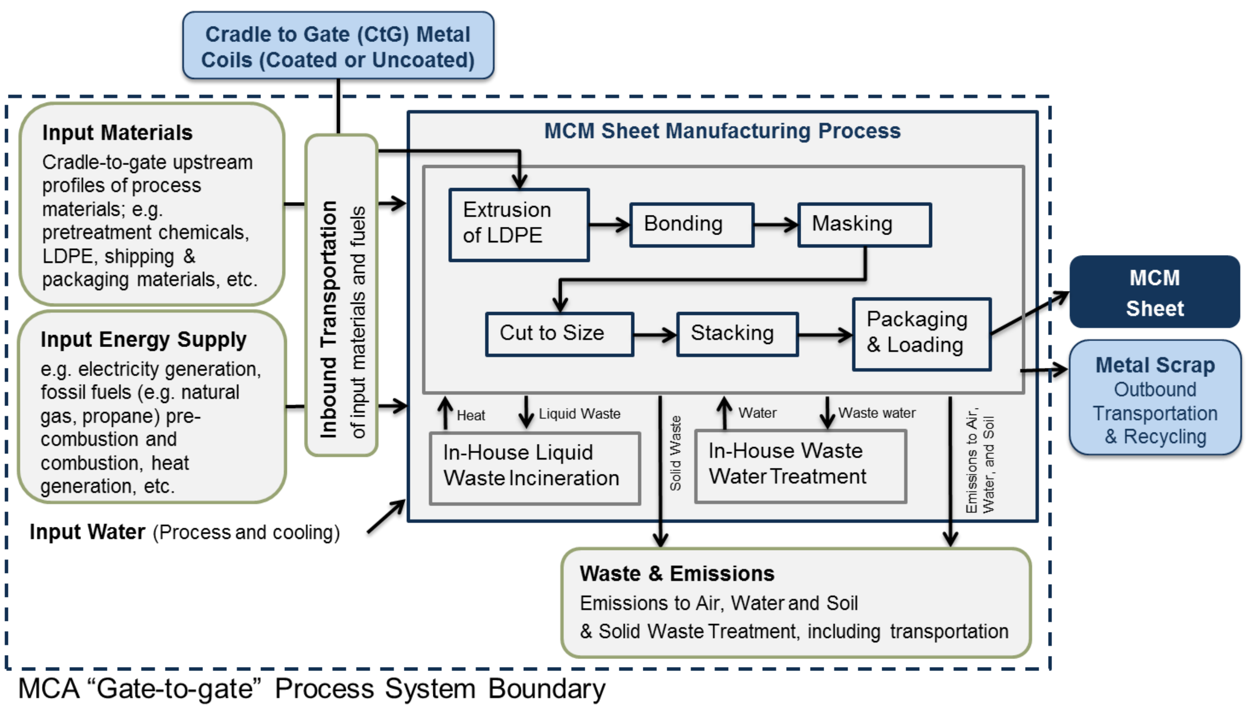


Figure 3: Gate-to-Gate System Boundary of the MCM Sheet Manufacturing Process

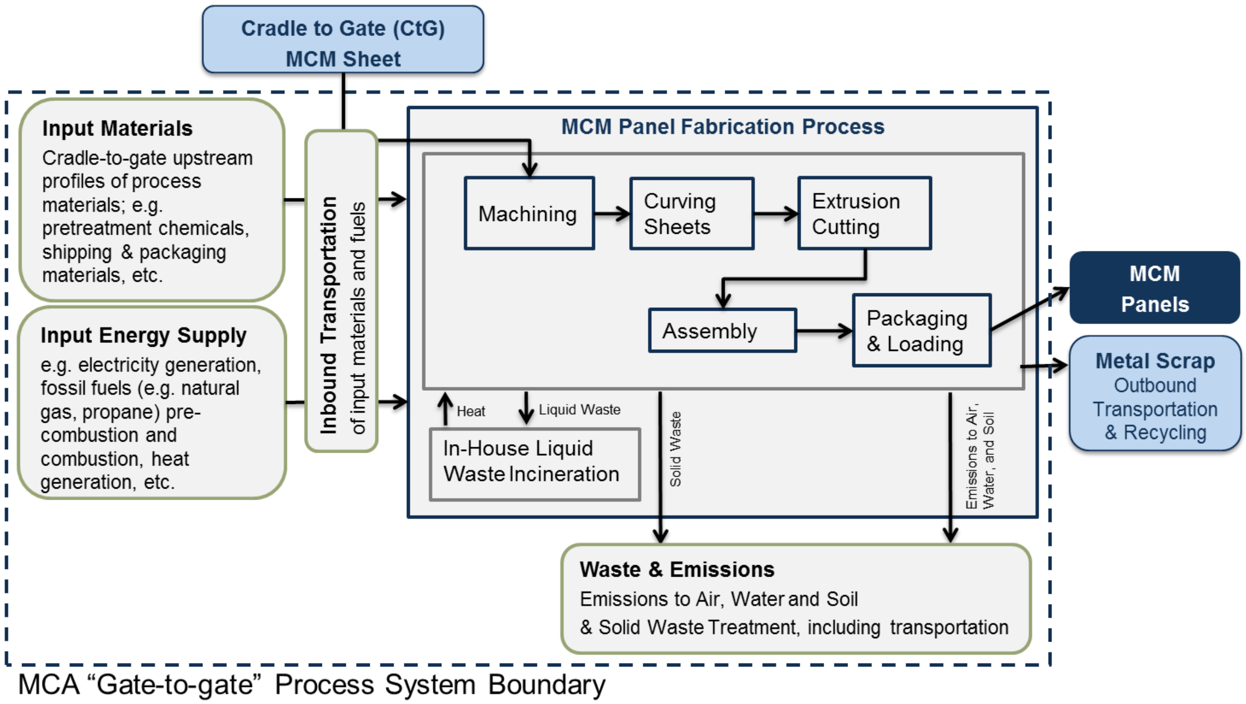


Figure 4: Gate-to-Gate System Boundary of the MCM Panel Fabrication Process

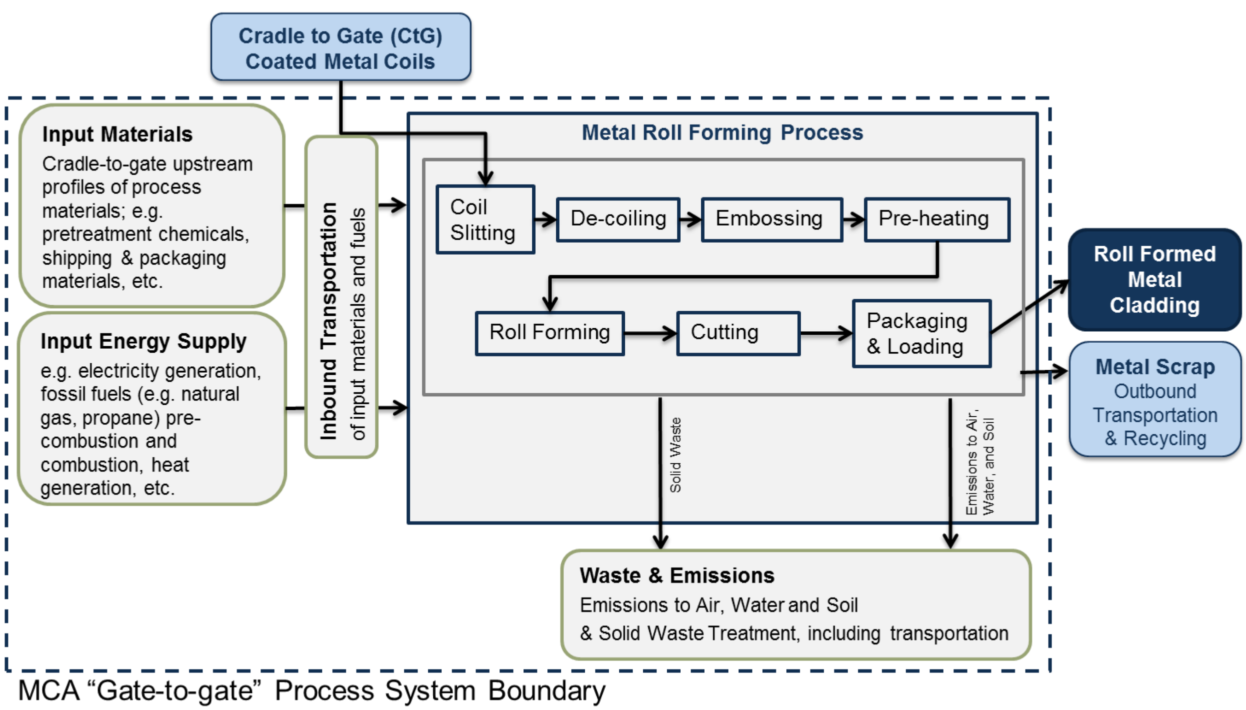


Figure 5: Gate-to-Gate System Boundary of the Metal Roll Forming Process

2.4 PRODUCT SYSTEM BOUNDARIES

A "cradle-to-gate" assessment is a product LCA that includes all impacts from resource extraction to the factory gate (i.e., before the product is transported to the consumer). Besides the product flows themselves, only elementary flows cross the system boundaries (resources, emissions, energy). Figure 6 through Figure 8 below illustrates the system boundaries for each of the three selected cradle-to-gate product systems.

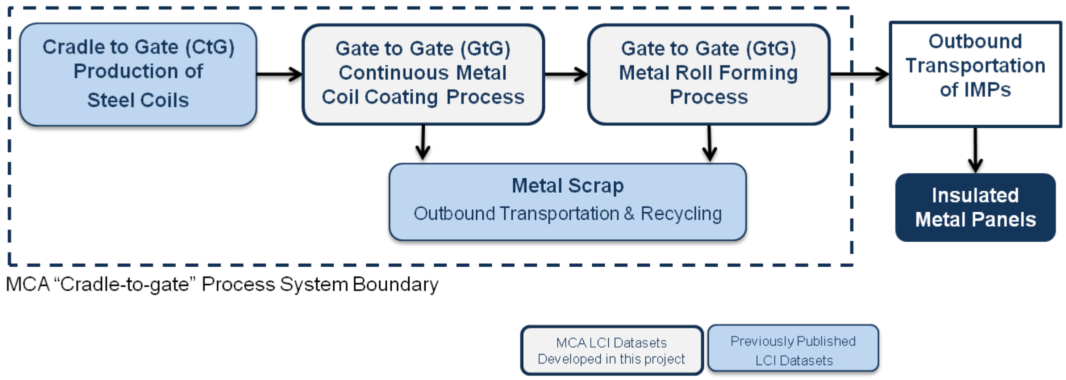


Figure 6: Cradle-to-Gate System Boundaries of IMP Products

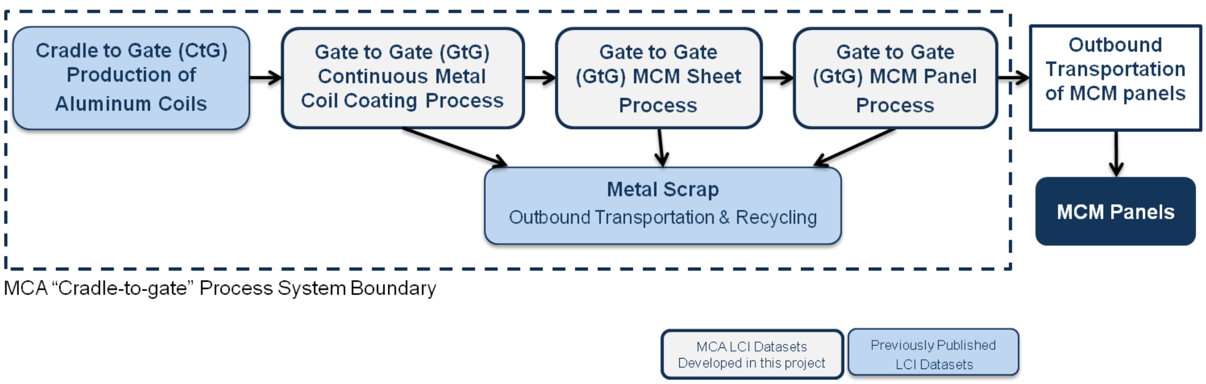


Figure 7: Cradle-to-Gate System Boundaries of MCM Panel Products

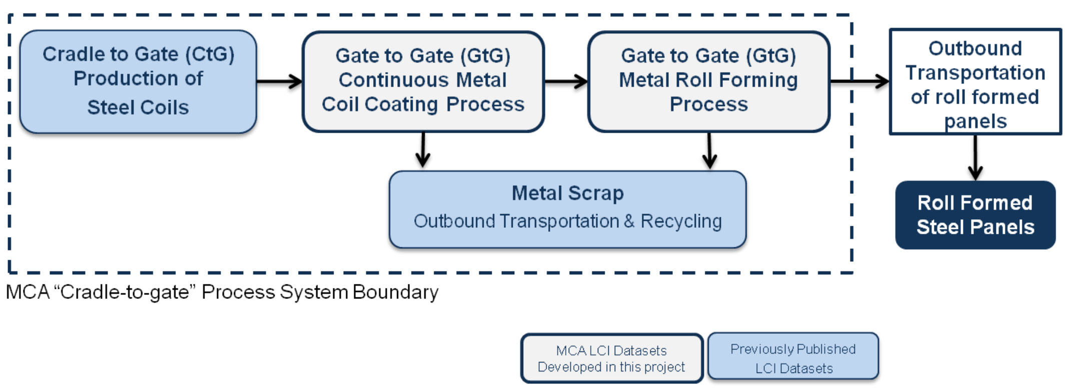


Figure 8: Cradle-to-Gate System Boundaries of Roll Formed Metal Cladding

Table 3 summarizes the elements included and excluded from the gate-to-gate and cradle-to-gate system boundaries for this study.

Table 3: System Boundaries Description for Process (GtG) and Product (CtG)

Included	Excluded
"Gate-to-Gate" System Boundaries	
✓ Process ancillary materials (e.g. fasteners) ✓ Energy supply ✓ Operation of primary production equipment ✓ Operation of mobile support equipment ✓ Input water (for process and cooling) ✓ Waste and on-site waste water treatment ✓ Manufacture and transport of product packaging ✓ In-bound transportation of all materials, intermediate products and fuels ✓ Overhead (heating, lighting) of manufacturing facilities ✓ Internal transportation of materials ✓ Waste & emissions	× The production of the metal sheet used in the product × The recycling of metal scrap generated × Maintenance and manufacture of fixed capital equipment × Maintenance of mobile support equipment × Outbound transportation of the main product/process output × Hygiene related water use × Employee commuting × Human labor × Installation and disposal of product
"Cradle-to-Gate" System Boundaries	
✓ All above elements ✓ Extraction of input raw materials, transportation and production of the metal sheet used in the product ✓ Transportation & recycling of metal sheet scrap	× All above elements except the production of metal sheet and the recycling of metal scrap, which are now included.

This study was completed using an attributional methodology, where average industry data was employed throughout the value chain. In the attributional approach, the elementary flows and potential environmental impacts are assigned to a specific product system based on average data. A twelve-month calendar year average (2010) was used to account for any seasonal variations.

2.5 Cut-Off Criteria

In order to reduce the extent and complexity of the LCA to a practicable degree, inventory data which are negligible (i.e., not relevant to the study) may have been omitted. The following criteria have been used to determine the inclusion of inputs and outputs within each system boundary:

- 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 a flow meets the above criteria for exclusion, yet is thought to potentially have a significant environmental impact, it is evaluated with proxies identified by chemical and material experts within PE. If the proxy for an excluded material has a significant contribution to the overall LCIA (5% or more of any impact category considered), more information is collected and evaluated in the system.

The sum of the neglected input flows must not exceed 5% of the total mass, energy or environmental relevance.

All data reported to PE INTERNATIONAL was included in the models built for each product. No reported data was excluded due to the above cut-off criteria.

2.6 ALLOCATION

Metal scrap generated during manufacturing is considered a valuable co-product and was addressed with the avoided burden modeling approach. The avoided burden approach subtracts impacts from the main product system for co-products or by-products that would have otherwise been produced from primary raw materials. To be consistent with the worldsteel dataset for galvanized Steel Coil, scrap steel input is given a burden based on the worldsteel "value of scrap" model which utilized the modeling approach described in a study of recycling methodologies (Avery & Coleman, Sept 2009). This "value of scrap" is used as the upstream burden of any scrap input in the production of Steel Coil, and its inverse is then consistently used again throughout the study to provide credit for any steel scrap generated. A corresponding "value of scrap" model was created for aluminum based upon the aluminum LCI data published by the International Aluminum Institute[2] and the Aluminum Association[3].

The environmental "value of scrap" is applied within the product lifecycle as shown in the simplified diagram of Figure 9. In this example, the steel contains 10 % scrap. Therefore, the Cradle-to-Gate production of 1 kg of steel receives the environmental burdens associated with combining 0.90 kg of primary steel with 0.10 kg of scrap steel represented by the "value of scrap". Upon end of life, 0.90 kg of scrap steel is produced, and therefore 0.90 kg worth of "value of scrap" is credited. In this example, the 0.90 kg of scrap mathematically cancels the 0.10 kg of scrap used during the initial manufacture, and provides a net 0.80 kg worth of the "value of scrap" credit plus 0.90 kg of primary steel production. Throughout this report, however, we separate the value of scrap used during product manufacture from

[2] International Aluminum Institute. "Life Cycle Assessment of Aluminum: Inventory Data for the Primary Aluminum Industry Year 2005 Update" 2007. Available at: http://www.world-aluminium.org/cache/fl0000166.pdf

[3] Aluminum Association Inc. "Life Cycle Assessment of Aluminum Beverage Cans" Prepared by PE Americas. 2010. Available at: http://www.aluminum.org/Content/ContentFolders/LCA/LCA_REPORT.pdf

that potentially available at end of life. This is done for two reasons: for transparency in modeling, and in recognition of the uncertainty around end of life treatment. The "value of scrap" itself is calculated as the difference between producing a given amount of material from 100% primary material and the same amount of material through secondary production means.

Given this is a cradle-to-gate study, no credit is applied for the potential end of life recycling of the products (post-consumer). Recycling credit is only given to scrap generated within the manufacturing process (post-production) which is known to be recycled.

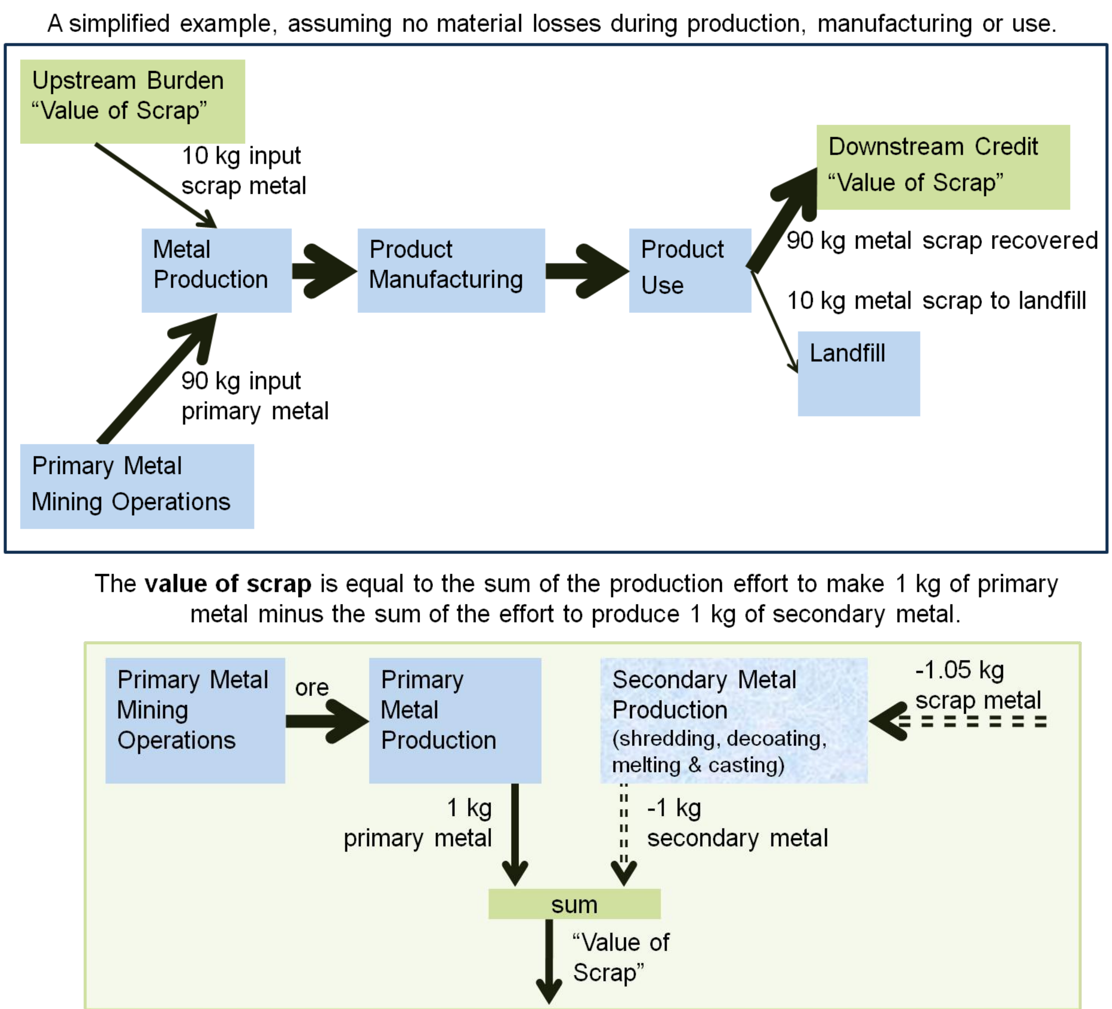


Figure 9: Value of Scrap as applied in a Life Cycle

Allocation was also used in creation of upstream datasets in the Gabi database, such as refinery products. Documentation for upstream data can be provided upon request or at: http://documentation.gabi-software.com/.

2.7 SELECTION OF IMPACT CATEGORIES AND ASSESSMENT METHODOLOGIES

For this study, the document ISO 21930:2007 "*Sustainability in Building Construction – Environmental Declaration of Building Products"* provides guidelines for the creation of Environmental Product Declarations (EPDs) for building products. The scope of this study does not include creation of EPDs, but ISO 21930:2007 provides a comprehensive list of environmental impacts relevant to the building products industry, so these categories are used for the Life Cycle Impact Assessment (LCIA). In referencing this standard for the selection of impact categories included, the authors of this study need not make independent value judgments regarding which indicators to evaluate. Given the North American geography of MCA products, the US EPA Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI 2.0)[4] was used as the LCIA baseline methodology. To provide results for abiotic depletion potential, an indicator not available in TRACI, impact characterization was taken from the University of Leiden (CML) methodology, last updated in 2010.

With respect to global warming potential, no credit was given for the sequestration of biogenic carbon during the growth of plants used in plant-derived materials such as wooden pallets. This ensures that when looking at the cradle-to-gate or gate-to-gate results in this report, the reader does not mistakenly draw the conclusion that the more wood is used, the lesser the overall environmental indicators. The carbon temporarily sequestered during the use of wooden pallets will be re-released to the atmosphere upon their decomposition. Since the lifetime of a wooden pallet is shorter than the 100 year time horizon of this impact category (GWP100), biogenic carbon was excluded from the global warming potential calculations.

The USEtox methodology is used to characterize toxicity, as per Rosenbaum et al. (2008)[5]. The precision of the current USEtox characterization factors is within a factor of 100–1,000 for human health and 10–100 for freshwater ecotoxicity. This is a substantial improvement over previously available toxicity characterization models, but still substantially higher than most other environmental indicators. Given the limitations of the characterization models for each of these USEtox characterization factors, results are reported as 'substances of high concern', but are not to be used to make quantitative assertions.

It shall be noted that the following impact categories represent impact *potentials*, i.e., they are approximations of environmental impacts that could occur if the emitted molecules would (a) actually follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so.

LCIA results are therefore relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

[4] Bare, J. TRACI 2.0: the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts 2.0. Clean Technologies and Environmental Policy. Volume 13, Number 5, 687-696. 2011.

[5] USEtox—the UNEP-SETAC toxicity model: recommended characterization factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment, IJLCA, Springer, 2008.

Table 4 summarizes the selected impact categories and LCI flows, their equivalence units, the source of the characterization method and geographic specificity used in this study.

Table 4: Impact categories considered

Impact Categories and LCI flows	Description	Indicator Result (Unit)	Source of Characterization Method	Level of Site Specificity Selected
Global Warming Potential / Climate Change / Carbon Footprint	A measure of greenhouse gas emissions, such as CO_2 and methane. These emissions are causing an increase in the absorption of radiation emitted by the earth, increasing the natural greenhouse effect. This may in turn have adverse impacts on ecosystem health, human health and material welfare.	kg CO_2 -equiv.	Bare J, TRACI 2.0: the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts, Clean Technologies and Environmental Policy, 2011.	Global
Acidification Potential	A measure of emissions that cause acidifying effects to the environment. The acidification potential is a measure of a molecule's capacity to increase the hydrogen ion (H^+) concentration in the presence of water, thus decreasing the pH value. Potential effects include fish mortality, forest decline and the deterioration of building materials.	mol H^+-equiv.	Bare J, TRACI 2.0: the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts, Clean Technologies and Environmental Policy, 2011.	North America
Ozone Depletion Potential	A measure of air emissions that contribute to the depletion of the stratospheric ozone layer. Depletion of the ozone to leads to higher levels of UVB ultraviolet rays.	kg CFC-11-equiv.	Bare J, TRACI 2.0: the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts, Clean Technologies and Environmental Policy, 2011.	Global

Eutrophication Potential / Water Pollution	Eutrophication covers all potential impacts of excessively high levels of macronutrients, the most important of which are nitrogen (N) and phosphorus (P). Nutrient enrichment may cause an undesirable shift in species composition and elevated biomass production in both aquatic and terrestrial ecosystems. In addition, high nutrient concentrations may also render surface waters unacceptable as a source of drinking water. In aquatic ecosystems increased biomass production may lead to depressed oxygen levels, because of the additional consumption of oxygen in biomass decomposition.	kg N-equiv.	Bare J, TRACI 2.0: the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts, Clean Technologies and Environmental Policy, 2011.	North America
Photochemical smog Potential	A measure of emissions of precursors that contribute to ground level smog formation (mainly ozone O_3), produced by the reaction of VOC and carbon monoxide in the presence of nitrogen oxides under the influence of UV light. Ground level ozone may be injurious to human health and ecosystems and may also damage crops	kg O_3 equiv.	Bare J, TRACI 2.0: the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts, Clean Technologies and Environmental Policy, 2011.	North America
Abiotic Depletion Potential	A measure of resource depletion from the earth's crust, as a function of the size of the reserves and their potential functions. After one or more industrial transformation steps, abiotic resources fulfill various valuable functions for mankind. These functions are the reason for their extraction and they may be delivered by elements, by compounds, or by a physical appearance independent of elements or compounds.	kg Sb-equiv.	An operational guide to the ISO-standards (Guinée et al.) Centre for Milieukunde (CML), Leiden 2001.	Global
Primary energy demand - total / non-renewable	A measure of the total amount of primary energy extracted from the earth. PED is expressed in energy demand from non-renewable resources (e.g., petroleum, natural gas, etc.) and energy demand from renewable resources (e.g., hydropower, wind energy, solar, etc.). Efficiencies in energy conversion (e.g., power, heat, steam, etc.) are taken into account. Lower heating Values (LHV) are used in this calculation.	MJ, net calorific value	LCI flow	Global
Solid Waste	A measure of the solid waste leaving the technical cycle, including manufacturing scrap, consumer waste, hazardous and radioactive waste, and stockpile goods. Solid waste is expressed in kg.	kg	LCI flow	Global
Water Use	Gate-to-gate process water and cooling water inputs are considered in this study. Water use is expressed in liters.	Liter	LCI flow	Global

Human and Eco-toxicity	USEtox calculates characterization factors for human toxicity and freshwater ecotoxicity based on a cause–effect chain that links emissions to impacts through three steps: environmental fate, exposure and effects. The systematic framework for toxic impacts modeling based on matrix algebra was developed within the OMNIITOX project.	[cases] and [Percent Affected Fraction m^3 day]	Rosenbaum et al.: USEtox—the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment, IJLCA, Springer, 2008.	Global

2.8 Data Quality

The following paragraphs document the comprehensive data quality requirements according to ISO 14044[6]. Data quality is judged by its precision (measured, calculated or estimated), completeness (e.g., unreported emissions), consistency (degree of uniformity of the methodology applied on a study serving as a data source) and representativeness (geographical, temporal, and technological).

A main deliverable of the project is the submission of the LCI data for each of the five primary processes and each of the three CtG products to the US LCI Database. Publishing these five processes will ensure transparent and consistent LCI data, which will facilitate their use by North American LCA practitioners and software tool developers.

2.8.1 Precision and Completeness

Primary data on raw materials, energy, and emissions were calculated by the participating mills based on annual purchases, production output, and reported process emissions. Many mills reported transportation distance data as estimates due to the complexity of their supply chains. All upstream and downstream data is consistently GaBi LCI data within the documented precision.

All components of the final product were modeled and all material flows, energy flows and emissions were included. Many companies had small inconsistencies in their mass balance due to imprecise calculations of material weight and inconsistency in tracking waste sent externally vs. waste reused in-house. Missing data were corrected by the mills when possible, and mass balances within 1% of discrepancy were achieved for metal and scrap, the most important contributors to the LCA results. Inconsistencies in the reported input/output mass of ancillary and packaging materials are often omitted due to the 1% mass cutoff rule.

[6] *International Standard, ISO, 14044, Environmental management – life cycle assessment – requirements and guidelines, 2006.* Geneva: International Standard Organization.

2.8.2 CONSISTENCY AND REPRODUCIBILITY

To ensure consistency, only primary data of the same level of detail and upstream data from the GaBi LCI databases were used. Internal quality assurance (QA) was performed at different stages of the project by a dedicated QA Manager. The objective of the QA process was to ensure that the data collection, the development of the LCI model, and the final results are consistent with the scope of the study, and that the study delivers the required information. The QA included a check of the precision and completeness of the collected primary data (e.g. mass balance), LCI datasets used, general model structure, results plausibility (e.g. comparison to other similar reports and best available technology documents), and report documentation. All data has been found to be in acceptable ranges compared to internally and publically available information.

Reproducibility by third parties is possible using the aggregated inventory data and background LCIs documented in chapter 3.

2.8.3 TEMPORAL COVERAGE

Primary data collected from MCA and NCCA member companies for their operational activities related to the five processes are representative for the year 2010 (reference year). Additional data necessary to model base material production and energy use, etc. was adopted from the GaBi 4.4 software system database and described further in Table 5.

2.8.4 GEOGRAPHICAL COVERAGE

The geographical coverage for this study is based on US and Canada system boundaries for all processes and products. Whenever US and Canada background data was not readily available, European data was used as a proxy.

2.8.5 TECHNOLOGICAL COVERAGE

Data were collected for representative technologies in the US and Canada - the participating mills operate in US and Canada and represent the majority of the market share. A minimum of three companies participated in the data collection for each product.

2.8.6 CRITICAL REVIEW

To ensure fidelity to the principles and requirements of the international standards on life cycle assessment, a three-member critical review panel evaluated the LCA report. The review chair Tom Gloria, Industrial Ecology Consultants, is an LCA expert and familiar with the chemical and buildings industries. Al Dunlop, independent coil coating industry expert, is an expert in the area of metal product assemblies and manufacture. Jamie Meil, Athena Institute, is an LCA expert and initially helped the MCA scope this project. Their review statement is appended to this report.

3 LIFE CYCLE INVENTORY

3.1 DATA COLLECTION, VALIDATION, & LIMITATIONS

3.1.1 DATA COLLECTION

The study included data collection in the following categories for each of the MCA processes and products.

- Fuel and energy use;
- Use of raw materials, ancillary materials;
- Products, co-products;
- Emissions to air, water, and soil; and
- Wastes.

Primary data collection of information, which is representative of specific manufacturing operations, was accomplished by distributing customized questionnaires to MCA member companies. Primary manufacturing data for the functional units were collected from manufacturing plants at different sites around North America. Raw material, energy, and waste data were collected on an annual, facility-wide basis and scaled down to a unit of production.

Secondary data from life cycle databases and outside studies were used for life cycle phases outside the member companies' system boundary. The sources for background data are documented in Table 5.

Complete LCI tables for each product are available from PE International upon request.

Table 5: Material datasets used

	Dataset Utilized and Source (if other than GaBi)	Region	Year
Metals			
24 gauge steel coil	Steel sheet, hot dipped galvanized (worldsteel, 10% recycled content)	Global	2010
0.020" aluminum coil	IAI primary aluminum mix[7] with a "value of scrap" dataset for recycled content based upon the aluminum recycling processes detailed in the Aluminum Association's 2010 LCI report[8],adjusted to 60% recycled content[9], and US boundary conditions[8].	US	2005
Transportation			
Large Truck - trailer	Truck - Trailer, basic enclosed / 45,000 lb payload – Class 8b	US	2008
Large Truck - flatbed	Truck - flatbed, platform / 49,000 lb payload – Class 8b	US	2008
Medium Truck	Medium Heavy-duty Diesel Truck - Class 6	US	2008
Small Truck	Medium Heavy-duty Diesel Truck - Class 3	US	2008
Large Truck - tanker	Truck - liquid or gas/ 50,000 lb payload – Class 8b	US	2008
Diesel	Diesel at refinery	US	2003
General Processes			
Lubricants/Grease	Lubricants at refinery	US	2007
Thermal Energy	Thermal Energy from natural gas	US	2002
	Thermal Energy from propane	US	2011
Electricity	Power grid mix (from appropriate US regions)	US	2002
Landfill	Landfill (commercial waste for municipal disposal)	Europe	2005
Steel Scrap Recycling	Value of Scrap (worldsteel)	Global	2010
Packaging			
Styrofoam	Expanded Polystyrene	Germany	2005
Protective Films (HDPE)	HDPE Granulate	US	2008
	Plastic film - PE, PP, PVC	Global	2005

[7] International Aluminum Institute. "Life Cycle Assessment of Aluminum: Inventory Data for the Primary Aluminum Industry Year 2005 Update" 2007. Available at: http://www.world-aluminium.org/cache/fl0000166.pdf

[8] Aluminum Association Inc. "Life Cycle Assessment of Aluminum Beverage Cans" Prepared by PE Americas. 2010. Available at: http://www.aluminum.org/Content/ContentFolders/LCA/LCA_REPORT.pdf

[9] The Aluminum Association. "LEED Fact Sheet. Aluminum Sheet & Plate for the Building & Construction Market." August 13, 2008. Available from: http://www.aluminum.org/Content/NavigationMenu/TheIndustry/BuildingConstructionMarket/LEED_Fact_Sheet_8_13_08.pdf

Stretch Wrap	Polypropylene Film	US	2008
Strip Film	LDPE Film	US	2008
Lumber/Shipping Skids	Surface Dried lumber, at planer mill (NREL USLCI)	US	2009
Plywood	Plywood, at plywood plant (NREL USLCI)	US	2009
Cardboard/Paper Wrapping	Corrugated Board Boxes (FEFCO)	Europe	2002
Steel Banding	Steel, hot rolled coil (worldsteel, 12% recycled content)	Global	2010
Plastic Banding	Polypropylene Granulate	US	2008
	Plastic extrusion profile unspecific	Global	2005
Wood Pallets	Surfaced dried lumber, at planer mill, South East (NREL USLCI)	US	2009
Flake Board	Oriented strand board	Europe	2005
Shims	Surfaced dried lumber, at planer mill, South East (NREL USLCI)	US	2009
Expanded Polystyrene	Polystyrene expandable granulate – EPS	Europe	2005
	Plastic injection molding part unspecific	Germany	2005
Coil Coating			
Primer (often with hexavalent chrome)	Primer	Germany	2005
Cleaner			
Ingredient 1	*Water deionized*	*US*	*2008*
Ingredient 2	*Potassium Hydroxide*	*US*	*2009*
Ingredient 3	*Trisodium Phosphate*	*Global*	*2005*
Ingredient 3	*Glucose (via starch hydrolysis)*	*US*	*2009*
Solvents	Methyl Ethyl Ketone	US	2008
Polyvinylidene Fluoride (PVDF)	Fluoropolymer	Germany	2006
Backside Finish	Solvent Borne Paint	Germany	2005
Pretreat	Chromic Acid	US	2008
Phosphate Pretreatment			
Ingredient 1	*Water deionized*	*US*	*2008*
Ingredient 2	*Phosphoric Acid*	*US*	*2009*
Ingredient 3	*Nitric Acid*	*Germany*	*2005*
IMP Foaming			
Polyester Polyol	Polyester Polyol (PIMA)	US	2010
MDI	Methylendiisocyanate (NREL USLCI)	US	2010
Pentane	Pentane (Plastics Europe)	Europe	2005
Glue/hot melt	TPU Adhesive	US	2008

R-134a	R-134a	US	2010
Polyethylene Foam	Polyethylene Foam	Germany	2010
Roll Forming			
Sealant			
Ingredient 1	*Kaolin (mining and processing)*	*US*	*2009*
Ingredient 2	*Calcium Carbonate*	*US*	*2009*
Ingredient 3	*Polybutadiene granulate*	*US*	*2009*
Tape Mastic	Joint Sealing Tape Butyl	Germany	2010
MCM Sheet Manufacturing			
LLDPE	Linear low density polyethylene resin, at plant (USLCI)	US	2009
LDPE	Polyethylene low density granulate (PE-LD)	US	2008
Recycled PE	Plastic resin secondary	US	2008
Masking – HDPE	Polyethylene high density granulate (PE-HD)	US	2008
Masking – LDPE	Polyethylene low density granulate (PE-LD)	US	2008
Masking – PVC	Polyvinyl chloride granulate (S-PVC)	US	2008
Bonding – HDPE	Polyethylene high density granulate (PE-HD)	US	2008
Bonding – LLDPE	Linear low density polyethylene resin, at plant (USLCI)	US	2009
MCM Panel Fabrication			
Aluminum Extrusions	IAI primary aluminum mix[10] with a "value of scrap" dataset for recycled content based upon the aluminum recycling processes detailed in the Aluminum Association's 2010 LCI report[11]	Global	2005
	Aluminum extrusion profile (EAA)	Europe	2005
Sealants	Silicone sealing compound	Germany	2010
Fasteners	Steel cast part alloyed	Europe	2005
	Value of scrap (worldsteel)	Global	2010

3.1.2 Data Validation & Quality Assessment Procedure

Primary data were collected from MCA companies' engineers, managers, and procurement managers. Upon receipt, each questionnaire was cross-checked for completeness and plausibility using mass balance, stoichiometry, and benchmarking. If gaps, outliers, or other inconsistencies occurred, PE International engaged with the data provider to resolve any open issues. As described above, mass balance discrepancies within 1% were achieved for metal inputs and outputs, but some mills were

[10] International Aluminum Institute. "Life Cycle Assessment of Aluminum: Inventory Data for the Primary Aluminum Industry Year 2005 Update" 2007. Available at: http://www.world-aluminium.org/cache/fl0000166.pdf
[11] Aluminum Association Inc. "Life Cycle Assessment of Aluminum Beverage Cans" Prepared by PE Americas. 2010. Available at: http://www.aluminum.org/Content/ContentFolders/LCA/LCA_REPORT.pdf

unable to balance all of their packaging and ancillary materials mass. This inability is mostly due to the fact that the products are all sold on an area basis, so accurate mass data is not typically collected on non-metal outputs. Each input parameter was averaged and then a coefficient of variation from the production-weighted average was calculated to identify inconsistencies and outliers – values less than 50% or greater than 200% of the weighted average were confirmed or corrected with the data providers on an individual basis.

3.1.3 DATA LIMITATIONS

Background data for ancillary materials were based on North American and European industry average production processes. These process technologies are mature and sufficiently represent current North American production activities. One notable exception is the use of a global steel average to model steel production in North America. The prevalent steel technology route in North America is the Electric Arc Furnace (EAF), whereas the global average includes considerably more steel made with higher-burden Basic Oxygen Furnace (BOF) technology. At this time, a North American steel dataset is under development but has not been published for use, so the global steel average is used. Until the US steel dataset is released, it is difficult to estimate how the US average impacts will compare to the global average impacts; however the higher average ratio of secondary steel and EAF furnaces in the US is expected to result in a lower average cradle-to-gate profile for US steel than global steel.

Additionally, the datasets available to represent US natural gas, diesel fuel, and electricity at the time of this study were representative of production of such fuels during the year 2002. These datasets are therefore not fully reflective of the average fuel compositions as used in the production of each product in the year 2010. It is recommended that any EPDs or other work derived from this study include updated electricity models.

Aside from these limitations associated with the datasets utilized for steel and energy, all other datasets applied in this report are of high quality, and fully appropriate to support the goal and scope of this project. The limitations associated with the steel and energy profiles most likely result in over-estimating the potential environmental impacts of the MCA products as the US steel is expected to have a lesser environmental impact than global steel, and the electricity grid has become more efficient over time.

3.2 GATE-TO-GATE LIFE CYCLE INVENTORIES

The following tables present the gate-to-gate inventory for each of the products assessed within this report. Each was calculated as the production-weighted average of minimally three manufacturers of each product. Due to slight differences in each manufacturer's processing steps (choice of blowing agent, packaging applied, etc.), not all listed flows are used by the same manufacturer. All flows provided by participating companies during the LCI assessment have been captured in the model. In the case of IMP foaming, quantities of major constituents (MDI and Polyol) were modeled based upon primary data collection from the participating companies whereas quantities of additives such as TCPP and catalyst were modeled according to the industry-wide-averages reported in the PIMA study[12]. Due to the use of production-weighted averages, the sum of inputs and outputs below does not necessarily create a 100% mass balance for each gate-to-gate process.

Table 6 - Gate-to-gate inventory for 1,000 sqft of Painted Metal Coil

Inputs	Quant.	Units	Outputs	Quant.	Units
Metal Coil (Steel)	541	kg	Painted Steel Coil	527	kg
Fluoropolymer paint	4.48	kg	Packaging	2.99	kg
Backside Finish	0.878	kg	**Solid Waste for Recycling**		
Cleaner	0.148	kg	Metal Scrap	14.6	kg
Sealer/Pretreat agent	0.169	kg	Waste Paints	0.266	kg
Grease	0.0115	kg	Waste Solvents	0.602	kg
Lubricant	0.157	kg	**Emissions to Air**		
Solvent	0.516	kg	Carbon monoxide	0.0125	kg
Electricity	97.4	MJ	Nitrogen oxides	0.077	kg
Shipping Skids	2.68	kg	PM (10)	0.00594	kg
Steel banding	0.09	kg	PM (2.5)	0.00323	kg
Primer	1.36	kg	Sulfur dioxide	1.55E-05	kg
Water	141	kg	VOC	0.0773	kg
Plastic Wrap	0.193	kg	**Emissions to Water**		
Thermal Energy from Natural Gas	16.7	MJ, net	Total Suspended Solids	0.0501	kg
Thermal Energy from Propane	5.23	MJ, net			

[12] PIMA. "Life Cycle Assessment of Polyiso Insulation for the Polyisocyanurate Insulation Manufacturers Association (PIMA)." February 7,2011.

Table 7 - Gate-to-gate inventory for 1,000 sqft of MCM Sheet

Inputs	Quant.	Units	Outputs	Quant.	Units
Prime side painted aluminum coil	149	kg	MCM Sheet	511	kg
Backer side painted aluminum coil	136	kg	Corrugate Packaging	0.966	kg
LLDPE	128	kg	**Solid Waste for Recycling**		
LDPE	81.1	kg	Metallic coated scrap	45.5	kg
Recycled PE	79.5	kg	Aluminum scrap	17.5	kg
Masking (HDPE, LDPE, PVC)	7.99	kg	PE Scrap	17.2	kg
Bonding (HDPE, LLDPE)	12.4	kg	Wood Scrap	1.9	kg
Lubricants	0.160	L			
Water	95.9	L			
Wood pallets	30.8	kg			
Corrugate	2.20	kg			
Flake board	1.39	kg			
Steel banding	0.032	kg			
Plastic banding	0.023	kg			
Shims	0.759	kg			
Electricity	938	MJ			
Thermal Energy from Natural Gas	221	MJ, net			
Thermal Energy from Propane	33.3	MJ, net			

Table 8 - Gate-to-gate inventory for 1,000 sqft of MCM Panel

Inputs	Quant.	Units	Outputs	Quant.	Units
Painted MCM sheet	533	kg	MCM Panel	564	kg
Aluminum extrusions	178	kg	**Solid Waste for Recycling**		
Sealants	1.46	kg	Metallic coated scrap	141	kg
Fasteners	2.48	kg	Aluminum scrap	10.3	kg
Lubricants	0.240	L	Wood scrap	8.18	kg
Wood pallets	159	kg	EPS scrap	0.113	kg
EPS	11.4	kg	**Solid Waste for Landfill**		
Electricity	2860	MJ	Other Waste	22.2	kg
Thermal Energy from Natural Gas	1630	MJ, net	**Emissions to Air**		
Thermal Energy from Propane	159	MJ, net	VOC	0.0355	kg

Table 9 - Gate-to-gate inventory for 1,000 sqft of roll formed metal cladding

Inputs	Quant.	Units	Outputs	Quant.	Units
Painted Steel Coil	576	kg	Roll Formed Cladding	526	kg
Banding	0.0844	kg	Packaging	9.48	kg
Plastic Films	0.236	kg	**Solid Waste for Recycling**		
Paper	0.0426	kg	Steel Scrap	7.54	kg
Lubricants	0.0208	kg			
Cardboard	0.268	kg			
Sealant	0.0769	kg			
Wood pallets	6.59	kg			
Electricity	55.6	MJ			
Thermal Energy from Natural Gas	10.9	MJ, net			
Thermal Energy from Propane	2.41	MJ, net			

Table 10 - Gate-to-gate inventory for 1,000 sqft of Insulated Metal Panel

Inputs	Quant.	Units	Outputs	Quant.	Units
Painted Steel Coil	1101	kg	Insulated Metal Panel	1370	kg
Polyester Polyol	93.3	kg	Packaging Materials	233	kg
MDI	163	kg	**Solid Waste for Recycling**		
Blowing agent	34.7	kg	Steel Scrap	44.4	kg
Glue	5.28	kg	Foam Scrap	20.9	kg
Electricity	1300	MJ	Acetone [to industrial soil]	6.21E-03	kg
Thermal Energy from Natural Gas	404	MJ, net	**Emissions to Air**		
Thermal Energy from Propane	577	MJ, net	VOC	1.34	kg
Plywood/Lumber	227	kg	Diethylene glycol	0.487	kg
Plastic Film	9.29	kg	Diphenylmethane-4,4 di-isocyanate (MDI)	0.237	kg
Styrofoam	8.48	kg	Ethyl benzene	8.25E-04	kg
			Hazardous Air Pollutants (HAPs)	0.110	kg
			Isocyanic acid	7.12E-05	kg
			Methanol	1.32E-02	kg
			Methyl isobutyl ketone	2.47E-03	kg
			Pentane (n-pentane)	8.31E-02	kg
			Toluene (methyl benzene)	9.14E-02	kg
			Xylene (dimethyl benzene)	2.47E-03	kg
			R-134a (tetrafluoroethane)	1.36	kg

4 LCIA RESULTS & INTERPRETATION

In this chapter, the LCIA results are shown for the continuous coil coating process, the Insulated Metal Panel (IMP) continuous foaming process, the Metal Composite Material (MCM) sheet manufacturing process, the Metal Composite Material (MCM) panel fabrication process, and the metal forming process. Cradle-to-gate LCA results are also displayed for three products: steel IMPs, aluminum MCM panels, and steel roll formed claddings. Unlike Life Cycle Inventories, which only report sums for individual emissions, the Life Cycle Impact Assessment (LCIA) includes a classification of individual emissions with regard to the impacts they are associated with, and a characterization of the emissions by a factor expressing their respective contribution to the impact. The end result is a single metric for quantifying each potential impact, such as "Global Warming Potential". The LCIA results are relative expressions and do not predict impacts on category endpoints such as human health or ecosystem quality, the exceeding of thresholds, safety margins, or risks.

As described in Section 2.7 of this report, the impact assessment results are calculated using characterization factors published by the United States Environmental Protection Agency and the Center for Environmental Sciences (CML) at the University of Leiden, The Netherlands. The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) methodology is the most widely applied impact assessment method for North American LCA studies.

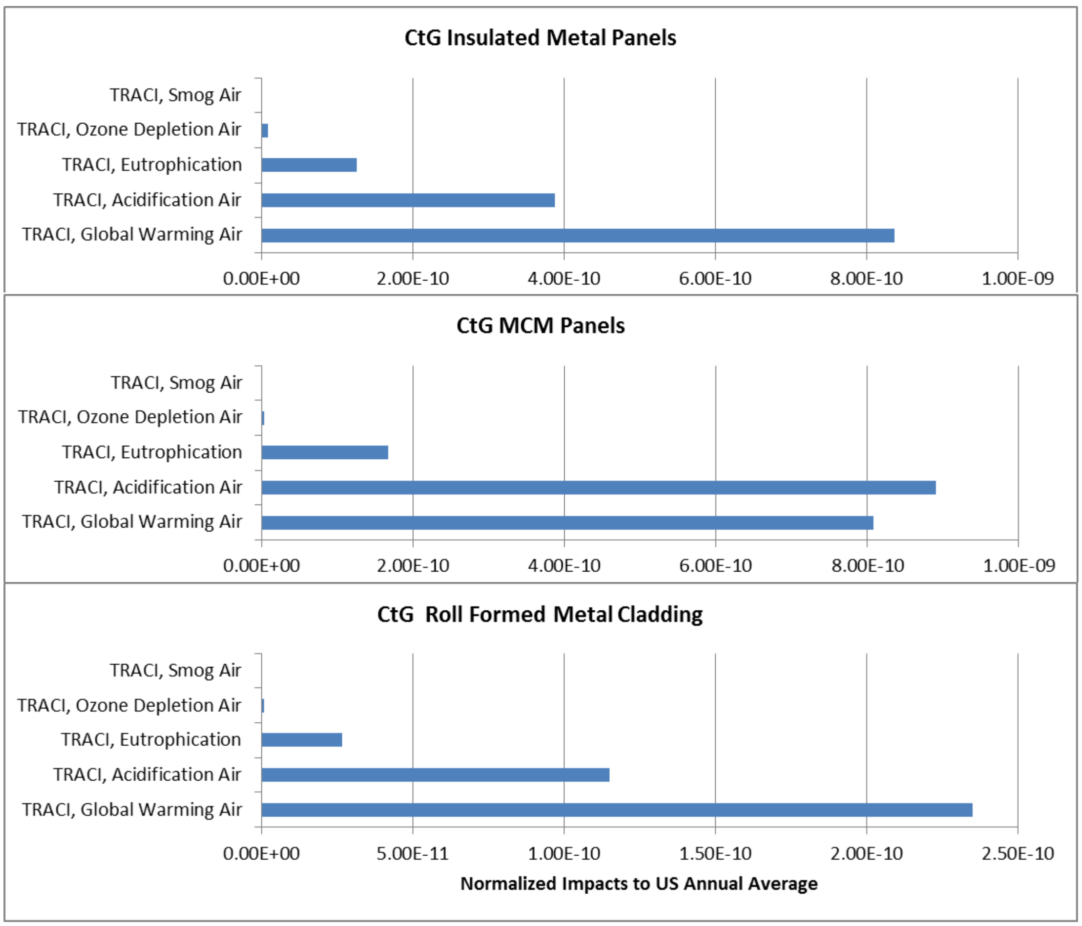
Impact Category / Indicator	Unit Equivalents Basis	Source & Region
Global Warming Potential (GWP)	[kg CO_2 eq]	TRACI 2.0 – Global
Acidification Potential (AP)	[mol H^+ eq]	TRACI 2.0–North America
Eutrophication Potential (EP)	[kg N eq]	TRACI 2.0–North America
Ozone Depletion Potential (ODP)	[kg CFC-11 eq]	TRACI 2.0 – Global
Smog Creation Potential (Smog)	[kg O_3 eq]	TRACI 2.0–North America
Primary Energy Demand (PED) – Total	[MJ, net calorific]	LCI – Global
Primary Energy Demand (PED) – Non-renewable	[MJ, net calorific]	LCI – Global
Abiotic Resource Depletion (ADP)	[kg Sb eq]	CML – Global
Solid Waste (Waste)	[kg]	LCI – Global
Water Use (Water)	[liters]	LCI – Global
Human & Ecological Toxicity	Qualitative description	USEtox - Global

Additional information on the background of these impact categories is included in Table 4. Abbreviations for the impacts are described above in Section 2.7, and are reproduced here for reference.

More detail for each of the environmental impact categories & environmental impact indicators is shown in Sections 4.1 and 0 below.

4.1 NORMALIZED NET IMPACT ASSESSMENT RESULTS

Normalization is an optional step within LCA to help interpret the relative magnitude of the multiple environmental indicators. The latest TRACI normalization factors[13] are applied in Figure 10 to convert the units of measure from each individual environmental indicator into a common, dimensionless scale. The normalization factors are based upon the 1999 annual total US emissions contributing to each of the TRACI environmental indicators. Figure 10 shows that the contributions for all three of the wall assemblies to smog and ozone depletion potential are orders of magnitude lower than global warming, acidification, and eutrophication potential. Comparison to these US average values is however just one value choice that can be applied and used in such an analysis. Although smog and ozone depletion appear to be marginal when compared to the national average emissions, this does not mean that these indicators are not significant in specific localities. The question of significance would have to be addressed employing either weighting or distance-to-target approaches, which is not part of the scope of this study.



[13] Jane Bare, Thomas Gloria, and, Gregory Norris. Development of the Method and U.S. Normalization Database for Life Cycle Impact Assessment and Sustainability Metrics. Environmental Science & Technology 2006 40 (16), 5108-5115

	TRACI, Global Warming Air	TRACI, Acidification Air	TRACI, Eutrophication	TRACI, Ozone Depletion Air	TRACI, Smog Air
CtG Insulated Metal Panels	8.36E-10	3.88E-10	1.26E-10	7.91E-12	3.00E-13
CtG MCM Panels	8.08E-10	8.91E-10	1.67E-10	2.69E-12	3.49E-13
CtG Roll Formed Metal Cladding	2.35E-10	1.15E-10	2.66E-11	7.26E-13	7.42E-14

Figure 10: Normalized TRACI Indicators for Cradle-to-gate Product Profiles

4.2 CRADLE-TO-GATE ENVIRONMENTAL PROFILES

Within this section, the life cycle stages of each cradle-to-gate process are broken into the following categories:

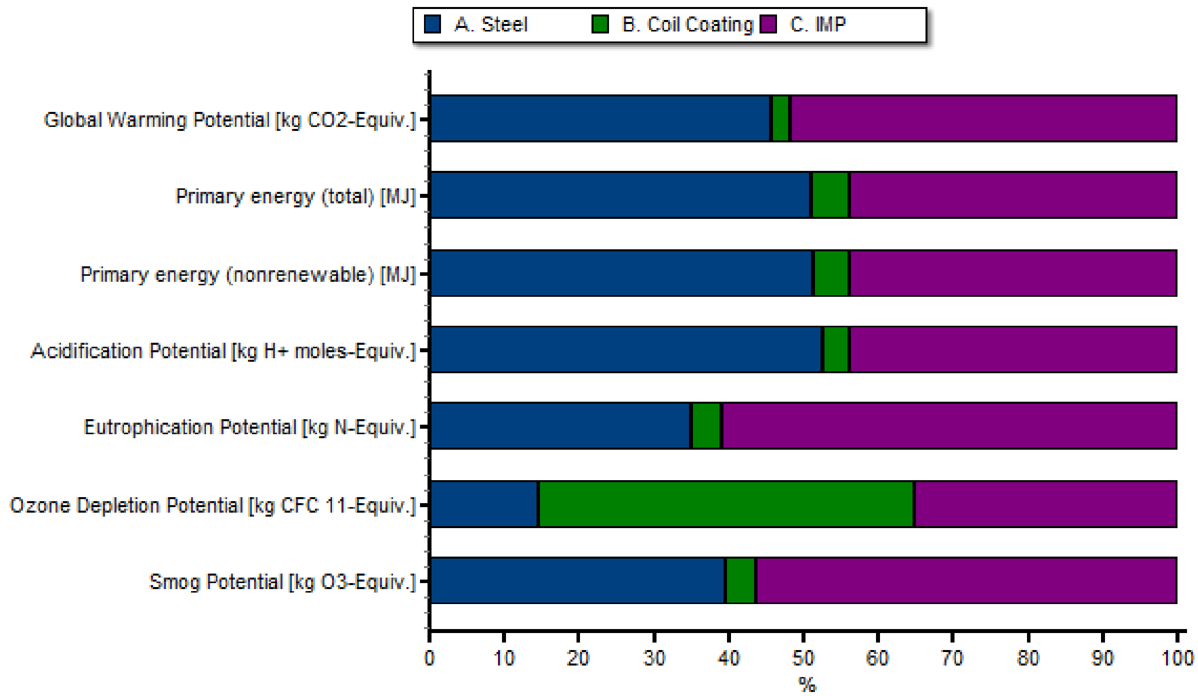
- **Steel / Aluminum:** Upstream raw material production
- **Coil Coating**: Paint, packaging materials, process energy, transport, wastes and emissions, including credits for recycling of scrap
- **IMP**: Foam components, packaging materials, process energy, transport, wastes and emissions, including credits for recycling of scrap
- **Roll Forming:** Packaging materials, process energy, transport, wastes and emissions, including credits for recycling of scrap
- **MCM Sheet:** Polyethylene core, packaging materials, process energy, transport, wastes and emissions, including credits for recycling of scrap
- **MCM Panel:** Packaging materials, process energy, transport, wastes and emissions, including credits for recycling of scrap

Note that the results displayed for each CtG and GtG profile are calculated based on a production weighted average of three or more mills' reported data. Since the reported inventory data had some variability across the mills, the overall results are also presented with a Coefficient of Variation (CV) for each impact category. The coefficient of variation is calculated for each impact category by dividing standard deviation of the CtG results by the average value.

In general, for the three CtG manufacturing processes considered, upstream metal production (Steel or Aluminum) contributes heavily to the environmental profiles. For Roll Formed Cladding, the metal clearly dominates the impacts. In the cradle-to-gate production of Insulated Metal Panels, the foaming process and upstream steel dominate the results across different categories.

4.2.1 Insulated Metal Panels

In the cradle-to-gate production of insulated metal panels, the steel production and the foaming process are responsible for the majority of burden (Figure 10) in all impact categories except ODP. In terms of mass, the chemicals used in the foaming process account for the lesser portion (20-25%) of the final product but contribute heavily to the overall environmental impacts. Steel also represents a significant fraction of the impacts, while the coil coating process contributes relatively little outside of ODP.



	Global Warming Potential	Primary energy (total)	Primary energy (non-renewable)	Primary energy (renewable)	Primary energy (feedstock)
	[kg CO2-Equiv.]	[MJ, net calorific]	[MJ, net calorific]	[MJ, net calorific]	[MJ, net calorific]
Total	**6310**	**62200**	**6.03E+04**	**1.81E+03**	**10.2**
A. Steel	2880	31800	3.10E+04	786	10.1
B. Coil Coating	165	3200	2.97E+03	235	0.01
C. IMP	3270	27200	2.64E+04	787	0.10
	Acidification Potential	**Eutrophication Potential**	**Ozone Depletion Potential**	**Smog Potential**	
	[mol H+ Equiv.]	[kg N-Equiv.]	[kg CFC 11-Equiv.]	[kg O3-Equiv.]	
Total	**844**	**6.48E-01**	**1.38E-04**	**241**	
A. Steel	4.44E+02	2.27E-01	2.01E-05	95.4	
B. Coil Coating	2.95E+01	2.55E-02	6.93E-05	9.83	
C. IMP	370	3.96E-01	4.86E-05	136	

Figure 11: Impacts for Cradle-to-Gate Production of 1000 ft^2 of Insulated Metal Panel

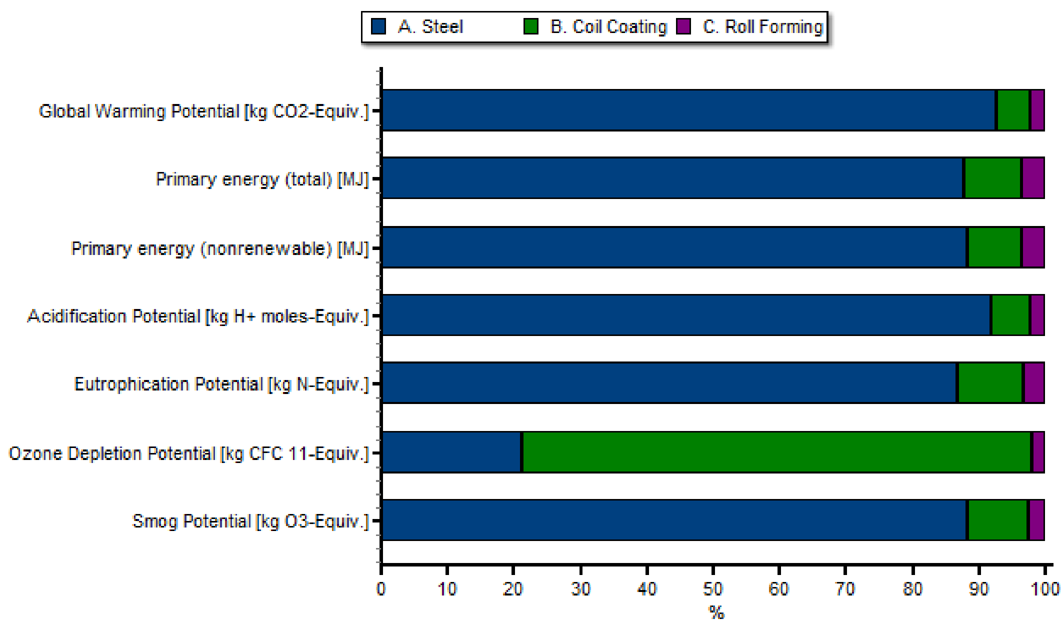
As indicated in the results above, upstream metal production and the foaming process clearly dominate the cradle-to-gate impacts. Table 11 provides details on the process of each product life cycle inventory which has the greatest influence on particular environmental indicators.

Table 11: Contribution Analysis of Insulated Metal Panels

Product	Environmental indicator	Main contributing step	%	Source of contribution
Insulated Metal Panel	PED (total)	Steel	51%	Fossil resources extraction for electricity production used to produce steel
	Global Warming Potential	IMP Foaming	52%	Production and emissions from some foaming chemicals, particularly R-134a
	TRACI 2.0, Acidification Air	Steel	53%	Coal combustion for electricity production associated with steel manufacturing
	TRACI 2.0, Eutrophication	IMP Foaming	61%	Production and emissions of foaming chemicals
	TRACI 2.0, Ozone Depletion Air	Coil Coating	50%	Release of trichloroethane during PVDF production
	TRACI 2.0, Smog Air	IMP Foaming	56%	Production and emissions of foaming chemicals
	USEtox Ecotoxicity	Steel	73%	Sulfuric acid used in steel production for pickling
	USEtox Human Toxicity	IMP Foaming	>99%	Acrolein from polyester polyol preparation

4.2.2 Roll Formed Metal Cladding

The roll forming process does not require the application of as many additional materials to the base metal sheet as the other cradle-to-gate processes, as is evident by the overwhelming share of burdens assumed by the original steel sheet production, as displayed in Figure 12. The paint systems utilized in coil coating have some impact, while the environmental load of the roll forming step is nearly entirely the result of energy demands associated with metal forming. Coil coating and roll forming make minimal contributions to this Cradle-to-Gate environmental profile compared to the energy and resources required to produce steel. The most significant component of this product's Cradle-to-Gate profile is identified in Table 12 for each environmental indicator.



	Global Warming Potential	Primary energy (total)	Primary energy (non-renewable)	Primary energy (renewable)	Primary energy (feedstock)
	[kg CO2-Equiv.]	[MJ, net calorific]	[MJ, net calorific]	[MJ, net calorific]	[MJ, net calorific]
Total	**1660**	**19200**	**1.87E+04**	**534**	**5.31**
A. Steel	1530	16800	1.64E+04	399	5.31
B. Coil Coating	86.4	1680	1550	123	0.00559
C. Roll Forming	37.4	669	658	11.2	0.00116
	Acidification Potential	**Eutrophication Potential**	**Ozone Depletion Potential**	**Smog Potential**	
	[mol H+ Equiv.]	[kg N-Equiv.]	[kg CFC 11-Equiv.]	[kg O3-Equiv.]	
Total	**257**	**1.34E-01**	**4.73E-05**	**57.2**	
A. Steel	2.36E+02	1.17E-01	1.01E-05	50.6	
B. Coil Coating	1.55E+01	1.34E-02	3.63E-05	5.15	
C. Roll Forming	5.63	4.54E-03	9.67E-07	1.5	

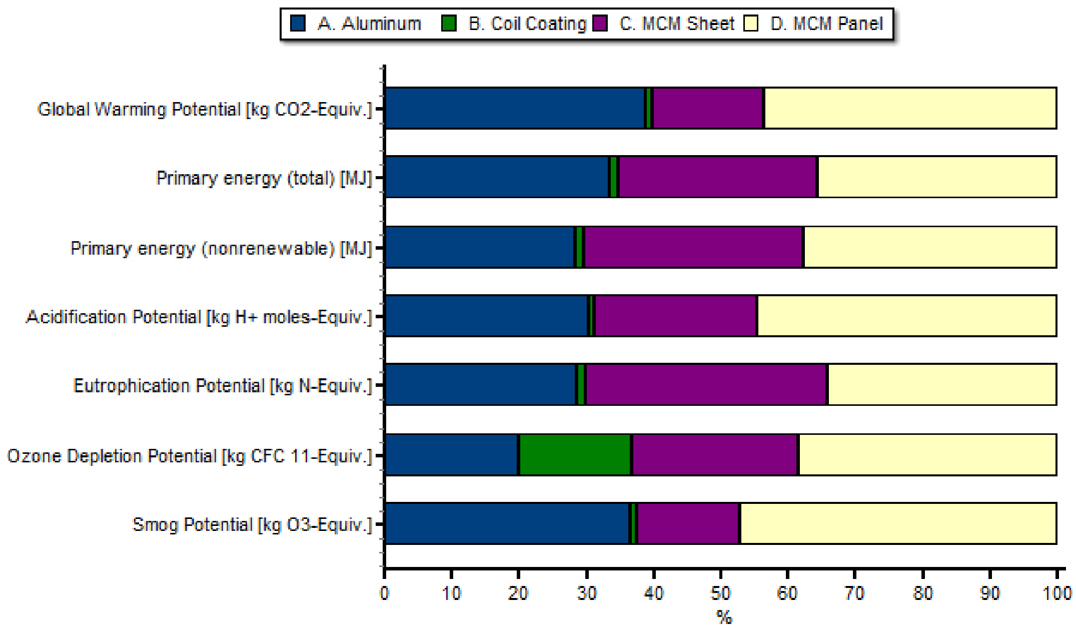
Figure 12: Impacts for Cradle-to-Gate Production of 1000 ft^2 of Roll Formed Metal Cladding

Product	Environmental indicator	Main contributing step	%	Source of contribution
Roll Formed Metal Cladding	PED (total)	Steel	88%	Fossil resources extraction for electricity production used in material mining and refinement for steel production
	Global Warming Potential	Steel	93%	Energy consumption and fossil fuel burning used in material mining and refinement for steel
	TRACI 2.0, Acidification Air	Steel	92%	Coal combustion for electricity production used in upstream steel manufacturing
	TRACI 2.0, Eutrophication	Steel	87%	Energy production for upstream steel manufacturing
	TRACI 2.0, Ozone Depletion Air	Coil Coating	76%	Release of trichloroethane during PVDF production
	TRACI 2.0, Smog Air	Steel	88%	Electricity production (emission of nitrogen oxides from combustion of fossil fuels)
	USEtox Ecotoxicity	Steel	98%	Sulfuric acid used in steel production for pickling
	USEtox Human Toxicity	Steel	53%	Formaldehyde released to air due to steel production

Table 12: Contribution Analysis of Roll Formed Metal Cladding

4.2.3 MCM Panels

The energy used by fabrication facilities, combined with the production of aluminum extrusions used in the MCM panel fabrication are responsible for the majority of MCM panel fabrication impacts. In cradle-to-gate MCM panel fabrication, total aluminum accounts for the majority of burdens (46-99% depending on the category), arising from both upstream primary material and as an ancillary material in the MCM panel process.



	Global Warming Potential	Primary energy (total)	Primary energy (non-renewable)	Primary energy (renewable)	Primary energy (feedstock)
	[kg CO2-Equiv.]	[MJ, net calorific]	[MJ, net calorific]	[MJ, net calorific]	[MJ, net calorific]
Total	**6120**	**99100**	**8.88E+04**	**10300**	**0.531**
A. Aluminum	2370	33200	2.52E+04	8003	0.315
B. Coil Coating	58.3	1130	1050	83.3	0.00378
C. MCM Sheet	1010	29300	2.90E+04	343	0.0217
D. MCM Panel	2680	35500	33600	1860	0.190
	Acidification Potential	**Eutrophication Potential**	**Ozone Depletion Potential**	**Smog Potential**	
	[mol H+ Equiv.]	[kg N-Equiv.]	[kg CFC 11-Equiv.]	[kg O3-Equiv.]	
Total	**1850**	**8.52E-01**	**1.45E-04**	**292**	
A. Aluminum	5.65E+02	2.45E-01	2.88E-05	106	
B. Coil Coating	1.05E+01	9.02E-03	2.45E-05	3.48	
C. MCM Sheet	453	3.07E-01	3.56E-05	44.6	
D. MCM Panel	8.26E+02	2.92E-01	5.58E-05	137	

Figure 13: Impacts for Cradle-to-Gate Production of 1000 ft^2 of MCM Panels

In the cradle-to-gate production of MCM panels, environmental burdens from material production and facility demand in the final MCM panel fabrication step, dominate across nearly all impact categories. Coil Coating is barely visible in Figure 12, while MCM sheet production and upstream Aluminum manufacturing impart similar burdens in most categories. Polymer production accounts for the burden associated with MCM sheet manufacturing.

Product	Environmental indicator	Main contributing step	%	Source of contribution
MCM Panel	PED (total)	MCM Panel	36%	Fossil resources extraction for electricity production used in facilities and for aluminum extrusion manufacturing
	Global Warming Potential	MCM Panel	44%	Energy consumption used in facilities and for material mining and refinement for aluminum extrusions
	TRACI 2.0, Acidification Air	MCM Panel	45%	Coal combustion for electricity production pertaining to facility demand and aluminum extrusion manufacturing
	TRACI 2.0, Eutrophication	MCM Sheet	36%	Byproducts of energy production required for upstream polymer manufacturing
	TRACI 2.0, Ozone Depletion Air	MCM Panel	39%	Electricity production (nuclear energy production emits R 11 and R 114 that contribute to ODP)
	TRACI 2.0, Smog Air	MCM Panel	47%	Electricity production (emission of nitrogen oxides from combustion of fossil fuels)
	USEtox Ecotoxicity	MCM sheet	89%	Cyanide released due to polymer production
	USEtox Human Toxicity	Aluminum	99%	Formaldehyde released to air due to aluminum (sheet + fasteners) production

Table 13: Contribution Analysis of MCM Panel Fabrication

Note that MCM sheet is an intermediate product in the manufacture of MCM panel. The MCM panel-making process (described in more detail below) shapes MCM sheets

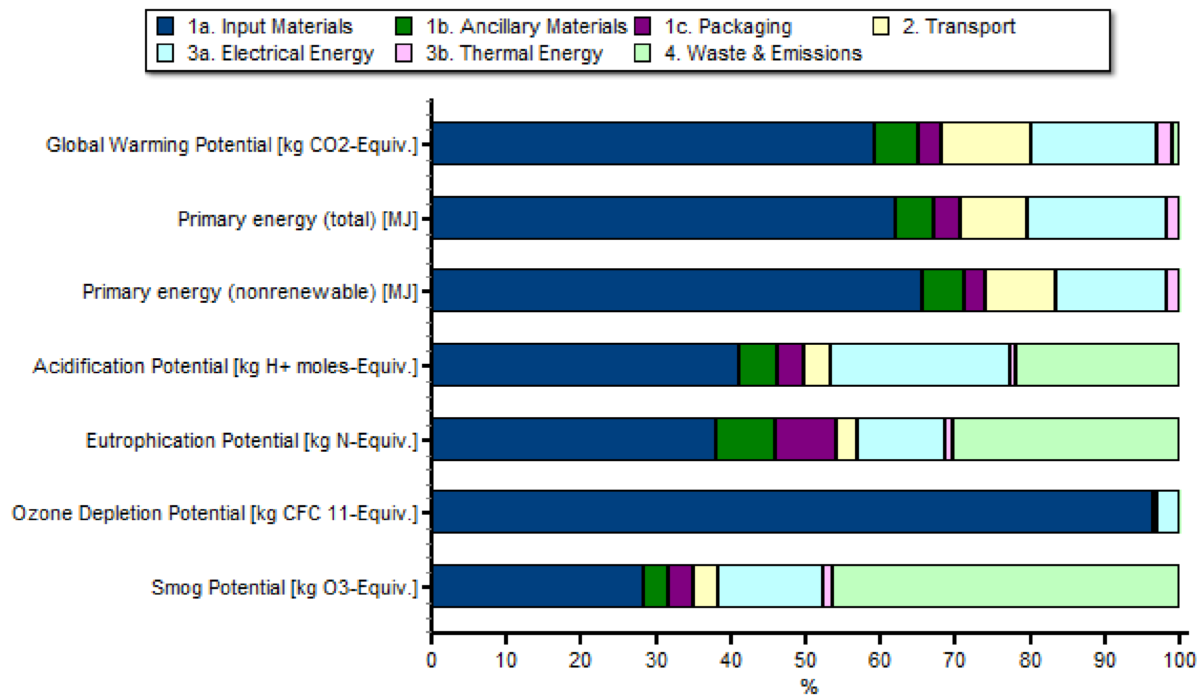
4.3 GATE-TO-GATE ENVIRONMENTAL PROFILES

Within this section, the life cycle stages are broken into the following categories:

1. **Materials –** see below
    a. Input Materials such as paints/coatings or foam components
    b. Ancillary Materials such as fasteners, sealants and lubricants that are used in support of the main product yet not part of the main product
    c. Packaging Materials such as plastic wrap and pallets
2. **Transport –** Upstream fuel production and direct combustion emissions
3. **Energy** – see below
    a. Electricity generation and transmission
    b. Thermal energy creation including production and emissions of the fuels
4. **Waste & Emissions** – disposal of process waste and process emissions

4.3.1 COIL COATING

The gate-to-gate environmental profile of the production-weighted average coil coating process is depicted in Figure 14. The greatest variation in data collected from participating companies was that with respect to natural gas use (due to different heating requirements as a function of geographic location) and choice of packaging materials.



	Global Warming Potential	Primary energy (total)	Primary energy (nonrenewable)	Acidification Potential	Eutrophication Potential	Ozone Depletion Potential	Smog Potential
	[kg CO2-Equiv.]	[MJ, net calorific]	[MJ, net calorific]	[mol H+ Equiv.]	[kg N-Equiv.]	[kg CFC 11-Equiv.]	[kg O3-Equiv.]
Total	**78.9**	**1530**	**1.42E+03**	**14.1**	**1.22E-02**	**3.31E-05**	**4.7**
1a. Input Materials	46.6	948	9.31E+02	5.82E+00	4.64E-03	3.20E-05	1.33
1b. Ancillary Materials	4.66	80.2	79.3	7.17E-01	9.42E-04	5.44E-08	0.166
1c. Packaging	2.47	55.2	3.80E+01	0.513	1.01E-03	8.11E-08	0.152
2. Transport	9.49	134	134	4.91E-01	3.60E-04	1.24E-08	0.157
3a. Electrical Energy	13.2	287	2.10E+02	3.37	1.43E-03	1.04E-06	0.66
3b. Thermal Energy	1.67	26.3	26.2	1.35E-01	1.06E-04	7.85E-09	0.0526
4. Waste & Emissions	0.77	0.359	3.60E-01	3.09	3.72E-03	1.99E-11	2.19
CV	44%	39%	117%	43%	109%	96%	36%

Figure 14: Impacts arising from the continuous coating of 1000 ft^2 of metal coils.

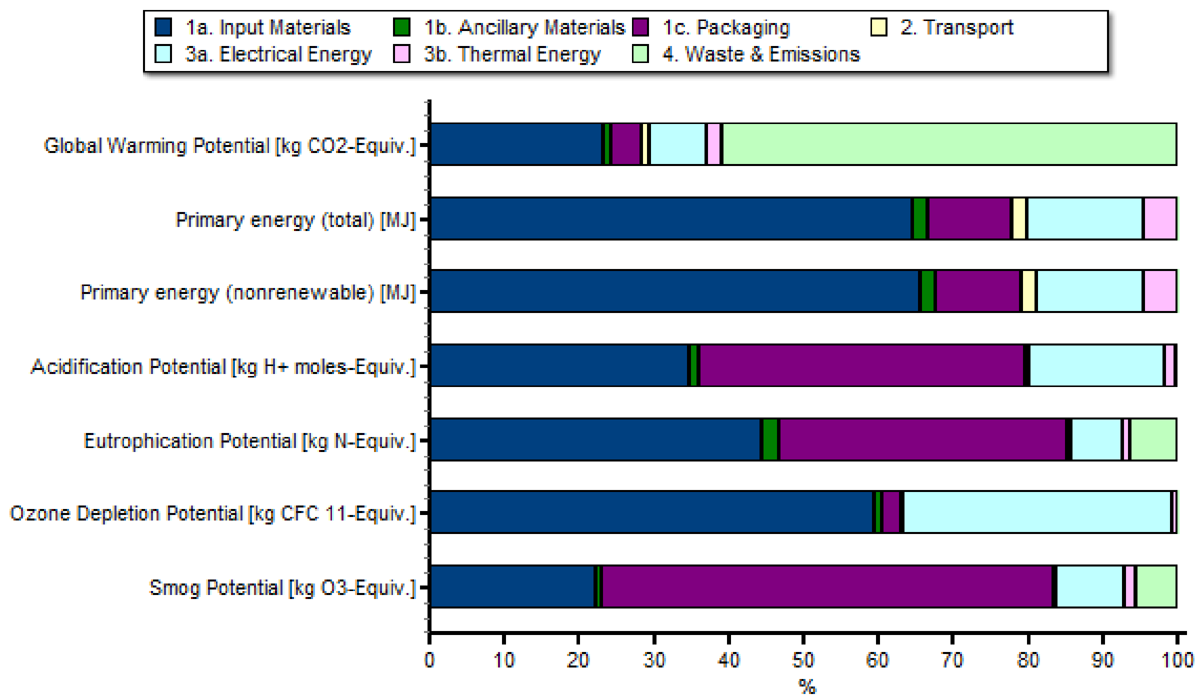
In the gate-to-gate process of coil coating, the input materials group, which in this case is primarily the paint system, causes the greatest burden in most impact categories as shown in Figure 13. Waste and emissions coming from the coil coating facilities contribute heavily to smog and eutrophication, but also provide some credit in primary energy and global warming from energy recovered from waste materials. Table 14 depicts the component of this gate-to-gate process which has the largest percentage impact for each environmental indicator.

Process	Environmental indicator	Main contributing step	%	Source of contribution
Coil Coating	PED (total)	Input Materials	59%	Fossil resources extraction for electricity production used in paint system and prep chemical manufacturing
	Global Warming Potential	Input Materials	62%	Energy consumption and fossil fuel burning used in paint system and prep chemical manufacturing
	TRACI 2.0, Acidification Air	Input Materials	41%	Sulfur dioxide and nitrogen oxides released during paint system production
	TRACI 2.0, Eutrophication	Input Materials	38%	Nitrogen oxide emissions and ammonia released to water from paint production
	TRACI 2.0, Ozone Depletion Air	Input Materials	96%	Release of trichloroethane during PVDF production
	TRACI 2.0, Smog Air	Waste & Emissions	46%	Nitrogen oxide emissions from coil coating facilities
	USEtox Ecotoxicity	Input Materials	69%	Cyanide released to water due to paint system production
	USEtox Human	Packaging	54%	Organic chemicals released to air due to polymer production

Table 14: Contribution Analysis of gate-to-gate Coil Coating Process

4.3.2 IMP FOAMING

The gate-to-gate environmental profile of IMP foaming process is depicted in Figure 15. The choice of blowing agent used by each facility contributed to a larger variation in impacts between individual participants. Those facilities using R-134a as a blowing agent have significantly higher global warming and ozone depletion potential than those facilities using pentanes. Direct emissions of R-134a affect GWP while production of R-134a causes the release of R-114 an ozone depleting CFC. The following figures therefore depict a production-weighted average using a combination of blowing agents rather than any one technology.



	Global Warming Potential	Primary energy (total)	Primary energy (nonrenewable)	Acidification Potential	Eutrophication Potential	Ozone Depletion Potential	Smog Potential
	[kg CO2-Equiv.]	[MJ, net calorific]	[MJ, net calorific]	[mol H+ Equiv.]	[kg N-Equiv.]	[kg CFC 11-Equiv.]	[kg O3-Equiv.]
Total	**3270**	**27200**	**2.64E+04**	**370**	**3.96E-01**	**4.86E-05**	**136**
1a. Input Materials	758	17600	1.73E+04	1.28E+02	1.75E-01	2.88E-05	30.1
1b. Ancillary Materials	30.3	512	506	4.46E+00	9.91E-03	4.96E-07	1.22
1c. Packaging	133	3100	3.09E+03	162	1.52E-01	1.35E-06	81.9
2. Transport	35.4	501	500	1.82E+00	1.33E-03	4.64E-08	0.581
3a. Electrical Energy	248	4290	3.78E+03	67.3	2.79E-02	1.75E-05	12.5
3b. Thermal Energy	72.9	1190	1190	5.70E+00	4.27E-03	3.18E-07	2.09
4. Waste & Emissions	1990	33.5	3.24E+01	0.733	2.49E-02	5.58E-08	7.51
CV	272%	282%	453%	640%	39%	36%	405%

Figure 15: Impacts arising from continuous foaming of 1000 ft^2 of insulated metal panels.

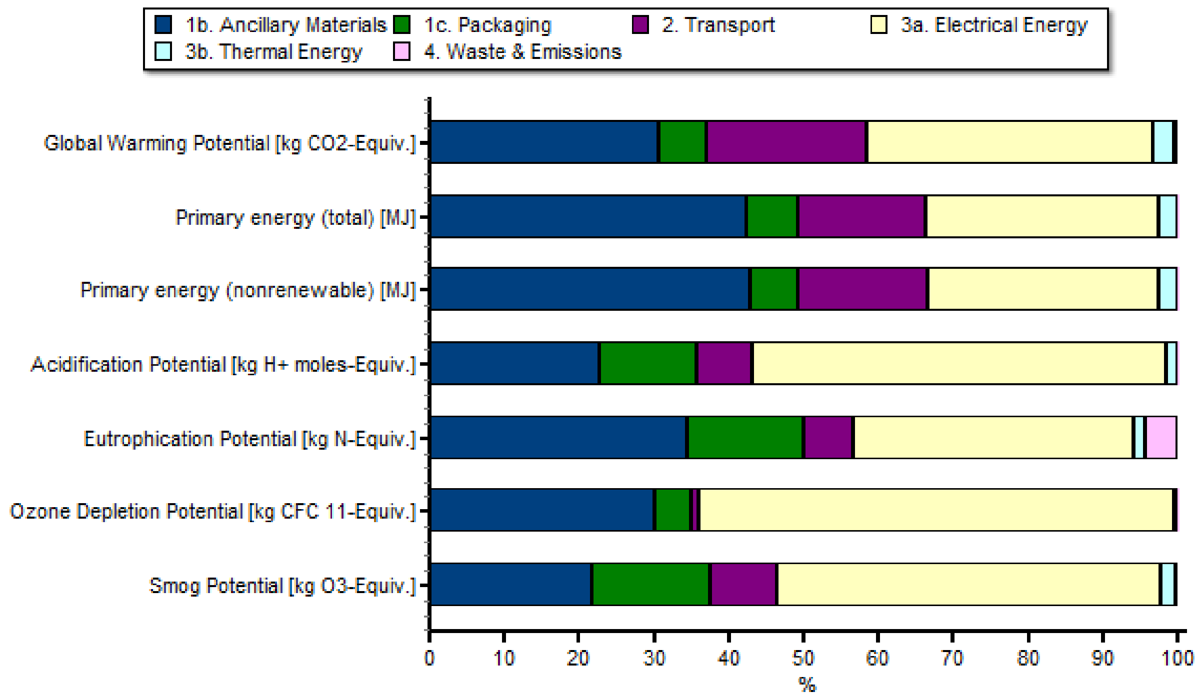
In the gate-to-gate foaming process used to create insulated metal panels, the environmental impacts (Figure 15) depict the input material group (foaming chemicals and blowing agent) as having a majority share of the burden. Additional information regarding the primary source of impacts within each environmental impact category is shown in Table 15.

Table 15: Contribution Analysis of gate-to-gate IMP Foaming Process

Process	Environmental indicator	Main contributing step	%	Source of contribution
IMP Foaming	PED (total)	Input Materials	65%	Fossil resources extraction for electricity production used in foaming chemical manufacturing
	Global Warming Potential	Emissions and Waste	61%	Blowing agent emissions from foaming process
	TRACI 2.0, Acidification Air	Packaging	44%	Nitrogen oxide emissions from plastic production
	TRACI 2.0, Eutrophication	Input Materials	44%	Foaming chemical production
	TRACI 2.0, Ozone Depletion Air	Input Materials	60%	Production of blowing agents
	TRACI 2.0, Smog Air	Packaging	60%	Nitrogen oxide emissions from packaging material production
	USEtox Ecotoxicity	Packaging	80%	Release of organic compounds from production of plastic films
	USEtox Human	Packaging	99%	Organics released from film production

4.3.3 Roll Forming

In the gate-to-gate roll forming process used to create metal cladding, the environmental impacts (Figure 16) show the electrical energy used by the roll forming facilities as comprising the major fraction of each impact category.



	Global Warming Potential	Primary energy (total)	Primary energy (nonrenewable)	Acidification Potential	Eutrophication Potential	Ozone Depletion Potential	Smog Potential
	[kg CO2-Equiv.]	[MJ, net calorific]	[MJ, net calorific]	[mol H+ Equiv.]	[kg N-Equiv.]	[kg CFC 11-Equiv.]	[kg O3-Equiv.]
Total	**37.4**	**669**	**6.58E+02**	**5.63**	**4.54E-03**	**9.67E-07**	**1.5**
1b. Ancillary Materials	11.4	283	2.81E+02	1.28E+00	1.56E-03	2.90E-07	0.324
1c. Packaging	2.41	45.4	42.5	7.36E-01	7.04E-04	4.72E-08	0.239
2. Transport	8.05	114	1.14E+02	0.416	3.05E-04	1.06E-08	0.133
3a. Electrical Energy	14.3	209	203	3.12E+00	1.70E-03	6.14E-07	0.771
3b. Thermal Energy	1.02	16.6	1.66E+01	0.0841	6.63E-05	4.88E-09	0.0327
4. Waste & Emissions	0.205	0.109	0.0899	3.64E-03	2.00E-04	7.95E-10	0.00266
CV	296%	197%	154%	193%	123%	123%	272%

Figure 16: Impacts arising from the roll forming of 1000 ft^2 of metal cladding.

Minimal material input enables energy consumption at roll forming facilities to have a major environmental influence in the GtG roll forming process. Given the overall low impact of the roll forming process, packaging and transport take a greater share than in other GtG systems.

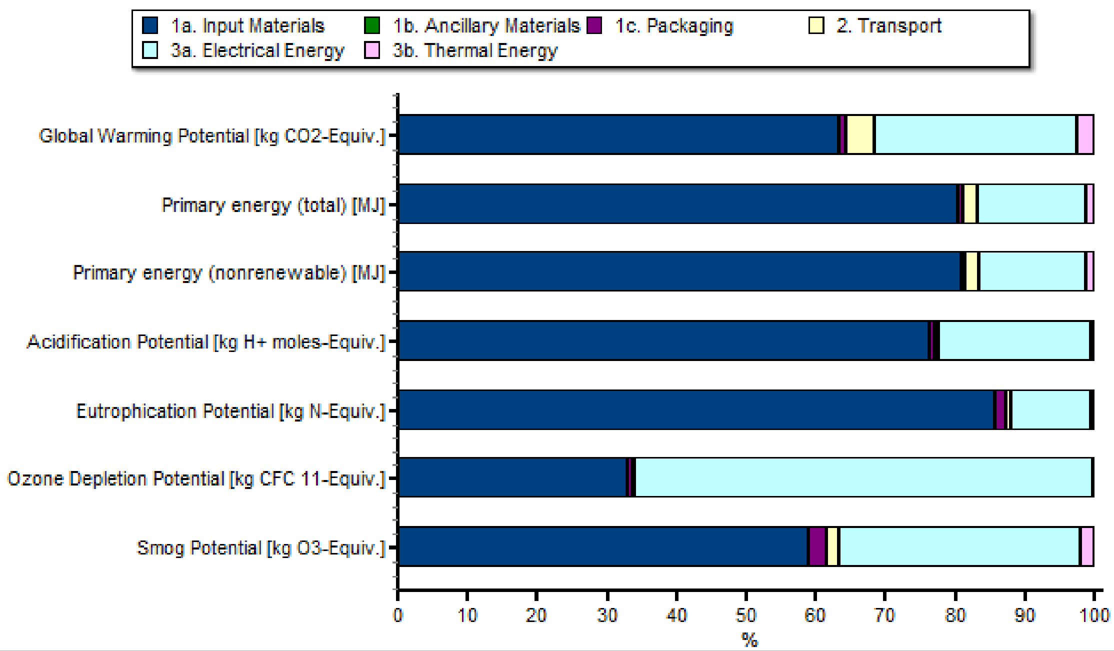
Process	Environmental indicator	Main contributing step	%	Source of contribution
Roll Forming	PED (nonrenewable)	Ancillary Materials	42%	Fossil resources extraction for electricity production used in sealants
	Global Warming Potential	Electrical Energy	38%	Emissions from fossil fuel burning for electricity production
	TRACI 2.0, Acidification Air	Electrical Energy	55%	Coal combustion for electricity production needed to power roll forming machines
	TRACI 2.0, Eutrophication	Electrical Energy	37%	Emissions from electricity production used to power roll forming machines
	TRACI 2.0, Ozone Depletion Air	Electrical Energy	63%	Electricity production (nuclear energy production emits R 11 and R 114 that contribute to ODP)
	TRACI 2.0, Smog Air	Electrical Energy	51%	Electricity production (emission of nitrogen oxides from combustion of fossil fuels)
	USEtox Ecotoxicity	Ancillary Materials	79%	Cyanide released to water as a byproduct of sealant production
	USEtox Human Toxicity	Ancillary Materials	46%	Formaldehyde and other organics released to air from sealant production

Table 16: Contribution Analysis of gate-to-gate roll forming process

4.3.4 MCM Sheet Manufacturing

The gate-to-gate environmental profile of MCM sheet manufacturing is depicted in Figure 16. The polymers comprising the input materials group account for a majority of the burdens. Of the three contributing mills, the LCA results vary significantly compared to the average. After the mills were averaged together, the CV of each LCA impact category ranges from 28% (ODP) to 71% (AP).

The large variation between the mills is based on the fact that the three mills used different polymers with a significant range of environmental profiles. For example, the acidification impacts per kilogram of LDPE, HDPE, and LLDPE are 0.51, 0.35, and 1.58 mol H+ equivalents, respectively. These differences drive the major swings across the three mills, though a small contribution comes from the economy of scale. Larger mills saw decreased process energy per unit of output than smaller mills. The three mills had similar product weights, scrap rates, and other inputs' mass.



	Global Warming Potential	Primary energy (total)	Primary energy (nonrenewable)	Acidification Potential	Eutrophication Potential	Ozone Depletion Potential	Smog Potential
	[kg CO2-Equiv.]	[MJ, net calorific]	[MJ, net calorific]	[mol H+ Equiv.]	[kg N-Equiv.]	[kg CFC 11-Equiv.]	[kg O3-Equiv.]
Total	**738**	**21400**	**2.12E+04**	**331**	**2.24E-01**	**2.60E-05**	**32.6**
1a. Input Materials	466	17200	1.71E+04	2.52E+02	1.92E-01	8.53E-06	19.2
1b. Ancillary Materials	0.0952	2.05	2	1.61E-02	4.27E-05	5.14E-09	0.00423
1c. Packaging	8.78	158	1.11E+02	2.62	3.43E-03	2.20E-07	0.902
2. Transport	29.6	422	421	1.63E+00	1.22E-03	3.90E-08	0.544
3a. Electrical Energy	214	3320	3.23E+03	73	2.59E-02	1.71E-05	11.3
3b. Thermal Energy	19	294	293	1.57E+00	1.28E-03	9.43E-08	0.638
CV	71%	34%	33%	28%	47%	46%	42%

Figure 17: Impacts arising from the manufacturing of 1000 ft^2 of MCM Sheet.

The share of burdens is coupled to the share of mass in the GtG MCM sheet process. With ~200kg of polyethylene added to the sheet, burdens allocated to the input material group are elevated. Electrical energy needed to power the facilities also accounts for a significant portion of the impacts. Details on the major environmental contributors are presented in Table 17 below.

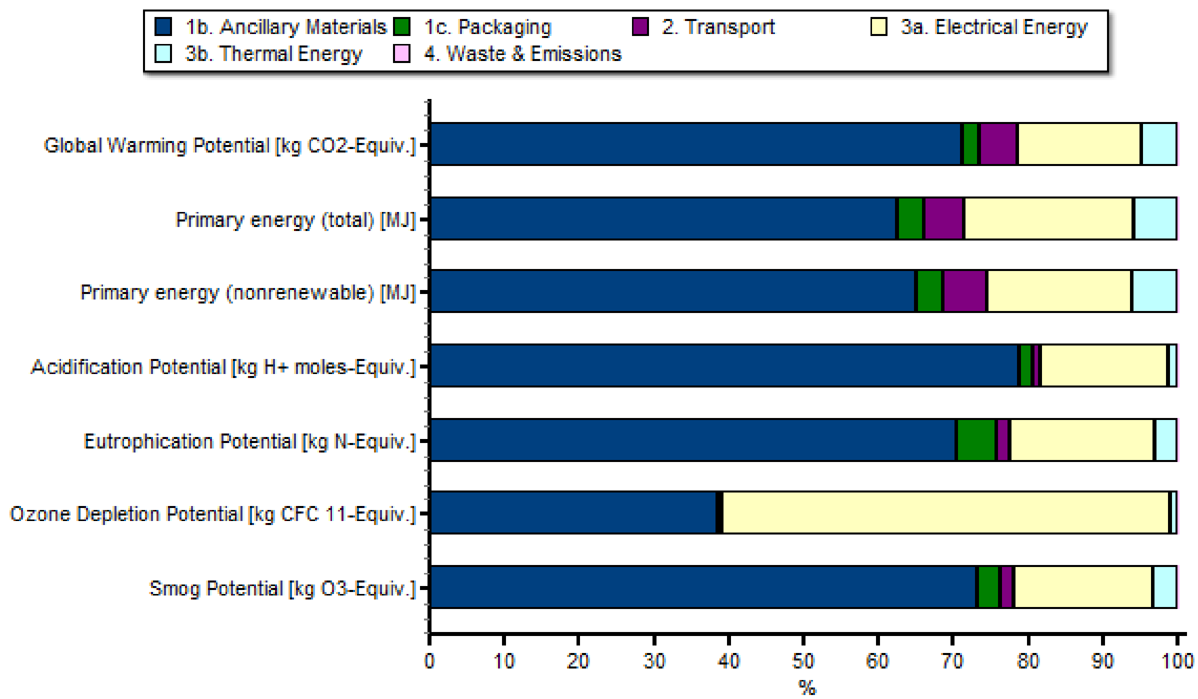
Process	Environmental indicator	Main contributing step	%	Source of contribution
MCM Sheet	PED (total)	Input Materials	80%	Energy and resource burdens from upstream polymer manufacturing
	Global Warming Potential	Input Materials	63%	Emissions from fossil fuel burning for electricity production used in polymer manufacturing
	TRACI 2.0, Acidification Air	Input Materials	76%	Coal combustion for electricity production used in upstream material manufacturing
	TRACI 2.0, Eutrophication	Input Materials	86%	Byproducts from electricity production used in upstream polymer manufacturing
	TRACI 2.0, Ozone Depletion Air	Electrical Energy	66%	Electricity production (nuclear energy production emits R 11 and R 114 that contribute to ODP)
	TRACI 2.0, Smog Air	Input Materials	57%	Electricity production (emission of nitrogen oxides from combustion of fossil fuels) for polymer manufacturing
	USEtox Ecotoxicity	Input Materials	99%	Cyanide released to fresh water from polymer production
	USEtox Human Toxicity	Input Materials	99%	Dioxins released to air during polymer production

Table 17: Contribution Analysis of gate-to-gate MCM sheet manufacturing

4.3.5 MCM Panel Manufacturing

Ancillary materials (primarily aluminum extrusions) and, to a lesser extent, electrical energy dominate the environmental profile of gate-to-gate MCM panel fabrication (Figure 17). Of the three contributing mills, the LCA results vary compared to the average. After the mills were rolled together, the coefficient of variation of each environmental impact category ranges from 37% (PED) to 70% (ODP).

The variation between the mills is based on the fact that mills in cold climates require significantly more energy to heat in the winter than their counterparts in temperate locations. The three mills had similar product weights, process energy demand, scrap rates, and other inputs' mass.



	Global Warming Potential	Primary energy (total)	Primary energy (nonrenewable)	Acidification Potential	Eutrophication Potential	Ozone Depletion Potential	Smog Potential
	[kg CO2-Equiv.]	[MJ, net calorific]	[MJ, net calorific]	[mol H+ Equiv.]	[kg N-Equiv.]	[kg CFC 11-Equiv.]	[kg O3-Equiv.]
Total	**2680**	**35500**	**3.36E+04**	**826**	**2.92E-01**	**5.58E-05**	**137**
1b. Ancillary Materials	1900	22200	2.18E+04	6.51E+02	2.05E-01	2.15E-05	100
1c. Packaging	59.8	1230	1220	1.59E+01	1.54E-02	5.82E-10	4.45
2. Transport	139	1970	1.97E+03	7.2	5.28E-03	1.83E-07	2.3
3a. Electrical Energy	441	8020	6500	1.41E+02	5.71E-02	3.34E-05	25.7
3b. Thermal Energy	133	2080	2.07E+03	10.9	8.76E-03	6.48E-07	4.37
4. Waste & Emissions	0.236						0.113
CV	45%	53%	39%	70%	42%	37%	46%

Figure 18: Impacts arising from the fabrication of 1000 ft^2 of MCM Panel.

Ancillary materials (i.e. aluminum extrusions) have the greatest share of burden in all categories except ozone depletion. Minimal contributions arise from transport and packaging, while reported emissions have a negligible effect on global warming potential (Table 18).

Process	Environmental indicator	Main contributing step	%	Source of contribution
MCM Panel	PED (total)	Ancillary Materials	63%	Energy and resource burdens from upstream aluminum extrusion manufacturing
	Global Warming Potential	Ancillary Materials	71%	Emissions from fossil fuel burning for electricity production used to extract and refine aluminum
	TRACI 2.0, Acidification Air	Ancillary Materials	79%	Coal combustion for electricity production used in upstream material manufacturing
	TRACI 2.0, Eutrophication	Ancillary Materials	70%	Byproducts from electricity production used in upstream manufacturing of aluminum
	TRACI 2.0, Ozone Depletion Air	Electrical Energy	61%	Electricity production (nuclear energy production emits R 11 and R 114 that contribute to ODP)
	TRACI 2.0, Smog Air	Ancillary Materials	74%	Electricity production (emission of nitrogen oxides from combustion of fossil fuels) used in aluminum manufacturing
	USEtox Ecotoxicity	Ancillary Materials	97%	Hydrogen cyanide released to air during mining of aluminum
	USEtox Human Toxicity	Ancillary Materials	86%	Hydrogen cyanide released to air during mining of aluminum

Table 18: Contribution Analysis of gate-to-gate MCM panel fabrication

Within the input materials category in the gate-to-gate processes, the main contributors are the materials with the greatest mass. In some cases, ancillary materials (such as the aluminum extrusions used in MCM panel fabrication) constitute a significant burden, because of the high environmental profiles associated with aluminum production. For IMP foaming, emissions arising from blowing agents and other chemicals, contribute heavily to global warming. All processes are energy intensive, but only for roll forming is the impact arising from electrical energy dominant over other groupings.

The GtG environmental profiles depict a demarcation between materially intensive processes (Coil Coating, IMP Foaming, MCM sheet and panel manufacturing) and processes primarily involving manipulation of metal (Roll Forming). In the former, input materials, such as paint systems and foaming materials, dominate the impacts. The plastic used in MCM sheet production and the aluminum extrusions used in MCM panel production account for the material impacts in Figures 16 and 17 respectively. With no materials added in roll forming, the energy required to shape metal contributes most to this product's environmental footprint.

4.4 Credits

Steel and aluminum scrap provide impact credits which are represented as negative burden values in the results presented herein.

Valuable steel and aluminum scrap are sent to recyclers, so the "Global Value of Scrap" data sets for steel and aluminum are connected to apply credit for these recovered material flows. Both these data sets as well as the upstream inputs of steel and aluminum were developed with a consistent methodology, as described in section 2.6.

4.5 Data Variability

It was theorized that data variability at each process could partially be attributed to size differences across the mills. Mills with higher output should achieve a better economy of scale when comparing production per 1000 ft^2, if the same technologies were used. The overall results were checked across the companies and in many cases small output mills did have higher impacts than big producers. Unfortunately, we can only describe the loose relationship between output and burden because there are so many other factors such as start-up / shut-down inefficiencies, product differences, and technology differences.

Since the study included energy for overhead heating and cooling at each site, large swings in reported energy were attributed to regional differences. Removing overhead from the study would isolate true differences in burden – unfortunately, many mills cannot separate their process energy from overhead without the addition of costly sub-metering. Overall, the inclusion of overhead is appropriate for this study because technologies and companies don't exist in a vacuum – the location of mills is important to consider in LCA when evaluating energy for heating and cooling, electricity grid differences, and transportation distances. As no product-related process steps were knowingly excluded or omitted from the model, there was no need to further refine the system boundaries of this work.

The data collection performed includes nineteen facilities and five processes. For each GtG evaluation, we collected data from between 3 and 5 mills using the same, or similar, technologies. Variability across the mills was evaluated by considering the coefficient of variation (CV) and highlighting specific process differences; the average results are considered representative of the current industry average. The reality is that different businesses have different consumption and emission profiles and that LCA results don't necessarily look the same for all.

4.6 Conclusions

The following general conclusions can be made based on the reported results:

- Raw materials acquisition and processing drives the environmental profile of all MCA products assessed.
- Appropriate treatment of waste material can result in significant credits beneficial to the environmental profile.
- Upstream metal production takes the most significant share of the environmental burdens.
- The contribution from transportation is minor in context of the overall manufacturing process.

4.7 Limitations

Human health risks related to the product systems studied (certain process chemicals) were evaluated qualitatively; these risks are not easily captured in LCIA indicators, and are better suited to analysis inside a toxicological risk model.

This study represents only a "cradle-to-gate" Life Cycle Assessment of the products, but does not integrate the use phase and end of life. Consequently, benefits of installing any of the wall materials in a building are not captured in this study.

The best steel and energy datasets available at the time of the model construction were used in this analysis. A global average dataset was used to represent US steel, an older electricity grid mix profile for the United States was used than the year of production, and a few European-average datasets were used to represent the production of other North American materials used in smaller quantities. Additionally, while the MCA selected manufacturers who together were believed to represent the average profile of each product included, not all manufacturing locations for each product were surveyed and thus a "true" average may differ.

4.8 Recommendations

This assessment reflects the existing technical situation for the year 2010 for a percentage of the total North American production. As technologies improve and process innovations emerge, efficiencies and overall environmental impacts will improve over time. For the IMP foaming process, an improved carbon-footprint profile can be realized if all companies move away from blowing agents such as R-134a. Pentane released to the atmosphere does not influence global warming potential, whereas 1 kilogram of

R-134a emissions is equivalent to 1430 kilograms of carbon dioxide equivalent global warming potential. However, for those more concerned with smog creation potential than global warming potential, pentane emissions to air contribute to smog creation potential (1.31 kg O_3-Equiv. smog potential per kg pentane emission), whereas R-134a emissions do not. In general, environmental benefits can be achieved through a broad effort to limit waste and to recycle all scrap material.

The intent of this study is not to carry out a comparative assessment of MCA products, but to assess the environmental impact of different products with different properties and applications. In order to carry out a comparative assessment, the functional unit(s) must be changed to ensure that only functionally equivalent systems are compared. This may not be possible with all products characterized within this study.

Also, as indicated in the limitations, this study does not include the use phase. It is recommended that MCA investigate the benefits of installing the relevant products in a building or other use phase scenario, and quantify the use phase benefits of these materials.

APPENDIX A. CRITICAL REVIEW REPORT

Critical Review by Panel of External Experts
In the capacity as the *original study commissioner*, the Metal Construction Association commissioned a panel of external experts to review the *Life Cycle Assessment of Metal Construction Association Production Processes, Metal Roof and Wall Panel Products* study. The following is a report of the review results of the *Draft Report*, April 24, 2012 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

Jamie K. Meil
Managing Director, Athena Sustainable Materials Institute

Alfred Dunlop
Independent Coil Coating Industry Expert

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 objectives to ensure conformance with applicable standards:

- The methods used to carry out the LCA were consistent with the applicable international standards
- The methods used to carry out the LCA were scientifically and technically valid
- The data used were appropriate and reasonable in relation to the goal of the study
- The interpretations reflected the limitations identified and the goal of the study, and
- The study report was transparent and consistent.

Review Results
The review results of the *Draft Report* of the study are as follows. Overall the LCA practitioners accomplished the goals set forth by the study. General areas in need of improvement include the following:

(1) Additional details on unit process descriptions should be included in the report,

(2) Any revisions made to the original goal and scope submitted to the reviewers and the goal and scope contained in the Draft Report reviewed should be justified and documented in the report,

(3) Provide additional details supporting the basis of the exclusion of the TRACI 2.0 human health criteria pollutant potential methodology that it "does not measure human health measures well".

(4) Provide discussion in Section 4.7 Limitations, regarding justification for not including uncertainty and sensitivity analysis based on reasons of not disclosing proprietary information, particularly as it relates to the inability to obtain representative data of US steel production activities.

(5) If this study is to be used as the basis for further analysis that includes fundamental changes in data, data modeling, or exclusion or modification of impact categories, such as in the support of environmental product declarations, any and all modifications should be clearly specified.

Additional detailed technical and editorial comments and recommendations were submitted by the review panel with responses to all comments by PE International, Inc. as an appendix to this report.

Conclusion

On the basis of the goals set forth to review this study, the review panel concludes that the study generally conforms to the applicable ISO standards as a comprehensive study that may be disclosed to the public. The reviewers recommend the careful consideration and incorporation of items 1-5 listed above, particularly item 5, the explicit mention of any changes to the data, data modeling, or the set of LCIA methods used in this analysis that are disclosed to the public.

The reviewers recognize that the practitioners do not have access to LCI data representative of US steel production activities. The reviewers believe that this is a serious technical limitation to the study based on the significant difference in production technologies used in the US versus globally. The MCA should seriously consider either the delay or the update of this LCA study to incorporate steel production data representative of US production activities when made available.

Respectfully,

Thomas P. Gloria, Critical Review Panel Chair

30 April 2012
Newton, Massachusetts

APPENDIX B. LCIA DESCRIPTIONS

Life Cycle Impact categories included in this report were based on Impact categories and methods appropriate for use in North America. The current state of the science of life cycle impact methodology consists of the US EPA TRACI (Tool for the Reduction and Assessment of Chemical and other Environmental Impacts) impact assessment methodology. The following is a summary description of the methods and applicable references.

TRACI Impact Categories referenced in this report:

- Acidification
- Eutrophication
- Climate Change
- Photo-Oxidant Formation
- Stratospheric Ozone Depletion

Primary energy demand was also included in the Table of Life Cycle Impact Assessment categories, indicators of contribution to environmental issues, units of measure, & brief descriptions; it is not included in the TRACI methodology. Primary energy demand is a direct measure of the energy (both renewable and nonrenewable) required to perform an activity or operate a process. It is typically measured in units of megajoules (MJ).

A detailed description of the TRACI impact categories used in this report are described below.

ACIDIFICATION

Acidification refers literally to processes that increase the acidity (hydrogen ion concentration) of water and soil systems. The common mechanism for acidification is deposition of negatively charged ions (anions) that are then removed via leaching, or biochemical processes, leaving excess (positive) hydrogen ion concentrations (H^+) in the system. The major acidifying emissions are oxides of nitrogen (NO_x) and sulfur dioxide (SO_2), as well as ammonia emissions that lead to ammonium deposition. Acid rain generally reduces the alkalinity of lakes; changes in the alkalinity of lakes, related to their acid neutralizing capacity (ANC) are used as a diagnostic for freshwater systems analogous to the use of H+ budgets in terrestrial watersheds (Schlesinger 1997). Acid deposition also has deleterious (corrosive) effects on buildings, monuments, and historical artifacts.

The stressor-effects for acidification has three stages. Emissions lead to deposition (via a complex set of atmospheric transport and chemistry processes), which in turn can lead to a variety of site-dependent ecosystem impacts – damages to plant and animal populations (via a complex set of chemical and ecological processes). Deposition occurs through three routes: wet (rain, snow, sleet, etc.), dry (direct deposition of particles and gasses onto leaves, soil, surface water, etc.) and cloud water deposition (from cloud and fog droplets onto leaves, soil, etc.).

As described in Norris (2002), the acidification model in TRACI makes use of the results of an empirically calibrated atmospheric chemistry and transport model to estimate total North American terrestrial deposition of expected H^+ equivalents due to atmospheric emissions of NO_x and SO_2, as a function of the emissions location.

The resulting acidification characterization factors are expressed in H+ mole equivalent deposition per kg emission. Characterization factors take account of expected differences in total deposition as a result of the pollutant release location. Factors for acidification are available for each U.S. state. In many LCIA applications the location of the emission source will be known with less precision than the state level for processes within the life cycle inventory. Therefore, additional characterization factors were developed for each of four U.S. regions, for two larger regional divisions (either east or west of the Mississippi river), and for the U.S. as a whole. For each of these larger regions, the composite factor was created using an annual emissions-weighted average of its constituent states.

As reported in (Norris 2002), regional characterization factors range from roughly 20% of the U.S. average to 160% of the U.S. average, and deviation from the U.S. average is variable between SO_2 and NOx; that is, the effect of source region upon a characterization factors' deviation from the national average values varies somewhat between SO_2 and NO_x. Although the majority of acidic deposition in North America stems from emissions of NO_x (NO and NO_2) and SO_2 (including SOx as SO_2), significant amounts are also due to emissions of ammonia, and trace amounts from emissions of HCl, and HF. TRACI adopts U.S. average characterization factors for these trace emissions, based on their H^+ formation potentials per kg emitted in relation to SO_2.

The benefits of the new TRACI method for characterization of acidifying emissions, relative to prior non-regionalized method like Heijungs et al. (1992), are the increased ability for LCIA results to take into account location-based differences in expected impact. These benefits stem from the fact that the TRACI acidification factors pertain to a focused midpoint within the impact chain – total terrestrial deposition -- for which there is considerable, well-understood, and quantifiable variability among source regions.

There are at least two ways in which the regional variability in deposition potential can have an impact on the acidification potential. In the event that the alternatives have their processes (and thus their emissions) clustered in different regions, the overall deposition potentials for both SO_2 and NOx can vary by as much as a factor of 5 or more (see Norris 2002). Another possibility is that the alternatives have their processes predominantly clustered in the same regions. If this is the case, then the relative deposition potentials of a kg of NOx versus SO_2 emissions can vary by nearly a factor of two from one region to another. In this instance, using the region-appropriate characterization factors may be important to the overall study outcome.

The modeling stops at the midpoint in the cause-effect chain (deposition) because in the U.S. there is no regional database of receiving environment sensitivities (as is available in Europe). Thus, the source region-based variability in total terrestrial deposition has been captured, but not the receiving region-based variability in sensitivity or ultimate damage. Future advances of the TRACI acidification method may address regionalized transport and deposition of ammonia emissions, and investigate the potential to account for regional differentiation of receiving environment sensitivities.

Units of Acidification Results: H+ moles equivalent deposition/kg emission

References

Heijungs, R., J. Guinée, G. Huppes, R. Lankreijer, H. Udo de Haes, A. Wegener Sleeswijk, A. Ansems, P. Eggels, R. van Duin, and H. de Goede. 1992. Environmental life cycle assessment of products. Vol. 1, Guide, Vol. 2, Backgrounds. Leiden, The Netherlands: Centre of Environmental Science, Leiden University.

Norris, G. 2002. Impact characterization in the tool for the reduction and assessment of chemical and other environmental impacts: Methods for acidification, eutrophication, and ozone formation. Journal of Industrial Ecology 6(3-4): 83–105.

Schlesinger, W. 1997. Biogeochemistry: An analysis of global change. Boston: Academic Press.

EUTROPHICATION POTENTIAL

"The most common impairment of surface waters in the U.S. is eutrophication caused by excessive inputs of phosphorus (P) and nitrogen (N). Impaired waters are defined as those that are not suitable for designated uses such as drinking, irrigation, by industry, recreation, or fishing. Eutrophication is responsible for about half of the impaired lake area, 60% of the impaired rivers in the U.S., and is also the most widespread pollution problem of U.S. estuaries" (Carpenter et al, 1998).

Eutrophication means fertilization of surface waters by nutrients that were previously scarce. When a previously scarce (limiting) nutrient is added, it leads to proliferation of algae. This may lead to a chain of further consequences, potentially including foul odors or taste, death or poisoning of fish or shellfish, reduced biodiversity, or production of chemical compounds toxic to humans, marine mammals, or livestock. The limiting nutrient issue is key to characterization analysis of P and N releases within LCIA. If equal quantities of N and P are released to a freshwater system that is strictly P-limited, then the characterization factors for these two nutrients should account for this fact (e.g., the characterization factor for N should approach zero in this instance).

Prior to utilization of TRACI, it is important to determine the actual emissions that will be transported into water. As an example, fertilizers are applied to provide nutrition to the vegetation that covers the soil and therefore, only the run-off of fertilizer makes it into the waterways. The over-application rate is highly variable and may depend on soil type, vegetation, topography, and even the timing of the application relative to weather events. The TRACI characterization factors for eutrophication are the product of a nutrient factor and a transport factor. The nutrient factor captures the relative strength of influence on algae growth in the photic zone of aquatic ecosystems of 1 kg of N versus 1 kg of P, when each is the limiting nutrient. The location or context-based "transport factors" vary between 1 and zero, and take account of the probability that the release arrives in an aquatic environment (either initially or via air or water transport) to which it is a limiting nutrient. The TRACI characterization method for eutrophication is described in more detail in the companion paper (Norris 2002).

The characterization factors estimate the eutrophication potential of a release of chemicals containing N or P to air or water, per kg, relative to 1 kg N discharged directly to surface freshwater. The regional variability in the resulting eutrophication factors shows that the source location will influence not only the relative strength of influence for a unit emission of a given pollutant, but it will also influence the relative strength of influence among pollutants. The benefits of the new TRACI method for characterization of eutrophying emissions, relative to a prior non-regionalized method like Heijungs et al. (1992) are increased ability for life cycle impact assessment results to take into account the expected influence of location on both atmospheric and hydrologic nutrient transport, and thus the expected influence of release location upon expected nutrient impact. The combined influence of atmospheric transport and deposition along with hydrologic transport can lead to total transport factors differing by a factor of 100 or more (Norris 2002).

As with both acidification and photochemical oxidant formation, TRACI provides characterization factors for nine different groups of U.S. states which are known as Census Regions, (see, for example, http://www.eia.doe.gov/emeu/reps/maps/us_census.html) for eastern and western regions, and for the U.S. as a whole, for use when the location of the release is not more precisely known. For each of these larger regions, the composite factor was created using an average of those for its constituent states.

Units of Eutrophication Results: Nitrogen equivalents/kg emission

References

Carpenter, S., N. Caraco, D. Correll, R. Howarth, A. Sharpley, and V. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecological Applications 8(3): 559–568.

Heijungs, R., J. Guinée, G. Huppes, R. Lankreijer, H. Udo de Haes, A. Wegener Sleeswijk, A. Ansems, P. Eggels, R. van Duin, and H. de Goede. 1992. Environmental life cycle assessment of products. Vol. 1, Guide, Vol. 2, Backgrounds. Leiden, The Netherlands: Centre of Environmental Science, Leiden University.

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Climate Change

Global climate change refers to the potential change in the earth's climate caused by the build-up of chemicals (i.e. "greenhouse gases") that trap heat from the reflected sunlight that would have otherwise passed out of the earth's atmosphere. Since pre-industrial times atmospheric concentrations of CO_2, CH_4, and N_20 have climbed by over 30%, 145% and 15%, respectively. While "sinks" exist for greenhouse gases (e.g. oceans and land vegetation absorb carbon dioxide), the rate of emissions in the industrial age has been exceeding the rate of absorption.

Simulations by researchers within the research community of global warming are currently being conducted to try to quantify the potential endpoint effects of these exceedences, including increased droughts, floods, loss of polar ice caps, sea level rise, soil moisture loss, forest loss, change in wind and ocean patterns, changes in agricultural production, decreased biodiversity and increasing occurrences of extreme weather events.

TRACI uses Global Warming Potentials (GWPs) - a midpoint metric. The global warming potentials (GWPs) are based on recommendations contained within the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report (TAR) (IPCC 2001) to adhere to the international agreement by parties of the United Nations Framework Convention on Climate Change (UNFCCC) (FCCC 1996) (EPA 2004):

The 100-year time horizons are recommended by the IPCC and are used by the U.S. for policy making and reporting, (EPA 2004) and are adopted within TRACI. The final sum, known as the Global Warming Index (GWI), indicates the potential contribution to global warming.

Units of Global Warming Potential Results: CO_2 equivalents/kg emission

References

Framework Convention on Climate Change (FCCC). 1996. Report to the Conference of the Parties at its second session, held at Geneva from 8 to 19 July 1996: Addendum Part Two: Action taken by the Conference of the Parties at its second session. Document FCCC/CP/1996/15/Add.1. United Nations Framework Convention on Climate Change, Bonn, Germany.

IPCC (Intergovernmental Panel on Climate Change). 2001. Climate change 2000: The science of climate change. Edited by Intergovernmental Panel on Climate Change: J. T. Houghton, L. G. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg, and K. Maskell. Cambridge, UK: Cambridge University Press.

U.S. Environmental Protection Agency (EPA). 2004. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2002, Annex 6 Additional Information. Document EPA 430-R-04-003. U.S. Environmental Protection Agency, Washington, DC.

OZONE / PHOTO-OXIDANT FORMATION

Ozone (O_3) is a reactive oxidant gas produced naturally in trace amounts in the earth's atmosphere. Rates of ozone formation in the troposphere are governed by complex chemical reactions, which are influenced by ambient concentrations of oxides of nitrogen (NO_x), volatile organic compounds (VOCs), the mix of OCs, temperature, sunlight, and convective flows. In addition, recent research in the Southern Oxidants Study (e.g., Chameides and Cowling 1995) indicates that carbon monoxide (CO) and methane (CH_4) can play a role in ozone formation.

There are over 100 different types of VOC emitted to the atmosphere, and they can differ by more than an order of magnitude in terms of their estimated influence on photochemical oxidant formation (e.g., [Carter 1994]). Further complicating the issue is the fact that in most regions of the U.S., ambient VOC concentrations are due largely to biological sources (trees). For example, in urban and suburban regions of the U.S. at midday, biogenic VOCs can account for a significant fraction (e.g., 10-40%) of the total ambient VOC reactivity (NRC 1991). In rural areas of the eastern U.S., biogenic VOCs contribute more than 90% of the total ambient VOC reactivity in near-surface air.

Ozone in the troposphere leads to detrimental impacts on human health and ecosystems. The mid-point associated with photochemical oxidant formation is the formation of ozone molecules (O_3) in the troposphere.

Conventional smog characterization factors for LCIA have been based on European modeling of the relative reactivities among VOCs, and have neglected NOx entirely. This neglect of NOx is a highly significant omission: throughout the past decade, numerous U.S. studies have found spatial and temporal observations of near-surface ozone concentrations to be strongly correlated with ambient NOx concentrations, and more weakly correlated with anthropogenic VOC emissions (see, for example, NRC 1991, Cardelino and Chameides 1995). Another omission in all existing smog characterization factors has been the potential influence of emission location.

The approach to smog characterization analysis for VOCs and NOx in TRACI has the following components: (1) relative influence of individual VOCs on smog formation; (2) relative influence of NOx concentrations versus average VOC mixture on smog formation; (3) impact of emissions (by release location) upon concentration by state; and (4) optional methods for aggregation of effects among receiving states – either by area or population-weighted area.

To characterize the relative influence on O_3 formation among the individual VOCs, Carter's latest maximum incremental reactivity calculations are used (Carter 2000). These reflect the estimated relative influence for conditions under which NOx availability is moderately high and VOCs are at their most influential upon O_3 formation. For the relative influence of NOx emissions in comparison to the base reactive organic gas mixture a mid-range factor of 2 is used, which is in agreement with empirical studies on regional impacts for the eastern U.S. (e.g., Cardelino and Chameides 1995), and is at the middle of a range of model-based studies (Rabl and Eyre 1997, Seppälä 1997).

The influence of NOx emissions upon regional ambient levels has been modeled using source/receptor matrices that relate the quantity of seasonal NOx emissions in a given source region to changes in ambient NOx concentrations in each receiving region across North America. These source/receptor matrices were obtained from simulations of the Advanced Statistical Trajectory Regional Air Pollution (ASTRAP) model (Shannon 1991, 1992, 1996). Source and receptor regions are the contiguous U.S. states, plus Washington, D.C., plus the 10 Canadian Provinces, plus northern Mexico. Recent empirical research (e.g., St. John et al. 1998, Kasibhatla et al. 1998) shows that average O_3 concentrations exhibit strong and stable correlations with regional ambient NOx concentrations.

The assumption was made that VOC emission impacts on regional O_3 concentrations have the same spatial distribution as the ambient NOx concentration impacts (i.e., similar regional transport for VOCs and NOx). Finally, the outcome of the source/transport modeling is proportional to estimated O_3 concentration impacts (g/m^2) per state, given an assumed linear relationship between the change in concentration in NOx (with VOC-concentrations converted to NOx equivalents).

Finally there is the question of how to aggregate the effects of estimated changes in smog concentration by state. Exposures leading to human health impacts will be related to the product of state level ambient concentrations times state populations, assuming uniform population density within a state, assuming linear relationship between dose and risk of impact. Damages from impacts on forest and agricultural productivity are related in part to the scale of sensitive agricultural and forest output per state. In the present version of TRACI, human health impacts are addressed, scaling the state level concentration outcomes by state population before aggregating across states. The TRACI method for photochemical oxidant formation is described in more detail in the companion paper (Norris 2002).

Units of Smog Formation Results: kg O_3 equivalents/kg emission

References

Cardelino, C. A. and W. L. Chameides. 1995. An observation-based model for analyzing ozone precursor relationships in the urban atmosphere. Journal of the Air and Waste Management Association 45: 161–180.

Carter, W. 1994. Development of ozone reactivity scales for volatile organic compounds. Journal of the Air and Waste Management Association 44:881–899.

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Chameides, W. L. and E. B. Cowling, eds. 1995. The state of the southern oxidants study: Policyrelevant findings in ozone pollution research 1988 to 1994. Raleigh, NC: North Carolina State University.

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PRIMARY ENERGY DEMAND

Primary energy demand is the quantity of energy directly withdrawn from the hydrosphere, atmosphere, geosphere, or energy source without any anthropogenic changes. It is a measure of the level resource used across the life cycle of a product.

For fossil fuels and uranium, this would be the amount of resource withdrawn expressed in its energy equivalent (i.e. the energy content of the raw material). For renewable resources, the energy-characterized amount of biomass consumed would be described. For hydropower, it would be based on the amount of energy that is gained from the change in the potential energy of the water (i.e. from the height difference). As aggregated values, the following primary energies are designated:

The total **“Primary energy demand non-renewable”**, given in MJ, essentially characterizes the gain from the energy sources natural gas, crude oil, lignite, coal and uranium. Natural gas and crude oil will be used both for energy production and as material constituents e.g. in plastics. Coal will primarily be used for energy production. Uranium will only be used for electricity production in nuclear power stations.

The total **“Primary energy demand renewable”**, given in MJ, is generally accounted separately and comprises hydropower, wind power, solar energy, and biomass. It is important that the end energy (e.g. 1 kWh of electricity) and the primary energy used are not miscalculated with each other; otherwise the efficiency for production or supply of the end energy will not be accounted for.

The energy content of the manufactured products will be considered as feedstock energy content. It will be characterized by the net calorific value of the product. It represents the still usable energy content.