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A Cradle-to-Gate Life Cycle Assessment of ½" Regular and $^5/_8$" Type X Gypsum Wallboard

Prepared for the Gypsum Association, Inc.

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Executive Summary

Goals and Scope

The Gypsum Association (GA) and its members engaged the Athena Sustainable Materials Institute to conduct a representative, transparent and ISO 14040/44:2006 compliant cradle-to-gate life cycle assessment (LCA) of 1,000 square feet (92.9 m2) of the industry's two most common gypsum wallboard products – ½" (12.7 mm) Regular and 5/8" (15.9 mm) Type X gypsum wallboard – as produced in the United States in 2010. Both of these gypsum wallboard (GWB) products are used extensively in building construction and renovation as an enclosing surface for interior walls and ceilings.

The GA intends to share the results of this benchmark study with suppliers and product users throughout its value (supply) chain, use the study results to support its marketing efforts, upload these reliable and up-to-date life cycle inventory (LCI) data to the US LCI Database (http://www.nrel.gov/lci/) and have these data integrated into key building LCA tools.

In support of the study, primary LCI data were collected for three major gate-to-gate processes in the production of gypsum wallboard (GWB): natural or crude gypsum ore extraction (six quarries and one underground mining site), gypsum paper manufacture (three plants) and GWB production (17 plants) for the reference year 2010. The GWB manufacturing plant study sample included all GA member companies and represented about 25% of all establishments producing gypsum and about 30% of all GWB produced in the USA. To ensure representativeness, the GWB manufacturing plant study also considered the scale of operations including a mix of small, medium and large facilities, their geographical location in each US census region and their source of gypsum – adjacent quarry, mine, imported gypsum ore and their use of FGD synthetic gypsum.

Methodology

Life cycle assessment is an analytical tool used to comprehensively quantify and interpret the energy and material flows to and from the environment over the life cycle of a product, process, or service. This LCA study is conducted in accordance with ISO 14040:2006 and ISO 14044:2006. The study data, methods, results and report underwent an independent critical review by an external LCA expert.

A cradle-to-gate LCA assessment was conducted to evaluate the environmental performance of ½" Regular and 5/8" Type X gypsum wallboard products by considering the potential impacts of the selected life cycle stages, starting with extracting raw materials from the earth (the "cradle") and ending at the plant exit "gate" where the product is ready to be shipped to a distributor or user.

Within all three gate-to-gate processes (natural gypsum ore extraction, gypsum paper and GWB manufacture), "mass" was deemed the most appropriate physical parameter for allocating the total environmental load between the reference or functional product of interest and co-product(s). Plant specific formulations for 1,000 square feet of the two products of interest were used to calculate the required input raw materials (both primary and secondary) and the ancillary materials.

To solve the "multi-functionality" of coal-fired power generation process and calculate the environmental profile of the flue gas desulfurized (FGD) synthetic gypsum input, a co-product of coal power plant, a "system expansion" approach was used to avoid allocation.

The study supported a comprehensive set of life cycle impact assessment (LCIA) impact categories based on ISO 21930:2007 "Sustainability in Building Construction – Environmental Declaration of Building Products", and the US EPA TRACI impact assessment characterization model provided a North American context for calculating the impact category indicator results. The study's large representative sample size, reliable, up-to date and transparent process data and its comprehensive set of supported environmental life cycle impact category indicators provide a credible LCA benchmark for the gypsum wallboard industry. Overall, the data quality underlying the study is considered "high" or "good".

Results

The cradle-to-gate weighted average environmental profile results for ½" Regular and $^{5}/_{8}$" Type X GWB finished products is reported in Table ES1. The cradle-to-gate manufacture of 1,000 sq. ft. of ½" Regular and $^{5}/_{8}$" Type X GWB embodies about 4.1 GJ and 5.5 GJ of primary energy use and emits in the order of 233 kg and 315 kg (CO_2 equivalent) of greenhouse gas emissions, respectively. For both GWB products, over 90% of the total primary energy inputs were derived from non-renewable fossil fuel resources.

Table ES1. Cradle-to-Gate Environmental Profile for GWB Products (1,000 sq. ft.)

Impact category indicator	Unit	1/2" Regular GWB	5/8" Type X GWB
Global warming	kg CO_2 eq	233.3	315.4
Acidification	H^+ moles eq	93.9	127.0
Respiratory effects	kg $PM_{2.5}$ eq	0.45	0.61
Eutrophication	kg N eq	0.30	0.37
Ozone depletion	kg CFC-11 eq	1.1E-05	1.5E-05
Smog	kg NO_x eq	0.467	0.632
Total Primary Energy	MJ	4051.4	5445.1
Non renewable, fossil	MJ	3725.7	5047.7
Non-renewable, nuclear	MJ	180.7	242.9
Non-renewable, biomass	MJ	2.4	2.6
Renewable, biomass	MJ	122.1	124.3
Renewable, wind, solar, geothermal	MJ	2.2	2.9
Renewable, water	MJ	18.3	24.7
Abiotic depletion	kg Sb eq	4.3E-03	6.2E-03
Water use	m^3	3.1	4.1

A dominance analysis revealed that the three main inputs of the GWB manufacturing system were, in descending order, on-site natural gas use, gypsum paper and on-site electricity use. Figure ES1 and ES2 illustrate the results of the dominance analysis for 1,000 sq. ft. (MSF) of 1/2” Regular and $^5/_8$” Type X GWB finished products.

In fact, the GWB plant’s energy use was the single largest contributor to the majority of the LCIA category indicator results - global warming, acidification, respiratory effects, ozone depletion, smog and total primary energy – often accounting for greater than 70% of the total impact results for the two GWB products.

The input of gypsum paper was the next most consistent and significant contributor to the majority of the LCIA category results (excluding abiotic resource depletion) and ranged from 8% to 30% of the total impact results for the two products.

Figure ES1. Dominance Analysis: 1/2” Regular GWB Product– %basis, per MSF

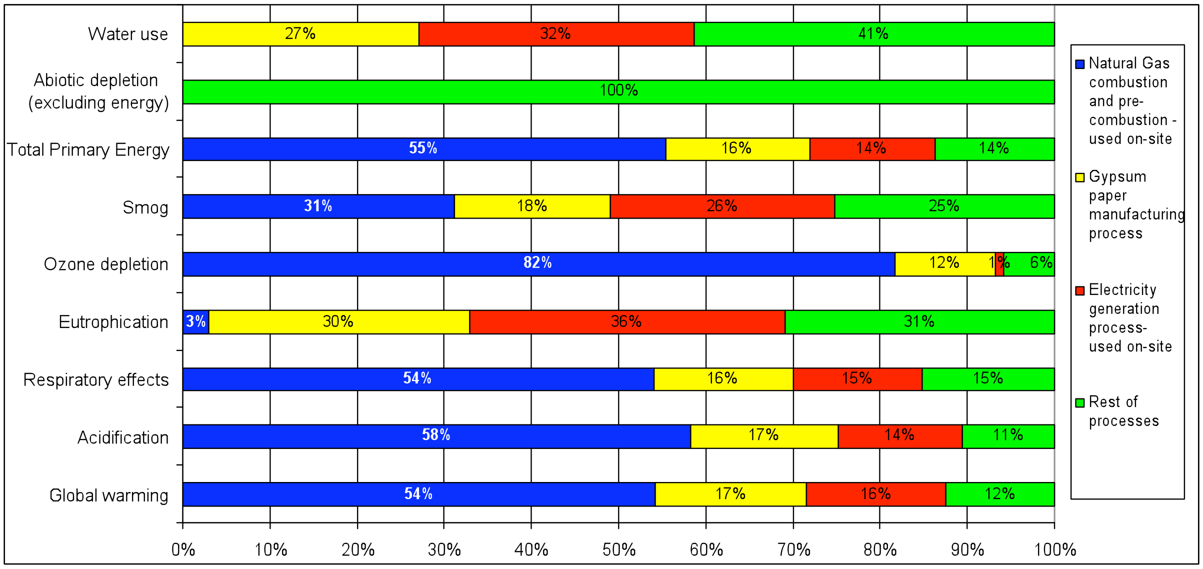
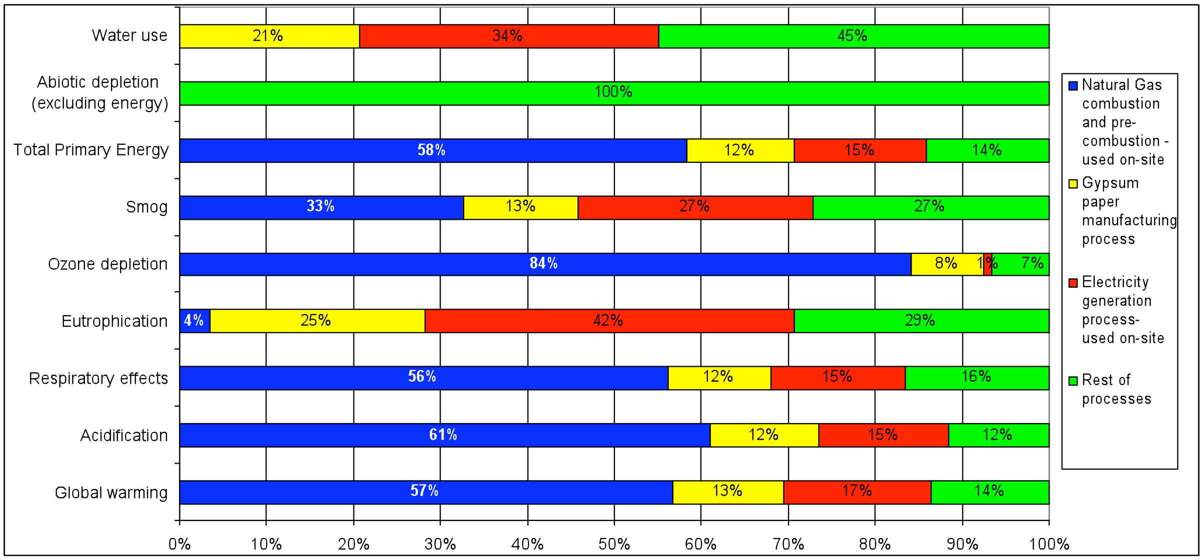


Figure ES2. Dominance Analysis: 5/8” Type X GWB Product System– % basis, per MSF



Dry and wet additives in the production of GWB products accounted for 25% to 27% of the total eutrophication potential impact across the two product systems. The contribution of additives to the rest of the LCIA category results ranged from 3% to 11% for the two products.

Inbound transportation of raw and ancillary materials and the outbound transportation of wastes for treatment accounted for 32% to 33% of the smog potential, but transportation contributed no more than 8% to the other LCIA category results for the two GWB products.

The contribution of the natural gypsum extraction system (both domestic & imported) to the depletion of abiotic resources potential was 98%. Natural gypsum's contribution to the rest of the LCIA category results ranged from 0.3% to 8% of the total impact results for the two products. The net impact of FGD synthetic gypsum use was an environmental benefit to the product system due the diversion/avoidance of landfilling FGD gypsum. The FGD gypsum impact credit ranged from 1% to 7% across the set of LCIA category measures; except for smog formation potential, where the credit effect was closer to 30% due to avoidance of transportation to the landfill.

On average, for every 1,000 sq. ft. of GWB product manufactured about 0.4% of all material inputs end up as solid waste. Of the total solid waste, 0.04% was deemed "hazardous waste" to be incinerated – the majority of the solid waste outputs were either recycled, used as agricultural gypsum, returned to the quarry site for the purpose of land reclamation or sent to landfill.

An influence analysis indicated that 78% to 82% of the total LCIA results were within the GWB plant's sphere of operational control of which, plant energy use was the prime contributor. A sensitivity analysis of "on-site energy use" at the GWB plant indicated that plant energy use was also about three times more sensitive to the use of natural gas than electricity. As a result, increased efforts to reduce natural gas use offers the most immediate opportunity to improve the environmental performance of GWB plants and products. Additional sensitivity analyses revealed that a change in the source location of natural gypsum imports (Canada or Mexico) had a minimal influence (<1%) on the overall LCIA results.

The study's scope was limited to the cradle-to-gate manufacture of the two products of interest. A logical expansion of the study would be to extend it to a full cradle-to-grave assessment, which would better demonstrate the full life cycle effect of GWB products by including its installation, maintenance, service life, possible recyclability and end-of-life disposal. These cradle-to-grave profiles can then be used to develop both Business-to-Business and Business-to-Consumer environmental product declarations (EPDs) for these products to support the GA's future marketing efforts.

Acknowledgements

The Athena Sustainable Materials Institute prepared this cradle-to-gate life cycle assessment of two gypsum wallboard products with sponsorship by the Gypsum Association (GA). The Institute would like to gratefully acknowledge the GA's LCA Working Task Group members listed below and especially Michael A. Gardner, Executive Director, and Dr. Robert Wessel, Assistant Executive Director of the Gypsum Association, for their valuable comments and support during the study and preparation of this report. The final report contents reflect the views of the authors, who are responsible for the facts and accuracy of the information presented and do not necessarily reflect the views of the Gypsum Association and its members.

Gypsum Association's LCA Working Task Group Members:

Michael A. Gardner	Executive Director, Gypsum Association
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Glossary of Terms

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Based on ISO 14021:1999(E)- Clause 7.8 Recycled content.

Pre-consumer material: Material diverted from the waste stream during a manufacturing process. Excluded is reutilization of materials such as rework, regrind or scrap generated in a process and capable of being reclaimed within the same process that generated it.

Post-consumer material: Material generated by households or by commercial, industrial and institutional facilities in their role as end-users of the product that can no longer be used for its intended purpose. This includes returns of material from the distribution chain.

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Acronyms and Abbreviations

ADP	Abiotic Depletion Potential
Btu	British thermal units
CED	Cumulative Energy Demand
CF	Characterization factors
CFCs	Chlorofluorocarbons
CFC-11	Trichlorofluoromethane
CML	Institute of Environmental Sciences (CML), Netherlands
DBS	Dunnage, Bunks, Sleutters
EPDs	Environmental Product Declarations
FGD	Flue Gas Desulfurization
GA	Gypsum Association
GWB	Gypsum Wallboard
GWP	Global Warming Potential
H+	Hydrogen ion
HFCs	Hydrochlorofluorocarbons
HHV	Higher Heating Value
IC	Impact categories
IPCC	International Panel on Climate Change

ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life cycle impact assessment
LEED	Leadership in Energy & Environmental Design
MJ	Megajoule
MSF	Thousand square feet
N	Nitrogen
NIST	National Institute of Standards and Technology
NOx	Nitrogen oxides
OCC	Old Corrugated Container
P	Phosphorous
PM 2.5	Particulate matter less than 2.5 micrometers in diameter
PM 10	Particulate matter less than 10 micrometers in diameter
POCP	Photochemical Ozone Creation Potential
Sb	Antimony
SETAC	The Society of Environmental Toxicology and Chemistry
SO2	Sulfur dioxide
STMP	Sodium Trimetaphosphate

TPM	Total Particulate Matter
TRA	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
UNEP	United Nations Environment Program
US EPA	United States Environmental Protection Agency
VOCs	Volatile Organic Compounds
WMO	World Meteorological Organization

1 Introduction

The objective of this study was to develop a transparent ISO 14040/44:2006 compliant, weighted average, benchmark cradle-to-gate life cycle assessment (LCA) of 1,000 square feet (92.9 m^2) of two common gypsum wallboard products produced by the Gypsum Association's (GA) member companies: namely, ½" Regular and $^5/_8$" Type X gypsum wallboard.

Gypsum wallboard (GWB) is ubiquitous in building construction, covering walls, ceilings and partitions in both residential and commercial building applications. In 2009,18.3 billion square feet of gypsum wallboard was consumed in the United States. Of this amount, Regular ½" and Type X accounted for 80% of all gypsum wallboard consumed [11]. Over time, the use of flue gas desulfurized (FGD) synthetic gypsum as a substitute for crude or raw quarried gypsum has grown to represent 50% or more of the gypsum furnish used in the USA to manufacture gypsum wallboard. This study is based on primary LCI data collected for quarried and mined natural gypsum, production of GWB facing and backing papers and GWB plant manufacturing for the reference year 2010. The study also incorporates a system expansion approach to estimate the environmental profile of synthetic FGD gypsum used in the production of the two board types.

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

The Gypsum Association is an international, not-for-profit trade association founded in 1930 and is based in the Washington, DC area. The mission of the Gypsum Association is to promote the use of gypsum while advancing the development growth, and general welfare of the gypsum industry in the United States and Canada on behalf of its member companies[1]. The GA and its member companies foster an accountable and environmentally responsible attitude toward the preservation of natural resources, the establishment of recycling and waste management

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[1] Gypsum Association website, 2011: http://www.gypsum.org

programs, and the many diverse issues relating to land reclamation and use. Present-day manufacturing processes enable gypsum panels to be manufactured using synthetic, recycled or recovered material, gypsum manufacturing facilities to employ energy-efficient technologies, and depleted gypsum mines and quarries to be rehabilitated to merge with the existing natural landscape. A full description of the GA and its activities can be found at www.gypsum.org.

The Gypsum Association engaged the Athena Sustainable Materials Institute to benchmark and characterize the key environmental life cycle flows to and from nature associated with the manufacture of ½” Regular and $^5/_8$” Type X gypsum wallboard products for the reference year 2010. Future work may focus on positioning these gypsum products relative to all materials within typical building archetypes from an environmental perspective over the full life cycle of a building. This initial effort of the GA and its members is a key-step in developing a more strategic approach for communicating and improving the sustainability of gypsum wallboard products.

The report is organized as follows:

Section 2 provides a brief overview of the LCA framework according to ISO 14040/44:2006.

Section 3 describes the goal and scope of the study including the study’s intent, applications and target audiences. It also sets out the system boundary, functional unit, cut-off criteria, allocation methods, data quality indicators, key data sources and the life cycle impact indicators supported by the study.

Section 4 provides an overview of the three gate-to-gate processes making up the GWB cradle-to-gate product system and summarizes the materials, energy and emission to air, water and land inventory flows associated with each of the processes.

Section 5 builds on Section 4 by linking the upstream materials, energy, and component processes back to earth to present the complete cradle-to-gate life cycle impact assessment (LCIA) results for the two reference product systems – quarried gypsum and gypsum paper production – and then for the functional unit of the two gypsum wallboard products of interest. The contribution of various raw and ancillary material inputs, energy types and processes to the various product system results are highlighted in this section.

Section 6 brings together the LCI and LCIA results to identify significant issues in the context of the goal and scope of the study. Issues are identified via dominance, influence and contribution analysis for the two product systems. This section then provides an evaluation of the study's completeness and methodology consistency in relation to the goal and scope of the study. Various sensitivity analyses are also performed to check the robustness of the results and to determine the extent to which changes in the product system may significantly impact GWB manufacture. Finally, the section presents the study's conclusions, limitations and makes some recommendations for possible next steps to extend the usefulness of the study.

2 Life Cycle Assessment

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

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

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

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

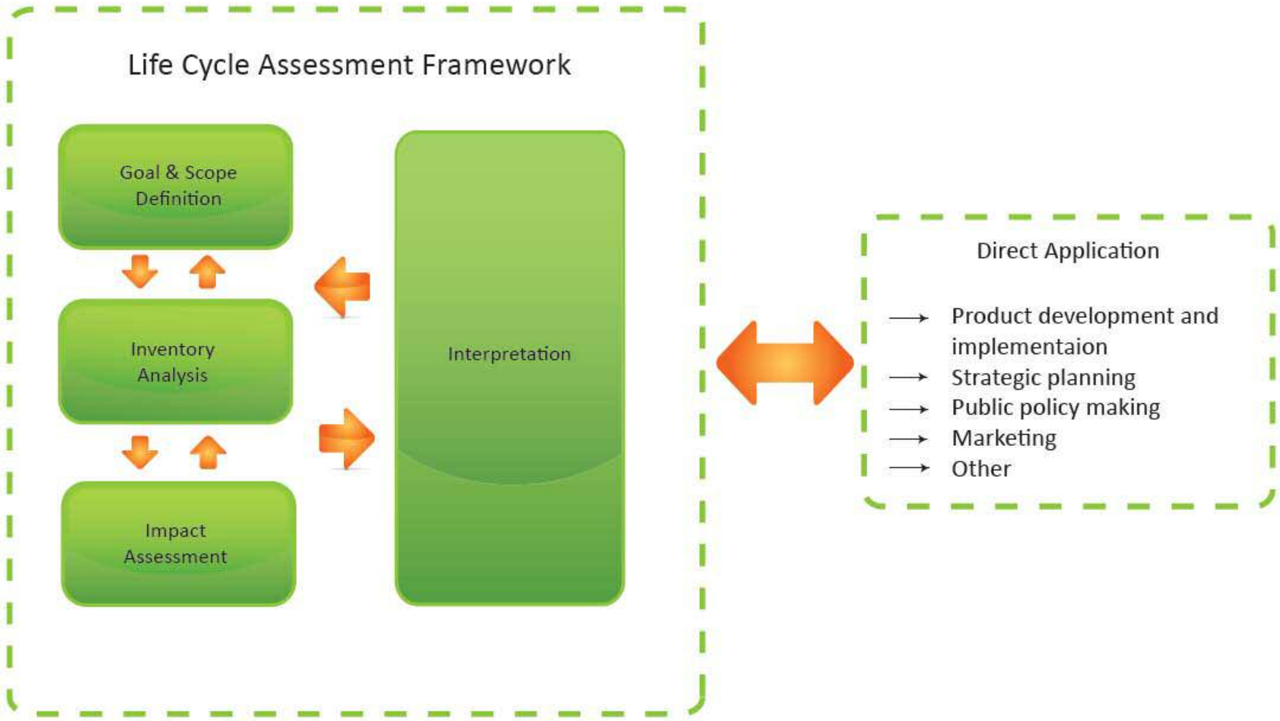

Figure 1. Stages of an LCA as per ISO 14044:2006

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

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

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

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

The working procedure of LCA is iterative, as illustrated by the back-and-forth arrows in Figure 1. The iteration means that information gathered in a latter stage can cause effects in a former stage. When this occurs, the former stage and the following stages have to be reworked taking into account the new information. At the end, the results and conclusions of the LCA will be completely and accurately reported to the intended audience. The data, methods, assumptions, limitations, and results will be transparent and presented in sufficient detail to allow the interested parties to comprehend the complexities and trade-offs inherent in the LCA. The report will also allow the results and interpretation to be used in a manner consistent with the goals of the study.

3 Goal and Scope Study Definition

This is a sector-driven initiative by the GA and its members to conduct a benchmarking LCA study of the industry's two primary products: ½" Regular and $^5/_8$" Type X gypsum wallboard. The geographical scope of the study is North America. Primary or foreground LCI data have been collected for quarried and mined gypsum, facing and backing gypsum paper manufacture and for the two commonly produced gypsum wallboard industry products for the reference year 2010.

3.1 Goals of the study

As per ISO 14044:2006, the goal of an LCA should state the following:

- the reasons for carrying out the study;
- the intended application;
- the intended audience, i.e., to whom the results of the study are intended to be communicated; and
- whether the results are intended to be used in comparative assertions intended to be disclosed to the public.

3.1.1 Reasons for carrying out the study

In collaboration with the GA LCA working team members, the following drivers for carrying out this LCA study were identified.

- To better characterize the overall environmental performance of the membership's primary products.
- To be able to share, and respond to customer and public requests for, accurate environmental information on GA member processes and products.
- To better understand the contribution of various GWB processes within the cradle-to-gate profile of GWB products.

- To assist other organizations in understanding and communicating the environmental footprint and performance of their products when incorporating GWB products.

More specifically the goals of this study are as follows:

1. Determine the cradle-to-gate environmental profile, on a production weighted average (representative) basis of 1,000 square feet of ½" Regular gypsum wallboard product, and identify key environmental inputs and outputs associated with the manufacture of this GWB product.
2. Determine the cradle-to-gate environmental profile, on a production weighted average (representative) basis of 1,000 square feet of $^5/_8$" Type X gypsum wallboard product, and identify key environmental inputs and outputs associated with the manufacture of this GWB product.

The manufacture of both board types conforms to ASTM C1396 / C1396M - 09a [3] providing a backing or finished surface to enclose walls, ceilings and floor surfaces; however, $^5/_8$" Type X gypsum wallboard also has a one hour fire rating (ASTM E119 - 10b[4]) – an additional functionality associated with its finished thickness and properties. While both products have similar applications they provide different functionality; therefore no immediate product based comparative assertion is inferred or implied across the two products of interest in this study.

3.1.2 Intended applications

Intended applications for the results of this study are as follows.

1. To update and benchmark the environmental implications associated with the industry's two primary GWB products which will support future projects such as:

- promoting and tracking the continuous improvement of the environmental performance of the gypsum based building materials as technology improves over time; and

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[3] ASTM C1396 / C1396M - 09a- Standard Specification for Gypsum Board. http://www.astm.org/Standards/C1396.htm.

[4] ASTM E119 - 10b-Standard Test Methods for Fire Tests of Building Construction and Materials. http://www.astm.org/Standards/E119.htm.

- industry average carbon footprint reporting or the preparation of an environmental product declaration (EPD).

2. Market Support. The LCA will provide detailed gate-to-gate process and cradle-to-gate product profiles, with key indicators of environmental performance. These product and process environmental profiles will support education and marketing efforts with environmentally conscious customers or organizations to properly position GWB products in the building construction industry (e.g., LEED – Leadership in Energy & Environmental Design green building certification system and Green Globes rating system, government procurement programs, etc.).

3. To populate the US LCI Database and have data incorporated into North American LCA software tools. The primary process LCI data will be submitted to the US LCI Database and made available to building related LCA software developers – the Athena Institute and the National Institute of Standards and Technology (NIST) – for inclusion in their tools (i.e., ATHENA® Impact Estimator for Buildings, ATHENA® EcoCalculator for Assemblies and/or BEES – Building for Environmental and Economic Sustainability).

3.1.3 Intended audience

The intended audience for the results of this LCA study include GA member companies, their suppliers, architectural, engineering, and specifying professionals, LCA practitioners and tool developers, academia, U.S. governmental organizations, policy makers and other interested supply/value chain parties who require reliable information on sustainable building products and processes.

3.1.4 Comparative assertions

This LCA does not include or support comparative assertions; however, it may lead to future comparative studies intended to be disclosed to the public. Therefore, an independent critical review process by an external expert was conducted in conformity with Clause 6.2, ISO 14044:2006 to verify whether this LCA has met the requirements for methodology, data, interpretation and reporting and whether it is consistent with the ISO 14040/44:2006 principles. Mr. David H. Reisdorph, LCA expert withtheGreenTeam Inc. conducted the critical review of the

GA LCA study. As per ISO requirements the full review statement and the response to reviewer’s recommendation are presented in Appendix B.

3.2 System Scope

The study’s scope was to develop an ISO14040/44 compliant cradle-to-gate life cycle assessment for two primary gypsum wallboard industry products – ½” Regular and $^5/_8$” Type X – for the 2010 reference year.

3.2.1 System boundaries

A cradle-to-gate assessment considers impacts starting with the extraction of raw materials from the earth (the “cradle”) and ending at the plant exit “gate” where the product is packaged and ready for shipment to either a distribution center or directly to the product user.

In-bound transportation of input fuels, primary raw materials, ancillary and packaging materials as well as the intermediate product inputs such as facing and backing paper delivered to the plant was included. Out-bound transportation of the finished gypsum wallboard was not included but it was recorded to support future projects. The use phase, maintenance and end-of-life phases of the product were also not included within the scope of the study. On-site transportation of materials and product (e.g., by forklift) and outbound transport and waste treatment were included. The impacts of FGD synthetic gypsum, a co-product of electricity generation at coal-fired plants, internal gypsum wallboard material which is recycled back in the GWB production system, and the collection and use of post-consumer GWB was also included within the system boundary.

For the gypsum wallboard plant, a plant gate-to-gate “black box” approach was applied, meaning that input/output data were rolled up and not reported for every single constituent operation occurring within the plant; e.g., secondary crushing and drying of the raw furnish, calcined stucco production, wet and dry additives blending, board lay-up, drying, scoring, cutting and packaging for final shipment were rolled up and were not reported or studied as separate unit processes. This “black box” approach necessitated using an allocation methodology to partition and allocate the input and output flows for the products of interest from the other products produced at the gypsum wallboard plant. See section 3.2.4 Allocation Methods for a discussion of the allocation methodology applied in this study. A similar “black box” approach was applied to the gypsum quarrying and gypsum papers production system boundaries. Figures 2 to 4 depict the cradle-to-gate system boundaries for the three primary product systems studied: gypsum wallboard manufacture; crude gypsum ore quarrying/mining; and gypsum facing and backing papers production.

The cradle-to-gate environmental profiles for the two GWB primary products can be used at a later stage to evaluate the full cradle-to-grave profile of these products. A cradle-to-grave assessment typically considers impacts at each stage of a product's life cycle, from the time natural resources are extracted from the ground and processed, through each subsequent stage of manufacturing, transportation, product use, recycling and, ultimately, disposal. These cradle-to-grave profiles can then be used to develop both Business-to-Business and Business-to-Consumer environmental product declarations (EPDs) for these products to further support the GA’s marketing efforts in the future.

Figure 2. "Cradle-to-Gate" System Boundaries of the Gypsum Wallboard Manufacturing

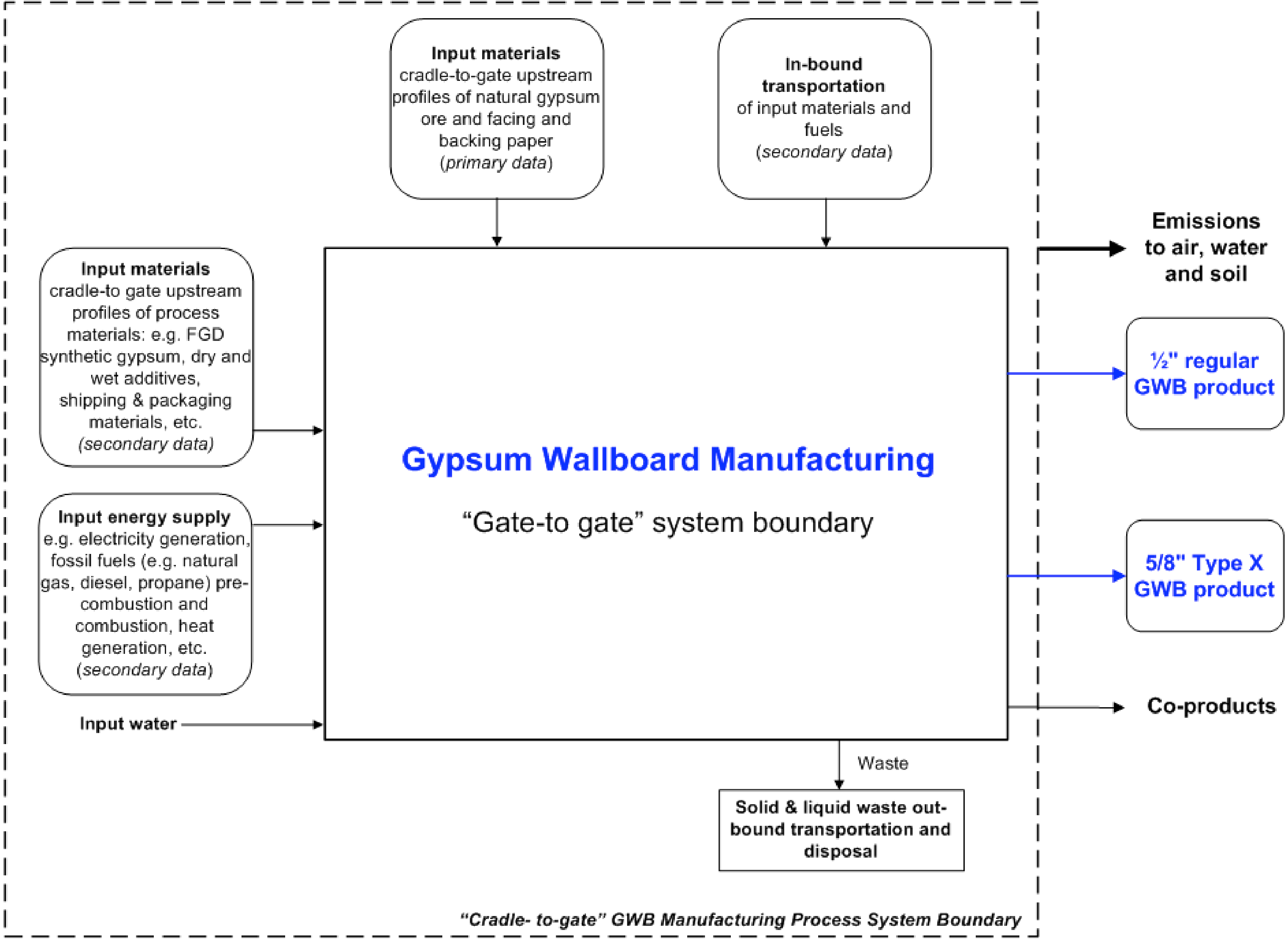


Figure 3. "Cradle-to-Gate" System Boundaries of the Gypsum Quarry

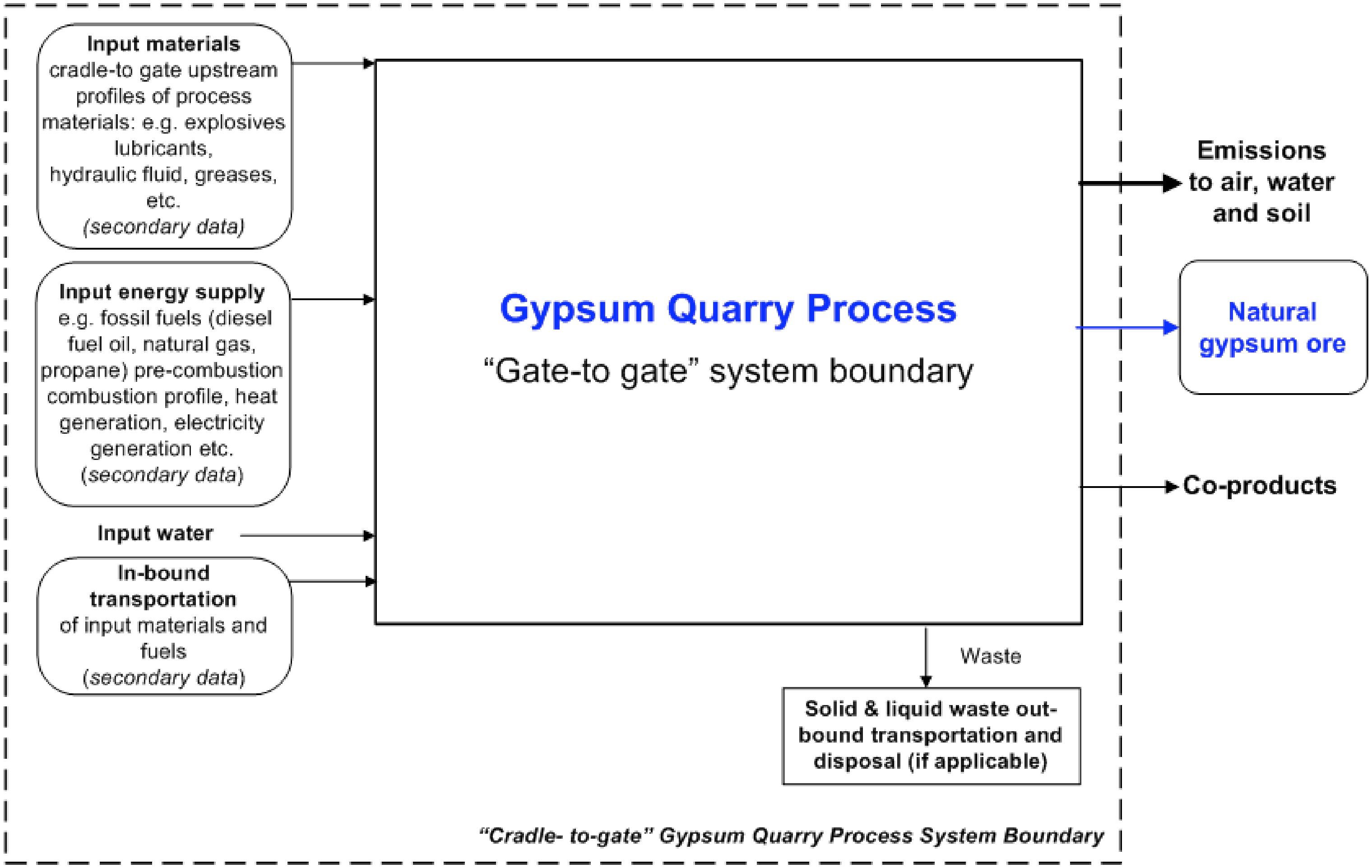


Figure 4. "Cradle-to-Gate" System Boundaries of the Gypsum Paper Manufacturing

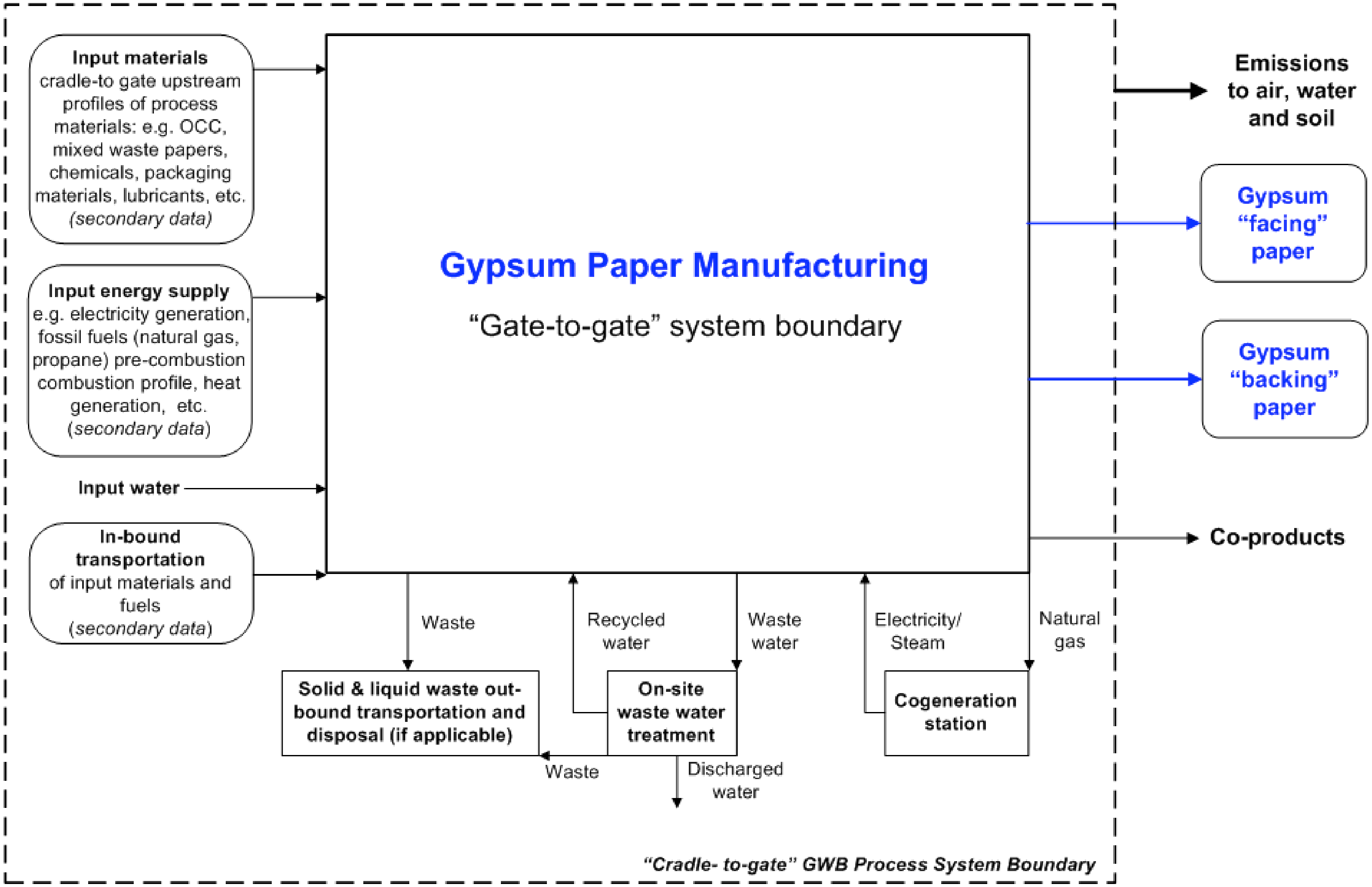


Table 1 presents a summary of the elements included and excluded from the cradle-to-gate system boundary.

Table 1. ***General Overview of the LCI System Boundary***

Included	**Excluded**
"Cradle-to-Gate" system boundary	
• Input raw materials • Input process ancillary materials • Input energy supply • Operation of primary production and pollution abatement equipment • Operation of mobile support equipment • Input water (for process and cooling) • On-site recycling of post-consumer GWB waste • Packaging of products • In-bound transportation of raw materials, ancillary materials, intermediate products and fuels • Overhead (heating, lighting) of manufacturing facilities • Out-bound transportation and disposal of generated waste	• Fixed capital equipment • Hygiene related water use • Transportation of employees

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

3.2.2 Functional unit definition

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

The functional units of the two GWB product systems of interest were as follows.

- Manufacture of 1000 square feet of ½" Regular gypsum wallboard ready for shipment at the plant gate.

- Manufacture of 1000 square feet of $^5/_8$" Type X gypsum wallboard ready for shipment at the plant gate.

The two GWBs of interest vary in thickness, constituent make-up and functionality with the $^5/_8$" Type X gypsum wallboard having a one-hour fire rating; as a result, no comparative assertion is inferred or implied. The two GWB products are capable of covering an area of 1,000 sq. ft. of wall, floor or ceiling (excluding any off-cut waste).

The functional unit of the gypsum quarry production system was the production of one short ton natural gypsum ore (2,000 lbs). The functional unit of gypsum facing and backing paper production system was the manufacture of 1,000 square feet (1 MSF) of gypsum paper. Both quarried gypsum and gypsum paper are reference flows for the production of the functional units. ISO defines the reference flow as a measure of the outputs from processes in a given product system required to fulfill the function expressed by functional unit. Since no functional comparison is being performed, the functional unit and reference flow for the two GWB of interest are the same.

3.2.3 Cut-off criteria

The cut-off criteria for input flows to be considered within the system boundary were as follows.

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

The sum of the neglected input flows was not to exceed 3% of the total mass, energy or environmental relevance. Similar cut-off criteria were used to identify which outputs needed to be traced to the environment; for example, by including waste treatment processes.

3.2.4 Allocation methods

The multi-functionality of many processes has been previously identified as a significant methodological LCA issue. The general situation is that most processes that constitute part of a product system are multi-functional: (1) they produce more than one product (co-production); (2) treat two or more waste inputs (combined waste treatment); (3) treat one waste input and produce one valuable output (open- or closed-loop recycling); or (4) serve three or more valuable functions from both an input and output perspective [10]. In such cases the materials and energy flows, as well as associated environmental releases, shall be allocated to the different products according to clearly stated procedures (ISO 14044:2006, Clause 4.3.4).

As per ISO 14044:2006, allocation means partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems. The guidance provided by ISO recognizes the variety of approaches that can be used to deal with multifunctional processes. Under the heading "Allocation", ISO 14044:2006 presents a hierarchy of different approaches to this multi-functionality problem. As the hierarchy addresses approaches other than allocation and also identifies the first two approaches as "avoiding allocation", it is argued that a clearer and more appropriate approach would be the encompassing title "Solving multi-functionality of processes" [22].

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

Step 1 Wherever possible allocation should be avoided by –

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

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

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

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

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

"Quarry" production system – "Mass" was deemed as the most appropriate physical parameter for allocation of the total environmental load of the quarry system between quarried gypsum (97%) and the "solid rock sold to other industries" co-product (3%). On average, 0.033 short tons of solid rock was sold to other industries per short ton of quarried gypsum produced (see Table 5). Overburden remained on-site for reclamation and was deemed "burden free".

"Gypsum Paper" production system – "Mass" was also deemed as the most appropriate physical parameter for allocation of the total environmental load of gypsum paper system between gypsum paper (97%) and the "downgraded and side-rolls" co-products (3%). On average, 29 sq. ft. of downgraded and side-rolls were generated during the manufacture of 1 MSF gypsum paper (see Table 7).

"Gypsum wallboard " production system – Gypsum wallboard manufacturing is a complex technical system with a wide range of input materials and gypsum product outputs. As a result, plant specific generic formulations for 1,000 square feet of the two products of interest were used to calibrate and calculate the required input raw (both primary and secondary) and ancillary materials. "Mass" was also deemed as the most appropriate physical parameter for allocation used for the gypsum wallboard system (between ½" Regular and $^5/_8$" Type X GWB products and other types of calcined GWB co-products) to estimate the input energy flows (electricity, natural gas, propane, etc.), water input, process emissions and waste flows.

Synthetic FGD Gypsum - Electricity generated at the coal-fired power station is the main product of the coal combustion multi-functional process. FGD synthetic gypsum is a co-product of coal-fired power generation process – a result of SO_2 scrubbing of stack emissions enforced by the US EPA Clean Air Act– and a major raw material used in the production of GWB.

For FGD gypsumto be a saleable co-product for use in GWB manufacturing it needs to undergo processing (dewatering) and transport to the GWB manufacturing facility. As a result, the intermediate processing (dewatering) and transport of FGD was included within the system boundary. It should be mentioned that salable FGD synthetic gypsum has the same molecular composition as crude or raw gypsum and displaces crude gypsum on a one-to-one basis. Typically, FGD gypsum undergoes additional secondary drying at the GWB plant; this drying is included in the facility level LCI data.

ISO requirements and recommendations were followed in this LCA study to solve "multi-functionality" of coal-fired power generation process and calculate the environmental profile of the FGD synthetic gypsum, a co-product of coal power plant.

As recommended by ISO Step 1.a, division of the process to sub-processed was not possible for the coal-fired power generation process as the product and co-product are intrinsically linked. Subdivision is often but not always possible to avoid allocation for black box unit processes and can be typically applied for example to products whose manufacture is not intrinsically linked (see Example A.1, Appendix A).

To avoid allocation, ISO recommends using Step 1.b - to expand the product system to include the additional functions related to the co-products (known as "system expansion" approach). System expansion/substitution are also called "system enlargement" and "crediting" / "avoided burden approach", respectively. This is a combined concept for ensuring the equality of multifunctional systems with each other [22].

System expansion is applicable for product system modeling that is interested to include existing interactions with other systems (Attributional LCA studies, Situation C1) [22]. ISO 14049:2000 provides some examples of allocation avoidance by expanding product system boundaries (see Section 6.4, 8.3.1, 8.3.2).

The LCA team also considered the possibility of splitting the input/output data between the primary product (electricity) and the co-product (FGD synthetic gypsum) in a way that reflects either the physical or economic relationships between them (ISO Step 2 and 3). As per ISO Step 2, the LCA team should determine whether a physical parameter could be identified as a basis for calculating the allocation factor. Any physical parameter, e.g., mass, surface, volume, feedstock energy, thermal conductivity, viscosity, specific mass, etc., could be taken into consideration in order to identify the physical parameter which reflects the underlying physical relationship between product and the other co-products [4].

Physical allocation is possible if the ratio between product and co-product (s) can be varied without changing the inputs and outputs (see examples A.2 and A3, Appendix A).
The fact that, the ratio between the electricity generated and FGD synthetic gypsum cannot be varied indicates that the pure physical allocation cannot be applied. ISO 14049:2000, Section 7.3.2, provides a similar example of bitumen production system as a typical case study where pure physical allocation cannot be applied (see example A.4, Appendix A).

Furthermore, the LCA team analyzed the system to determine if the economic allocation can be applied (ISO step 3). As per economic allocation rules, the total environmental burden of the coal-fired power generation process is "shared" between the product (electricity) and co-product (FGD synthetic gypsum) according to total proceeds of the multi-functional process. The proceeds are based on “prices” per unit of product and co-products.

Three major difficulties are identified below which made the application of economic allocation uncertain:

(1) Because this was not an LCA study of US coal-fired power plants it was not possible to get access to total proceeds and prices per unit of electricity generated and FGD synthetic gypsum (FOB –free on board prices for product and co-product are unknown);

(2) Price fluctuations is another issue which add to the argument and it would have required to look at the minimum three-year averages of proceeds and prices [23];

(3) FGD synthetic gypsum is not a *pure* output functional flow (co-product); US Statistics show that FGD material generated at the coal-fired power plants is not fully utilized and a

significant portion of it is regarded as waste. As per EPA 2008 report, 12 million short tons of FGD gypsum were generated in 2005 in US and 9.27 million short tons of FGD gypsum were used overall by all industries. Over 8 million short tons of FGD gypsum were used as a substitute for raw gypsum in wallboard manufacturing [18]. Of the total synthetic gypsum sold and used in the US in 2009, 81% was used for wallboard production, 7% was used in cement and concrete manufacture, 5% for structural fills or embankments, 3% in agriculture, and the remaining amount for other miscellaneous applications [11]. Still, 50% of all synthetic gypsum produced in 2009 was neither sold, nor used, and in most cases was landfilled [14]. In such cases, ISO recommends that it is necessary to identify the ratio between co-products and waste since the inputs and outputs shall be allocated to the co-products part only [2]. This can only be conducted if you have access to US coal power plant specific data and information – which is not the case (see point 1).

System expansion was deemed the most appropriate approach to solve the multi-functionality of coal-fired power generation process not just because ISO recommends this approach as step 1, but also because neither the correct physical nor economic allocation factor could be effectively applied.

Figure 5 describes the model for system expansion applied for the FGD synthetic gypsum co-product generated at coal-fired power plants. Based on the US statistics, the supply for FGD gypsum is already higher than the demand, which means that FGD is not fully used. For that reason, the gypsum wallboard production system (B) is debited for intermittent treatment of FGD (de-watering, transportation) and credited for avoided landfilling of FGD (as per “system expansion” rules [16], [17], [22]) and the coal-fired power generation process (A) is debited for FGD landfilling.

Environmental burden of Product A (Electricity, coal) = Process A + Process W
Environmental burden of Product B (GWB products) = Process B + Process I - Process W

It should be noted that the GWB production system is modeled based on the 2008 US electricity grid mix and electricity generated from coal-fired power plants is a major contributor of the US electricity grid (see Table 2). This means, that GWB system is directly “credited” for the FGD synthetic gypsum diverted from landfilling and “in-directly” debited for the FGD which ends-up to landfill through the use of Product A (electricity, coal-fired power plants).

Figure 5. Model for describing system expansion approach for the FGD synthetic gypsum, co-products generated at coal fired power plants

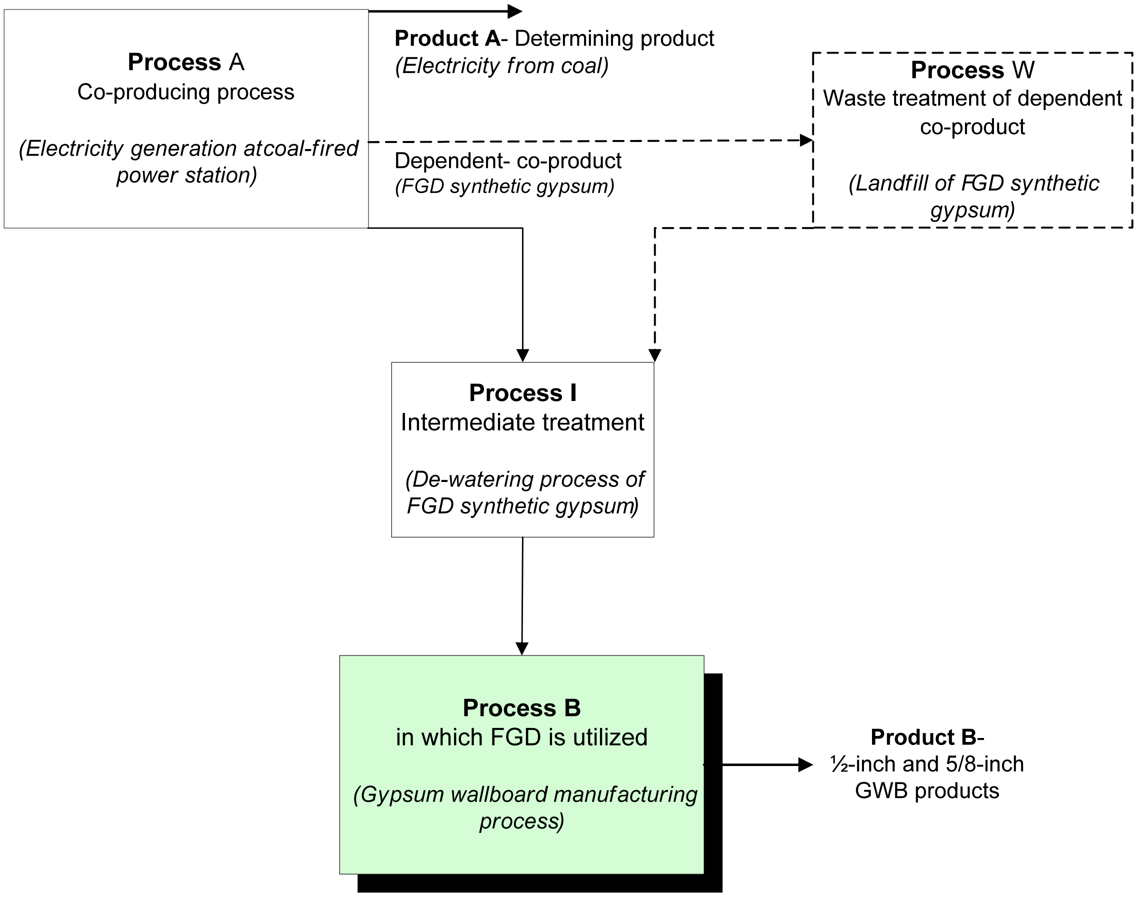
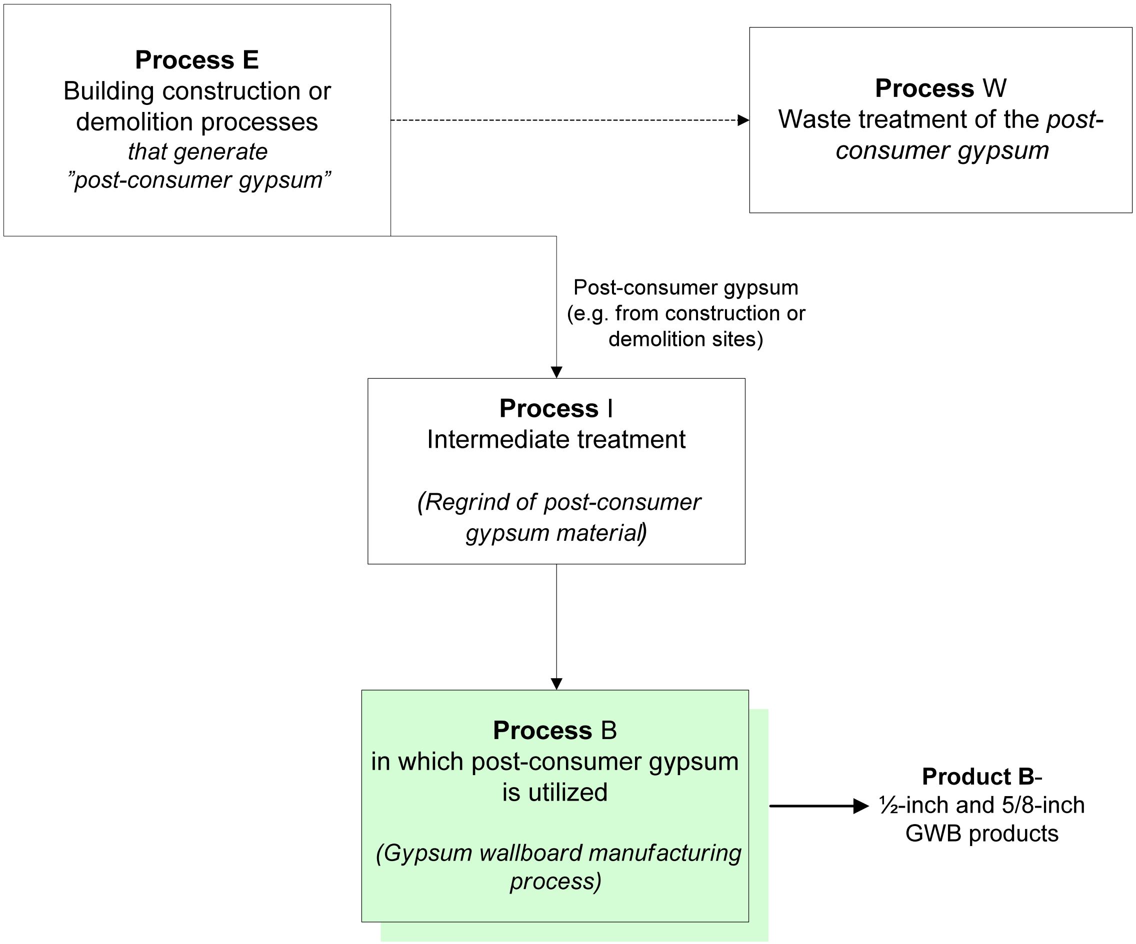


Figure 6 describes the model for system expansion applied for the post-consumer gypsum material (GWB on-site construction off-cuts). Post consumer GWB material collected from construction/demolition sites isn’t always fully utilized and part of it is regarded as waste. For that reason, the GWB production system (B) is debited for intermittent treatment (collection, transportation and plant specific processing) of the post-consumer gypsum input and credited for the avoided waste disposal and transportation to landfill of the post consumer gypsum waste according to the LCA system expansion rules [16], [17], [22].

Figure 6. Model for describing system expansion for the utilization of post-consumer gypsum material



Furthermore, the application of FGD synthetic gypsum and post consumer gypsum material in the manufacturing process is beneficial for the gypsum industry as it reduces the dependency on abiotic resources (natural gypsum ore).

Similarly, the closed-loop recycling of internal gypsum waste contributes to a sustainable GWB manufacturing process as it also reduces the need for primary gypsum material and thereby, reduces the overall environmental load of the GWB products.

3.3 Data Quality

3.3.1 Primary and secondary data sources and modeling software

The study encompasses three inter-connected primary processes producing natural or crude gypsum ore, gypsum facing and backing papers and the two selected GWB products: ½" Regular and $^5/_8$" Type X.

Primary LCI data were collected for each of these three processes: quarried/mined gypsum ore, gypsum papers production and GWB production for the reference year 2010.

The study LCI data collected from the GA member companies was done with the expressed intent of attaining an acceptable representation of the US industry average technology mix. The GA's LCA Working Task Group identified a representative sample of GWB plants within its membership on the basis of technical attributes, production scale and geographic location to arrive at a representative weighted average profile. Described below is the GA's well-defined platform for plant selection for inclusion in the study sample.

- In 2010, about 60 GWB manufacturing plants were operating in the US.
- Of these, 17 plants were selected to adequately represent:

  - GA's membership production volume (including having at least *one plant* from each GA member company participate in the study);

  - the scale of plant operations including a mix of small, medium and large operations;

  - the geographical spread of the participating facilities included having at least *one plant* in each US census region included in the study.
- To approximate the gypsum source ratio, a mix of plants processing either natural (crude) gypsum rock or flue gas desulfurized (FGD) synthetically derived gypsum or a blend of both these two major inputs was selected.
- A mix of plants using locally derived gypsum ore (adjacent quarry operation) versus imported natural gypsum ore transported by various modes and distances were included

in the sample (crude gypsum ore imports include Canada or Mexico depending on plant location).

- A mix of plants that are dependent on local versus more distant sources of FGD synthetic gypsum were also included in the sample.

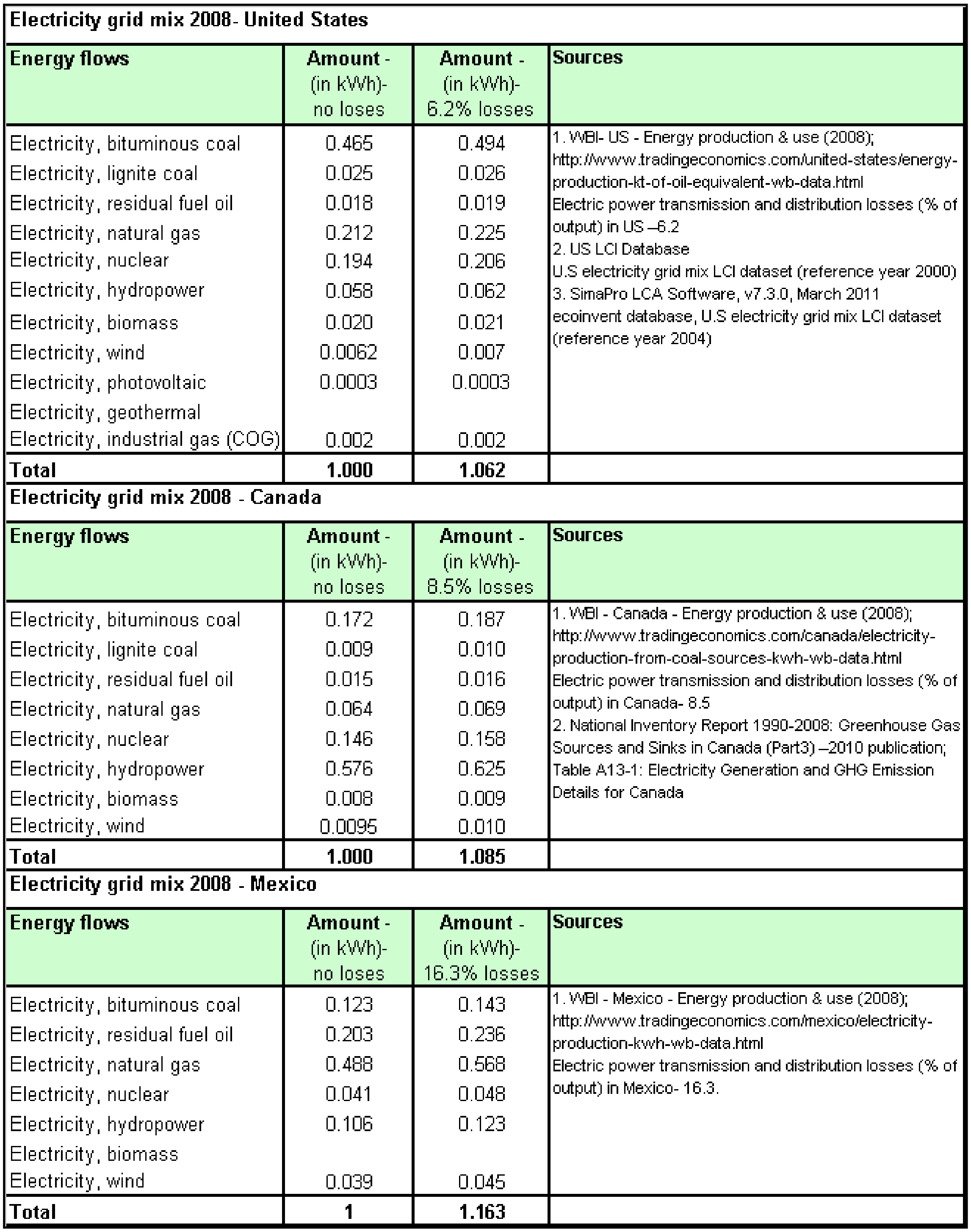
For GWB manufacturing process, 17 LCI data questionnaires were completed to provide a GWB representative production weighted sample. For the gypsum paper manufacturing, three plants provided primary LCI data. Six quarries and one gypsum ore underground mining operation provided primary data on raw gypsum ore production for the reference year 2010. Two of the quarrying operations were located in Canada with the remaining operations located in the US.

For other ancillary or process materials, such as the production of chemical inputs, fuels and electricity, secondary data from commercially available LCI databases were deemed acceptable (e.g., US LCI Database, North American adjusted ecoinvent, etc.) [8], [20]. Whenever available, cradle-to-gate material and energy input flow data were derived from the US LCI Database, incorporated in the SimaPro v.7.3.0 LCA Software, March 2011. The study drew on these data to model environmental impacts of fuel(s) extraction, processing and combustion, and various transportation modes for input material and waste transportation. The US adjusted European ecoinvent v.2.2 LCI database ("US-EI"), from May 2010, a European database that contains over 4,000 unit processes (http://www.ecoinvent.ch/) was used to address the environmental impact of numerous chemical inputs and ancillary materials and other relevant unit processes. The complete cradle-to-gate LCI modeling of all intermediate and final product systems was performed using SimaPro v 7.3.

Based on 2010 World Resource Institute (WRI) statistical data, the American, Canadian and Mexican electricity grid mixes for the reference year 2008 were modeled using the US LCI Database and ecoinvent upstream LCI datasets. The US electricity grid model accounts for the generation fuel mix for 2008 and also facilitated the co-product modeling of FGD gypsum from coal combustion and making adjustments to coal combustion solid waste flows as per the "system expansion" approach (see Section 3.3.4).

Table 2 shows the electricity grid mixes for the US, Canada and Mexico. Table 3 below summarizes key secondary source data for the major upstream material and energy flows.

Table 2. 2008 Electricity Grid Mixes for United States, Canada and Mexico



Electricity grid mix 2008- United States			
Energy flows	**Amount -** (in kWh)- no loses	**Amount -** (in kWh)- 6.2% losses	**Sources**
Electricity, bituminous coal	0.465	0.494	1. WBI- US - Energy production & use (2008); http://www.tradingeconomics.com/united-states/energy-production-kt-of-oil-equivalent-wb-data.html Electric power transmission and distribution losses (% of output) in US –6.2 2. US LCI Database U.S electricity grid mix LCI dataset (reference year 2000) 3. SimaPro LCA Software, v7.3.0, March 2011 ecoinvent database, U.S electricity grid mix LCI dataset (reference year 2004)
Electricity, lignite coal	0.025	0.026	
Electricity, residual fuel oil	0.018	0.019	
Electricity, natural gas	0.212	0.225	
Electricity, nuclear	0.194	0.206	
Electricity, hydropower	0.058	0.062	
Electricity, biomass	0.020	0.021	
Electricity, wind	0.0062	0.007	
Electricity, photovoltaic	0.0003	0.0003	
Electricity, geothermal			
Electricity, industrial gas (COG)	0.002	0.002	
Total	**1.000**	**1.062**	

Electricity grid mix 2008 - Canada			
Energy flows	**Amount -** (in kWh)- no loses	**Amount -** (in kWh)- 8.5% losses	**Sources**
Electricity, bituminous coal	0.172	0.187	1. WBI - Canada - Energy production & use (2008); http://www.tradingeconomics.com/canada/electricity-production-from-coal-sources-kwh-wb-data.html Electric power transmission and distribution losses (% of output) in Canada- 8.5 2. National Inventory Report 1990-2008: Greenhouse Gas Sources and Sinks in Canada (Part3) –2010 publication; Table A13-1: Electricity Generation and GHG Emission Details for Canada
Electricity, lignite coal	0.009	0.010	
Electricity, residual fuel oil	0.015	0.016	
Electricity, natural gas	0.064	0.069	
Electricity, nuclear	0.146	0.158	
Electricity, hydropower	0.576	0.625	
Electricity, biomass	0.008	0.009	
Electricity, wind	0.0095	0.010	
Total	**1.000**	**1.085**	

Electricity grid mix 2008 - Mexico			
Energy flows	**Amount -** (in kWh)- no loses	**Amount -** (in kWh)- 16.3% losses	**Sources**
Electricity, bituminous coal	0.123	0.143	1. WBI - Mexico - Energy production & use (2008); http://www.tradingeconomics.com/mexico/electricity-production-kwh-wb-data.html Electric power transmission and distribution losses (% of output) in Mexico- 16.3.
Electricity, residual fuel oil	0.203	0.236	
Electricity, natural gas	0.488	0.568	
Electricity, nuclear	0.041	0.048	
Electricity, hydropower	0.106	0.123	
Electricity, biomass			
Electricity, wind	0.039	0.045	
Total	**1**	**1.163**	

Table 3. Key Primary and Secondary LCI Data Sources

LCI data sets	Source of LCI Database[*)]
Natural Gypsum System	
Gate-to-gate activity data- natural gypsum extraction	Primary data collected from 7 sites
Inbound/outbound transportation- natural gypsum extraction	Primary data collected from 7 sites
Explosives	US adjusted ecoinvent v 2.2 LCI database
Lubricating oil, hydraulic fluid, greases, engine oil and antifreeze	US adjusted ecoinvent v 2.2 LCI database
US, Canada and Mexico electricity grid	US LCI Database ecoinvent v 2.2 LCI LCI datasets developed for U.S conditions US adjusted ecoinvent v 2.2 LCI database
Diesel, gasoline, propane and natural gas	US LCI Database
Rail, road and barge transportation	US LCI Database
Waste treatment	US adjusted ecoinvent v 2.2 LCI database
Gypsum Paper System	
Gate-to gate activity data- gypsum paper production	Primary data collected from 3 plants
Inbound/outbound transportation- gypsum paper production	Primary data collected from 3 plants
Waste paper sorting	US adjusted ecoinvent v 2.2 LCI database
Starch, retention chemicals, sizing agents, polymer emulsifier, other chemicals, chemicals used for on-site water treatment.	Material Safety Data Sheet (MSDSs) provided by 3 surveyed plants; US LCI Database US adjusted ecoinvent v 2.2 LCI database
Lubricating oil, hydraulic fluid and greases	US adjusted ecoinvent v 2.2 LCI database
Packaging materials	US LCI Database US adjusted ecoinvent v 2.2 LCI database
US electricity grid	US LCI Database ecoinvent v 2.2 LCI LCI datasets developed for U.S conditions US adjusted ecoinvent v 2.2 LCI database

LCI data sets	**Source of LCI Database**[*)]
Natural gas, diesel and propane	US LCI Database
Rail, road and barge transportation	US LCI Database
Waste treatment	US adjusted ecoinvent v 2.2 LCI database
GWB Manufacturing System	
Gate-to gate activity data- gypsum wallboard manufacturing	Primary data collected from 17 plants
Inbound/outbound transportation- gypsum wallboard manufacturing system	Primary data collected from 17 plants
Quarried natural gypsum (imported Canada, Mexico)	Gate to gate U.S 2010 average profile adjusted for Canadian and Mexico electricity grid;
FGD synthetic gypsum	ecoinvent v 2.2 LCI datasets developed for US coal-fired plants in 2006 (based on US statistics, EPA data and eGrid 2006) [19]; industry data on dewatering; EPA 2008 final report [18]
Dry and wet additives	Material Safety Data Sheet (MSDSs) provided by 17 surveyed plants; US LCI Database US adjusted ecoinvent v 2.2 LCI database
Packaging material	US LCI Database US adjusted ecoinvent v 2.2 LCI database
Motor oils, transmission oils, lubricating oil, hydraulic fluid, greases, antifreeze and locomotive oils	US adjusted ecoinvent v 2.2 LCI database
US electricity grid	US LCI Database ecoinvent v 2.2 LCI datasets developed for U.S conditions US adjusted ecoinvent v 2.2 LCI database
Natural gas, diesel, propane and gasoline	US LCI Database
Rail, road and water transportation	US LCI Database
Waste treatment	US adjusted ecoinvent v 2.2 LCI database

[*)] Reference: SimaPro v 7.3.0 LCA Software, March 2011.

3.3.2 Primary data collection system

This section describes the data collection system (DCS) for this LCA study.

The GA study team followed the following generic DCS procedures.

- Identification of the data that needs to be collected.
- Planning when, where, and how data are to be collected and by whom.
- Identification and treatment of data gaps.
- The actual data collection (measurement, estimations as per EPA factors, expert knowledge, etc.).
- Documentation of the resulting data, together with possible sources of error, bias or lack of knowledge.
- Data review.
- Averaging the data across the plants on a suitable technical format to reveal any outliers.
- Internal validation of the data collection system, the collected data and its documentation.
- Communication of the data and its documentation.

3.3.3 Precision and Completeness

Precision: the GA participating companies through measurement and calculation collected primary data on the production of natural gypsum, gypsum paper and gypsum wallboard products. The gate-to-gate input and output plant data was individually validated by the LCA team for accuracy.

Completeness: All relevant, specific processes including inputs (raw materials, energy and auxiliary materials) and outputs (emission and production volume) are considered and modeled to represent the gypsum wallboard products. The relevant background processes are taken from the US LCI Database and US adjusted ecoinvent v 2.2 LCI database and modeled in SimaPro software v.7.3.0, March 2011.

3.3.4 Consistency and Reproducibility

Consistency: To ensure consistency, the LCI modeling of the seven quarries/mines, three gypsum paper and 17 gypsum wallboard scenarios applied the same modeling structure across the respective product system, which consists of input raw and ancillary material, energy flows, water resource inputs, product and co-products outputs, emissions to air, water, and soil and waste disposal, and the same background LCI data from the new GA SimaPro LCI database were used. Cross-checks concerning the plausibility of mass and energy flows were continuously conducted. Each input material and energy flow as well as output flow was checked and rechecked using a mass and energy balance approach to maintain a high level of consistency.

Reproducibility: Internal reproducibility is possible since the data and the models are stored and available in a database (GA SimaPro LCI database, 2011). A high level of transparency is provided throughout the report as the weighted average LCI profiles are presented for both the reference flows and products of interest (see Section 4). The provision of more detailed data to allow full external reproducibility was not possible due to reasons of confidentiality.

3.3.5 Representativeness

The representativeness of the data is summarized as follows.

- Time related coverage of the *primary* collected data: 2010.
- *Secondary*data: the most appropriate LCI datasets were used as found in the US LCI Database and US adjusted ecoinvent v.2.2 database, 2011.
- Geographical coverage: the geographical coverage was primarily the US with the exception of the imported natural gypsum from Canada and Mexico (North America).
- Technological coverage: typical or average.

The representativeness of the data has been deemed “good to fair” as the best available data are used and these data adequately reflect North American geographic representativeness and prevailing technologies.

3.4 Life Cycle Impact Assessment Indicators

Life cycle impact assessment is the phase in which the set of results of the inventory analysis – mainly the inventory flow table – is further processed and characterized in terms of environmental impacts. According to LCA-based ISO 14040/44, the mandatory elements of the life cycle impact assessment (LCIA) include:

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

It should be noted that while LCI enjoys a fairly consistent methodology, the life cycle impact assessment phase is very much a "work in progress" and there is no overall agreement on which LCIA categories should be included in an LCA or a single accepted methodology for calculating all of the impact categories to be included. ISO 14044:2006, Clause 4.4.2.2.1, states: "The selection of impact categories, category indicators and characterization models shall be both justified and consistent with the goal and scope of the LCA". Typically, LCIA is completed in isolation of the LCI; that is, the LCI requests a complete mass and energy balance for each unit process or product system under consideration, and once completed the LCI is "sifted" (classified and characterized) through various LCIA indicator methods and categories to determine potential impacts. When defining the impact categories, an indicator must be chosen somewhere in the environmental mechanism. Often indicators are chosen at an intermediate level somewhere along that mechanism (mid-point indicators). Sometimes they are chosen at endpoint level (end-point indicators) [5].

For this study, ISO 21930:2007 "Sustainability in Building Construction – Environmental Declaration of Building Products" [3] was used to identify and select the various impact categories to be included in the LCIA, and the US EPA Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) was used as the LCIA baseline characterization model [21]. ISO 21930 provides an internationally accepted scope for decisions as to which LCIA categories should be supported for building sustainability metric analysis, while the TRACI LCIA methodology provides a North American context for the actual measures to be supported. ISO 21930 stipulates a number of mid-point LCIA characterization measures to be supported and while not opposing end-point measures, discourages their use until they are more internationally accepted. The measures advocated by ISO 21930 include the following:

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

Optional end-point LCIA measures listed in ISO 21930 include human toxicity and eco-toxicity; however, uncertainty increases, often exponentially, with movement from mid-point to end-point measures and, therefore, these end-point measures have been excluded from this study. Absent from the TRACI list is any impact category dealing with solid waste. While TRACI supports fossil fuel depletion (on a global scale), it does not readily report primary energy use – primary energy use is not an impact category, but rather an intermediate flow indicator between the environment and the productive anthropogenic technosphere. As a result, for the purposes of this study, water use and total primary energy use are tabulated and summarized with the other impact category indicators directly from the LCI results. Further, the abiotic resource depletion (excluding energy) impact category is based on the CML2001 LCIA method[5] [9] and the cumulative energy demand (CED) LCIA method (ecoinvent 2001 [8]) is adopted to organize and report primary resource and energy use. Total primary energy is the sum of all energy sources drawn directly from the earth, such as natural gas, oil, coal, biomass, and hydropower energy. The total primary energy can be further broken down into categories. For this reason, a measure of total primary energy derived from LCI flows broken down into renewable and non-renewable and feedstock energy sources is also included. As per North American convention,

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[5] A problem-oriented Life Cycle Assessment method developed by the Institute of Environmental Sciences of the University of Leiden (CML), The Netherlands.

higher heating value (HHV) of primary energy carriers is used to calculate the primary energy values used in the study. Higher heating value, gross heating value, or total heating value includes the latent heat of vaporization and is determined when water vapor in the fuel combustion products is condensed. Conversely, lower heating value or net heating value does not include the latent heat of vaporization. In the US, when the heating value of a fuel is specified without designating higher or lower, it generally means the higher heating value.

With respect to the other LCIA measures, the following (see list below) TRACI and CML impact categories (IC) and characterization basis were used in this study. A characterization factor is a factor derived from a characterization model, which is applied to convert an assigned life cycle inventory analysis result to the common unit of the category indicator. The common unit allows calculation of the category indicator result.

a. **Global warming potential** (IC) – TRACI uses global warming potentials characterization factors (CF), a midpoint metric proposed by the International Panel on Climate Change (IPCC, 2007), for the calculation of the potency of greenhouse gases relative to that of carbon dioxide (CO_2). The 100-year time horizons recommended by the IPCC and used internationally for policy making and reporting are adopted within TRACI. The methodology and science behind the global warming potential (GWP) calculation can be considered one of the most accepted LCIA categories. GWP100 is expressed on equivalency basis relative to CO_2, that is, equivalent CO_2 mass basis.

b. **Acidification potential** (IC) – As per TRACI, acidification comprises processes that increase the acidity (hydrogen ion concentration, [H+]) of water and soil systems. Acidification is a more regional rather than global impact affecting fresh water and forests as well as human health when high concentrations of sulfur dioxide (SO_2) are attained. The acidification potential (CF) of an air emission is calculated on the basis of the number of H+ ions which can be produced and therefore is expressed as potential H+ equivalents on a mass basis.

c. **Respiratory effects** (IC)– The midpoint level selected by TRACI was used based on exposure to elevated particulate matter less than 2.5 micrometers in diameter (PM 2.5). Particulate matter is the term for particles found in the air, including dust, dirt, soot, smoke, and liquid droplets (i.e. filterable particulates). Emissions of SO_2 and NO_x lead to formation of the secondary particulates sulfate and nitrate (i.e., condensable particulates).Particles can be suspended in the air for long periods of time. Some particles are large or dark enough to be seen as soot or smoke. Others are so small that individually they can only be detected with an electron microscope. Many man-made and natural sources emit PM directly or emit other pollutants that react in the atmosphere to form PM. These solid and liquid particles come in a wide range of sizes. Particles less than 10 micrometers in diameter (PM10) pose a health concern because they can be inhaled into and accumulate in the respiratory system. Particles less than 2.5 micrometers in diameter (PM2.5) are referred to as "fine" particles and are believed to pose the greatest health risks. Because of their small size (approximately 1/30th the average width of a human hair), fine particles can lodge deep within the lungs.

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

e. **Ozone depletion potential** (IC) – Stratospheric ozone depletion is the reduction of the protective ozone within the stratosphere caused by emissions of ozone-depleting substances. International consensus exists on the use of ozone depletion potentials (CF), a metric proposed by the World Meteorological Organization (WMO) for calculating the relative importance of chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HFCs), and halons expected to contribute significantly to the breakdown of the ozone layer. TRACI uses the ozone depletion potentials published in the Handbook for the International Treaties for the Protection of the Ozone Layer (UNEP-SETAC 2000), where chemicals are characterized relative to trichlorofluoromethane (CFC-11).

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

g. **Total primary energy**– Total primary energy is the sum of all energy sources that are drawn directly from the earth, such as natural gas, oil, coal, biomass or hydropower energy. The total primary energy contains further categories, namely non-renewable and renewable energy, and fuel and feedstock energy. Non-renewable energy includes all fossil and mineral primary energy sources, such as natural gas, oil, coal and nuclear energy. Renewable energy includes all other primary energy sources, such as hydropower and biomass. Feedstock energy is that part of the primary energy entering the system which is not consumed and/or is available as fuel energy and for use outside the system boundary. Total primary energy is expressed in mega joules (MJ).

h. **Abiotic resource depletion potential** (IC)– As per CML 2001 method, the abiotic depletion potential (ADP) factors for characterizing abiotic resources are based on ultimate reserves and extraction rates. According to Guinee & Heijungs (1995) a method based on ultimate reserves and rates of extraction is the best option, as these parameters best indicate the seriousness of resource depletion. As the notion of economic reserves involves a variety of economic considerations not directly related to the environmental problem of resource depletion, the measure of ultimate reserves appears to be a more appropriate yardstick. The indicator is expressed in kg of the reference resource antimony (Sb). For the full list of the natural resources included, please see the referenced link to Leiden University’s Guide on Environmental Life Cycle Assessment. Fossil fuels are excluded because they were reported separately within total primary energy (see below).

i. **Water use**– summarizes the cradle-to-gate LCI water usage flows, and is expressed in kg.

In North America, the impact method and characterization factors for land use are still in development. Although it can have a significant bearing on the results of an LCA, most North American LCI data do not support measures of land use (e.g., US LCI Database) nor is there a platform for collecting or characterizing this inventory flow; therefore land use has been excluded from this study. Table 2 summarizes the selected impact categories and intermediate indicators, their unit equivalence basis (or reporting basis), source of the characterization method and geographic specificity supported and used in the study.

Table 4. Selected LCIA & LCI Flow Indicators

LCIA and LCI flow category	**Unit equivalence basis (indicator result)**	**Source of the characterization method**	**Level of site specificity selected**
Global warming	kg CO_2 – equivalents (eq)	TRACI	Global
Acidification	kg H^+-eq	TRACI	North America
Respiratory effects	kg $PM_{2.5}$-eq	TRACI	North America
Eutrophication	kg N water-eq	TRACI	North America
Ozone depletion	kg CFC-11-eq	TRACI	Global
Photochemical smog	kg NO_x-eq	TRACI	North America
Total primary energy*)	MJ	CED 2001 adapted	Global
Non-renewable, fossil†	MJ		
Non-renewable, nuclear†	MJ		
Renewable (solar, wind, hydro, geothermal)†	MJ		
Renewable (biomass)†	MJ		
Feedstock, fossil†	MJ		
Feedstock, biomass†	MJ		
Abiotic resource depletion, excluding energy	kg Sb-eq	CML 2001	Global
Water use*)	kg	Sum of LCI flows	North America

† Sub-set of primary energy.
*) LCI flow category

4 LCI Flow Reporting for Key System Processes

This section first presents an overview of the input material and energy flows and outputs (on a weighted average basis) for the two primary upstream processes (natural gypsum quarrying and gypsum paper production) for the reference year 2010. It then presents the ½-inch Regular and $^5/_8$-inch Type X GWB product formulations and input material and energy flows and outputs (on a weighted average basis) for the gypsum wallboard manufacturing process for the 2010 reference year. To respect the confidentiality agreement with the GA participating plants, input and output data are rolled up to the level that assures confidentially of each individual plant and provides optimal data transparency for the interested parties.

4.1 Gypsum Quarrying Overview

Natural or crude gypsum is a relatively soft, rock-like mineral that was deposited in ancient seas. Chemically, gypsum is calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$). Most of the gypsum quarries operating in North America are vertically integrated with GWB manufacturing companies and board plants are often located in close proximity to gypsum quarry operations. However, the US is also the largest importer of crude gypsum in the world, most of which comes from Canada (70% of imports), serving the US East coast and Mexico (25% of all imports), serving the US West coast [11].

Gypsum rock is open pit quarried or mined underground, generally by drilling and blasting, then moved to a primary crusher on the quarry/mine site. In North America, high quality gypsum ore is typically open-pit quarried as opposed to mined. The quarry process begins with the removal of overburden (earth) over the gypsum deposit. The gypsum rock is then drilled and blasted loose where it is then extracted and transported to the primary crusher. At the primary crusher the gypsum rock is reduced to approximately 2” (50mm) to 5” (125mm) or less in size. From here the crushed rock can be sent to the board plant (trucked or belt conveyed) for secondary crushing. It may be also be transported by ship, rail or truck to board manufacturing plants farther away.

For the purposes of this study, six gypsum quarries and one mine site were surveyed for the reference year 2010 and provided their material and energy inputs and related process emissions. According to the 2009 Minerals Yearbook [11] there were a total 48 gypsum extraction sites operating in the US in 2009 – the study sample represents about 15% of these operations.

The gate-to-gate system boundaries for quarrying and mining process included the following activities:

- Drilling
- Blasting
- Excavating
- Pit loading
- Primary crushing
- Screening
- Conveying
- Truck hauling
- Water spraying
- Benefication Operations
- Surface Milling
- Road Grading
- Stock piling
- Scaling (scrape loose rock from ceiling and walls)
- Drilling/installing roof bolts to stabilize roofing system

Table 5 presents the material, energy and process (non-combustion) related emissions per short ton (2000 lb) of natural gypsum rock on a weighted average basis. Additional information on inbound and outbound transportation was collected and is reported in Table 6. The participating sites also reported additional information on annual unpaved road transport to better estimate particulate emissions associated with the system process.

A three-year (2008 to 2010) weighted average of gypsum production from each participating site was used to estimate the weighted average factors for the population sample and reference year (2010). The three-year production average factors were used to smooth out any major production changes at individual production sites and to better protect confidential company information. Co-product production for this process amounted to less than 4% of total outputs;

where necessary, mass allocation was used to partition flows between the primary product and co-products. All reported flows are for the reference year 2010.

The source of natural or crude gypsum rock identified in the GWB manufacturing profile included the US, Canada and Mexico. The weighted average profile for the six quarries and one mine site was adjusted to reflect the national delivered electricity mix for each of these sources, which resulted in three LCI profiles – Natural Gypsum Rock (domestic US), Natural Gypsum Rock (Canada) and Natural Gypsum Rock (Mexico). All three natural gypsum rock reference profiles were drawn upon when constructing the weighted average profile for the two GWB products of interest.

Table 5. Material, Energy and Process Related Emissions per Short Ton of Natural Gypsum

Input/Output Flows	**Units**	**Quantity**
1. Material Inputs		
Explosives	Pounds	0.547
Lubricants	Pounds	0.035
Hydraulic fluid	Pounds	0.033
Greases	Pounds	0.007
Engine Oil	Pounds	0.019
Antifreeze	Pounds	0.007
2. Energy Inputs		
Diesel fuel oil	Gallons	0.404
Gasoline	Gallons	0.008
Propane	Pound	0.00059
Purchased Electricity	kWh	1.210
Natural Gas	MMBtu	0.059
3. Water Consumption		
Fresh water used for water spraying and benefication	Gallons	36
Recycled water used for water spraying	Gallons	34
4. Product and Co-product Outputs		
Quarried gypsum	tons (short)	1.0
Overburden	tons (short)	1.94
Other solid rock sold to other industries	tons (short)	0.033
5. Process (non-combustion) Emissions to air		
Total Particulate Matter (TPM)	Pounds	0.277
PM_{10} (PM<10 microns, but > 2.5 microns)	Pounds	0.109
$PM_{2.5}$ (PM< 2.5 microns)	Pounds	0.057
Mercury	Pounds	4.869E-06
On-site air emissions from unpaved-road transportation		
Total Particulate Matter (TPM)	Pounds	0.288
PM_{10} (PM<10 microns, but > 2.5 microns)	Pounds	0.091
$PM_{2.5}$ (PM< 2.5 microns)	Pounds	0.013

Input/Output Flows	Units	Quantity
6. Emissions to water (water effluent)		
Total suspended solids (TSS)- storm water discharge	Pounds	0.002
Total suspended solids (TSS)- ground water	Pounds	2.3E-06
Oil and Grease, hexane- ground water	Pounds	1.8E-06
Chloride- ground water	Pounds	1.1E-04
Sulfate, total (as SO4)- ground water	Pounds	5.3E-04
7. Solid Waste		
Solid waste	Pounds	0.075
Waste Oil	Pounds	0.0032

Table 6. Inbound and outbound transportation data- Quarry System

In-bound transportation (one way)	**Road** (in miles)	**Barge** (in miles)
Explosives	398	
Lubricants	205	
Hydraulic fluid	195	
Greases	205	
Engine Oil	960	
Antifreeze	960	
Out-bound transportation (one-way)	**Road** (in miles)	**Barge** (in miles)
Solid ore/rock sold to other industries	2	646
Solid waste	25	
Waste oil for disposal	280	

4.1.1 Other Sources of Gypsum

In addition to quarried/mined natural gypsum production, synthetic gypsum is generated as a co-product of various industrial processes and is used in the manufacture of GWB. The primary source of synthetic gypsum used in GWB manufacture is flue gas desulfurization (FGD) from coal-fired electric power plants. Most coal-burning power plants in the United States are required by the US Environmental Protection Agency to install sulfur dioxide scrubbing systems. This creates a significant source of gypsum, at a lower price than the cost of its quarried or mined counterpart, which has led to the construction of wallboard production facilities near or adjacent to coal-fired power plants. Of the total synthetic gypsum sold and used in the US in 2009, 81% was used for wallboard production, 7% was used in cement and concrete manufacture, 5% for structural fills or embankments, 3% for agricultural use, and the remaining amount for other miscellaneous applications [11]. Still, 50% of all synthetic gypsum produced in 2009 was neither sold, nor used, and in most cases was landfilled [14].The use of synthetic gypsum from flue gas desulfurization (FGD) has increased and will likely continue to do so as more coal-fired electric power plants convert their desulfurization processes to produce marketable gypsum.

In the US, the most widely used flue gas SO_2 abatement method is non-regenerative, forced oxidation wet scrubbers using calcium based sorbents producing calcium-sulfur compounds. The use of a widely available and inexpensive sorbent (limestone), production of a usable co-product (gypsum, calcium sulfate dehydrate, $CaSO_4 \cdot 2H_2O$), reliability, availability, and most importantly, the efficiency achievements that can be as high as 99% are the incentives behind the popularity of this technology especially at large-scale utilities. Since the flue gas contains sulfur as SO_2, the initial reaction outcome is calcium sulfite hemi-hydrate. To generate the more inert calcium sulfate dihydrate, the calcium sulfite must be oxidized. This is typically done in the scrubber system with a process called ‘in situ forced oxidation’. In this process, excess air is added to the system to oxidize the calcium sulfite to calcium sulfate (gypsum). Large gypsum crystals are then separated by means of a hydrocyclone and collected in a separate vessel. In the last stage, the gypsum crystal suspension is filtered or centrifuged, and the gypsum cake is washed with clean water to remove water-soluble substances – especially chlorides, sodium and magnesium ions. Dewatering to less than 10% moisture is achieved by means of vacuum filter beds or centrifuges. It is this last step, dewatering, that differentiates the gypsum from a potential waste to a saleable co-product suitable for use in gypsum board manufacturing [15]. Utilities will sometimes employ dewatering to further reduce the mass of the co-product waste to reduce landfill transportation and disposal costs.

For the purposes of this study, a “system expansion” approach was employed to model and account for the use of FGD synthetic gypsum in the US GWB industry (see Section 3.2.4).

4.2 Gypsum Paper Manufacturing Overview

Gypsum wallboard is often described as a sandwich, with gypsum in its core and paper as its facings (known as facing and backing gypsum paper). The raw materials used for gypsum paper facings are all from recycled sources, either post industrial or post consumer newspaper, Kraft clippings, mixed waste papers and old corrugated container (OCC).

The manufacture of gypsum facing papers is similar to other paper making processes and starts with the recycled paper furnish being fed into a pulper, a large blender that disintegrates and dissolves the old paper into a pulp – a slurry of paper fibers. The paper slurry is also cleaned of various contaminants (e.g., bailing wire, staples, and glue) before it is fed into the paper-making machine. Two types of paper making equipment – rotating cylinders or a Fourdrinier flat wire machine, may be used to produce gypsum paper. A cylinder machine rotates a large drum through the pulp slurry vat. A wide felt belt passes over the top of the turning drum cylinder. The cylinder pulls the pulp up and presses it against the bottom felt, where it sticks to form a single ply of paper – depending on the machine and slurry composition it can take as few as three to up to nine cylinder made plies pressed together to make a continuous sheet of gypsum board paper. The characteristics of the pulp entering the vats determine whether the system produces cream stock, often called “ivory”, used for the face of the gypsum wallboard or gray stock, which makes the backside paper of gypsum wallboard. The gray stock is derived exclusively from OCC, while the cream or ivory uses a combination of all recycled inputs for its pulp plies. Instead of a set of cylinder machines, the Fourdrinier uses two machines to make a two-ply paper with the same characteristics as the multi-ply cylinder made paper. The pulp slurry is systematically fed onto a continuous running wire screen (the Fourdrinier). As the screen moves forward, water drains from the pulp through the screen to create paper. One Fourdrinier machine makes the surface (top) ply, which may be cream or gray stock depending on the pulp mixture and the desired paper type. The second machine produces a gray (bottom) ply.

From this point, both systems operate in the same way. In the press section, the paper plies are pressed together to squeeze out excess water. Next the paper enters a series of high-temperature dryers where any remaining water is removed. The dry paper is then sent to a calendar stack, where different chemicals or treatments are applied (e.g., retention chemicals and sizing agents). The paper is then gathered on a roll, trimmed and packaged for shipment. Overall, the gate-to-gate system boundaries for gypsum paper manufacturing process included the following activities:

- Pulper
- Agitator
- Cleaning
- High density cleaning
- Primary coarse screening
- Secondary screening
- Thickening
- Digester
- Storage tank
- Refining
- Blending
- Paper machining
- Drying
- Pressing
- Rewinding
- Cutting
- Wrapping
- Shipping
- Overhead operations

Three gypsum paper plants participated in this study and provided material and energy inputs and process related emission flows for the reference year 2010 (Table 7). They also provided annual production outputs and transportation mode and distances for all process inputs and outputs (Table 8).

The collection, sorting and bailing of recycled paper inputs was included, based on secondary sourced LCI data, and primary data were used for inbound transportation of recycled paper. Both cylinder and Fourdrinier production methods were represented in the study sample and all three plants produced both ivory (2, 3, 6 and 9-base layers) and gray stock gypsum papers, made 100% of OCC (2, 3, 6 and 9-base layers).

All three gypsum paper plants provided Material Safety Data Sheets (MSDSs) for all input chemicals. Due to confidentiality agreements a rolled-up value is presented for the main types of chemicals used, such as sizing agents, retention chemicals, polymer emulsifier, dyes, defoamer and water treatment chemicals. All chemicals provided by plants were individually modeled as per MSDS ingredients and were followed back to nature using adjusted secondary LCI data sources for chemical production adjusted to US conditions.

The reference flow for the cradle-to-gate gypsum paper process was one thousand (1,000) square feet of paper (MSF). On average, cream or ivory paper is slightly heavier (44.1 lbs/MSF) than gray backing paper (41.5 lbs./MSF).

The weighted average LCI profile of 1 MSF facing and backing gypsum paper was calculated based on the total input and output flows and the annual production for 2010 at the plant level. The LCI modeling did account for the variation in the type of recycled paper input and their amounts used in the production of ivory and gray stock gypsum papers (see Table 7). The weighted average profile across the three plants was again based on a three-year average production level from 2008 to 2010; however, all recorded flow data was for the 2010 reference year. With the exception of a “Low NOx burner”, the participating plants reported no other use of environmental abatement pollution equipment.

Table 7 presents the weighted average technosphere flows, process (non-combustion) related emissions and outputs for the production of one thousand square feet of facing and backing gypsum paper. The major material input in the production of gypsum paper was OCC, followed by mixed waste papers and Kraft clippings. Relative to the paper inputs, the large assortment of chemicals represented less than 1% of the total mass of material inputs.

Electricity and natural gas were the major energy types used in the production of gypsum papers – a portion of the electricity used is produced on-site in natural gas boilers (equipped with low NO_x burners) in tandem with steam driven turbines. The other portion of the low-pressure steam was used to dry paper. As per confidentiality agreements, the breakdown of natural gas consumption for electricity and heat can't be presented but this does not influence the project results in any form. Paper production involves considerable water use with evaporative losses; however, about a quarter of this water is recycled within the process.

Table 7. Material, Energy and Process Related Emissions per MSF of Gypsum Paper

Input/Output Flows	**Units**	**1 MSF – Facing gypsum paper**	**1 MSF – Backing gypsum paper**
1. Material Inputs			
Old Corrugated Container (OCC)	Pounds	25.6	46.3
Kraft clippings	Pounds	6.3	
Mixed waste papers/ flyleaves & signature/ white news blank, magazine blank, coated fly	Pounds	17.4	
Starch	Pounds	4.31E-03	4.24E-03
Retention chemicals (Flocculant/Coagulant)	Pounds	8.66E-02	8.38E-02
Sizing agents	Pounds	2.51E-01	2.29E-01
Polymer emulsifier	Pounds	1.08E-02	1.08E-02
Other chemicals (Defoamer/Dyes/Fungicide)	Pounds	1.32E-02	1.30E-02
Chemicals used for on-site water treatment (P & N based)	Pounds	2.67E-02	2.42E-02
Packaging materials	Pounds	1.05E-01	9.57E-02
Lubricants	Pounds	4.04E-03	3.71E-03
Hydraulic fluid	Pounds	1.55E-04	1.55E-04
Greases	Pounds	1.60E-04	1.57E-04
2. Energy Inputs			
Total electricity (both purchased and on-site co-generated)	kWh	13.84	12.84
Total natural gas (excluding electricity production)	Cubic Feet	122.80	117.32
Diesel fuel oil	Gallons	1.61E-03	1.43E-03
Propane	Pounds	1.37E-02	1.34E-02
3. Water Consumption			
Fresh well water	Gallons	40.857	36.834
Fresh water from “municipality city water system”	Gallons	8.360	7.646

Input/Output Flows	**Units**	**1 MSF – Facing gypsum paper**	**1 MSF – Backing gypsum paper**
Recycled water re-entering the paper production system	Gallons	11.430	11.242
Water discharged	Gallons	47.397	42.442
4. Product and -product Outputs			
Gypsum Paper	**MSF**	**1.000**	**1.000**
	Pounds	**44.1**	**41.5**
Co-products - downgraded & side rolls	MSF	0.029	0.029
	Pounds	1.30	1.22
5. Process (non-combustion) Emissions to air			
Non-Methane VOCs	Pounds	3.86E-04	3.80E-04
6. Emissions to water (water effluent)			
Total suspended solids (TSS)	Pounds	2.81E-02	2.57E-02
Biological Oxygen Demand (BOD)	Pounds	3.50E-02	3.40E-02
Lead	Pounds	2.60E-07	2.59E-07
Zinc	Pounds	7.15E-06	7.15E-06
Copper	Pounds	2.73E-06	2.73E-06
Total Nitrogen	Pounds	5.48E-05	5.39E-05
Total Phosphorus	Pounds	4.50E-06	4.43E-06
7. Emissions to industrial soil (on-site)			
Lead	Pounds	5.84E-08	5.74E-08
8. Solid Waste			
Non-hazardous solid waste	Pounds	4.45E+00	4.18E+00
Hazardous solid waste	Pounds	3.85E-04	3.85E-04
9. Wastewater and other liquid waste			
Wastewater	Gallons	2.86E+01	2.58E+01
Sludge waste	Pounds	1.99E+00	1.76E+00
Solvent mixture waste	Gallons	3.40E-05	3.40E-05

Table 8. Inbound and outbound transportation mode and distances - Gypsum Paper System

In-bound transportation (one-way)	**Rail** (in miles)	**Road** (in miles)
OCC- Old Corrugated Container		92
Kraft clipping		39
Mixed waste papers/ flyleaves & signature	313	143
Starch		239
Retention chemicals		667
Sizing agents		833
Fire resistant chemical additives		0
Other chemicals	40	268
Packaging material		82
Lubricants		82
Hydraulic fluid		57
Grease		82
Chemicals used for on-site water treatment		30
Out-bound transportation (one-way)	**Rail** (in miles)	**Road** (in miles)
Non-hazardous solid waste		35
Hazardous solid waste		10
Sludge waste		25
Solvent mixture waste		16

4.3 Gypsum Wallboard Manufacturing Overview

Gypsum wallboard is manufactured in a two-step process. In the first step finely crushed and ground gypsum, calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$), is heated and partially dehydrated (calcined) to calcium sulfate hemihydrate ($CaSO_4 \cdot {}^1/_2H_2O$), called stucco in the industry, also popularly known as “Plaster of Paris”. A unique characteristic of stucco is that when mixed with the proper amount of water, it forms a smooth plastic mass that can be molded to various shapes. When hardening is complete, the mass has been chemically restored to its rock like state – calcium sulfate dihydrate. In the second step of the manufacturing process the stucco is mixed with a number of additives. A foaming agent and an excess amount of water is also added to prepare a gypsum slurry which is extruded on a fast moving, board production line between two layers of gypsum paper. The “raw” gypsum board is then allowed to fully hydrate – calcium sulfate hemihydrate is converted back to dihydrate – before it is cut to the desired size and before it enters a heated kiln, where at elevated temperatures excess water is driven off. The gypsum board is then packaged and stacked, ready to be shipped.

The GWB industry produces a range of different boards in various thicknesses for different applications. While some boards, such as Regular and Type X, are commodities produced in large volumes, others are more specialty or proprietary products – e.g., water-resistant gypsum board, exterior grade gypsum board and specialty faced (foil and vinyl) boards. A number of plants also produce joint compounds used in the installation of GWB products.

Seventeen (17) US gypsum wallboard manufacturing plants provided their board formulation data for the two products of interest and their annual technosphere material and energy inputs and reported process emissions for their total production for the 2010 reference year. The GA estimates that 60 GWB plants were operating in 2010. All GA member companies participated by providing their company information to GA to support the GA plant sample selection process. One-quarter of the industry’s plants were selected to participate and provided LCI data to the study, underscoring the high degree of representativeness of the sample as well as the gypsum industry’s overall support of the project. It is estimated that the study sample plants accounted for about one-third of all GWB produced in the US in 2010.

With the exception of specific product formulations for ½” Regular and ${}^5/_8$” Type X GWB, the plants provided their LCI elementary flow data for their total production of GWB. Each plant’s specific product formulation was modeled separately, but their energy use and process emissions were allocated on the basis of equivalent total mass processed. The weighted average result was estimated by horizontal averaging of each plant's product formulation for the 2010 reference year by its production contribution to the total output for the plant sample.

The gate-to-gate system boundaries for gypsum wallboard manufacturing process included the following activities:

- Secondary crushing
- Screening
- Gypsum furnish drying and conveying
- Calcining
- Dry and wet mixing
- Board lay-up
- Scoring and chamfering
- Board drying
- Cutting and stacking
- Packaging and bundling
- Overhead operations

The following environmental abatement pollution equipment were installed at the surveyed plants to control particulate matter (PM) emissions:

- Fabric Filter - High temperature (baghouses)
- Fabric Filter- Low temperature (baghouse)
- Bin Vents
- Drum Filter
- Dry Filter
- Cartridge Filters
- Precipitator
- Water Sprinklers for Dust Control

Table 9 presents the weighted average formulations for the two GWB products of interest across the 17 plants. In terms of gypsum sources, 41% was natural, 57% FGD synthetic and 2% was from post-consumer onsite construction off-cuts. Major additive differences between the two products were noted for vermiculite, fiberglass and fire resistance chemical usage; all three of these inputs contribute to the greater fire resistance of the Type X GWB. Water usage differences were directly proportional to the quantity of gypsum used to satisfy the final GWB product thickness. Both product formulations attained a final free moisture content of 3.3% (non-chemically bound water). On average, ½" Regular and $^5/_8$" Type X GWB have a finished density (with 3.3% MC) of 1.57 and of 2.22 lbs. per sq. ft., respectively.

Figure 7 shows the weighted average breakdown in percentage of gypsum material by source.

Figure 7. Contribution of Gypsum Sources to total input gypsum – Percent basis

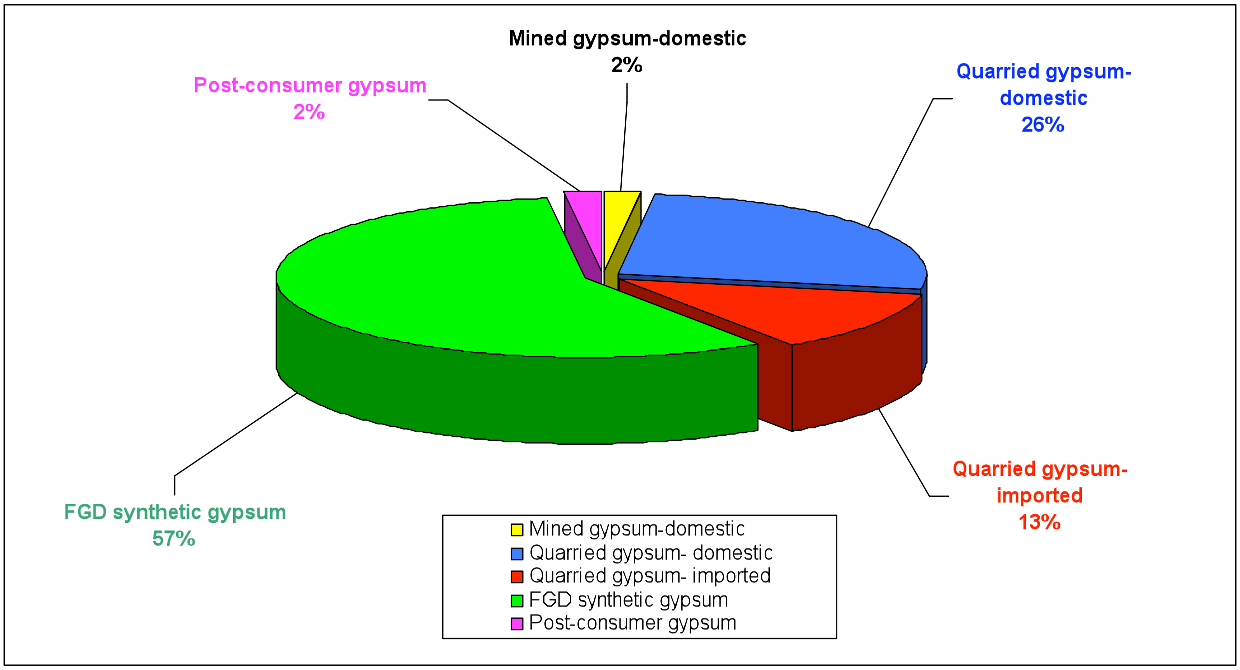


Table 9. Product Formulations per MSF of Regular and Type "X" Gypsum Wallboard (weighted average)

Inputs	**Units**	**½" Regular gypsum wallboard**	**$^5/_8$" Type X gypsum wallboard**
Gypsum material			
Natural gypsum ore	Pounds	602	858
Synthetic gypsum-FGD	Pounds	852.1	1218.4
Post-consumer gypsum	Pounds	27.7	41.2
Gypsum Paper			
Facing paper	Pounds	43.3	43.1
Backing paper	Pounds	41.5	41.5
Additives (both dry and wet)			
Starch	Pounds	7.2	7.2
Vermiculite	Pounds	7.75	9.73
Fiberglass	Pounds	0.7	5.5
Dispersant	Pounds	4.9	5.4
Retarder	Pounds	0.9	0.8
Potassium Sulfate	Pounds	0.3	0.3
Dextrose	Pounds	1.13	0.9
Clay, kaolin	Pounds	0.00	1.27
Water	Pounds	942	1312
Boric Acid	Pounds	0.22	0.13
Land Plaster	Pounds	2.36	1.53
Foaming agent (soap)	Pounds	1.24	1.32
BM Accelerator	Pounds	1.67	1.38
Ammonium Sulfate	Pounds	0.11	0.01
Edge Paste	Pounds	0.64	0.64
STMP	Pounds	0.12	0.12
Shredded Paper	Pounds	0.56	0.42
Total (wet weight)	Pounds	2,318	3,248
Finished density (with 3.3% MC)	**Pounds**	**1,567**	**2,220**
Final moisture content (MC)	**%**	**3.3%**	**3.3%**

Table 10 summarizes the weighted average technosphere materials and allocated energy flows and process (non-combustion) related emissions for the two products. About 30% of the natural gypsum rock input was imported from either Canada or Mexico. On average its takes about 47 kWh and 1,820 cubic feet of natural gas to produce an MSF of ½-inch gypsum board and 67 kWh and 2,577 cubic feet of natural gas to produce an MSF of $^{5}/_{8}$-inch gypsum board.

While the electricity is used at all production stages most of the natural gas is used during the drying of the raw gypsum, calcining or stucco production and drying the final board product.

Process emissions to air were dominated by particulate releases. Small amounts of lead and mercury were also reported, which was attributed to the use of FGD synthetic gypsum. A small amount of gypsum was recycled within the plant (closed loop recycling) and some off-spec GWB production was used for packaging and transportation related activities. For every MSF of GWB product manufactured about 0.4% by mass of solid waste was generated. The total solid waste consisted of 44% “non-hazardous (including packaging)” waste sent to landfill, 47% “other” waste that was either recycled by conversion to agricultural gypsum or taken by the mines and quarries for reclamation use, 8% miscellaneous material (paper, plastic, wood and steel) sent to recyclers and 0.04% was categorized as “hazardous” waste (dry oil, oil filters, batteries, lamps, etc.) sent to an incinerator.

Table 10. Material, Energy and Process Related Emissions per MSF of Gypsum Wallboard

Inputs/Outputs	**Units**	**1 MSF - ½” Regular GWB**	**1 MSF - $^{5}/_{8}$” Type X GWB**
1. Material Inputs			
Mined/quarried natural gypsum ore (US source)	Pounds	415.9	583.9
Mined/quarried natural gypsum ore (imported from Canada/Mexico)	Pounds	186.3	274.0
Synthetic gypsum (FGD)	Pounds	852.1	1218.4
Post-consumer gypsum	Pounds	27.8	41.2
Additives (both dry and wet)			
Starch	Pounds	7.2	7.2
Vermiculite	Pounds	7.75	9.73
Fiberglass	Pounds	0.70	5.47

Inputs/Outputs	**Units**	**1 MSF - ½" Regular GWB**	**1 MSF - $^5/_8$" Type X GWB**
Dispersant	Pounds	4.88	5.42
Retarder	Pounds	0.903	0.816
Potassium Sulfate	Pounds	0.342	0.255
Dextrose	Pounds	1.135	0.903
Clay, kaolin	Pounds	0.00	1.27
Boric Acid	Pounds	0.22	0.13
Land Plaster	Pounds	2.36	1.53
Foaming agent (soap)	Pounds	1.24	1.32
BM Acclerator	Pounds	1.67	1.38
Ammonium Sulfate	Pounds	0.11	0.01
Edge Paste	Pounds	0.63	0.64
STMP	Pounds	0.12	0.12
Shredded Paper	Pounds	0.56	0.42
Talc	Pounds	3.9E-04	3.9E-04
Packaging materials			
Paper End tape	Pounds	7.07E-01	9.96E-01
Ink (water based)	Pounds	4.85E-03	6.87E-03
Ink (oil based)	Pounds	3.11E-04	4.32E-04
Ink (alcohol based)	Pounds	3.64E-03	5.15E-03
Shrink-wrap	Pounds	4.49E-02	6.34E-02
Plastic slip sheets	Pounds	4.36E-02	6.25E-02
Rail bags	Pounds	6.52E-02	9.10E-02
Other Plastics	Pounds	2.70E-02	3.87E-02
Cardboard Edge Protectors	Pounds	2.15E-03	3.04E-03
Plastic Banding	Pounds	9.27E-04	1.34E-03
Steel Banding	Pounds	2.25E-03	3.27E-03
Zip tape	Pounds	1.64E-02	2.34E-02
Dunnage/Bunks/Sleutters (DBS)	Pounds	2.52E+01	3.55E+01

Inputs/Outputs	**Units**	**1 MSF - ½" Regular GWB**	**1 MSF - $^5/_8$" Type X GWB**
Adhesive for DBS	Pounds	4.12E-04	5.89E-04
Consumables			
Motor Oils	Pounds	1.92E-03	2.63E-03
Gear Oil (Transmission)	Pounds	2.60E-03	3.57E-03
Lubricants	Pounds	5.59E-03	7.91E-03
Hydraulic Fluid	Pounds	7.31E-05	1.03E-04
Greases	Pounds	2.16E-04	2.80E-04
Antifreeze	Pounds	1.27E-03	1.80E-03
Locomotive Oil	Pounds	2.68E-03	3.47E-03
2. Energy Inputs			
Electricity	kWh	47.11	66.93
Natural gas	Cubic Feet	1819.86	2576.51
Diesel fuel oil	Gallons	0.0439	0.0628
Propane	Pounds	9.665	13.827
Gasoline	Gallons	4.059E-04	5.804E-04
3. Water Consumption			
Water (process)	Pounds	942	1312
Fresh water	%	95.8%	
Reclaimed water	%	4.2%	
Fresh water used for cooling or steam production	Gallons	101	142
4. Product and Co-product Outputs			
Reference flow	**Square Feet**	**1,000**	**1,000**
Total final weight	Pounds	1,567	2,220
Co-product Outputs			
Internal gypsum waste - recycled back into the production system	Pounds	42.3	60.6
Off-spec GWB used as BDS	Square feet	9.77	9.77

Inputs/Outputs	**Units**	**1 MSF - ½" Regular GWB**	**1 MSF - $^5/_8$" Type X GWB**
	Pounds	14.84	20.77
5. Process (non-combustion) emissions to air			
Total Particulate Matter (PM)	Pounds	1.01E-01	1.44E-01
as PM10	Pounds	7.32E-02	1.05E-01
as PM2.5	Pounds	2.79E-02	3.94E-02
VOC	Pounds	5.10E-03	7.53E-03
Lead (Pb)	Pounds	2.77E-05	3.90E-05
Mercury (Hg)	Pounds	1.52E-05	2.20E-05
6. Emissions to water			
Total suspended solids (TSS)	Pounds	3.75E-05	5.02E-05
Total Organic Carbon (TOC)	Pounds	1.66E-05	2.41E-05
Lead	Pounds	4.09E-11	5.94E-11
Zinc	Pounds	1.95E-08	2.49E-08
Copper	Pounds	3.25E-09	4.15E-09
Sulfates	Pounds	6.09E-06	7.79E-06
Sulfide	Pounds	1.87E-07	2.39E-07
Oil & Grease	Pounds	1.33E-05	1.85E-05
Ammonia	Pounds	2.05E-06	2.97E-06
7. Solid Waste			
Non-hazardous solid waste (including packaging) to landfill	Pounds	2.72E+00	3.84E+00
Other(s) solid waste	Pounds	2.90E+00	4.05E+00
Paper to recycler	Pounds	2.98E-01	4.30E-01
Plastic to recycler	Pounds	5.67E-03	8.15E-03
Wood to recycler	Pounds	1.40E-01	2.02E-01
Steel scrap to recycler	Pounds	5.34E-02	7.60E-02
Hazardous solid waste to incinerator	Pounds	2.66E-03	3.69E-03
8. Wastewater and other liquid waste			
Wastewater to waste treatment facility	Gallons	1.75E-02	2.44E-02
Solvent mixture waste to incinerator	Gallons	5.54E-03	7.87E-03
Sludge waste to landfill	Pounds	2.23E-02	3.20E-02

Table 11 shows the transportation mode and distances for all inputs into the process and outputs. Trucking was the primary mode of transport for materials and waste flows followed by rail. Barges are primarily used for transportation of quarried natural gypsum (both domestic and imported) and FGD synthetic gypsum. Belt conveyors were often used by gypsum wallboard plants for the transportation of gypsum raw materials from adjacent quarry operations and on-site.

Table 11. Inbound and outbound transportation mode and distances - Gypsum Wallboard System

In-bound transportation (one-way)	**Rail** (in miles)	**Road** (in miles)	**Barge** (in miles)	**Conveyor** (in feet)
Input gypsum material				
Mined natural gypsum ore (domestic)				1.24E+04
Quarried natural gypsum ore (domestic)		2.21E+01	7.40E+01	1.34E+03
Quarried natural gypsum ore (imported)			1.60E+03	
Synthetic gypsum (FGD)	2.45E-02	2.30E+01	4.56E+01	1.02E+03
Post-consumer gypsum		1.25E+02		1.12E+02
Additives (both dry and wet)				
Starch	5.30E+02	4.72E+02		
Vermiculite		3.27E+02		
Fiberglass	6.09E+01	5.94E+02		
Edge Glue		4.04E+02		
Retarder		6.56E+02		
Dispersant	1.62E+02	6.50E+02		
Boric Acid	1.98E+02	1.58E+02		
Soap Foam	1.69E+02	7.74E+02		
BM Accelerator		5.88E+01		
Shredded paper	1.57E+02	8.17E-01		
Potasium sulfate		4.46E+02		
Ammonium Sulfate		5.60E+01		
Sugar		5.73E+02		
Talc		2.18E+02		
STMP		2.52E+02		
Clay		1.25E+01		
Gypsum paper				
Facing paper	1.77E+02	4.52E+02		
Backing Paper	2.00E+02	4.56E+02		

In-bound transportation (one-way)	**Rail** (in miles)	**Road** (in miles)	**Barge** (in miles)	**Conveyor** (in feet)
Packaging material				
Gypsum board end paper (Bundling Tape)	2.30E+02	9.20E+02		
Other Paper (Zip Tape)		3.66E+02		
Ink (water and oil based)	5.21E+00	5.73E+02		
Shrink-wrap		3.51E+02		
Plastic Banding		2.21E+02		
Rail bags		3.99E+02		
Other Plastic		5.81E+01		
Plastic Slip Sheets		3.46E+02		
Adhesive for Dunnage/bunks/sleutters		1.32E+02		
Cardboard Edge Protectors		4.53E+01		
Steel Banding		1.02E+02		
Lubricants				
Lubricants	2.26E+01	2.08E+02		
Hydraulic fluid	2.26E+01	1.46E+02		
Motor oil	2.26E+01	6.15E+01		
Gear Oil	2.26E+01	5.38E+01		
Grease	2.26E+01	1.46E+02		
Locomotive Oil	2.26E+01	0.00E+00		
Antifreeze		5.47E+01		
Out-bound transportation (one-way)	**Rail** (in miles)	**Road** (in miles)	**Barge** (in miles)	**Conveyor** (in feet)
½" Regular gypsum wallboard	1.31E+02	2.79E+02	2.06E+00	
5/8" Type X gypsum wallboard	1.33E+02	2.78E+02	2.06E+00	
Non-hazardous solid waste		3.53E+01		
Hazardous solid waste		4.13E+01		
Packaging Waste		3.38E+01		
Wastewater		1.65E+00		
Solvent mixture waste		1.43E+01		
Sludge waste		4.12E+00		
Paper Recycled		3.34E+01		
Plastic Recycled		8.56E+00		
Wood recycled		9.42E+00		
Steel recycled		3.84E+00		
Non-hazardous solid waste (2)		3.90E+01		

The cradle-to-gate Life Cycle Inventories for the 5 (five) selected product systems are summarized in an MS Excel spreadsheet" as follows:

Table S1.1 Cradle-to-gate LCI Results for 1,000 sq. ft. of 1/2-inch Regular GWB product;

Table S1.2 Cradle-to-gate LCI Results for 1 m2 of 1/2-inch Regular GWB product
- to be submitted at US LCI Database in 2011;

Table S2.1 Cradle-to-gate LCI Results for 1,000 sq. ft. of 5/8-inch Type X GWB product;

Table S2.2 Cradle-to-gate LCI Results for 1 m2 of 5/8-inch Regular GWB product
- to be submitted at US LCI Database in 2011;

Table S3 Cradle-to-gate LCI Results for 1,000 sq. ft. of backing gypsum paper;

Table S4 Cradle-to-gate LCI Results for 1,000 sq. ft. of facing gypsum paper; and

Table S5 Cradle-to-gate LCI Results for 1 short ton natural gypsum ore.

These LCI profiles are generated with Sima Pro LCA Software v.7.3.0, 2011 and consist of input resources and output emissions to air, water and land and solid waste and are available upon request at:

Gypsum Association
6525 Belcrest Road, Suite 480,
Hyattsville, MD 20782,
Phone: 301.277.8686,
Fax: 301.277.8747,
E-mail: info@gypsum.org
http://www.gypsum.org

5 LCA Results

This section builds on the previous discussion by linking the upstream energy, materials and component processes back to earth to present the complete cradle-to-gate life cycle impact assessment (LCIA) results for the two reference product systems – gypsum quarrying and paper production – and then for the functional unit of the two gypsum wallboard products of interest. All results in this section were internally checked for plausibility and a mass balance was completed on each product system. All flows were modeled in their entirety – that is, no cut-off criteria were applied. The results have been categorized as geographically applicable to the United States (specific) and North America (general), temporally to the reference year 2010 and representative of the average technology mix.

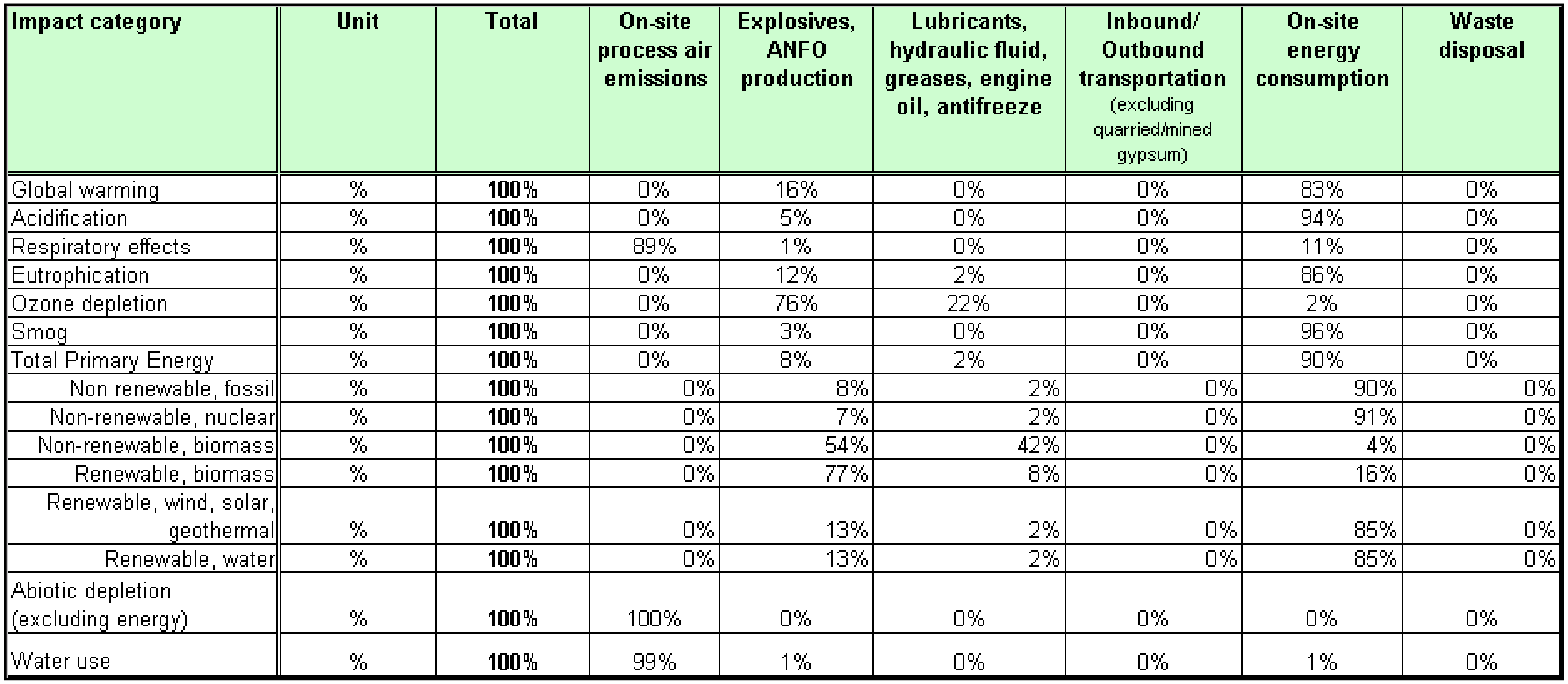
5.1 Gypsum Quarrying LCIA Results

Table 12 presents the cradle-to-gate life cycle impact assessment results for the production of one short ton of natural quarried/mined gypsum rock by major input and contributing process. In 2010, it took 169 MJ of primary energy to produce a ton of crude gypsum rock. Almost all of the energy used is derived from fossil sources. Further, 90% of all energy use was ascribed to on-site fuel use (see Table 12), of which diesel, natural gas and electricity use accounted for 46%, 44% and 10%, respectively (see Figure 8). The production of each ton of gypsum rock results in the emission of 11.4 kg of greenhouse gases on a CO_2 equivalent basis. On-site energy was also the primary source of the greenhouse gas emissions accounting for 83% of the total. In fact, on-site energy use was the major contributor to the acidification, eutrophication and smog potential indicators. The production of explosives was the major component contributing to ozone depletion (76%), while on-site processes were the largest main contributing process to the respiratory effects indicator (89%) and abiotic depletion (100%) which is a direct impact of the crude gypsum extraction. Table 13 summarizes the percent contribution of each process or component to each category impact indicator. Table 14 shows the absolute contribution of each fuel type used to the total on-site energy consumption.

Table 12. Weighted Average Gypsum Quarrying/Mining LCIA results – absolute basis, per short ton natural gypsum

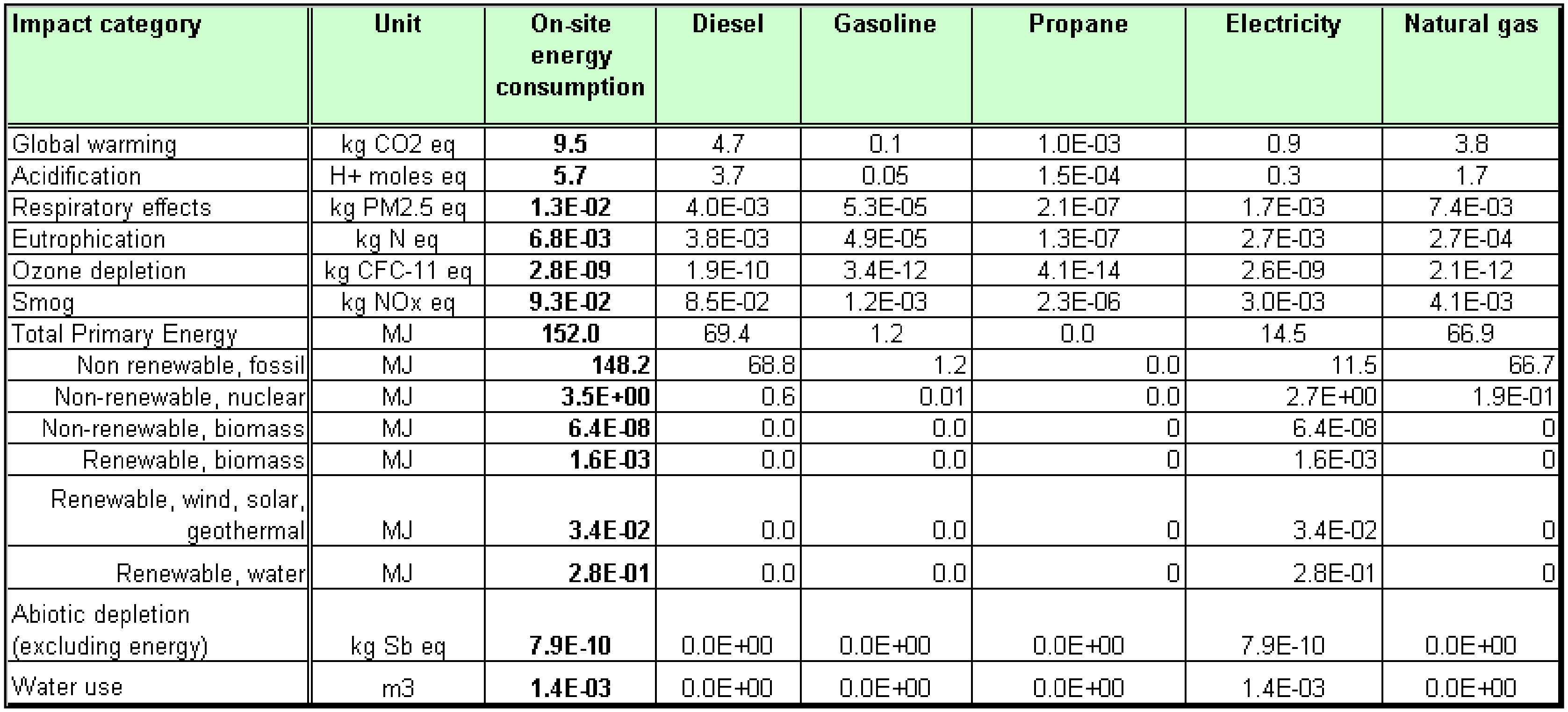
Impact category	**Unit**	**Total**	**On-site process air emissions**	**Explosives, ANFO production**	**Lubricants, hydraulic fluid, greases, engine oil, antifreeze**	**Inbound/ Outbound transportation** (excluding quarried/mined gypsum)	**On-site energy consumption**	**Waste disposal**
Global warming	kg CO2 eq	**11.4**	0	1.9	4.3E-02	2.9E-02	9.5	4.1E-03
Acidification	H+ moles eq	**6.0**	0	0.3	2.0E-02	1.0E-02	5.7	4.7E-05
Respiratory effects	kg PM2.5 eq	**0.1**	0.108	0.001	9.3E-05	1.2E-05	1.3E-02	1.7E-07
Eutrophication	kg N eq	**7.9E-03**	0	9.3E-04	1.5E-04	9.8E-06	6.8E-03	3.7E-06
Ozone depletion	kg CFC-11 eq	**1.3E-07**	0	9.5E-08	2.8E-08	1.1E-12	2.8E-09	1.2E-11
Smog	kg NOx eq	**0.1**	0	0.003	1.3E-04	2.1E-04	0.1	9.7E-07
Total Primary Energy	MJ	**168.6**	0.0	12.8	3.4	0.4	152	1.3E-03
Non renewable, fossil	MJ	**164.4**	0	12.4	3.4	3.9E-01	148.2	1.3E-03
Non-renewable, nuclear	MJ	**3.8**	0	0.3	0.1	0	3.5E+00	4.7E-05
Non-renewable, biomass	MJ	**1.7E-06**	0	9.5E-07	7.3E-07	0	6.4E-08	4.7E-10
Renewable, biomass	MJ	**1.0E-02**	0	7.7E-03	7.7E-04	0	1.6E-03	2.0E-06
Renewable, wind, solar, geothermal	MJ	**4.0E-02**	0	5.1E-03	8.7E-04	0	3.4E-02	7.3E-07
Renewable, water	MJ	**3.3E-01**	0	4.2E-02	6.3E-03	0	2.8E-01	6.5E-06
Abiotic depletion (excluding energy)	kg Sb eq	**1.4E-02**	0.0141	1.3E-08	5.5E-10	0	7.9E-10	4.3E-12
Water use	m3	**0.260**	0.257	2.1E-03	2.8E-04	0	1.4E-03	3.8E-07

Table 13. Weighted Average Gypsum Quarrying/Mining LCIA results – percent basis



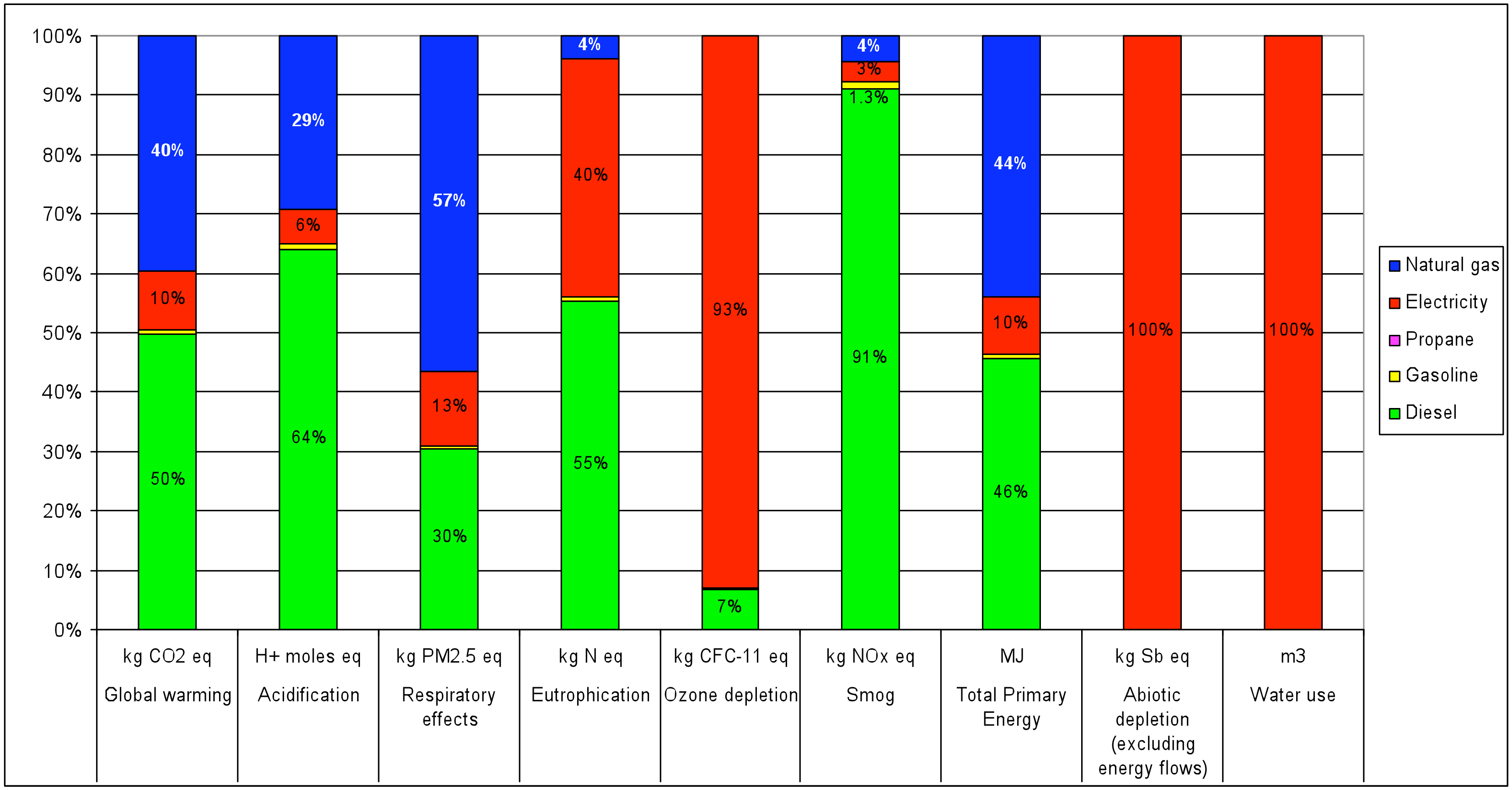
Impact category	**Unit**	**Total**	**On-site process air emissions**	**Explosives, ANFO production**	**Lubricants, hydraulic fluid, greases, engine oil, antifreeze**	**Inbound/ Outbound transportation** (excluding quarried/mined gypsum)	**On-site energy consumption**	**Waste disposal**
Global warming	%	**100%**	0%	16%	0%	0%	83%	0%
Acidification	%	**100%**	0%	5%	0%	0%	94%	0%
Respiratory effects	%	**100%**	89%	1%	0%	0%	11%	0%
Eutrophication	%	**100%**	0%	12%	2%	0%	86%	0%
Ozone depletion	%	**100%**	0%	76%	22%	0%	2%	0%
Smog	%	**100%**	0%	3%	0%	0%	96%	0%
Total Primary Energy	%	**100%**	0%	8%	2%	0%	90%	0%
Non renewable, fossil	%	**100%**	0%	8%	2%	0%	90%	0%
Non-renewable, nuclear	%	**100%**	0%	7%	2%	0%	91%	0%
Non-renewable, biomass	%	**100%**	0%	54%	42%	0%	4%	0%
Renewable, biomass	%	**100%**	0%	77%	8%	0%	16%	0%
Renewable, wind, solar, geothermal	%	**100%**	0%	13%	2%	0%	85%	0%
Renewable, water	%	**100%**	0%	13%	2%	0%	85%	0%
Abiotic depletion (excluding energy)	%	**100%**	100%	0%	0%	0%	0%	0%
Water use	%	**100%**	99%	1%	0%	0%	1%	0%

Table 14. Contribution of Fuel Types to "On-site Energy Consumption" Category Indicators – absolute basis, per short ton natural gypsum



Impact category	**Unit**	**On-site energy consumption**	**Diesel**	**Gasoline**	**Propane**	**Electricity**	**Natural gas**
Global warming	kg CO2 eq	**9.5**	4.7	0.1	1.0E-03	0.9	3.8
Acidification	H+ moles eq	**5.7**	3.7	0.05	1.5E-04	0.3	1.7
Respiratory effects	kg PM2.5 eq	**1.3E-02**	4.0E-03	5.3E-05	2.1E-07	1.7E-03	7.4E-03
Eutrophication	kg N eq	**6.8E-03**	3.8E-03	4.9E-05	1.3E-07	2.7E-03	2.7E-04
Ozone depletion	kg CFC-11 eq	**2.8E-09**	1.9E-10	3.4E-12	4.1E-14	2.6E-09	2.1E-12
Smog	kg NOx eq	**9.3E-02**	8.5E-02	1.2E-03	2.3E-06	3.0E-03	4.1E-03
Total Primary Energy	MJ	**152.0**	69.4	1.2	0.0	14.5	66.9
Non renewable, fossil	MJ	**148.2**	68.8	1.2	0.0	11.5	66.7
Non-renewable, nuclear	MJ	**3.5E+00**	0.6	0.01	0.0	2.7E+00	1.9E-01
Non-renewable, biomass	MJ	**6.4E-08**	0.0	0.0	0	6.4E-08	0
Renewable, biomass	MJ	**1.6E-03**	0.0	0.0	0	1.6E-03	0
Renewable, wind, solar, geothermal	MJ	**3.4E-02**	0.0	0.0	0	3.4E-02	0
Renewable, water	MJ	**2.8E-01**	0.0	0.0	0	2.8E-01	0
Abiotic depletion (excluding energy)	kg Sb eq	**7.9E-10**	0.0E+00	0.0E+00	0.0E+00	7.9E-10	0.0E+00
Water use	m3	**1.4E-03**	0.0E+00	0.0E+00	0.0E+00	1.4E-03	0.0E+00

Figure 8. Contribution of Fuel Types to "On-site Energy Consumption" Category Indicators – percent basis



Note: Gasoline and propane combined contribute less than 1% to all the category indicators with the exception of "Smog" (1.3%). For example, the global warming impact category is dominated by diesel (50%), natural gas (40%) and electricity (10%).

5.2 Gypsum Paper LCIA Results

Tables 15 and 16 present the LCIA results for the cradle-to-gate production of 1,000 sq. ft. of backing and facing papers in the US by input or process, respectively. Because of the similar densities between facing and backing gypsum paper, respectively 44.1 and 41.5 lbs/MSF, the overall results for the two gypsum paper types are very similar. The cradle-to-gate manufacture of gypsum backing paper incorporates about 322 MJ of primary energy and emits in the order of 19.5 kg of greenhouse gases (CO_2 equivalent basis). The cradle-to-gate manufacture of gypsum facing paper incorporates about 345 MJ of primary energy and emits in the order of 20.9 kg of greenhouse gases (CO_2 equivalent basis).

Over 90% of the primary energy use was due to the consumption of energy at the gypsum paper plant (see Tables 17 and 18 for the percent contribution to each indicator for backing and facing papers). Further, on-site energy use accounted for over 90% of the fossil hydrocarbon fuel use attributed to the manufacture of gypsum paper, which consequently was also the primary source of the greenhouse gas emissions. With the exception of eutrophication, abiotic resource depletion and water use impacts, on-site energy consumption at the gypsum paper plant contributed 80% or more to each of the impact indicator category results. Waste disposal and treatment accounted for 50% of the eutrophication effect primarily due to the treatment of effluent flows. On-site process and energy use were two main contributors to water use, over 50% and 41% respectively.

Figure 9 isolates the contribution of various fuel use types to the “on-site energy consumption process” for gypsum backing paper. While electricity, natural gas, diesel and propane were all used within the plant gate, it was electricity and natural gas use that were the primary contributor to the impact category results (diesel and propane combined contribute less than one percent to any of the category indicators).

As noted previously, gypsum paper manufacturing requires the input of several chemical types; however, these chemicals typically represent less than one percent of the total resource flows and were a minor contributor to the overall LCIA results for the manufacture of gypsum papers with the exception of the abiotic depletion impact which was over 57%. Table 19 and 20 document the contribution (in absolute and percent basis) of the various chemical families to the total chemical usage effect for gypsum backing paper system. Of the array of chemical inputs, sizing agents and effluent treatment chemicals were found to be the most significant contributors to the category impact indicators.

Lastly, Figure 10 depicts the contribution of the various recycled paper input types to the total waste paper sorting and inbound transport category for the cradle-to-gate manufacture of gypsum facing paper. The contribution of Kraft clippings was found to be lower than that of either OCC or mixed writing paper.

Table 15. Weighted Average Gypsum Backing Paper LCIA results – absolute basis, per MSF

Impact category	**Unit**	**Total**	**On-site process emissions to water**	**OCC paper sorting & inbound transportation**	**Input chemicals** (including starch)	**Lubricants, hydraulic fluid, and greases**	**Packaging materials**	**On-site energy consumption**	**Inbound/ Outbound transportation** (excluding OCC and "backing" gypsum paper)	**Waste disposal**
Global warming	kg CO2 eq	**19.51**	0	0.46	0.21	1.7E-03	5.4E-02	17.5	3.0E-02	1.2
Acidification	H+ moles eq	**7.62**	0	0.15	6.2E-02	8.0E-04	2.9E-02	7.1E+00	9.9E-03	2.5E-01
Respiratory effects	kg PM2.5 eq	**0.035**	0	3.9E-04	2.7E-04	3.7E-06	1.3E-04	3.3E-02	1.1E-05	1.2E-03
Eutrophication	kg N eq	**4.3E-02**	7.9E-04	5.4E-04	1.2E-03	6.0E-06	1.4E-04	2.0E-02	9.5E-06	2.1E-02
Ozone depletion	kg CFC-11 eq	**6.1E-07**	0	4.6E-09	2.3E-08	1.1E-09	1.4E-09	5.7E-07	1.1E-12	5.3E-09
Smog	kg NOx eq	**0.039**	0	2.4E-03	3.9E-04	5.1E-06	2.2E-04	3.4E-02	2.1E-04	2.4E-03
Total Primary Energy	MJ	**322.03**	0.00	6.630	5.138	0.137	2.560	297.100	0.410	10.052
Non renewable, fossil	MJ	**295.77**	0	6.1	4.7	0.13	1.2E+00	275.3	0.4	8.0
nuclear	MJ	**22.24**	0	4.8E-01	2.7E-01	2.3E-03	0.1	2.0E+01	0	1.9E+00
biomass	MJ	**0.01**	0	1.1E-07	9.8E-03	2.9E-08	2.9E-04	4.6E-07	0	8.1E-08
Renewable, biomass	MJ	**1.49**	0	3.8E-04	1.6E-01	3.1E-05	1.3E+00	1.1E-02	0	1.5E-03
Renewable, wind, solar, geothermal	MJ	**0.27**	0	5.5E-03	3.5E-03	3.5E-05	9.9E-04	2.4E-01	0	2.3E-02
Renewable, water	MJ	**2.25**	0	4.7E-02	3.2E-02	2.5E-04	8.5E-03	2.0E+00	0	1.9E-01
Abiotic depletion (excluding energy)	kg Sb eq	**2.0E-07**	0	1.8E-10	1.2E-07	2.2E-11	7.8E-08	5.6E-09	0.0E+00	2.6E-09
Water use	m3	**0.408**	0.205	4.1E-03	5.9E-03	3.7E-05	4.7E-03	1.7E-01	0.0E+00	1.7E-02

Table 16. Weighted Average Gypsum Facing Paper LCIA results – absolute basis, per MSF

Impact category	**Unit**	**Total**	**On-site process emissions to water**	**OCC paper, kraft clippings, mixed waste paper sorting & inbound transportation**	**Input chemicals** (including starch)	**Lubricants, hydraulic fluid, and greases**	**Packaging materials**	**On-site energy consumption**	**Inbound/ Outbound transportation** (excluding OCC and "backing" gypsum paper)	**Waste disposal**
Global warming	kg CO2 eq	**20.94**	0	0.61	0.23	1.9E-03	5.9E-02	18.6	3.2E-02	1.4
Acidification	H+ moles eq	**8.22**	0	0.26	6.8E-02	8.7E-04	3.2E-02	7.6E+00	1.1E-02	2.8E-01
Respiratory effects	kg PM2.5 eq	**0.037**	0	5.2E-04	3.0E-04	4.0E-06	1.5E-04	3.5E-02	1.2E-05	1.3E-03
Eutrophication	kg N eq	**4.7E-02**	8.1E-04	6.8E-04	1.3E-03	6.5E-06	1.5E-04	2.1E-02	1.0E-05	2.3E-02
Ozone depletion	kg CFC-11 eq	**6.4E-07**	0	4.9E-09	2.5E-08	1.2E-09	1.5E-09	6.0E-07	1.2E-12	5.9E-09
Smog	kg NOx eq	**0.044**	0	4.9E-03	4.3E-04	5.5E-06	2.4E-04	3.6E-02	2.2E-04	2.7E-03
Total Primary Energy	MJ	**344.71**	0.00	8.73	5.52	0.15	2.81	315.89	0.44	11.17
Non renewable, fossil	MJ	**316.87**	0	8.2	5.0	0.15	1.3E+00	293.0	0.4	8.9
nuclear	MJ	**23.54**	0	5.3E-01	2.9E-01	2.5E-03	9.3E-02	2.1E+01	0	2.1E+00
biomass	MJ	**0.01**	0	1.1E-07	1.1E-02	3.2E-08	3.2E-04	4.8E-07	0	8.9E-08
Renewable, biomass	MJ	**1.63**	0	4.1E-04	1.8E-01	3.3E-05	1.4E+00	1.2E-02	0	1.7E-03
Renewable, wind, solar, geothermal	MJ	**0.28**	0	5.9E-03	3.8E-03	3.8E-05	1.1E-03	2.5E-01	0	2.6E-02
Renewable, water	MJ	**2.38**	0	5.0E-02	3.4E-02	2.7E-04	9.4E-03	2.1E+00	0	2.1E-01
Abiotic depletion (excluding energy)	kg Sb eq	**2.2E-07**	0	1.9E-10	1.3E-07	2.4E-11	8.6E-08	5.9E-09	0	2.9E-09
Water use	m3	**0.438**	0.223	4.3E-03	6.4E-03	4.0E-05	5.1E-03	1.8E-01	0	1.9E-02

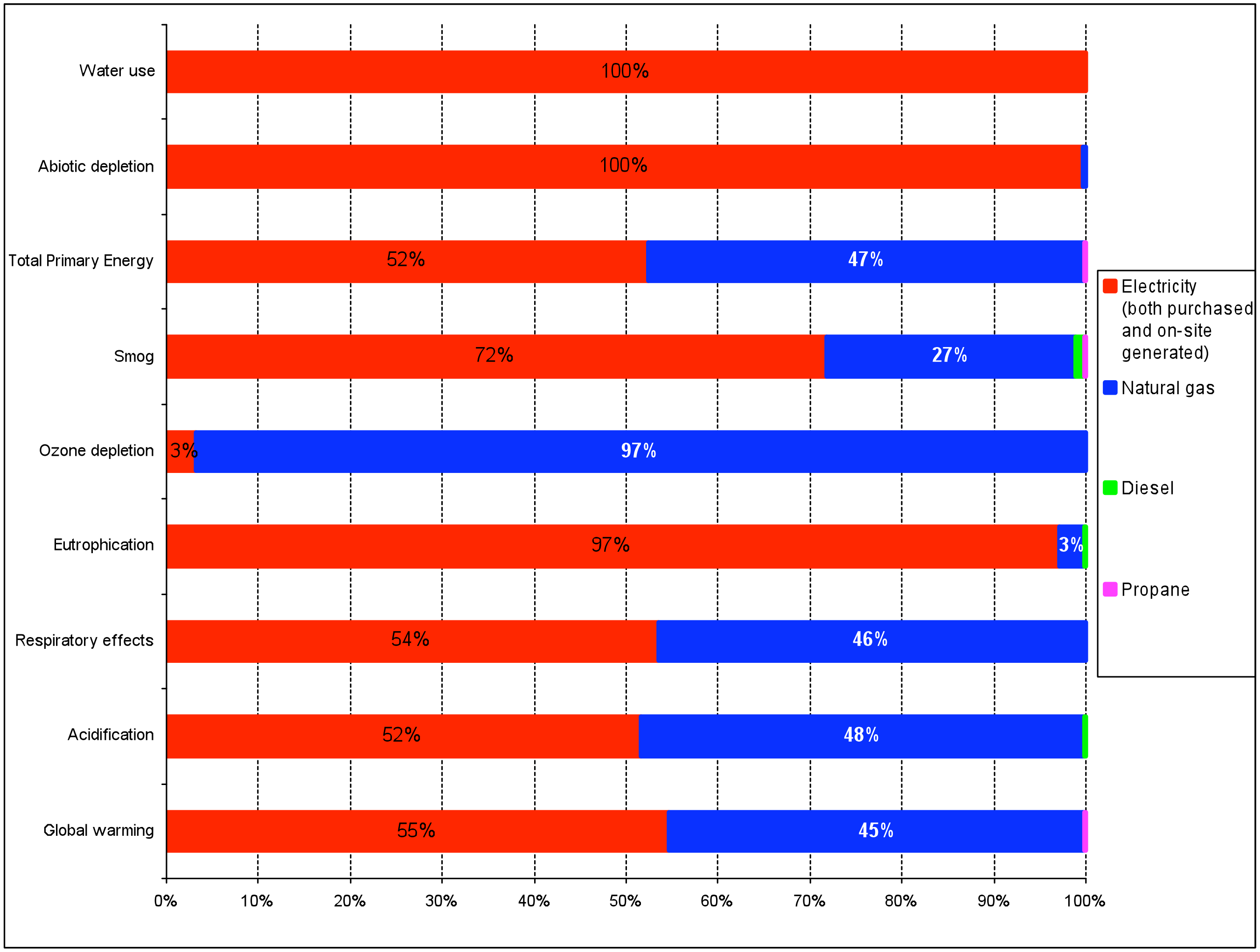
Table 17. Weighted Average Gypsum Backing Paper LCIA results – percent basis, per MSF

Impact category	**Total**	**On-site process emissions to water**	**OCC paper sorting & inbound transportation**	**Input chemicals** (including starch)	**Lubricants, hydraulic fluid, and greases**	**Packaging materials**	**On-site energy consumption**	**Inbound/ Outbound transportation** (excluding OCC and "backing" gypsum paper)	**Waste disposal**
Global warming	**100%**	0%	2%	1%	0%	0%	90%	0%	6%
Acidification	**100%**	0%	2%	1%	0%	0%	93%	0%	3%
Respiratory effects	**100%**	0%	1%	1%	0%	0%	94%	0%	3%
Eutrophication	**100%**	2%	1%	3%	0%	0%	46%	0%	48%
Ozone depletion	**100%**	0%	1%	4%	0%	0%	94%	0%	1%
Smog	**100%**	0%	6%	1%	0%	1%	86%	1%	6%
Total Primary Energy	**100%**	0%	2%	2%	0%	1%	92%	0%	3%
Non renewable, fossil	**100%**	0%	2%	2%	0%	0%	93%	0%	3%
Non-renewable, nuclear	**100%**	0%	2%	1%	0%	0%	88%	0%	8%
Non-renewable, biomass	**100%**	0%	0%	97%	0%	3%	0%	0%	0%
Renewable, biomass	**100%**	0%	0%	11%	0%	88%	1%	0%	0%
Renewable, wind, solar, geothermal	**100%**	0%	2%	1%	0%	0%	88%	0%	9%
Renewable, water	**100%**	0%	2%	1%	0%	0%	88%	0%	9%
Abiotic depletion (excluding energy)	**100%**	0%	0%	58%	0%	38%	3%	0%	1%
Water use	**100%**	50%	1%	1%	0%	1%	42%	0%	4%

Table 18. Weighted Average Gypsum Facing Paper LCIA results – percent basis, per MSF

Impact category	Total	On-site process emissions to water	OCC paper, kraft clippings, mixed waste paper sorting & inbound transportation	Input chemicals (including starch)	Lubricants, hydraulic fluid, and greases	Packaging materials	On-site energy consumption	Inbound/ Outbound transportation (excluding OCC and "backing" gypsum paper)	Waste disposal
Global warming	**100%**	0%	3%	1%	0%	0%	89%	0%	7%
Acidification	**100%**	0%	3%	1%	0%	0%	92%	0%	3%
Respiratory effects	**100%**	0%	1%	1%	0%	0%	94%	0%	4%
Eutrophication	**100%**	2%	1%	3%	0%	0%	44%	0%	50%
Ozone depletion	**100%**	0%	1%	4%	0%	0%	94%	0%	1%
Smog	**100%**	0%	11%	1%	0%	1%	81%	1%	6%
Total Primary Energy	**100%**	0%	3%	2%	0%	1%	92%	0%	3%
Non renewable, fossil	**100%**	0%	3%	2%	0%	0%	92%	0%	3%
Non-renewable, nuclear	**100%**	0%	2%	1%	0%	0%	87%	0%	9%
Non-renewable, biomass	**100%**	0%	0%	97%	0%	3%	0%	0%	0%
Renewable, biomass	**100%**	0%	0%	11%	0%	88%	1%	0%	0%
Renewable, wind, solar, geothermal	**100%**	0%	2%	1%	0%	0%	87%	0%	9%
Renewable, water	**100%**	0%	2%	1%	0%	0%	87%	0%	9%
Abiotic depletion (excluding energy)	**100%**	0%	0%	57%	0%	39%	3%	0%	1%
Water use	**100%**	51%	1%	1%	0%	1%	41%	0%	4%

Figure 9. Contribution of Fuel Types to "On-site Energy Consumption" Category Indicators – Gypsum Backing Paper– percent basis, per MSF



Note: Diesel and propane combined contribute less than 1% to any of the category indicators. For example, the global warming impact category is dominated by electricity and natural gas, 55% and 45% respectively.

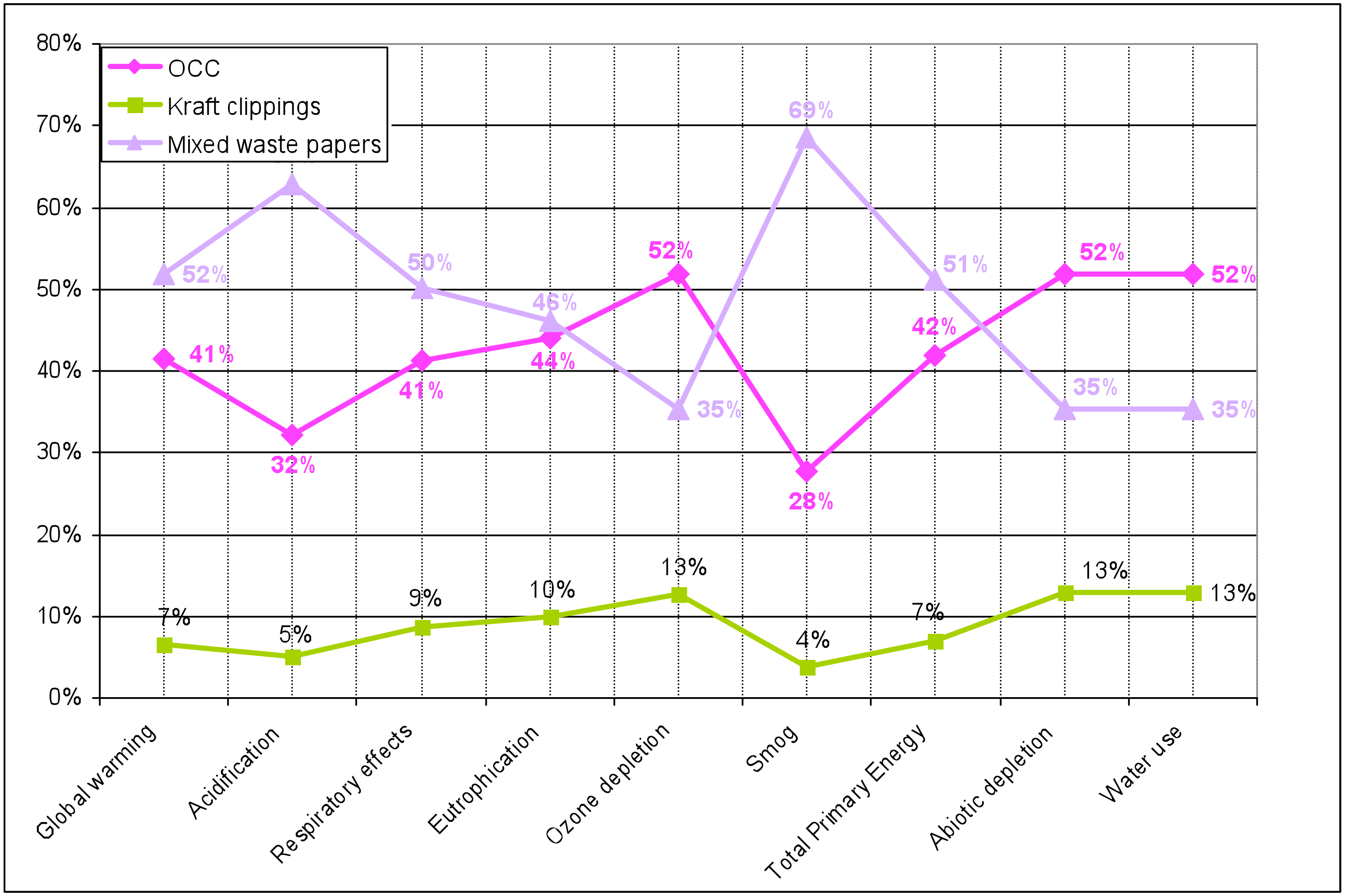
Table 19. Contribution of Chemical Types to Total Chemical Usage for Gypsum Backing Paper Manufacturing LCIA Results– absolute basis, per MSF

Impact category	Unit	Total Chemicals	Starch	Retention chemicals	Sizing agents	Polymer emulsifier	Other chemicals (defoamer, dyes)	Chemicals used for on-site water treatment
Global warming	kg CO2 eq	**0.21**	0.002	0.01	0.15	0.014	0.011	0.02
Acidification	H+ moles eq	**6.2E-02**	7.8E-04	3.3E-03	4.4E-02	3.7E-03	2.0E-03	8.6E-03
Respiratory effects	kg PM2.5 eq	**2.7E-04**	1.3E-06	1.5E-05	2.0E-04	9.6E-06	9.3E-06	3.4E-05
Eutrophication	kg N eq	**1.2E-03**	3.1E-05	6.7E-06	4.7E-04	8.0E-05	1.6E-05	5.9E-04
Ozone depletion	kg CFC-11 eq	**2.3E-08**	1.5E-10	5.0E-10	1.7E-08	7.3E-10	2.4E-09	2.2E-09
Smog	kg NOx eq	**3.9E-04**	4.4E-06	1.4E-05	2.9E-04	2.1E-05	2.2E-05	4.5E-05
Total Primary Energy	MJ	**5.138**	0.061	0.631	3.370	0.405	0.363	0.307
Non renewable, fossil	MJ	**4.7**	0.022	0.624	2.996	0.392	0.334	2.9E-01
Non-renewable, nuclear	MJ	**2.7E-01**	0.002	0.006	0.216	0.012	0.020	1.4E-02
Non-renewable, biomass	MJ	**9.8E-03**	1.32E-07	1.10E-07	0.010	0.000	1.16E-07	1.0E-05
Renewable, biomass	MJ	**1.6E-01**	0.038	1.63E-04	0.123	0.001	0.003	4.6E-04
Renewable, wind, solar, geothermal	MJ	**3.5E-03**	1.83E-05	5.25E-05	2.93E-03	5.64E-05	2.14E-04	2.2E-04
Renewable, water	MJ	**3.2E-02**	2.47E-04	4.53E-04	2.29E-02	1.03E-03	5.64E-03	1.6E-03
Abiotic depletion (excluding energy)	kg Sb eq	**1.2E-07**	3.0E-10	1.2E-09	9.1E-08	1.6E-10	6.2E-09	1.8E-08
Water use	m3	**5.9E-03**	2.2E-05	2.1E-04	4.5E-03	3.4E-04	6.7E-04	2.1E-04

Table 20. Contribution of Chemical Types to Total Chemical Usage Category Indicators for Gypsum Backing Paper Manufacturing– percent basis, per MSF

Impact category	Total Chemicals	Starch	Retention chemicals	Sizing agents	Polymer emulsifier	Other chemicals (defoamer, dyes)	Chemicals used for on-site water treatment
Global warming	**100.0%**	1.0%	3.7%	71.8%	6.8%	5.4%	11.4%
Acidification	**100.0%**	1.3%	5.2%	70.5%	6.0%	3.2%	13.8%
Respiratory effects	**100.0%**	0.5%	5.4%	74.7%	3.5%	3.4%	12.6%
Eutrophication	**100.0%**	2.6%	0.6%	39.2%	6.7%	1.3%	49.6%
Ozone depletion	**100.0%**	0.7%	2.2%	73.6%	3.2%	10.5%	9.9%
Smog	**100.0%**	1.1%	3.6%	72.9%	5.3%	5.7%	11.3%
Total Primary Energy	**100.0%**	1.2%	12.3%	65.6%	7.9%	7.1%	6.0%
Abiotic depletion	**100.0%**	0.3%	1.0%	78.1%	0.1%	5.3%	15.2%
Water use	**100.0%**	0.4%	3.5%	75.5%	5.8%	11.3%	3.6%
	1st highest	2nd highest	3rd highest				

Figure 10. Contribution of Recycled Paper Input Types to "Total Waste Paper Sorting and Transportation" Category Indicators- Gypsum Facing Paper Manufacturing– percent basis, per MSF



5.3 Gypsum Wallboard LCIA Results

This section presents and discusses the cradle-to-gate LCIA results for the two gypsum wallboard products of interest: ½" (12.7 mm) Regular and $^5/_8$" (15.9 mm) Type X gypsum wallboard. The functional unit for each product was a 1,000 sq. ft. (92.9 m^2) of GWB. The tabulated results include the previously presented reference flow products (natural gypsum ore by source location and gypsum backing and facing papers) as well the aforementioned system expansion methodology for modeling the input synthetic FGD gypsum.

5.3.1 ½" Regular Gypsum Board

Tables 21 and 22 summarize the cradle-to-gate LCIA results for 1,000 sq. ft. of ½" Regular GWB by material input and contributing process activity. The cradle-to-gate manufacture of 1,000 sq. ft. of ½" Regular GWB embodies about 4.05 GJ of primary energy use and emits in the order of 233 kg of greenhouse gas emissions. Over 92% of the total primary energy is derived from non-renewable fossil fuels. On-site energy use at the GWB plant and the input of gypsum paper were the major contributing sources to both total primary (76% and 16%, respectively) and fossil energy use (79% and 16%).

Table 23, 24 and Figure 11 show the contribution of gypsum source inputs (both in absolute and percent basis) to the LCIA category indicator results. Positive (+) values/percentages present an environmental burden related to the activity e.g. the extraction of natural gypsum ore (both domestic & imported). The contribution of the natural gypsum extraction system (both domestic & imported) to the depletion of abiotic resources potential was 98%. Its contribution to the rest of the LCIA category results ranged from 0.3% to 8% of the total impact results for the two products. Negative (-) values/percentages represent a reduction of the environmental burden (a benefit to the environment). The net impact of synthetic FGD gypsum use resulted in net benefit to the environment due to its diversion from landfilling. The reduction of the environmental burden (the environmental benefit) across the LCIA category results was relatively minor (generally ranging between 1% and 7%) with the exception of smog (29%).

Overall, the GWB plant's energy use was the single largest contributor to the majority of the LCIA category results. With the exception of eutrophication, abiotic depletion potential and water use, plant energy use generally accounted for greater than 70% of the impact outcome. Gypsum paper inputs were the next most consistent and significant contributor to the impact categories and ranged from 12% (ozone depletion potential) to accounting for 30% of the eutrophication potential for the product system. Dry and wet additives accounted for 27% of the eutrophication potential effect. In-bound transportation of raw and ancillary materials and the out-bound transportation of wastes for treatment accounted for about 32% of the smog potential, but otherwise it's contribution ranged from 2% to 8% to the supported impact category indicators. Packaging (including the use of off-spec GWB as bunks and sluetters), on-site process emissions/effluent control and waste disposal were also relatively minor contributors to the supported impact indicators.

Table 25 and Figure 12 summarizes the weighted average GWB plant energy use contribution by fuel type to each impact indicator for the production of 1,000 sq. ft. of ½" Regular GWB. Both electricity and natural gas use dominated the majority of the impacts. Propane was also a contributor to global warming, smog formation and primary energy use. Diesel and gasoline use had only a minor impact across all impact category results.

Figure 13 summarizes the contribution of inbound materials and outbound waste transportation by mode to the LCIA results for total transportation. The impact of transportation was driven by the input of gypsum by barge and truck followed by the input of additives by truck. Waste treatment transportation by truck was a minor contributor the overall effect of transportation.

Tables 26 and 27 show the contribution of the various additives to the overall LCIA contribution of additives category indicators in absolute and on a percent basis. The input of starch, glass fiber, dispersant and soap foam were the major inputs contributing to the LCIA indicators for additives.

Table 21. Weighted Average ½" Regular GWB LCIA results –absolute basis, per MSF

Impact category	**Unit**	**Total**	**On-site process emissions/ flows**	**Gypsum material** (mined, quarried, and FGD gypsum; post-consumer gypsum)	**Gypsum paper**	**Dry and wet additives**	**Lubricants, hydraulic fluid, and greases**	**On-site energy consumption**	**Inbound/ Outbound transportation**	**Packaging material**	**Off-spec GWBs used as bunks**	**Internal gypsum waste - close-loop recycling**	**Waste disposal**
Global warming	kg CO2 eq	**233.321**	0	-13.148	40.458	8.498	0.006	182.095	14.666	0.619	0.496	-0.455	0.083
Acidification	H+ moles eq	**93.920**	0	-4.168	15.846	3.095	0.003	71.186	7.729	0.274	0.220	-0.249	-0.014
Respiratory effects	kg PM2.5 eq	**0.448**	1.3E-02	0.028	0.072	0.014	0.000	0.313	0.008	0.001	0.001	-0.001	0.000
Eutrophication	kg N eq	**3.0E-01**	0	-1.1E-03	9.1E-02	8.1E-02	2.2E-05	1.2E-01	6.9E-03	2.3E-03	1.8E-03	-3.3E-04	0.000
Ozone depletion	kg CFC-11 eq	**1.1E-05**	0	-1.4E-07	1.2E-06	6.8E-07	4.1E-09	8.9E-06	6.1E-10	5.4E-08	1.8E-08	-9.2E-10	0.000
Smog	kg NOx eq	**0.467**	0	-0.105	0.083	0.023	0.000	0.315	0.151	0.002	0.001	-0.004	0.000
Total Primary Energy	MJ	**4051.4**	0.0	-173.9	666.8	237.4	0.5	3090.9	199.3	32.4	9.1	-6.4	-4.8
Non renewable, fossil	MJ	**3725.7**	0	-177.0	612.7	115.6	0.5	2960.7	197.5	13.7	7.4	-6.2	0.837
Non-renewable, nuclear	MJ	**180.7**	0	2.6	45.8	10.5	0.0	117.5	1.7	1.8	0.6	-1.7E-01	0.285
Non-renewable, biomass	MJ	**2.4**	0	0.0	0.0	2.4	0.0	0.0	0.0	0.0	0.0	-1.2E-08	0.010
Renewable, biomass	MJ	**122.1**	0	0.0	3.1	107.3	0.0	0.1	0.0	16.5	1.1	-1.3E-04	-5.962
Renewable, wind, solar, geothermal	MJ	**2.2**	0	0.1	0.6	0.1	0.0	1.4	0.0	0.0	0.0	-2.1E-03	0.006
Renewable, water	MJ	**18.3**	0	0.5	4.6	1.4	0.0	11.3	0.0	0.4	0.1	-1.5E-02	0.026
Abiotic depletion (excluding energy)	kg Sb eq	**4.3E-03**	0	4.2E-03	4.3E-07	1.7E-04	8.0E-11	3.2E-08	1.9E-11	1.5E-07	4.2E-05	-1.2E-04	-3.4E-08
Water use	m3	**3.127**	1	0.117	0.847	0.310	0.000	0.988	0.001	0.041	0.021	-3.5E-03	-0.005

Table 22. Weighted Average ½" Regular GWB LCIA results – percent basis, per MSF

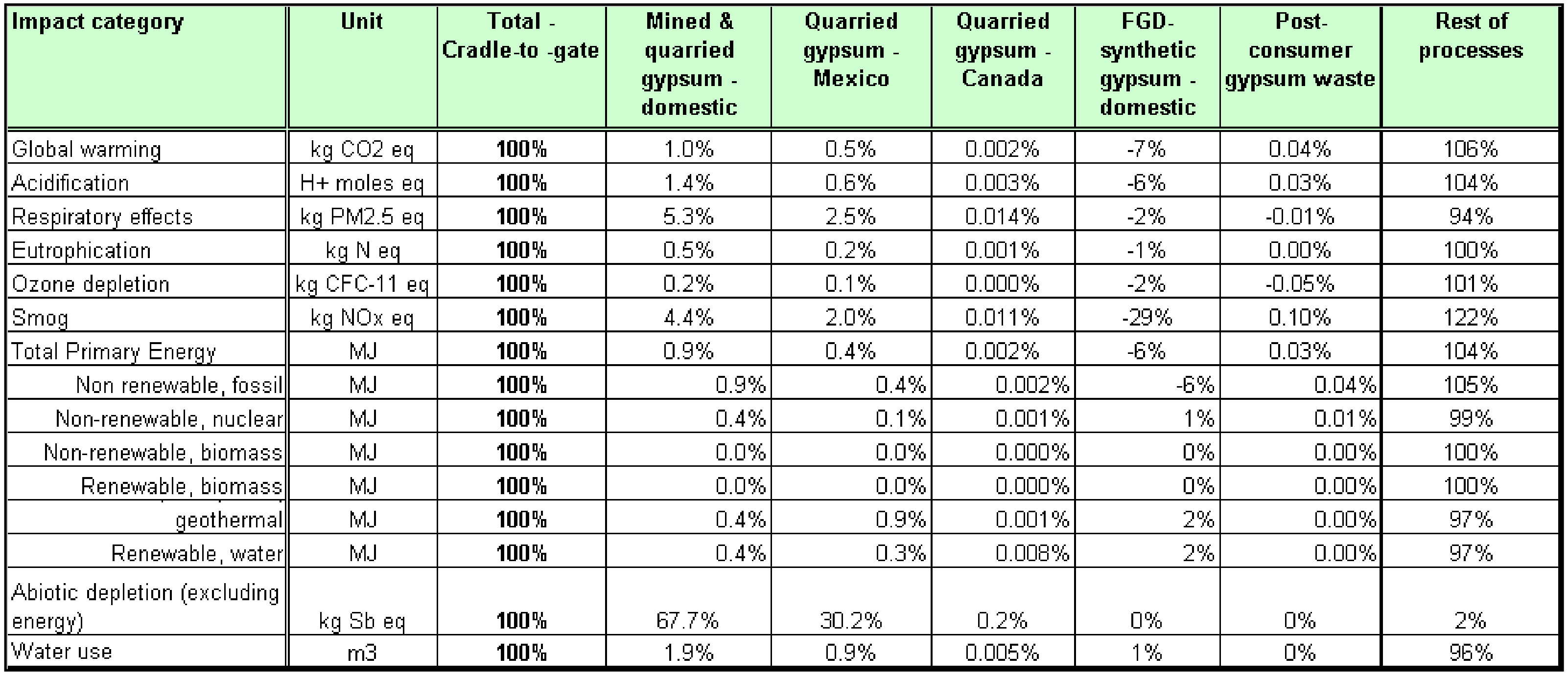
Impact category	**Total**	**On-site process emissions/ flows**	**Gypsum material** (mined, quarried, and FGD gypsum; post-consumer gypsum)	**Gypsum paper**	**Dry and wet additives**	**Lubricants, hydraulic fluid, and greases**	**On-site energy consumption**	**Inbound/ Outbound transportation**	**Packaging material**	**Off-spec GWBs used as bunks**	**Internal gypsum waste - close-loop recycling**	**Waste disposal**
Global warming	**100%**	0%	-6%	17%	4%	0%	78%	6%	0%	0.2%	-0.2%	0.0%
Acidification	**100%**	0%	-4%	17%	3%	0%	76%	8%	0%	0.2%	-0.3%	0.0%
Respiratory effects	**100%**	3%	6%	16%	3%	0%	70%	2%	0%	0.3%	-0.3%	0.0%
Eutrophication	**100%**	0%	0%	30%	27%	0%	40%	2%	1%	0.6%	-0.1%	0.1%
Ozone depletion	**100%**	0%	-1%	12%	6%	0%	83%	0%	1%	0.2%	0.0%	0.1%
Smog	**100%**	0%	-22%	18%	5%	0%	67%	32%	0%	0.3%	-1.0%	-0.1%
Total Primary Energy	**100%**	0%	-4%	16%	6%	0%	76%	5%	1%	0.2%	-0.2%	-0.1%
Non renewable, fossil	**100%**	0%	-5%	16%	3%	0%	79%	5%	0%	0.2%	-0.2%	0.0%
Non-renewable, nuclear	**100%**	0%	1%	25%	6%	0%	65%	1%	1%	0.3%	-0.1%	0.2%
Non-renewable, biomass	**100%**	0%	0%	1%	98%	0%	0%	0%	0%	1.0%	0.0%	0.4%
Renewable, biomass	**100%**	0%	0%	3%	88%	0%	0%	0%	13%	0.9%	0.0%	-4.9%
Renewable, wind, solar, geothermal	**100%**	0%	3%	26%	6%	0%	63%	0%	2%	0.3%	-0.1%	0.3%
Renewable, water	**100%**	0%	3%	25%	7%	0%	62%	0%	2%	0.3%	-0.1%	0.1%
Abiotic depletion (excluding energy)	**100%**	0%	98%	0%	4%	0%	0%	0%	0%	1.0%	-2.8%	0.0%
Water use	**100%**	26%	4%	27%	10%	0%	32%	0%	1%	0.7%	-0.1%	-0.2%

Table 23. Summary: Gypsum Input LCIA Contribution Analysis -½" Regular GWB– absolute basis, per MSF

Impact category	**Unit**	**Total - Cradle-to -gate**	**Mined & quarried gypsum - domestic**	**Quarried gypsum - Mexico**	**Quarried gypsum - Canada**	**FGD-synthetic gypsum - domestic**	**Post-consumer gypsum waste**	**Rest of processes**
Global warming	kg CO2 eq	**233.32**	2.39	1.08	0.01	-16.73	0.10	246.47
Acidification	H+ moles eq	**93.92**	1.28	0.59	0.00	-6.06	0.02	98.09
Respiratory effects	kg PM2.5 eq	**0.45**	0.02	1.1E-02	6.1E-05	-7.0E-03	-3.3E-05	0.42
Eutrophication	kg N eq	**0.30**	0.00	4.9E-04	2.6E-06	-3.3E-03	-1.2E-06	0.30
Ozone depletion	kg CFC-11 eq	**1.1E-05**	0.00	9.4E-09	5.1E-11	-1.7E-07	-5.5E-09	1.1E-05
Smog	kg NOx eq	**0.467**	0.02	9.3E-03	5.0E-05	-1.3E-01	4.7E-04	0.571
Total Primary Energy	MJ	**4051.39**	35.6	16.6	0.1	-227.4	1.4	4225.27
Non renewable, fossil	MJ	**3725.65**	34.70	16.32	0.08	-229.50	1.35	3902.70
Non-renewable, nuclear	MJ	**180.70**	0.79	0.16	0.00	1.65	0.01	178.09
Non-renewable, biomass	MJ	**2.43**	3.5E-07	1.4E-07	7.4E-10	-4.5E-06	-1.5E-07	2.43
Renewable, biomass	MJ	**122.11**	2.0E-03	6.1E-04	3.3E-06	-2.8E-03	-1.6E-04	122.11
geothermal	MJ	**2.16**	8.1E-03	1.9E-02	2.5E-05	4.3E-02	-9.6E-05	2.09
Renewable, water	MJ	**18.34**	6.7E-02	5.3E-02	1.4E-03	3.7E-01	-5.7E-04	17.85
Abiotic depletion (excluding energy)	kg Sb eq	**0.004**	2.9E-03	1.3E-03	7.0E-06	-2.3E-09	-1.1E-10	8.6E-05
Water use	m3	**3.13**	6.09E-02	2.67E-02	1.44E-04	2.98E-02	-1.27E-04	3.01

Note: Positive (+) values represent an environmental burden related to the activity e.g. the extraction of natural gypsum ore. Negative (-) values represent a reduction of the environmental burden (a benefit to the environment). The net impact of synthetic FGD gypsum use resulted in *net benefit* to the environment due to its diversion from landfilling.

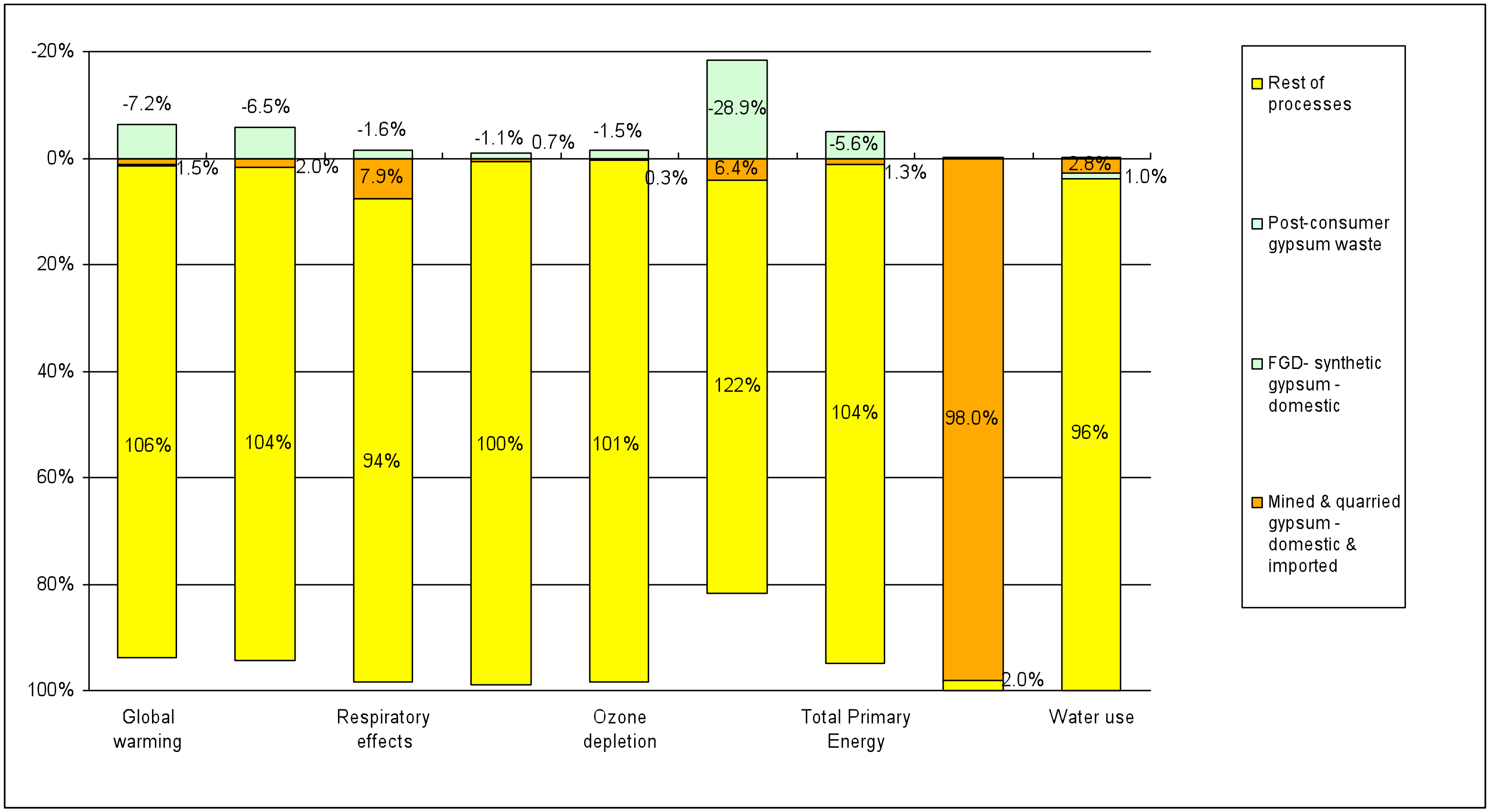
Table 24. Summary: Gypsum Input LCIA Contribution Analysis -½" Regular GWB– percent basis, per MSF



Impact category	Unit	Total - Cradle-to -gate	Mined & quarried gypsum - domestic	Quarried gypsum - Mexico	Quarried gypsum - Canada	FGD- synthetic gypsum - domestic	Post- consumer gypsum waste	Rest of processes
Global warming	kg CO2 eq	**100%**	1.0%	0.5%	0.002%	-7%	0.04%	106%
Acidification	H+ moles eq	**100%**	1.4%	0.6%	0.003%	-6%	0.03%	104%
Respiratory effects	kg PM2.5 eq	**100%**	5.3%	2.5%	0.014%	-2%	-0.01%	94%
Eutrophication	kg N eq	**100%**	0.5%	0.2%	0.001%	-1%	0.00%	100%
Ozone depletion	kg CFC-11 eq	**100%**	0.2%	0.1%	0.000%	-2%	-0.05%	101%
Smog	kg NOx eq	**100%**	4.4%	2.0%	0.011%	-29%	0.10%	122%
Total Primary Energy	MJ	**100%**	0.9%	0.4%	0.002%	-6%	0.03%	104%
Non renewable, fossil	MJ	**100%**	0.9%	0.4%	0.002%	-6%	0.04%	105%
Non-renewable, nuclear	MJ	**100%**	0.4%	0.1%	0.001%	1%	0.01%	99%
Non-renewable, biomass	MJ	**100%**	0.0%	0.0%	0.000%	0%	0.00%	100%
Renewable, biomass	MJ	**100%**	0.0%	0.0%	0.000%	0%	0.00%	100%
geothermal	MJ	**100%**	0.4%	0.9%	0.001%	2%	0.00%	97%
Renewable, water	MJ	**100%**	0.4%	0.3%	0.008%	2%	0.00%	97%
Abiotic depletion (excluding energy)	kg Sb eq	**100%**	67.7%	30.2%	0.2%	0%	0%	2%
Water use	m3	**100%**	1.9%	0.9%	0.005%	1%	0%	96%

Note: Positive (+) values represent an environmental burden related to the activity e.g. the extraction of natural gypsum ore. Negative (-) values represent a reduction of the environmental burden (a benefit to the environment). The net impact of synthetic FGD gypsum use resulted in *net benefit* to the environment due to its diversion from landfilling.

Figure 11. Summary: Gypsum Input LCIA Contribution Analysis - ½" Regular GWB– percent basis, per MSF



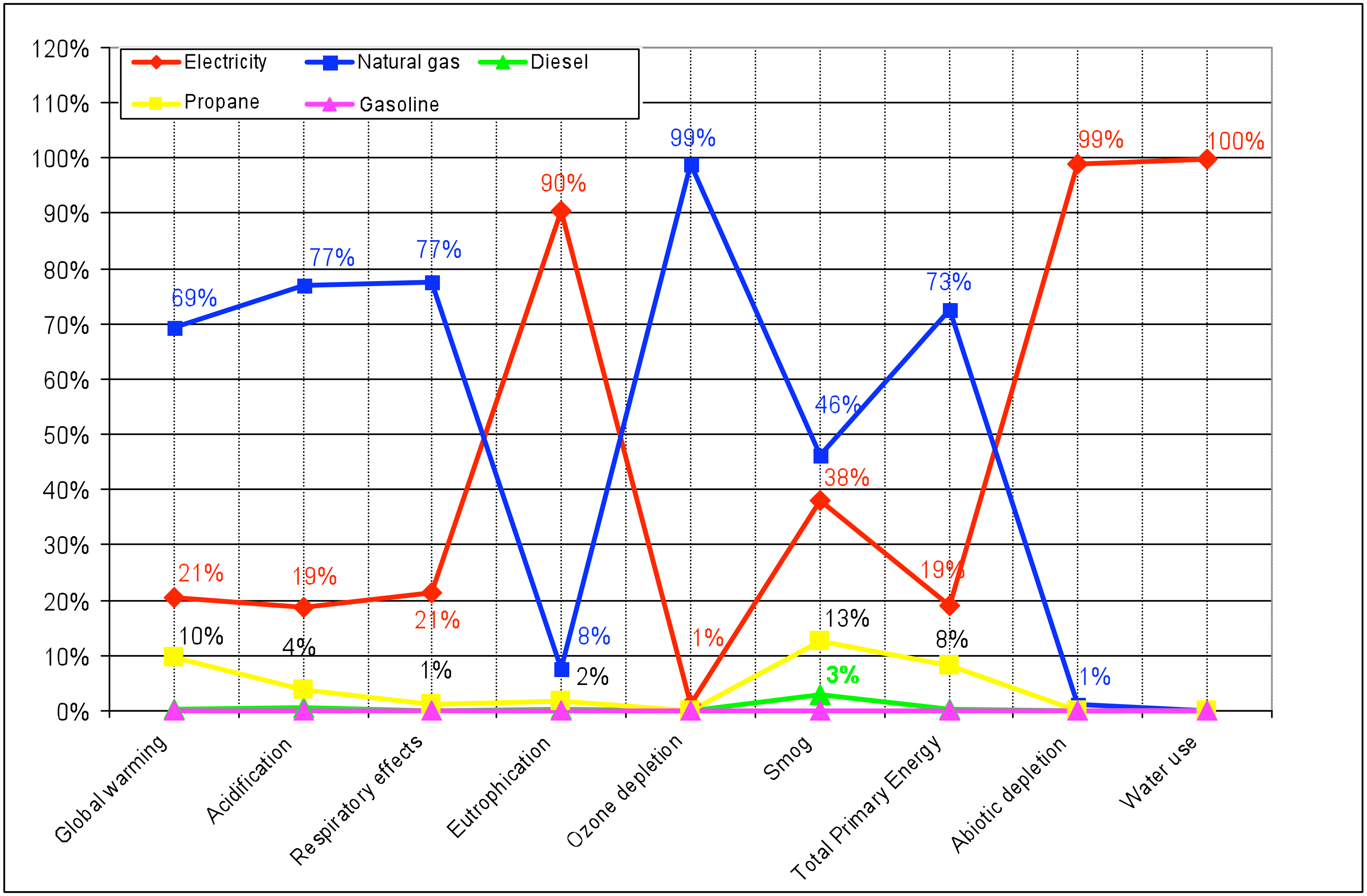
Note: Positive (+) percentages represent an environmental burden related to the activity e.g. the extraction of natural gypsum ore. The contribution of the natural gypsum extraction system (both domestic & imported) to the depletion of abiotic resources potential was 98%. Its contribution to the rest of the LCIA category results ranged from 0.3% to 8% of the total impact results for the two products.

Negative (-) percentages represent a reduction of the environmental burden (a benefit to the environment). The net impact of the FGD synthetic gypsum use was *beneficial* to the environment due to the avoidance of synthetic FGD landfilling. The reduction of the environmental burden (the environmental benefit) across the LCIA category results was relatively minor (generally ranging between 1% and 7%) with the exception of smog (29%).

Table 25. Summary: Gypsum Plant Energy Use LCIA Contribution Analysis - ½” Regular GWB– absolute basis, per MSF

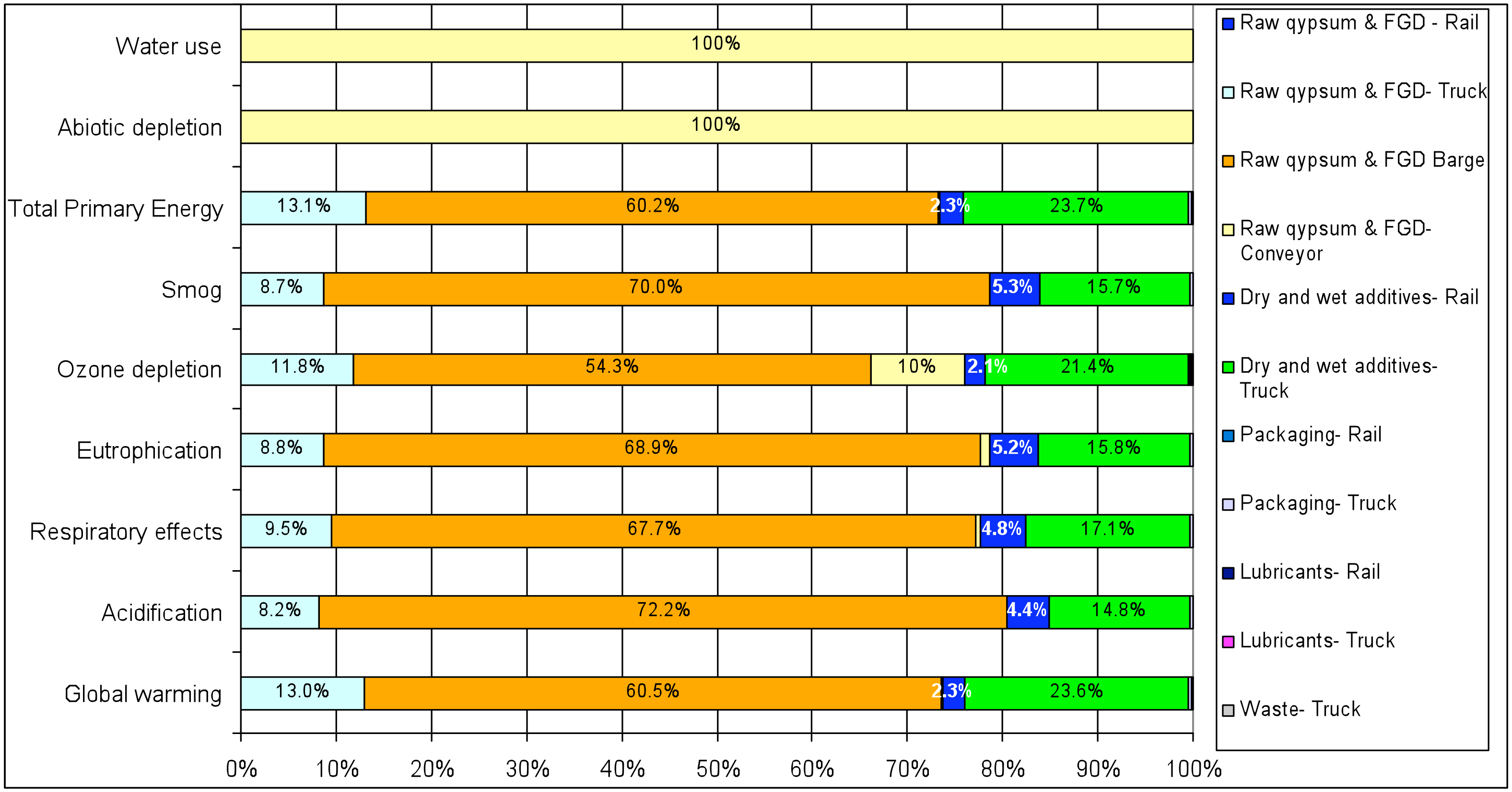
Impact category	**Unit**	**Total on-site energy consumption**	**Electricity**	**Natural gas**	**Diesel**	**Propane**	**Gasoline**
Global warming	kg CO2 eq	**182.10**	37.52	126.36	0.53	17.68	0.004
Acidification	H+ moles eq	**71.19**	13.40	54.75	0.41	2.61	0.003
Respiratory effects	kg PM2.5 eq	**0.31**	0.07	0.24	0.00	0.00	2.8E-06
Eutrophication	kg N eq	**0.12**	0.11	0.01	0.00	0.00	2.6E-06
Ozone depletion	kg CFC-11 eq	**8.93E-06**	1.04E-07	8.83E-06	2.14E-11	6.93E-10	1.77E-13
Smog	kg NOx eq	**0.31**	0.12	0.15	0.01	0.04	0.00
Total Primary Energy	MJ	**3090.93**	584.62	2245.93	7.79	252.53	0.06
Non renewable, fossil	MJ	**2960.7**	462.8	2239.7	7.7	250.4	0.1
Non-renewable, nuclear	MJ	**117.5**	109.2	6.1	0.1	2.1	0.0
Non-renewable, biomass	MJ	**0.0**	0.0	0.0	0.0	0.0	0.0
Renewable, biomass	MJ	**0.1**	0.1	0.0	0.0	0.0	0.0
Renewable, wind, solar, geothermal	MJ	**1.4**	1.4	0.0	0.0	0.0	0.0
Renewable, water	MJ	**11.3**	11.3	0.1	0.0	0.0	0.0
Abiotic depletion (excluding energy)	kg Sb eq	**3.23E-08**	3.19E-08	3.32E-10	0.00E+00	0.00E+00	0.00E+00
Water use	m3	**0.988**	0.987	0.001	0.000	0.000	0.000

Figure 12. Summary: Gypsum Plant Energy Use LCIA Contribution Analysis - ½" Regular GWB– percent basis, per MSF



Note: Diesel and propane combined contribute less than 1% to all the category indicators with the exception of smog (3%). For example, the global warming impact category is dominated by natural gas (69%), electricity (21%) and gasoline (10%) usage.

Figure 13. Summary: Inbound/Outbound Transportation LCIA Contribution Analysis - ½" Regular GWB– percent basis, per MSF



Note: Raw gypsum and FGD (rail), packaging (both rail and truck), lubricants (both rail and truck) and waste (truck) combined contribute less than 1% to any of the category indicators. For example, the global warming impact category is dominated by raw gypsum & FGD-trucking (13.0%), raw gypsum & FGD-barge (60.5%) transportation, additives by rail (2.3%), additives by truck (23.6%) and rest (0.6%- less than 1%).

Table 26. Summary: Additives Input LCIA Contribution Analysis - ½” Regular GWB – absolute basis, per MSF

Impact category	**Unit**	**Total additives**	**Starch**	**Vermiculite**	**Glass fibre**	**Dispersant**	**Retarder**	**Potassium sulphate**	**Dextrose**	**Boric acid**
Global warming	kg CO2 eq	**8.50**	3.78	0.01	0.95	0.60	0.79	0.06	0.31	0.07
Acidification	H+ moles eq	**3.09**	1.37	0.01	0.34	0.39	0.12	0.02	0.13	0.10
Respiratory effects	kg PM2.5 eq	**1.44E-02**	2.25E-03	2.83E-04	1.53E-03	5.11E-03	5.84E-04	3.70E-05	2.65E-04	6.30E-04
Eutrophication	kg N eq	**8.12E-02**	5.44E-02	2.01E-05	1.59E-03	5.26E-03	3.38E-03	5.25E-04	2.56E-03	1.45E-04
Ozone depletion	kg CFC-11 eq	**6.77E-07**	2.62E-07	7.42E-10	5.78E-08	1.18E-07	9.36E-08	3.81E-09	1.80E-08	4.92E-09
Smog	kg NOx eq	**2.33E-02**	7.77E-03	2.26E-04	3.34E-03	2.25E-03	1.41E-03	1.51E-04	9.77E-04	3.76E-04
Total Primary Energy	MJ	**237.4**	107.0	0.1	14.8	26.1	15.8	1.6	14.7	1.1
Abiotic depletion (excluding energy)	kg Sb eq	**1.66E-04**	5.25E-07	8.90E-05	1.83E-05	9.42E-08	6.72E-07	6.39E-08	2.88E-08	2.90E-05
Water use	m3	**0.31**	0.04	0.00	0.02	0.02	0.04	0.00	0.01	0.01

Impact category	**Unit**	**Plaster**	**Soap foam**	**BM Accelerator**	**Ammonium sulphate**	**Edge glue**	**Sodium tripolyphosphate**	**Shredded paper**	**Talc**
Global warming	kg CO2 eq	0.01	0.89	0.27	0.12	0.34	0.28	0.01	0.00
Acidification	H+ moles eq	0.01	0.21	0.10	0.02	0.08	0.19	0.01	0.00
Respiratory effects	kg PM2.5 eq	1.45E-04	1.93E-03	2.27E-04	9.36E-05	3.39E-04	9.96E-04	1.05E-05	2.24E-07
Eutrophication	kg N eq	9.33E-06	3.94E-03	3.80E-03	6.58E-05	8.38E-04	4.69E-03	1.35E-05	1.70E-07
Ozone depletion	kg CFC-11 eq	1.22E-10	4.24E-08	1.90E-08	1.36E-08	2.64E-08	1.57E-08	6.04E-11	6.30E-13
Smog	kg NOx eq	1.20E-04	4.11E-03	6.07E-04	2.24E-04	1.09E-03	4.81E-04	1.13E-04	1.11E-07
Total Primary Energy	MJ	0.2	34.6	7.6	1.9	8.8	2.7	0.2	0.0
Abiotic depletion (excluding energy)	kg Sb eq	1.66E-05	1.81E-07	7.68E-06	6.53E-11	3.15E-08	3.59E-06	3.18E-12	3.67E-13
Water use	m3	0.00	0.13	0.00	0.00	0.02	0.02	0.00	0.00

Table 27. Summary: Additives Input LCIA Contribution Analysis - ½" Regular GWB– percent basis, per MSF

Impact category	**Total additives**	**Starch**	**Vermiculite**	**Glass fibre**	**Dispersant**	**Retarder**	**Potassium sulphate**	**Dextrose**	**Boric acid**
Global warming	**100.0%**	44.4%	0.1%	11.2%	7.0%	9.3%	0.7%	3.6%	0.8%
Acidification	**100.0%**	44.3%	0.4%	10.9%	12.6%	4.0%	0.6%	4.3%	3.1%
Respiratory effects	**100.0%**	15.6%	2.0%	10.6%	35.4%	4.0%	0.3%	1.8%	4.4%
Eutrophication	**100.0%**	67.0%	0.0%	2.0%	6.5%	4.2%	0.6%	3.2%	0.2%
Ozone depletion	**100.0%**	38.8%	0.1%	8.5%	17.4%	13.8%	0.6%	2.7%	0.7%
Smog	**100.0%**	33.4%	1.0%	14.4%	9.7%	6.1%	0.6%	4.2%	1.6%
Total Primary Energy	**100.0%**	45.1%	0.0%	6.2%	11.0%	6.7%	0.7%	6.2%	0.5%
Abiotic depletion	**100.0%**	0.3%	53.7%	11.0%	0.1%	0.4%	0.0%	0.0%	17.5%
Water use	**100.0%**	12.3%	0.0%	7.2%	7.8%	12.0%	0.7%	3.4%	2.9%

Impact category	**Plaster**	**Soap foam**	**BM Accelerator**	**Ammonium sulphate**	**Edge glue**	**Sodium tripolyphosphate**	**Shredded paper**	**Talc**
Global warming	0.2%	10.5%	3.2%	1.4%	4.0%	3.4%	0.1%	0.0%
Acidification	0.2%	6.9%	3.2%	0.6%	2.5%	6.0%	0.2%	0.0%
Respiratory effects	1.0%	13.4%	1.6%	0.6%	2.3%	6.9%	0.1%	0.0%
Eutrophication	0.0%	4.9%	4.7%	0.1%	1.0%	5.8%	0.0%	0.0%
Ozone depletion	0.0%	6.3%	2.8%	2.0%	3.9%	2.3%	0.0%	0.0%
Smog	0.5%	17.7%	2.6%	1.0%	4.7%	2.1%	0.5%	0.0%
Total Primary Energy	0.1%	14.6%	3.2%	0.8%	3.7%	1.1%	0.1%	0.0%
Abiotic depletion	10.0%	0.1%	4.6%	0.0%	0.0%	2.2%	0.0%	0.0%
Water use	0.1%	41.7%	1.0%	0.1%	5.0%	5.8%	0.0%	0.0%
	1st highest	2nd highest	3rd highest					

5.3.2 5/8" Type X Gypsum Board

Tables 28 and 29 summarize the cradle-to-gate LCIA results for 1,000 sq. ft. of $^5/_8$" Type X GWB by material input and contributing process activity. The cradle-to-gate manufacture of 1,000 sq. ft. of $^5/_8$" Type X GWB embodies about 5.45 GJ of primary energy use and emits in the order of 315 kg of greenhouse gas emissions. Over 90% of the total primary energy is derived from non-renewable fossil fuels. On-site energy use at the GWB plant and the input of gypsum paper were the major contributing sources to both total primary (80% and 12%, respectively) and fossil energy use (83% and 12%).

Tables 30 and 31 and Figure 14 show the contribution of gypsum source inputs (both in absolute and percent basis) to the LCIA category indicator results. Positive (+) values/percentages present an environmental burden related to the activity e.g. the extraction of natural gypsum ore (both domestic & imported). The contribution of the natural gypsum extraction system (both domestic & imported) to the depletion of abiotic resources potential was 97%. Its contribution to the rest of the LCIA category results ranged from 0.3% to 8% of the total impact results for the two products. Negative (-) values/percentages present a reduction of the environmental burden (a benefit to the environment). The net impact of synthetic FGD gypsum use resulted in net benefit to the environment due to its diversion from landfilling. The reduction of the environmental burden (the environmental benefit) across the LCIA category results was relatively minor (generally ranging between 1% and 8%) with the exception of smog (30%).

Overall, the GWB plant's energy use was the single largest contributor to the majority of the LCIA category results for the product of interest. With the exception of eutrophication, abiotic depletion potential and water use, plant energy use generally accounted for greater than 70% of the impact outcome for $^5/_8$" Type X GWB. Gypsum paper inputs were the next most consistent and significant contributor to the impact categories and ranged from 8% (ozone depletion potential) to accounting for 25% of the eutrophication potential for the product system. Dry and wet additives accounted for 25% of the eutrophication potential effect, but were otherwise a minor contributor to the LCIA indicator results. In-bound transportation of raw and ancillary materials and the out-bound transportation of wastes for treatment accounted for 33% of the smog potential, but otherwise it's contribution ranged from 2% to 8% to the supported impact category indicators. Packaging (including the use of off-spec GWB as bunks and sluetters), production consumables (lubricants, etc.), on-site process emissions/effluent control (except for water use) and waste disposal were also relatively minor contributors to the LCIA impact indicators.

Table 32 and Figure 15 summarize the weighted average GWB plant energy use contribution by fuel type to each impact indicator for the production of 1,000 sq. ft. of $^5/_8$" Type X GWB. Both electricity and natural gas use dominated the majority of the impacts. Propane was also a contributor to global warming, smog formation and total primary energy use. Diesel and gasoline use had only a minor impact across all impact category results.

Figure 16 presents the contribution of the inbound transportation of materials and the outbound transportation of waste outputs by mode for the total transportation LCIA effect related to the $^5/_8$" Type X GWB product system. The transport of gypsum (all sources) by barge and truck dominates the contribution to all impact category indicators. The water use and abiotic depletion indicator was dominated by conveyance of raw gypsum from the quarry to the GWB plant. Additives transportation by truck was a second order contributor to the total transportation effect. Waste treatment transportation by truck was an insignificant contributor to the total effect of transportation.

Tables 33 and 34 provide a contribution analysis by additive (absolute and percent basis) to the overall impact of the dry and wet additives used in the manufacture of 1,000 sq. ft. of $^5/_8$" Type X GWB. The contribution analysis identified starch and glass fiber as the two primary impact sources for additive inputs in the manufacture of $^5/_8$" Type X GWB. Dispersants, retarders and soap foam as a grouping were the next most significant contributors to the impact of all additives.

Table 28. Weighted Average$^{5}/_{8}$” Type X GWB LCIA results –absolute basis, per MSF

Impact category	Unit	Total	On-site process emissions/ flows	Gypsum material (mined, quarried, and FGD gypsum; post-consumer gypsum)	Gypsum paper	Dry and wet additives	Lubricants, hydraulic fluid, and greases	On-site energy consumption	Inbound/ Outbound transportation	Packaging material	Off-spec GWBs used as bunks	Internal gypsum waste - close-loop recycling	Waste disposal
Global warming	kg CO2 eq	**315.429**	0	-18.814	40.458	14.774	0.009	258.261	19.847	0.874	0.550	-0.651	0.121
Acidification	H+ moles eq	**127.037**	0	-5.968	15.846	5.333	0.004	100.894	10.668	0.386	0.252	-0.357	-0.020
Respiratory effects	kg PM2.5 eq	**0.609**	1.8E-02	0.040	0.072	0.025	0.000	0.443	0.010	0.002	0.001	-0.002	0.000
Eutrophication	kg N eq	**3.7E-01**	0	-1.6E-03	9.1E-02	9.1E-02	3.0E-05	1.7E-01	9.5E-03	3.2E-03	1.9E-03	-4.7E-04	5.4E-04
Ozone depletion	kg CFC-11 eq	**1.5E-05**	0	-2.0E-07	1.2E-06	1.1E-06	5.6E-09	1.3E-05	8.2E-10	7.7E-08	2.1E-08	-1.3E-09	1.2E-08
Smog	kg NOx eq	**0.632**	0	-0.150	0.083	0.046	0.000	0.447	0.207	0.003	0.002	-0.006	-0.001
Total Primary Energy	MJ	**5445.1**	0.0	-248.8	666.8	334.3	0.7	4382.8	269.5	45.7	10.0	-9.1	-6.9
Non renewable, fossil	MJ	**5047.7**	0	-253.3	612.7	203.0	0.7	4197.8	267.1	19.3	8.1	-8.9	1.2
Non-renewable, nuclear	MJ	**242.9**	0	3.7	45.8	20.7	1.2E-02	166.9	2.4E+00	2.6E+00	7.1E-01	-2.5E-01	4.1E-01
Non-renewable, biomass	MJ	**2.6**	0	-6.0E-06	2.1E-02	2.5	1.5E-07	0.0	2.1E-09	1.1E-04	2.5E-02	-1.7E-08	1.5E-02
Renewable, biomass	MJ	**124.3**	0	-5.3E-04	3.1	105.4	1.6E-04	0.1	5.2E-05	2.3E+01	1.1E+00	-1.9E-04	-8.6E+00
Renewable, wind, solar, geothermal	MJ	**2.9**	0	1.0E-01	0.6	0.3	1.8E-04	1.9	1.1E-03	5.1E-02	9.0E-03	-3.1E-03	8.0E-03
Renewable, water	MJ	**24.7**	0	0.7	4.6	2.5	1.3E-03	16.1	9.3E-03	6.0E-01	7.7E-02	-2.1E-02	3.7E-02
Abiotic depletion (excluding energy)	kg Sb eq	**6.2E-03**	0	6.0E-03	4.3E-07	2.9E-04	1.1E-10	4.6E-08	2.6E-11	2.1E-07	6.0E-05	-1.7E-04	-4.9E-08
Water use	m3	**4.086**	1	0.167	0.847	0.461	1.9E-04	1.4E+00	8.1E-04	5.8E-02	2.6E-02	-5.0E-03	-6.9E-03

Table 29. Weighted Average$^{5}/_{8}$” Type X GWB LCIA results –percent basis, per MSF

Impact category	Total	On-site process emissions/ flows	Gypsum material (mined, quarried, and FGD gypsum; post-consumer gypsum)	Gypsum paper	Dry and wet additives	Lubricants, hydraulic fluid, and greases	On-site energy consumption	Inbound/ Outbound transportation	Packaging material	Off-spec GWBs used as bunks	Internal gypsum waste - close-loop recycling	Waste disposal
Global warming	**100%**	0%	-6%	13%	5%	0%	82%	6%	0%	0%	-0.2%	0%
Acidification	**100%**	0%	-5%	12%	4%	0%	79%	8%	0%	0%	-0.3%	0%
Respiratory effects	**100%**	3%	7%	12%	4%	0%	73%	2%	0%	0%	-0.3%	0%
Eutrophication	**100%**	0%	0%	25%	25%	0%	47%	3%	1%	1%	-0.1%	0%
Ozone depletion	**100%**	0%	-1%	8%	7%	0%	85%	0%	1%	0%	0.0%	0%
Smog	**100%**	0%	-24%	13%	7%	0%	71%	33%	0%	0%	-1.0%	0%
Total Primary Energy	**100%**	0%	-5%	12%	6%	0%	80%	5%	1%	0%	-0.2%	0%
Non renewable, fossil	**100%**	0%	-5%	12%	4%	0%	83%	5%	0%	0%	-0.2%	0%
Non-renewable, nuclear	**100%**	0%	2%	19%	9%	0%	69%	1%	1%	0%	-0.1%	0%
Non-renewable, biomass	**100%**	0%	0%	1%	98%	0%	0%	0%	0%	1%	0.0%	1%
Renewable, biomass	**100%**	0%	0%	3%	85%	0%	0%	0%	19%	1%	0.0%	-7%
Renewable, wind, solar, geothermal	**100%**	0%	3%	19%	9%	0%	66%	0%	2%	0%	-0.1%	0%
Renewable, water	**100%**	0%	3%	19%	10%	0%	65%	0%	2%	0%	-0.1%	0%
Abiotic depletion (excluding energy)	**100%**	0%	97%	0%	5%	0%	0%	0%	0%	1%	-2.8%	0%
Water use	**100%**	28%	4%	21%	11%	0%	34%	0%	1%	1%	-0.1%	0%

Table 30. Summary: Gypsum Input LCIA Contribution Analysis - $^5/_8$" Type X GWB– absolute basis, per MSF

Impact category	**Unit**	**Total - Cradle-to - gate**	**Mined & quarried gypsum - domestic**	**Quarried gypsum - Mexico**	**Quarried gypsum - Canada**	**FGD-synthetic gypsum - domestic**	**Post-consumer gypsum waste**	**Rest of processes**
Global warming	kg CO2 eq	**315.43**	3.36	1.59	0.01	-23.93	0.15	334.24
Acidification	H+ moles eq	**127.04**	1.79	0.87	0.00	-8.67	0.04	133.01
Respiratory effects	kg PM2.5 eq	**0.61**	0.03	1.7E-02	8.5E-05	-1.0E-02	-4.9E-05	0.57
Eutrophication	kg N eq	**0.37**	0.00	7.2E-04	3.6E-06	-4.7E-03	-1.8E-06	0.37
Ozone depletion	kg CFC-11 eq	**1.5E-05**	0.00	1.4E-08	7.1E-11	-2.4E-07	-8.2E-09	1.5E-05
Smog	kg NOx eq	**0.632**	0.03	1.4E-02	7.0E-05	-1.9E-01	6.9E-04	0.781
Total Primary Energy	MJ	**5445.06**	49.9	24.3	0.1	-325.2	2.0	5693.86
Non renewable, fossil	MJ	**5047.72**	48.71	24.00	0.12	-328.16	2.00	5301.05
Non-renewable, nuclear	MJ	**242.93**	1.11	0.24	0.00	2.35	0.02	239.20
Non-renewable, biomass	MJ	**2.58**	4.9E-07	2.0E-07	1.0E-09	-6.5E-06	-2.2E-07	2.58
Renewable, biomass	MJ	**124.25**	2.8E-03	9.0E-04	4.6E-06	-4.0E-03	-2.4E-04	124.25
geothermal	MJ	**2.91**	1.1E-02	2.8E-02	3.5E-05	6.2E-02	-1.4E-04	2.81
Renewable, water	MJ	**24.66**	9.4E-02	7.9E-02	2.0E-03	5.3E-01	-8.4E-04	23.96
Abiotic depletion (excluding energy)	kg Sb eq	**0.006**	4.1E-03	1.9E-03	9.8E-06	-3.3E-09	-1.7E-10	1.8E-04
Water use	m3	**4.09**	8.55E-02	3.92E-02	2.01E-04	4.26E-02	-1.88E-04	3.92

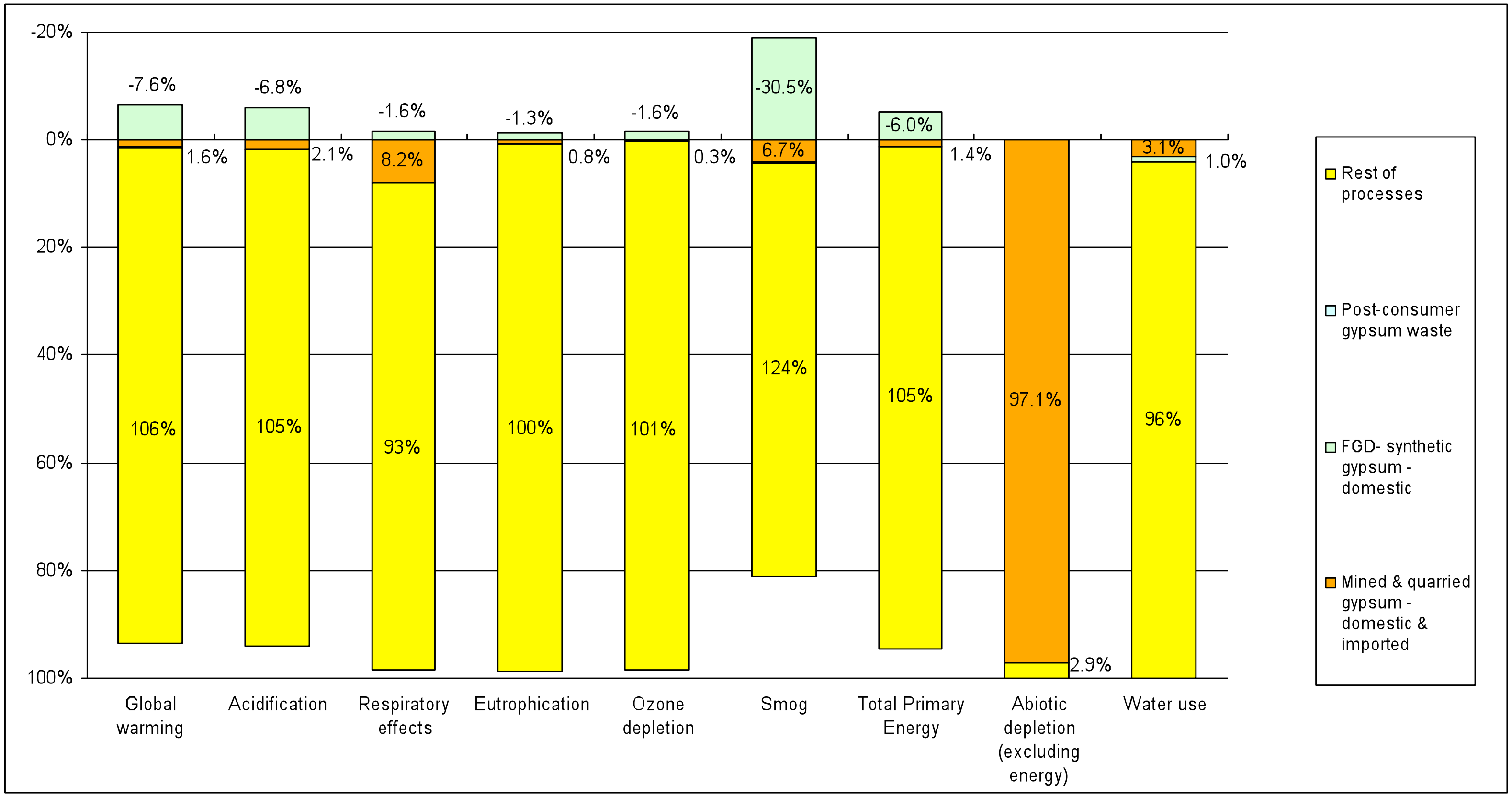
Note: Positive (+) values represent an environmental burden related to the activity e.g. the extraction of natural gypsum ore. Negative (-) values represent a reduction of the environmental burden (a benefit to the environment). The net impact of synthetic FGD gypsum use resulted in *net benefit* to the environment due to its diversion from landfilling.

Table 31. Summary: Gypsum Input LCIA Contribution Analysis - $^{5}/_{8}$” Type X GWB–percentage basis, per MSF

Impact category	**Unit**	**Total - Cradle-to - gate**	**Mined & quarried gypsum - domestic**	**Quarried gypsum - Mexico**	**Quarried gypsum - Canada**	**FGD-synthetic gypsum - domestic**	**Post-consumer gypsum waste**	**Rest of processes**
Global warming	kg CO2 eq	**100%**	1.1%	0.5%	0.002%	-8%	0.05%	106%
Acidification	H+ moles eq	**100%**	1.4%	0.7%	0.003%	-7%	0.03%	105%
Respiratory effects	kg PM2.5 eq	**100%**	5.5%	2.7%	0.014%	-2%	-0.01%	93%
Eutrophication	kg N eq	**100%**	0.6%	0.2%	0.001%	-1%	0.00%	100%
Ozone depletion	kg CFC-11 eq	**100%**	0.2%	0.1%	0.000%	-2%	-0.06%	101%
Smog	kg NOx eq	**100%**	4.5%	2.2%	0.011%	-31%	0.11%	124%
Total Primary Energy	MJ	**100%**	0.9%	0.4%	0.002%	-6%	0.04%	105%
Non renewable, fossil	MJ	**100%**	1.0%	0.5%	0.002%	-7%	0.04%	105%
Non-renewable, nuclear	MJ	**100%**	0.5%	0.1%	0.001%	1%	0.01%	98%
Non-renewable, biomass	MJ	**100%**	0.0%	0.0%	0.000%	0%	0.00%	100%
Renewable, biomass	MJ	**100%**	0.0%	0.0%	0.000%	0%	0.00%	100%
geothermal	MJ	**100%**	0.4%	1.0%	0.001%	2%	0.00%	97%
Renewable, water	MJ	**100%**	0.4%	0.3%	0.008%	2%	0.00%	97%
Abiotic depletion (excluding energy)	kg Sb eq	**100%**	66.1%	30.9%	0.2%	0%	0%	3%
Water use	m3	**100%**	2.1%	1.0%	0.005%	1%	0%	96%

Note: Positive (+) values represent an environmental burden related to the activity e.g. the extraction of natural gypsum ore. Negative (-) values represent a reduction of the environmental burden (a benefit to the environment). The net impact of synthetic FGD gypsum use resulted in *net benefit* to the environment due to its diversion from landfilling.

Figure 14. Summary: Gypsum Input LCIA Contribution Analysis - $^5/_8$" Type X GWB– percent basis, per MSF



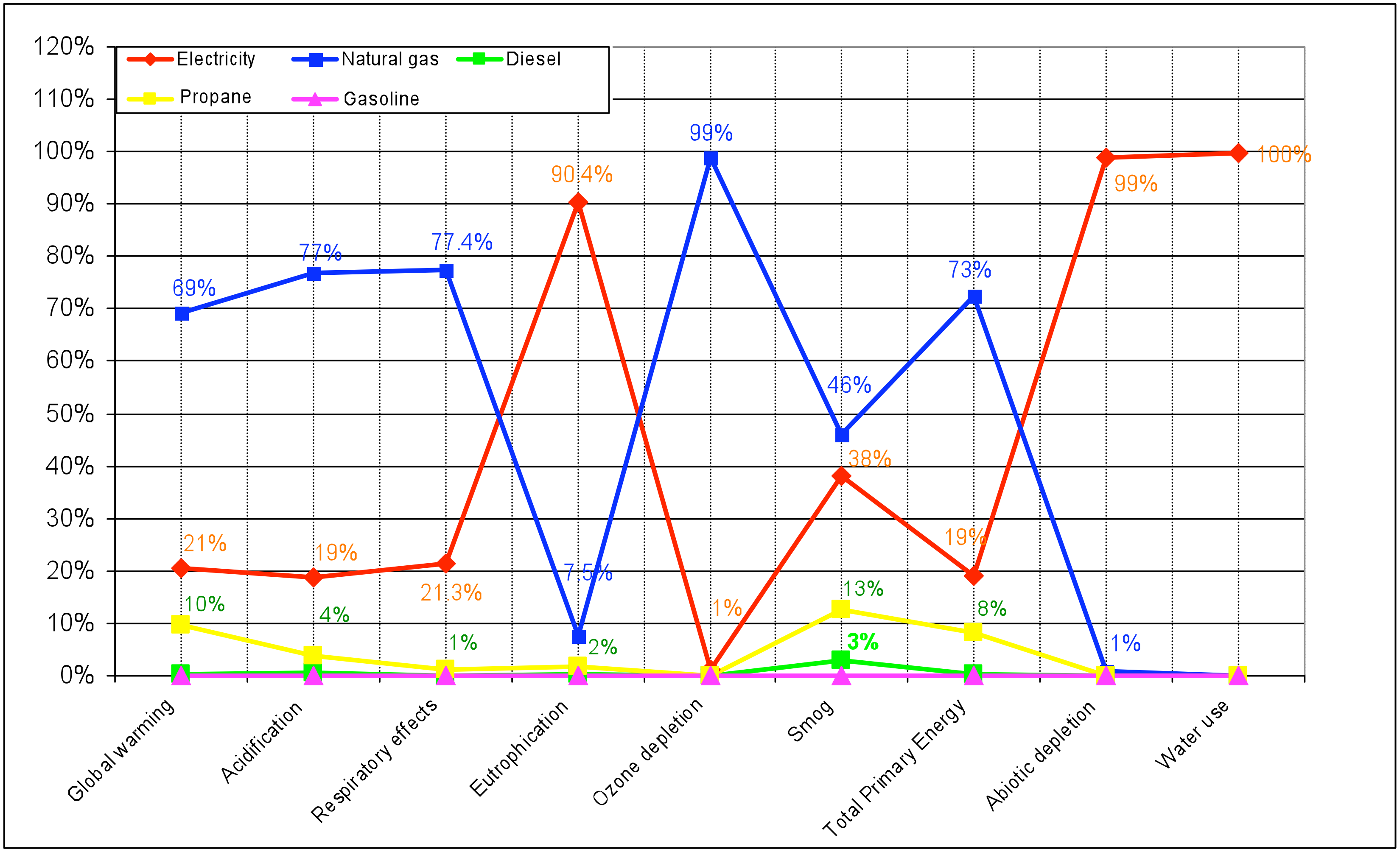
Note: Positive (+) percentages represent an environmental burden related to the activity e.g. the extraction of natural gypsum ore. The contribution of the natural gypsum extraction system (both domestic & imported) to the depletion of abiotic resources potential was 97%. Its contribution to the rest of the LCIA category results ranged from 0.3% to 8% of the total impact results for the two products.

Negative (-) percentages represent a reduction of the environmental burden (a benefit to the environment). The net impact of the FGD synthetic gypsum use was *beneficial* to the environment due to the avoidance of synthetic FGD landfilling. The reduction of the environmental burden (the environmental benefit) across the LCIA category results was relatively minor (generally ranging between 1% and 8%) with the exception of smog (30%).

Table 32. Summary: Gypsum Plant Energy Use LCIA Contribution Analysis - $^{5}/_{8}$" Type X GWB^{-}absolute basis, per MSF

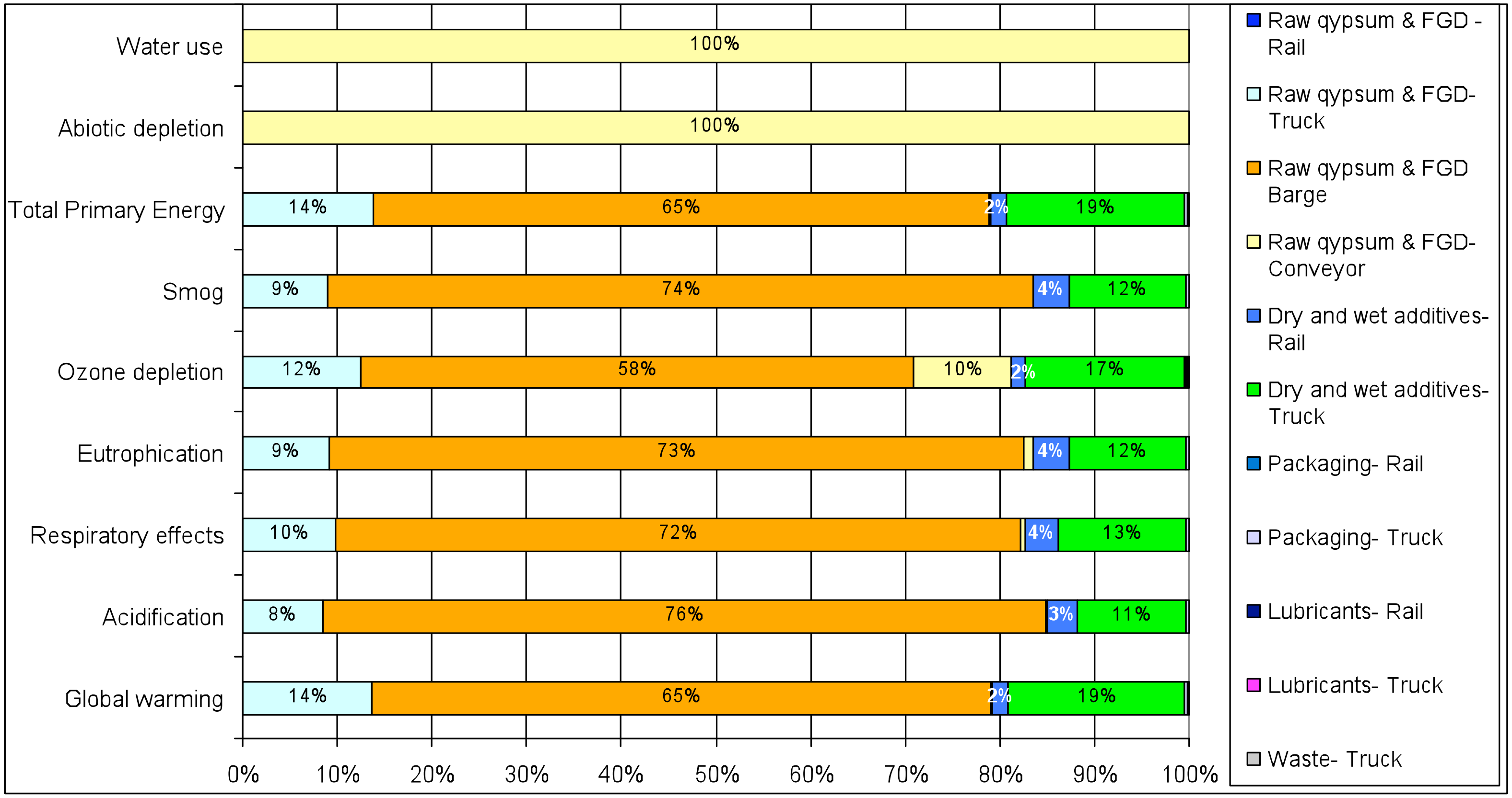
Impact category	Unit	Total on-site energy consumption	Electricity	Natural gas	Diesel	Propane	Gasoline
Global warming	kg CO2 eq	**258.26**	53.31	178.89	0.76	25.30	6.04E-03
Acidification	H+ moles eq	**100.89**	19.04	77.52	0.59	3.74	3.62E-03
Respiratory effects	kg PM2.5 eq	**0.44**	0.09	0.34	0.00	0.01	4.01E-06
Eutrophication	kg N eq	**0.17**	0.16	0.01	0.00	0.00	3.68E-06
Ozone depletion	kg CFC-11 eq	**1.27E-05**	1.47E-07	1.25E-05	3.06E-11	9.91E-10	2.53E-13
Smog	kg NOx eq	**0.45**	0.17	0.21	0.01	0.06	8.89E-05
Total Primary Energy	MJ	**4382.81**	830.59	3179.71	11.14	361.28	0.09
Non renewable, fossil	MJ	**4197.8**	657.5	3170.9	11.0	358.2	0.1
Non-renewable, nuclear	MJ	**166.9**	155.1	8.7	0.1	3.1	7.79E-04
Non-renewable, biomass	MJ	**0.0**	3.7E-06	1.2E-07	0	0	0
Renewable, biomass	MJ	**0.1**	9.0E-02	6.3E-03	0	0	0
Renewable, wind, solar, geothermal	MJ	**1.9**	1.9E+00	1.6E-03	0	0	0
Renewable, water	MJ	**16.1**	1.6E+01	9.3E-02	0	0	0
Abiotic depletion (excluding energy)	kg Sb eq	**4.58E-08**	4.54E-08	4.70E-10	0	0	0
Water use	m3	**1.404**	1.402	0.002	0	0	0

Figure 15. Summary: Gypsum Plant Energy Use LCIA Contribution Analysis - $^{5}/_{8}$” Type X GWB– percent basis, per MSF



Note: Diesel and propane combined contribute less than 1% to all the category indicators with the exception of smog (3%). For example, global warming impact category is dominated by natural gas (69%), electricity (21%) and gasoline (10%) use.

Figure 16. Summary: Inbound/Outbound Transportation LCIA Contribution Analysis - $^5/_8$" Regular GWB– percent basis, per MSF



Note: Raw gypsum and FGD (rail), packaging (both rail and truck), lubricants (both rail and truck) and waste (truck) combined contribute less than 1% to any of the category indicators. For example, the global warming impact category is dominated by raw gypsum & FGD-truck (14%), raw gypsum & FGD-barge (65%), additives-rail (2%) and additives-truck (19%).

Table 33. Summary: Additives Input LCIA Contribution Analysis - $^5/_8$" Type X GWB– absolute basis, per MSF

Impact category	**Unit**	**Total additives**	**Starch**	**Vermiculite**	**Glass fibre**	**Dispersant**	**Retarder**	**Potassium sulphate**	**Dextrose**	**Clay**
Global warming	kg CO2 eq	**14.77**	3.77	0.01	7.46	0.66	0.71	0.04	0.24	0.00
Acidification	H+ moles eq	**5.33**	1.37	0.02	2.64	0.43	0.11	0.01	0.11	0.00
Respiratory effects	kg PM2.5 eq	**2.50E-02**	2.25E-03	3.55E-04	1.19E-02	5.68E-03	5.28E-04	2.76E-05	2.11E-04	3.23E-06
Eutrophication	kg N eq	**9.11E-02**	5.43E-02	2.52E-05	1.24E-02	5.84E-03	3.05E-03	3.91E-04	2.04E-03	1.74E-06
Ozone depletion	kg CFC-11 eq	**1.05E-06**	2.62E-07	9.31E-10	4.52E-07	1.31E-07	8.46E-08	2.84E-09	1.43E-08	2.02E-10
Smog	kg NOx eq	**4.57E-02**	7.76E-03	2.84E-04	2.61E-02	2.50E-03	1.27E-03	1.12E-04	7.77E-04	1.96E-05
Total Primary Energy	MJ	**334.3**	106.9	0.1	115.5	29.0	14.3	1.2	11.7	
Abiotic depletion (excluding energy)	kg Sb eq	**2.94E-04**	5.25E-07	1.12E-04	1.43E-04	1.05E-07	6.07E-07	4.77E-08	2.29E-08	1.21E-09
Water use	m3	**0.46**	0.04	0.00	0.17	0.03	0.03	0.00	0.01	0.00

Impact category	**Unit**	**Boric acid**	**Plaster**	**Soap foam**	**BM Accelerator**	**Ammonium sulphate**	**Edge glue**	**Sodium tripolyphosphate**	**Shredded paper**	**Talc**
Global warming	kg CO2 eq	0.04	0.01	0.95	0.23	0.01	0.34	0.29	0.01	0.00
Acidification	H+ moles eq	0.06	0.00	0.22	0.08	0.00	0.08	0.19	0.00	0.00
Respiratory effects	kg PM2.5 eq	3.69E-04	9.41E-05	2.05E-03	1.87E-04	4.55E-06	3.41E-04	1.01E-03	7.86E-06	2.24E-07
Eutrophication	kg N eq	8.49E-05	6.05E-06	4.17E-03	3.13E-03	3.20E-06	8.43E-04	4.76E-03	1.01E-05	1.70E-07
Ozone depletion	kg CFC-11 eq	2.88E-09	7.94E-11	4.49E-08	1.56E-08	6.63E-10	2.66E-08	1.59E-08	4.53E-11	6.30E-13
Smog	kg NOx eq	2.20E-04	7.80E-05	4.35E-03	5.00E-04	1.09E-05	1.10E-03	4.89E-04	8.48E-05	1.11E-07
Total Primary Energy	MJ	0.7	0.1	36.7	6.3	0.1	8.8	2.8	0.1	0.0
Abiotic depletion (excluding energy)	kg Sb eq	1.70E-05	1.08E-05	1.92E-07	6.32E-06	3.17E-12	3.17E-08	3.65E-06	2.38E-12	3.67E-13
Water use	m3	0.01	0.00	0.14	0.00	0.00	0.02	0.02	0.00	0.00

Table 34. Summary: Additives Input LCIA Contribution Analysis - $^{5}/_{8}$” Type X GWB– percent basis, per MSF

Impact category	**Total**	**Starch**	**Vermiculite**	**Glass fibre**	**Dispersant**	**Retarder**	**Potassium sulphate**	**Dextrose**	**Clay**
Global warming	**100.0%**	25.5%	0.0%	50.5%	4.5%	4.8%	0.3%	1.7%	0.01%
Acidification	**100.0%**	25.7%	0.3%	49.5%	8.1%	2.1%	0.3%	2.0%	0.02%
Respiratory effects	**100.0%**	9.0%	1.4%	47.6%	22.7%	2.1%	0.1%	0.8%	0.01%
Eutrophication	**100.0%**	59.6%	0.0%	13.7%	6.4%	3.4%	0.4%	2.2%	0.00%
Ozone depletion	**100.0%**	24.9%	0.1%	42.8%	12.4%	8.0%	0.3%	1.4%	0.02%
Smog	**100.0%**	17.0%	0.6%	57.1%	5.5%	2.8%	0.2%	1.7%	0.04%
Total Primary Energy	**100.0%**	32.0%	0.0%	34.6%	8.7%	4.3%	0.4%	3.5%	0.00%
Abiotic depletion	**100.0%**	0.2%	38.0%	48.6%	0.0%	0.2%	0.0%	0.0%	0.00%
Water use	**100.0%**	8.2%	0.0%	37.6%	5.8%	7.3%	0.3%	1.8%	0.00%

Impact category	**Boric acid**	**Plaster**	**Soap foam**	**BM Accelerator**	**Ammonium sulphate**	**Edge glue**	**Sodium tripolyphosphate**	**Shredded paper**	**Talc**
Global warming	0.3%	0.1%	6.4%	1.5%	0.0%	2.3%	2.0%	0.1%	0.0%
Acidification	1.1%	0.1%	4.2%	1.5%	0.0%	1.5%	3.5%	0.1%	0.0%
Respiratory effects	1.5%	0.4%	8.2%	0.7%	0.0%	1.4%	4.0%	0.0%	0.0%
Eutrophication	0.1%	0.0%	4.6%	3.4%	0.0%	0.9%	5.2%	0.0%	0.0%
Ozone depletion	0.3%	0.0%	4.3%	1.5%	0.1%	2.5%	1.5%	0.0%	0.0%
Smog	0.5%	0.2%	9.5%	1.1%	0.0%	2.4%	1.1%	0.2%	0.0%
Total Primary Energy	0.2%	0.0%	11.0%	1.9%	0.0%	2.6%	0.8%	0.0%	0.0%
Abiotic depletion	5.8%	3.7%	0.1%	2.2%	0.0%	0.0%	1.2%	0.0%	0.0%
Water use	1.1%	0.1%	29.7%	0.6%	0.0%	3.4%	4.0%	0.0%	0.0%
	1st highest	2nd highest	3rd highest						

6 LCA Interpretation

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

6.1 Identification of the significant issues

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

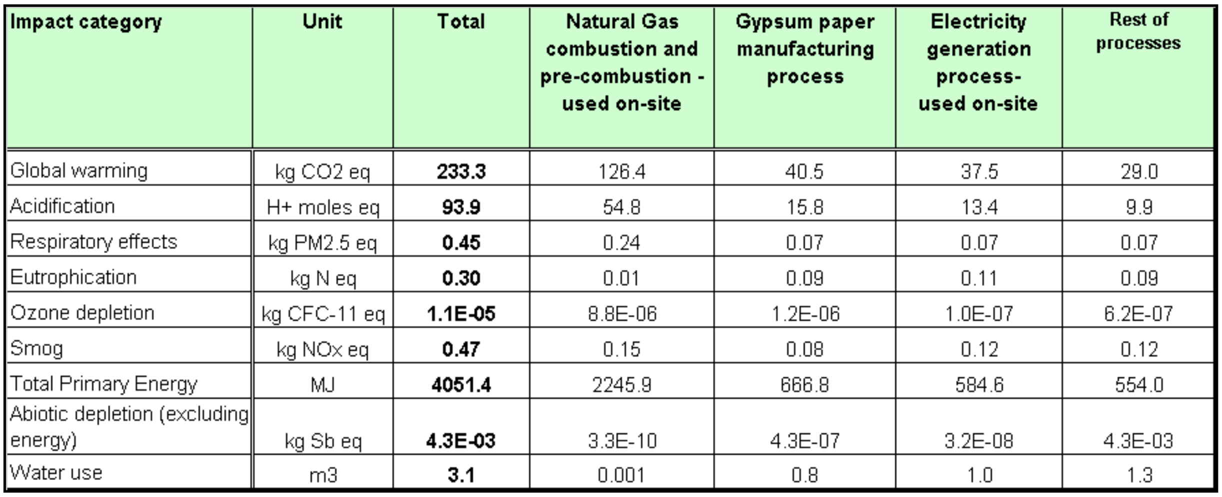
- *Dominance Analysis:* in whichremarkable or significant contributions are examined [2].
- *Influence Analysis*: in which the possibility of influencing the environmental issues is examined for the product system of interest [2].
- *Contribution Analysis*: in which the contribution of life cycle stages, groups of processes or specific substances to the total results are examined [2].
  Contribution analysis may also be dealt with in the interpretation phase; however, Section 5 of this report already detailed the key contributing life cycle stages, processes, material, energy inputs and transportation modes for each product system. In this section, the contribution analysis was limited to the examination of the three major contributing flows for each of the selected impact indicators categories. Overall the findings of the contribution analysis are highlighted in the conclusion section.

6.1.1 Dominance Analysis

Tables 35 and 36 present the three most significant inputs that dominate the overall LCIA category indicators for the cradle-to-gate production of ½” Regular GWB on an absolute and percent basis. Similarly, Tables 37 and 38 show that the same three inputs (on-site natural gas combustion and pre-combustion, gypsum paper manufacturing, and on-site electricity use) also dominate the overall LCIA category indicators for the cradle-to-gate production of $^5/_8$" Type X GWB on an absolute and percent basis.

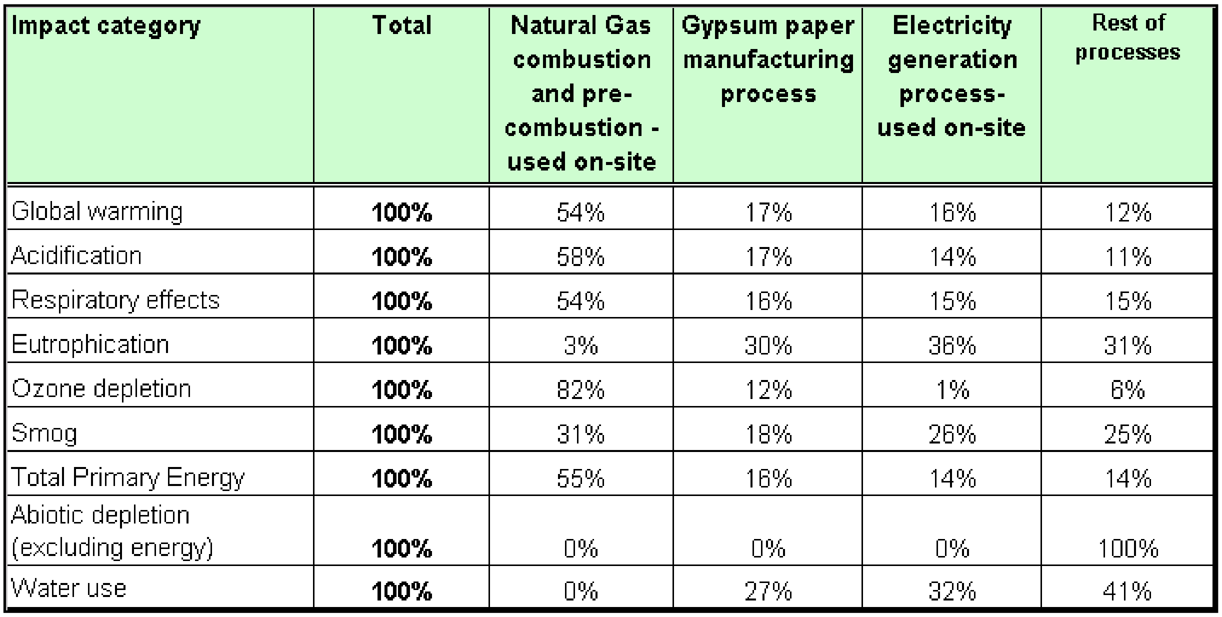
The use of natural gas at the GWB plant dominates the resulting LCIA profile for both product systems of interest. Both gypsum paper manufacturing and electricity use at the GWB plant followed a distant second and third in terms of dominance, but the three inputs together account for upwards of 86% of total primary energy use and 88% of the GWP effect. The abiotic resource depletion and to some extent water use were driven by other inputs to the product systems.

Table 35. Dominance Analysis: ½" Regular GWB Product System – absolute basis, per MSF



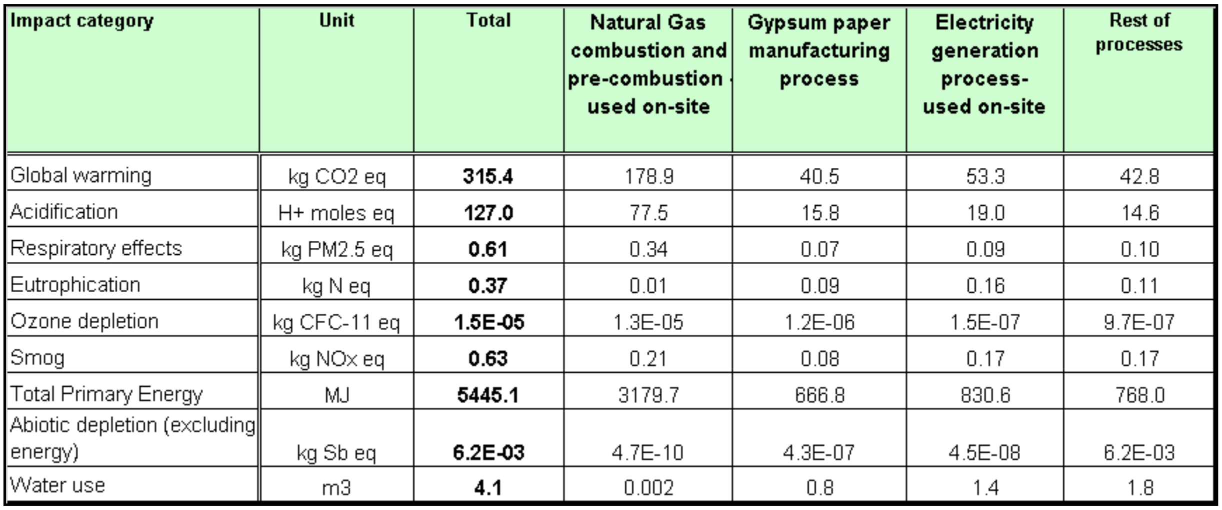
Impact category	**Unit**	**Total**	**Natural Gas combustion and pre-combustion - used on-site**	**Gypsum paper manufacturing process**	**Electricity generation process- used on-site**	**Rest of processes**
Global warming	kg CO2 eq	**233.3**	126.4	40.5	37.5	29.0
Acidification	H+ moles eq	**93.9**	54.8	15.8	13.4	9.9
Respiratory effects	kg PM2.5 eq	**0.45**	0.24	0.07	0.07	0.07
Eutrophication	kg N eq	**0.30**	0.01	0.09	0.11	0.09
Ozone depletion	kg CFC-11 eq	**1.1E-05**	8.8E-06	1.2E-06	1.0E-07	6.2E-07
Smog	kg NOx eq	**0.47**	0.15	0.08	0.12	0.12
Total Primary Energy	MJ	**4051.4**	2245.9	666.8	584.6	554.0
Abiotic depletion (excluding energy)	kg Sb eq	**4.3E-03**	3.3E-10	4.3E-07	3.2E-08	4.3E-03
Water use	m3	**3.1**	0.001	0.8	1.0	1.3

Table 36 Dominance Analysis: ½" Regular GWB Product System – percent basis, per MSF



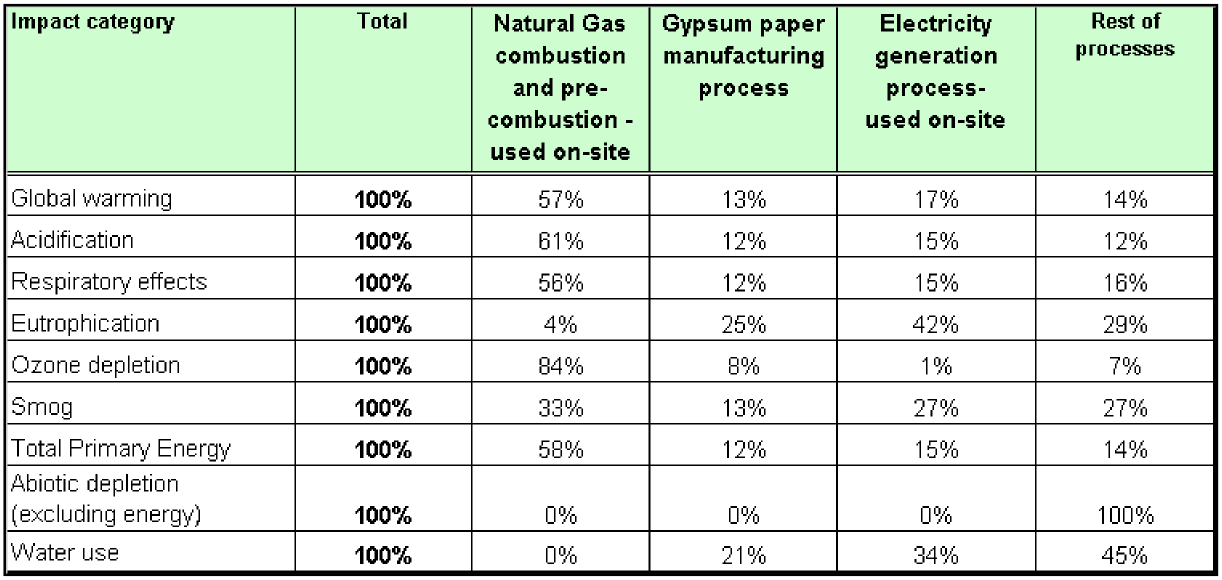
Impact category	Total	Natural Gas combustion and pre-combustion - used on-site	Gypsum paper manufacturing process	Electricity generation process- used on-site	Rest of processes
Global warming	**100%**	54%	17%	16%	12%
Acidification	**100%**	58%	17%	14%	11%
Respiratory effects	**100%**	54%	16%	15%	15%
Eutrophication	**100%**	3%	30%	36%	31%
Ozone depletion	**100%**	82%	12%	1%	6%
Smog	**100%**	31%	18%	26%	25%
Total Primary Energy	**100%**	55%	16%	14%	14%
Abiotic depletion (excluding energy)	**100%**	0%	0%	0%	100%
Water use	**100%**	0%	27%	32%	41%

Table 37 Dominance Analysis: $^5/_8$" Type X GWB Product System– absolute basis, per MSF



Impact category	Unit	Total	Natural Gas combustion and pre-combustion used on-site	Gypsum paper manufacturing process	Electricity generation process- used on-site	Rest of processes
Global warming	kg CO2 eq	**315.4**	178.9	40.5	53.3	42.8
Acidification	H+ moles eq	**127.0**	77.5	15.8	19.0	14.6
Respiratory effects	kg PM2.5 eq	**0.61**	0.34	0.07	0.09	0.10
Eutrophication	kg N eq	**0.37**	0.01	0.09	0.16	0.11
Ozone depletion	kg CFC-11 eq	**1.5E-05**	1.3E-05	1.2E-06	1.5E-07	9.7E-07
Smog	kg NOx eq	**0.63**	0.21	0.08	0.17	0.17
Total Primary Energy	MJ	**5445.1**	3179.7	666.8	830.6	768.0
Abiotic depletion (excluding energy)	kg Sb eq	**6.2E-03**	4.7E-10	4.3E-07	4.5E-08	6.2E-03
Water use	m3	**4.1**	0.002	0.8	1.4	1.8

Table 38. Dominance Analysis: $^5/_8$" Type X GWB Product System– percent basis, per MSF

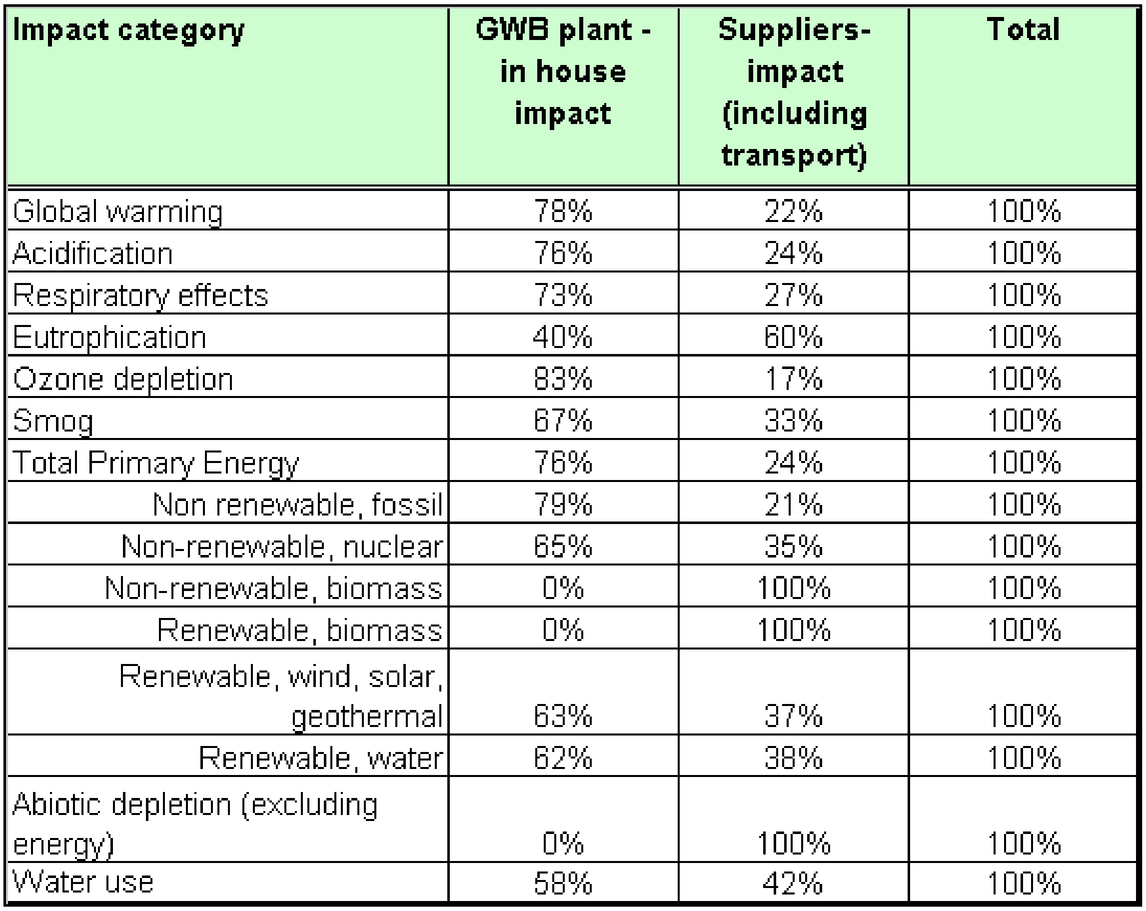


Impact category	Total	Natural Gas combustion and pre-combustion - used on-site	Gypsum paper manufacturing process	Electricity generation process- used on-site	Rest of processes
Global warming	**100%**	57%	13%	17%	14%
Acidification	**100%**	61%	12%	15%	12%
Respiratory effects	**100%**	56%	12%	15%	16%
Eutrophication	**100%**	4%	25%	42%	29%
Ozone depletion	**100%**	84%	8%	1%	7%
Smog	**100%**	33%	13%	27%	27%
Total Primary Energy	**100%**	58%	12%	15%	14%
Abiotic depletion (excluding energy)	**100%**	0%	0%	0%	100%
Water use	**100%**	0%	21%	34%	45%

6.1.2 Influence Analysis

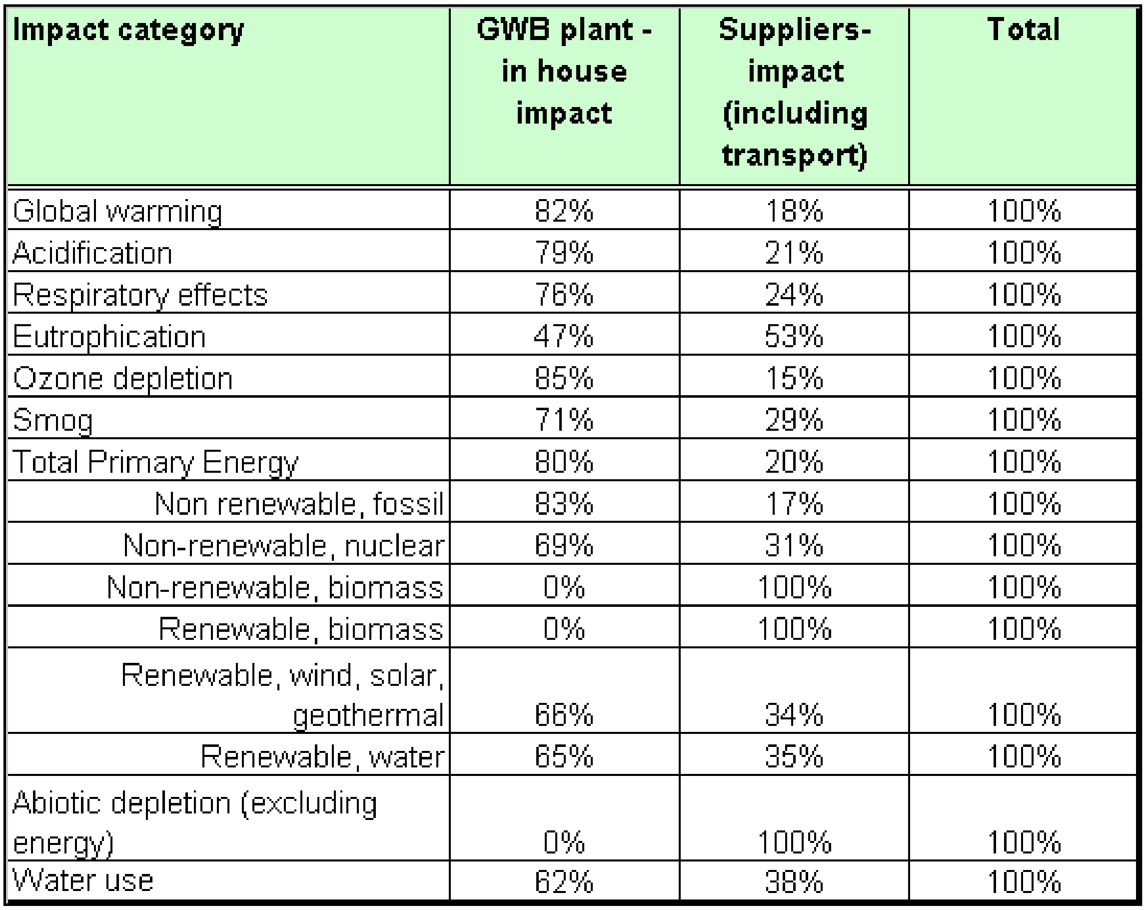
Table 39 and 40 depict the results of the cradle-to-gate influence analysis by impact category for the ½" Regular and $^5/_8$" Type X GWB product systems. The influence analysis conducted for this project shows the degree to which the various LCIA results are controlled by the GWB plant as opposed to the suppliers of inputs to the plant (both materials and energy). With the exception of water use and eutrophication potential, the analysis indicates that about 78% of the LCIA results are within the sphere of the GWB plant's control and 22% of the impacts are due to upstream suppliers over which the plants may have limited control. The difference between the two product systems (½" Regular and $^5/_8$" Type X) is minimal, but consistently about 4% - with the $^5/_8$" Type X product influenced less by suppliers, reflecting a slightly higher impact of on-site energy consumption and air emissions to the total environmental impact.

Table 39. Influence Analysis: ½" Regular GWB Product System– percent basis, per MSF



Impact category	**GWB plant - in house impact**	**Suppliers- impact (including transport)**	**Total**
Global warming	78%	22%	100%
Acidification	76%	24%	100%
Respiratory effects	73%	27%	100%
Eutrophication	40%	60%	100%
Ozone depletion	83%	17%	100%
Smog	67%	33%	100%
Total Primary Energy	76%	24%	100%
Non renewable, fossil	79%	21%	100%
Non-renewable, nuclear	65%	35%	100%
Non-renewable, biomass	0%	100%	100%
Renewable, biomass	0%	100%	100%
Renewable, wind, solar, geothermal	63%	37%	100%
Renewable, water	62%	38%	100%
Abiotic depletion (excluding energy)	0%	100%	100%
Water use	58%	42%	100%

Table 40. Influence Analysis: $^5/_8$" Type X GWB Product System– percent basis, per MSF

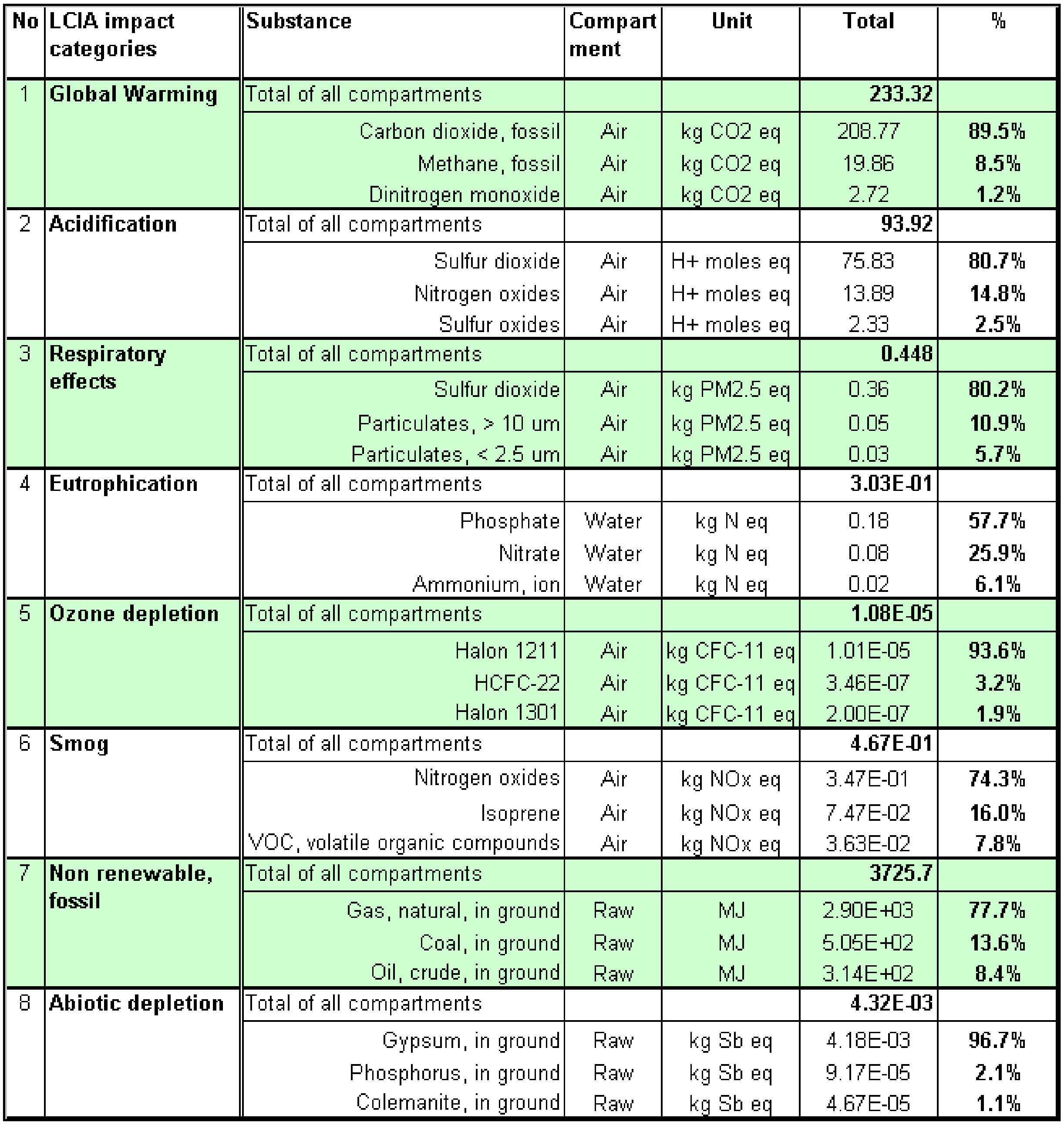


Impact category	GWB plant - in house impact	Suppliers- impact (including transport)	Total
Global warming	82%	18%	100%
Acidification	79%	21%	100%
Respiratory effects	76%	24%	100%
Eutrophication	47%	53%	100%
Ozone depletion	85%	15%	100%
Smog	71%	29%	100%
Total Primary Energy	80%	20%	100%
Non renewable, fossil	83%	17%	100%
Non-renewable, nuclear	69%	31%	100%
Non-renewable, biomass	0%	100%	100%
Renewable, biomass	0%	100%	100%
Renewable, wind, solar, geothermal	66%	34%	100%
Renewable, water	65%	35%	100%
Abiotic depletion (excluding energy)	0%	100%	100%
Water use	62%	38%	100%

6.1.3 Contribution Analysis

In the framework of the interpretation phase, substance contribution analysis is conducted and consists of identifying the three major contributing substances/flows per each selected LCIA impact category. Table 41 provides an LCIA indicator substance contribution summary, which highlights the contributing substance flows to the total cradle-to-gate indicator outcome. For example, just three greenhouse gases (carbon dioxide-CO_2, methane-CH_4 and nitrous oxide-N_2O) were responsible for over 99% of the global warming potential. Gypsum (in ground) is responsible for 97% of the abiotic resource depletion for the ½" Regular GWB product system. Nitrogen oxides (NO_x) is responsible for 74%% of the overall smog potential and sulfur dioxide (SO_2) and particulate air emissions were the main contributors to the respiratory effects potential indicators (99%).

Table 41. Substance Contribution Analysis: ½"Regular GWB Product System–Absolute and percent basis, per MSF



No	LCIA impact categories	Substance	Compartment	Unit	Total	%
1	**Global Warming**	Total of all compartments			**233.32**	
		Carbon dioxide, fossil	Air	kg CO2 eq	208.77	**89.5%**
		Methane, fossil	Air	kg CO2 eq	19.86	**8.5%**
		Dinitrogen monoxide	Air	kg CO2 eq	2.72	**1.2%**
2	**Acidification**	Total of all compartments			**93.92**	
		Sulfur dioxide	Air	H+ moles eq	75.83	**80.7%**
		Nitrogen oxides	Air	H+ moles eq	13.89	**14.8%**
		Sulfur oxides	Air	H+ moles eq	2.33	**2.5%**
3	**Respiratory effects**	Total of all compartments			**0.448**	
		Sulfur dioxide	Air	kg PM2.5 eq	0.36	**80.2%**
		Particulates, > 10 um	Air	kg PM2.5 eq	0.05	**10.9%**
		Particulates, < 2.5 um	Air	kg PM2.5 eq	0.03	**5.7%**
4	**Eutrophication**	Total of all compartments			**3.03E-01**	
		Phosphate	Water	kg N eq	0.18	**57.7%**
		Nitrate	Water	kg N eq	0.08	**25.9%**
		Ammonium, ion	Water	kg N eq	0.02	**6.1%**
5	**Ozone depletion**	Total of all compartments			**1.08E-05**	
		Halon 1211	Air	kg CFC-11 eq	1.01E-05	**93.6%**
		HCFC-22	Air	kg CFC-11 eq	3.46E-07	**3.2%**
		Halon 1301	Air	kg CFC-11 eq	2.00E-07	**1.9%**
6	**Smog**	Total of all compartments			**4.67E-01**	
		Nitrogen oxides	Air	kg NOx eq	3.47E-01	**74.3%**
		Isoprene	Air	kg NOx eq	7.47E-02	**16.0%**
		VOC, volatile organic compounds	Air	kg NOx eq	3.63E-02	**7.8%**
7	**Non renewable, fossil**	Total of all compartments			**3725.7**	
		Gas, natural, in ground	Raw	MJ	2.90E+03	**77.7%**
		Coal, in ground	Raw	MJ	5.05E+02	**13.6%**
		Oil, crude, in ground	Raw	MJ	3.14E+02	**8.4%**
8	**Abiotic depletion**	Total of all compartments			**4.32E-03**	
		Gypsum, in ground	Raw	kg Sb eq	4.18E-03	**96.7%**
		Phosphorus, in ground	Raw	kg Sb eq	9.17E-05	**2.1%**
		Colemanite, in ground	Raw	kg Sb eq	4.67E-05	**1.1%**

6.2 Completeness, Consistency and Sensitivity Checks

Evaluating the study's completeness, consistency and sensitivity helps to establish and enhance confidence in, and the reliability of, the results of the LCA study, including the significant issues identified in the first element of the interpretation [2].

The objective of the ***completeness check*** is to ensure that all relevant information and data needed for the interpretation are available and complete [2]. Three selected production systems (gypsum wallboard, gypsum paper and natural gypsum extraction) were checked for data completeness including all elements such as raw and ancillary material input, energy input, transportation, water consumption, product and co-products outputs, emissions to air, water and land and waste disposal. All the input and output data were found to be complete and no data gaps were identified along the three selected production systems or between the products of interest such as ½" Regular and $^5/_8$" Type X GWB or backing and facing gypsum paper.

The objective of the ***consistency check*** is to determine whether the assumptions, methods, models and data are consistent with the goal and scope of the study [2]. Through a rigorous iterative process, consistency was ensured between the ½" Regular and $^5/_8$" Type X GWB production systems in terms of assumptions, methods, models and data quality including data source, accuracy, data age, time-related coverage, technology and geographical coverage (see Section 3.3 Data Quality).

6.2.1 Sensitivity Checks

A sensitivity check is defined, as process of verifying that the information obtained from a sensitivity analysis is relevant for reaching the conclusions and making recommendations. *Sensitivity analysis* tries to determine the influence of variations in assumptions, methods and data on the results of the study [2]. Sensitivity analysis is a procedural comparison of the results obtained using baseline assumptions, methods or data with the results obtained using altered assumptions, methods or data. Sensitivity analysis was conducted on two key production parameters – the relative mix of natural gypsum rock and synthetic FGD gypsum used to produce GWB and the source of the natural gypsum against underlying industry norms (6.2.1.1

and 6.2.1.2). Sensitivity of the LCIA results to a change in “on-site energy consumption” within the GWB plant by fuel type is also investigates and presented in section 6.2.1.3. Section 6.2.1.4 shows the results of a sensitivity analysis of the “system expansion/ avoided burden” approach used in this LCA study relative to a “cut-off” approach to solve the “multi-functionality” of coal-fired power generation process to calculate the environmental profile of the synthetic FGD gypsum input, a co-product of coal power plant.

6.2.1.1 Sensitivity Analysis- 50/50 Mix of Natural and Synthetic FGD Gypsum

As little as a decade ago, synthetic FGD gypsum use represented only 20% of total gypsum input in the manufacture of gypsum wallboard. The Gypsum Association’s records, and statistics suggest, that the mix of natural and synthetic FGD gypsum use in the US is now about 50/50[6]. The weighted average sample of GWB plants participating in this study attained an overall 41/59 mix of natural to synthetic FGD gypsum use. In order to better understand the influence of a change in the source type of gypsum, a sensitivity analysis was performed whereby the gypsum inputs were recast as a 50/50 mix of natural and synthetic FGD gypsum – an approximately 10% change in the mix of gypsum inputs.

Table 42 summarizes the LCIA results of the sensitivity analysis for an approximate 10% change in the mix of natural to synthetic gypsum on the ½” Regular GWB cradle-to-gate product system. The first “Baseline total” column reflects the cradle-to gate results of the ½” Regular GWB baseline scenario which consists of the weighted average mix of 41/59 natural to synthetic FGD (see Table 21). The second “Sensitivity total” column reports the cradle-to gate results of the ½” Regular GWB sensitivity scenario assuming a 50/50 mix of natural to synthetic FGD. The sensitivity results indicated that an approximately 10% increase in the use of natural gypsum with a corresponding decrease in the use of synthetic FGD gypsum would amount to a 2% increase in the overall indicator results for the ½” Regular GWB product system with the exception of the abiotic resource depletion and smog potential which increased by 20% and 9% respectively. Similar conclusions are applicable to the $^{5}/_{8}$” Type X GWB product system.

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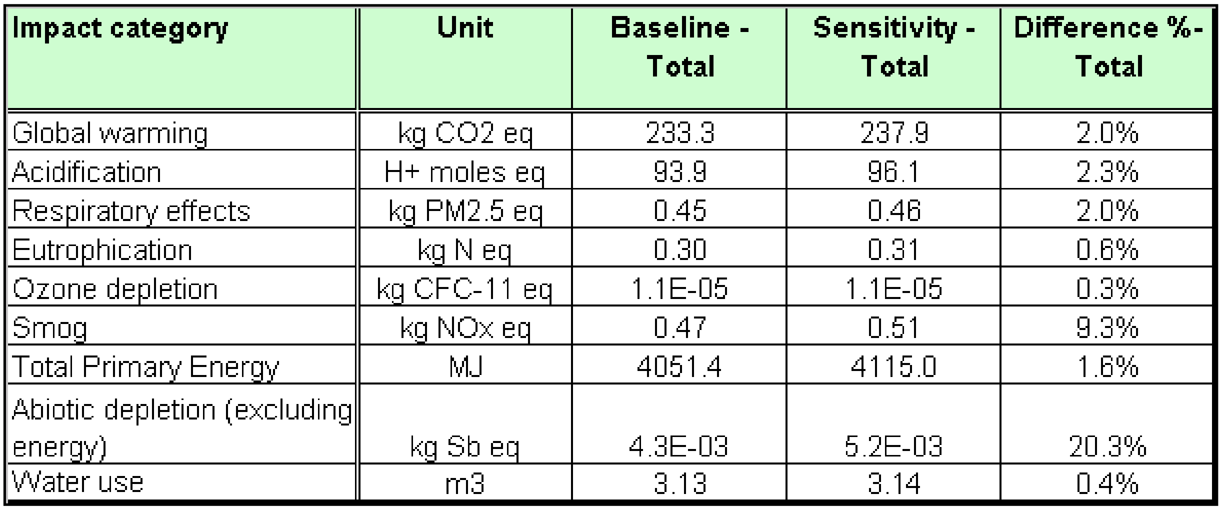
[6] See http://www.gypsumsustainability.org/recycled.html

Table 42 Sensitivity Analysis: Change of the Baseline from 41/59 to 50/50 natural to synthetic FGD mix- ½" Regular GWB Product System– absolute and percent basis, per MSF



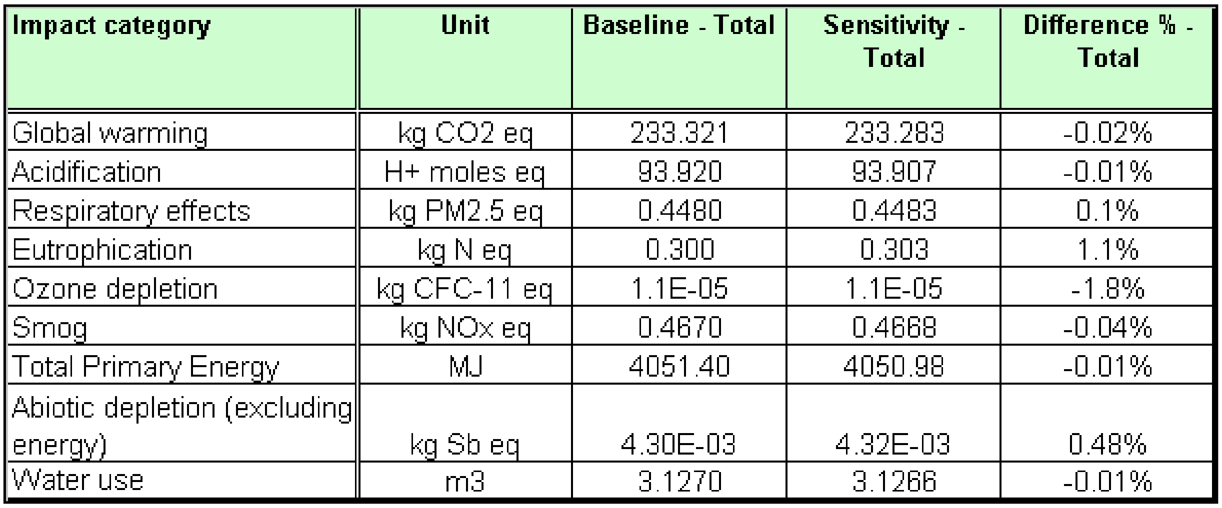
Impact category	Unit	Baseline - Total	Sensitivity - Total	Difference %- Total
Global warming	kg CO2 eq	233.3	237.9	2.0%
Acidification	H+ moles eq	93.9	96.1	2.3%
Respiratory effects	kg PM2.5 eq	0.45	0.46	2.0%
Eutrophication	kg N eq	0.30	0.31	0.6%
Ozone depletion	kg CFC-11 eq	1.1E-05	1.1E-05	0.3%
Smog	kg NOx eq	0.47	0.51	9.3%
Total Primary Energy	MJ	4051.4	4115.0	1.6%
Abiotic depletion (excluding energy)	kg Sb eq	4.3E-03	5.2E-03	20.3%
Water use	m3	3.13	3.14	0.4%

6.2.1.2 Sensitivity Analysis- 70/30 Mix of Natural Gypsum Imports from Canada/Mexico

A second sensitivity analysis was performed to determine the influence of variations of the source of imported natural gypsum on the GWB product system – again using the ½" Regular GWB product system as the basis for the analysis. The baseline study indicated a mix of imported raw gypsum rock that was sourced almost exclusively from Mexico (99%). The Mineral Yearbook statistics indicate that Canada is the primary source of gypsum imports (66%) with imports from Mexico accounting for roughly 26%, Spain 7% and the remaining 1% from other countries [11]. A possible reason for this study's departure from the national gypsum import statistics was the fact that in the process of selecting a geographical and technological representative plant sample, more plants were located in the southwest region, where they source their imported gypsum from Mexico. To determine the significance of a change in gypsum import source, the imported natural gypsum inputs were reset with Canada and Mexico as the source regions for 70% and 30% of imports, respectively. A limitation of this sensitivity analysis was that, while the baseline study results reflect natural gypsum mining and quarrying activities, the only difference modeled for the two import countries was the source electricity grid (Canada's and Mexico's). However, this limitation may not be significant given that diesel fuel use was the largest energy input in the production of natural gypsum and would likely have a similar influence in either Canada or Mexico.

The sensitivity results indicated that the source location of the natural gypsum input had a minimal influence (<1%) on the LCIA results reported for the ½” Regular GWB product system (Table 43). While Canada’s electricity grid is cleaner than Mexico’s (less reliance on fossil fuels used to generate and deliver electricity), quarrying itself was not found to be an electricity use intensive operation. As a result, the baseline results are not significantly influenced by a significant change in the source region and may well adequately reflect the statistics reported by the Minerals Yearbook. Similar conclusions are applicable to the $^{5}/_{8}$” Type X GWB product system.

Table 43. Sensitivity Analysis: 70%/30% of Natural Gypsum Imports from Canada/Mexico - ½” Regular GWB Product System LCIA Results – absolute basis and percent, per MSF



Impact category	**Unit**	**Baseline - Total**	**Sensitivity - Total**	**Difference % - Total**
Global warming	kg CO2 eq	233.321	233.283	-0.02%
Acidification	H+ moles eq	93.920	93.907	-0.01%
Respiratory effects	kg PM2.5 eq	0.4480	0.4483	0.1%
Eutrophication	kg N eq	0.300	0.303	1.1%
Ozone depletion	kg CFC-11 eq	1.1E-05	1.1E-05	-1.8%
Smog	kg NOx eq	0.4670	0.4668	-0.04%
Total Primary Energy	MJ	4051.40	4050.98	-0.01%
Abiotic depletion (excluding energy)	kg Sb eq	4.30E-03	4.32E-03	0.48%
Water use	m3	3.1270	3.1266	-0.01%

6.2.1.3 Sensitivity Analysis- On-site energy consumption

A third sensitivity analysis was constructed around “on-site energy consumption” at the GWB plant – by far the most significant contributor to the LCIA results for both GWB product systems. The weighted average energy use for ½-inch Regular product result was dominated by the use of electricity (47 kWh/MSF) and natural gas (1820 ft.^{3}/MSF) at the GWB plant. A statistical analysis of the 17 GWB plants that participated in the study indicated that 71% of the sample fell within a range of +/- 21% (coefficient of variation[7] of the electricity data sample) and 76% of the plant sample were within +/- 16% (coefficient of variation of the natural gas data sample) for

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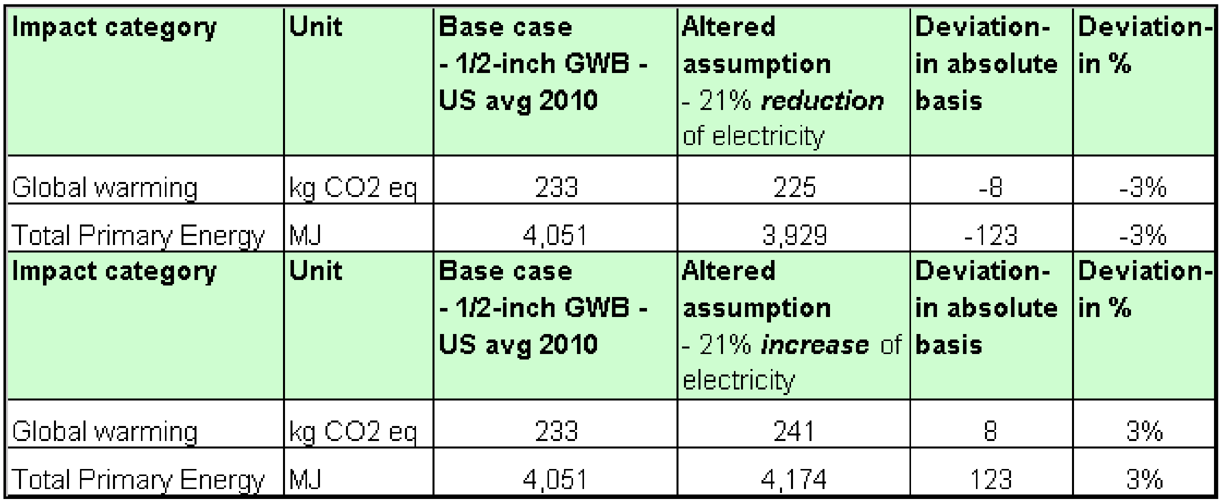
[7] The coefficient of variation COV is the ratio of the standard deviation to the arithmetic mean, and represents a normalized measure of the dispersion of the sample data,

both ½” Regular and $^{5}/_{8}$” Type X GWB products. The sensitivity analysis considered the extent to which a 21% and 16% change in electricity and natural gas usage (respectively and separately) would have on the LCIA for the ½” Regular GWB product system.

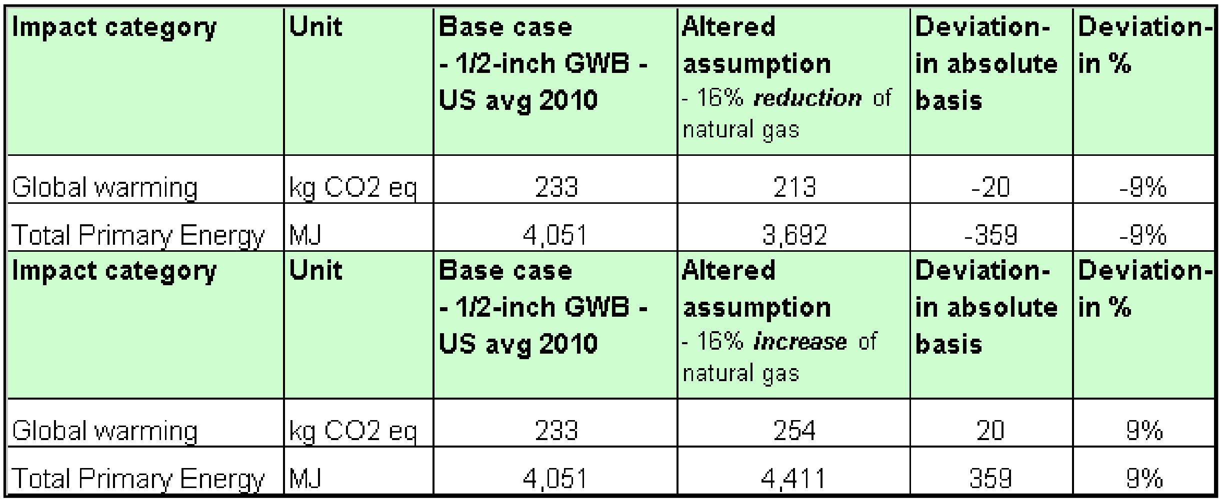
Tables 44 and 45 summarize the sensitivity of the global warming potential indicator (greenhouse gas emissions) and primary energy use LCIA results associated with a 21% and 16% change in the use of electricity and natural gas for the ½” Regular GWB product system (cradle-to-gate). The results indicate an equal and proportional change in both global warming potential (GWP) and total primary energy use (TPE) and they are symmetric with either a decrease or increase in a specific fuel usage. The sensitivity analysis indicated that a 21% change in plant electricity use would result in a 3% change in GWP and TPE for the product system (see Table 44). However, a 16% change in natural gas use would result in a 9% change in GWP and TPE (see Table 45). Plant energy use was about three times more sensitive to natural gas use than electricity use; therefore GWB Plant energy conservation efforts should first be directed at the possibility reducing natural gas use. Similar conclusions are applicable for the $^{5}/_{8}$” Type X GWB product system.

Table 44. Sensitivity Analysis: 18% Change in GWB Plant Electricity Use- ½” Regular GWB Product System - GWP and TPE LCIA Results – absolute and percent basis, per MSF



Impact category	**Unit**	**Base case - 1/2-inch GWB - US avg 2010**	**Altered assumption** - 21% ***reduction*** of electricity	**Deviation- in absolute basis**	**Deviation- in %**
Global warming	kg CO2 eq	233	225	-8	-3%
Total Primary Energy	MJ	4,051	3,929	-123	-3%
Impact category	**Unit**	**Base case - 1/2-inch GWB - US avg 2010**	**Altered assumption** - 21% ***increase*** of electricity	**Deviation- in absolute basis**	**Deviation- in %**
Global warming	kg CO2 eq	233	241	8	3%
Total Primary Energy	MJ	4,051	4,174	123	3%

Table 45. Sensitivity Analysis: 16% Change in GWB Plant Natural Gas Use - ½" Regular GWB Product System- GWP and TPE LCIA Results– absolute and percent basis, per MSF



Impact category	**Unit**	**Base case - 1/2-inch GWB - US avg 2010**	**Altered assumption** - 16% ***reduction*** of natural gas	**Deviation- in absolute basis**	**Deviation- in %**
Global warming	kg CO2 eq	233	213	-20	-9%
Total Primary Energy	MJ	4,051	3,692	-359	-9%

Impact category	**Unit**	**Base case - 1/2-inch GWB - US avg 2010**	**Altered assumption** - 16% ***increase*** of natural gas	**Deviation- in absolute basis**	**Deviation- in %**
Global warming	kg CO2 eq	233	254	20	9%
Total Primary Energy	MJ	4,051	4,411	359	9%

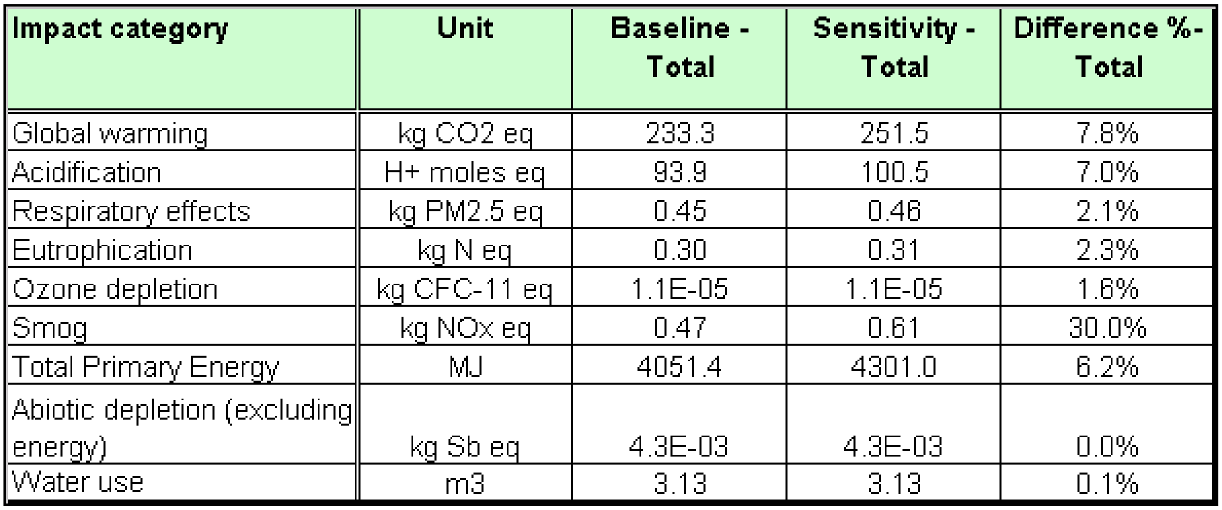
6.2.1.4 Sensitivity Analysis- FGD system expansion approach

A fourth sensitivity analysis was conducted around the system expansion/ avoided burden approach to solve the "multi-functionality" of coal-fired power generation process and calculate the environmental profile of the FGD synthetic gypsum, a co-product of coal power plant. Based on system expansion/ avoided burden approach, the reported baseline results included the "*dewatering*" of FGD gypsum and its "*transport*" to the GWB plant, but also credited the FGD gypsum system with the avoidance of the "*FGD landfilling*" process.

As presented in Section 3.2.4 Allocation procedures and Appendix A, it's not possible to find pure physical causal or economic relationship between the product and co-product of the multi-functional coal-fired power generation process. The sensitivity analysis uses a *"cut-off" approach* and considers only the "*dewatering*" of FGD gypsum and its "*transport*" to the GWB plants. That is, no FGD landfilling "credit" and "burden" is applied to the GWB production system and coal-fired electricity generation system, respectively. It should be noted that using a "cut-off" approach is not recommended by ISO, but it's a simple approach used by LCA practitioners in classical LCA studies (known as Situation C2 [5]).

Table 46 depicts the sensitivity of the LCIA results when using the “cut-off” approach for the ½” Regular GWB cradle-to-gate product system. The sensitivity analysis indicated that the overall effect on the LCIA results for the ½” Regular GWB cradle-to-gate product system would be marginally higher. With the exception of the smog potential indicator, the LCIA results for the product system increased between 0% and 8%. In this sensitivity scenario, the FGD synthetic gypsum is now contributing to an increase in the environmental burden as opposed to an offset in the baseline result for the ½”Regular GWB cradle-to-gate product system. Similar conclusions would be applicable to the $^5/_8$” Type X GWB product system. This sensitivity analysis does not call into question the validity of the ISO 14044:2006 recommended methodology for using a “system expansion” approach, but rather indicates the power and appropriateness of this methodology to solve the multi-functionality problem associated with the coal-fired power generation process and thus, providing a reasonable estimate of the respective environmental burden of electricity generation (determining product) and FGD synthetic gypsum (co-product).

Table 46. Sensitivity Analysis: Exclusion of “System Expansion Avoidance” Effect - ½” Regular GWB Product System– absolute basis, per MSF



Impact category	Unit	Baseline - Total	Sensitivity - Total	Difference %- Total
Global warming	kg CO2 eq	233.3	251.5	7.8%
Acidification	H+ moles eq	93.9	100.5	7.0%
Respiratory effects	kg PM2.5 eq	0.45	0.46	2.1%
Eutrophication	kg N eq	0.30	0.31	2.3%
Ozone depletion	kg CFC-11 eq	1.1E-05	1.1E-05	1.6%
Smog	kg NOx eq	0.47	0.61	30.0%
Total Primary Energy	MJ	4051.4	4301.0	6.2%
Abiotic depletion (excluding energy)	kg Sb eq	4.3E-03	4.3E-03	0.0%
Water use	m3	3.13	3.13	0.1%

6.3 Conclusions, limitations and recommendations

The study's major conclusions for the two GWB finished product systems and each intermediate reference flow input (natural gypsum extraction and gypsum paper production) is reported below.

½" Regular and $^5/_8$" Type X Gypsum Wallboard (cradle-to-gate)

- The manufacture of 1,000 sq. ft. of ½" Regular and $^5/_8$" Type X GWB products embodies about 4.05 GJ and 5.45 GJ of primary energy use. For both GWB product types, over 90% of the total primary energy were derived from non-renewable fossil fuels. Over 76% of the primary energy use was due to the "on-site" consumption of energy at the GWB plants in the form of natural gas (73%), electricity (19%) and gasoline (8%) with diesel and propane use making up less than 1%.
- The manufacture of 1,000 sq. ft. of ½" Regular and $^5/_8$" Type X GWB products resulted to 233 kg and 315 kg (CO2 equivalent) of greenhouse gas emissions, respectively. On-site energy use was also the primary source of the greenhouse gas emissions accounting for over 78% of the total.
- Two major on-site energy flows used at GWB plants (natural gas and electricity) and the input of gypsum paper were the *three* major contributing sources to the cradle-to-gate life cycle impact assessment (LCIA) results for the two products of interest.
- On-site energy use was the single largest contributor to the majority of the LCIA category results for the products of interest such as total primary energy, global warming, acidification, respiratory effects, ozone depletion and smog and accounted; typically accounting for greater than 70% of the total impact results across the two products.
- The input of gypsum paper was the next most consistent and significant contributor to the majority of the LCIA category results (excluding abiotic resource depletion) and ranged from 8% to 30% of the total impact results for the two product systems.
- Dry and wet additives in the production of GWB products accounted for 25% to 27% of the total eutrophication potential impact. The contribution to the rest of the LCIA category results ranged from 3% to 11% of the total impact results for the two product systems.

- Inbound transportation of raw and ancillary materials and the outbound transportation of wastes for treatment accounted for 32% to 33% of the smog potential. The contribution to the rest of the LCIA category results ranged from 0% to 8% of the total impact results for the two products.
- The contribution of the natural gypsum extraction system (both domestic & imported) to the depletion of abiotic resources potential was 98%. The contribution to the rest of the LCIA category results ranged from 0.3% to 8% of the total impact results for the two products.
- The net impact of the FGD synthetic gypsum use resulted in a beneficial credit to the product system due to the diversion or avoidance of landfilling FGD gypsum. With the exception of the smog potential indicator, the reduction of the environmental burden attributed to synthetic FGD gypsum use across the majority of the LCIA category results was rather minimal (ranging between 1% and 8%).
- While on-site natural gas use, gypsum paper and on-site electricity use dominated the resulting GWB environmental profile, an influence analysis indicated that 78% to 82% of the total LCIA results are within the plant's sphere of operational control. A sensitivity analysis of "on-site energy use" indicated that plant energy use is about three times more sensitive to the use of natural gas than electricity.
- The results indicated that the source location of the natural gypsum input (Canada or Mexico) had a minimal influence (<1%) on the LCIA results reported for the ½" Regular GWB product system. Similar conclusions are applicable to the $^5/_8$" Type X GWB product system.
- The results indicated that a 10% increase in the use of natural gypsum with a corresponding decrease in the use of synthetic FGD gypsum would result in about a 2% increase of the overall LCIA indicator results for the ½" Regular GWB product system with the exception of the abiotic resource depletion and smog potential which would increased by 20% and 9%, respectively. Similar conclusions are again applicable to the $^5/_8$" Type X GWB product system.

Natural Gypsum Rock Extraction (cradle-to-gate)

- The total primary energy use in the manufacture of one short ton of natural gypsum ore was 169 MJ and was dominated by the on-site energy use (90%), of which diesel, natural gas and electricity use accounted for 46%, 44% and 10%, respectively.
- The production of each short ton of natural gypsum ore results in the emission of 11.4 kg of greenhouse gases on a CO_2 equivalent basis. On-site energy use was also the primary source of the greenhouse gas emissions accounting for 83% of the total.
- On-site energy use was the major contributor to the acidification (94%), eutrophication (86%) and smog potential indicators (96%).
- On-site processes were the largest main contributing process to the respiratory effects indicator (89%), and abiotic depletion (100%), which is a direct impact of the crude gypsum extraction and water use (99%).

Gypsum Paper Production (cradle-to-gate)

- The cradle-to-gate manufacture of gypsum paper is entirely based on the input of post-industrial and consumer recycled papers, of which old corrugated container stock was the primary raw material input.
- The manufacture of 1,000 sq. ft of backing and facing gypsum papers incorporates about 322 MJ and 345 MJ of primary energy, respectively. Over 90% of the primary energy use was due to the consumption of energy at the gypsum paper plant in the form of electricity (52%) and natural gas (47%) with diesel and propane use making up less than 1% of the total energy use.
- The manufacture of 1,000 sq. ft of backing and facing gypsum papers resulted in the emission of 20 kg and 21 kg of greenhouse gases on a CO2 equivalent basis. On-site energy use was also the primary source of the greenhouse gas emissions accounting for 90% of the total.
- On-site energy use was the major contributor to the acidification potential (over 92%), respiratory effects (94%), smog (over 80%) and ozone depletion potential (94%).
- On-site processes and energy use were two main contributors to water use, over 50% and 41% respectively. Waste disposal and treatment accounted for 50% of the eutrophication impact primarily due to the treatment of effluent flows.

- Gypsum paper manufacturing involves numerous and varied chemical inputs; however, these chemicals account for less than one percent of the total mass of inputs and were a relatively minor contributor to the overall LCIA results for the manufacture of gypsum papers with the exception of the abiotic depletion impact which amounted to over 55%.

Limitations

- Human toxicity and eco-toxicity impact categories related to the product systems studied were not evaluated as these end-point LCIA measures were deemed as "optional" measures in ISO 21930:2007 "Sustainability in Building Construction – Environmental Declaration of Building Products". It's to be mentioned that "uncertainty" of the results increases, often exponentially, with movement from mid-point to end-point measures. Therefore, these end-point measures have been excluded from this study.
- Land use (and its occupation), as a possible impact category, was also not evaluated in this LCA study. There is currently no North American based platform to collect or measure these flows, let alone characterize them. So far, the US LCI generic datasets used in this project do not report these flows. Furthermore, the land use and occupation impact category is not advocated by ISO 21930:2007. Hence, for a number of reasons land use was excluded from the scope of this study.
- This study scope was limited to a cradle-to-gate Life Cycle Assessment of ½" Regular and $^5/_8$" Type X GWB products and did not integrate the installation, maintenance, use phase and end of life activity stages associated with the product system. Consequently, the impact of these downstream life cycle activities is not captured in this LCA study.

Recommendations

- The journey toward sustainable development requires that businesses find innovative ways to be profitable and at the same time improve the environmental performance of production processes and products through:
  - Cleaner production processess → Resource saving/ Margins
  - Environmental management →Continual improvements/ Reputation
  - Clean and sustainable products → Competitive advantage/ Revenues

Reducing the dependency on earth's natural resources (e.g. natural gypsum ore) by incorporating the FGD synthetic gypsum, which is diverted from landfill, contributes to an improved environmental profile for GWB products. This sustainability aspect should be further explored by taking into consideration the social and economic dimensions ("triple bottom line") of synthetic FGD gypsum use and how it has and may positively influence the sustainability of the industry in the future.

- "On-site" energy conservation efforts at GWB facilities are strongly recommended. The study results indicate that "on-site" energy use is the single largest contributor to the overall LCIA results and these results are particularly sensitive to changes in on-site energy use. More specifically, efforts to reduce natural gas use offer the most immediate opportunity to improve the environmental performance of GWB plants and products. Gypsum quarries conservation efforts should target the reduction of diesel fuel and natural gas use. Gypsum paper plants energy conservation efforts should be directed to the reduction of the electricity and natural gas use.
- As mentioned previously, the study's scope was limited to the cradle-to-gate manufacture of the two GWB products of interest. A logical expansion of the study would be to extend it to a full cradle-to-grave assessment, which would better demonstrate the full life cycle impact of these two GWB products by including their respective service lives, possible recyclability and end-of-life. The possibility of having a Gypsum Association level EPD prepared for the two products of interest is also recommended.

7 References

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4 ISO/TR 14049: Environmental management — Life cycle assessment — Examples of application of ISO 14041 to goal and scope definition and inventory analysis

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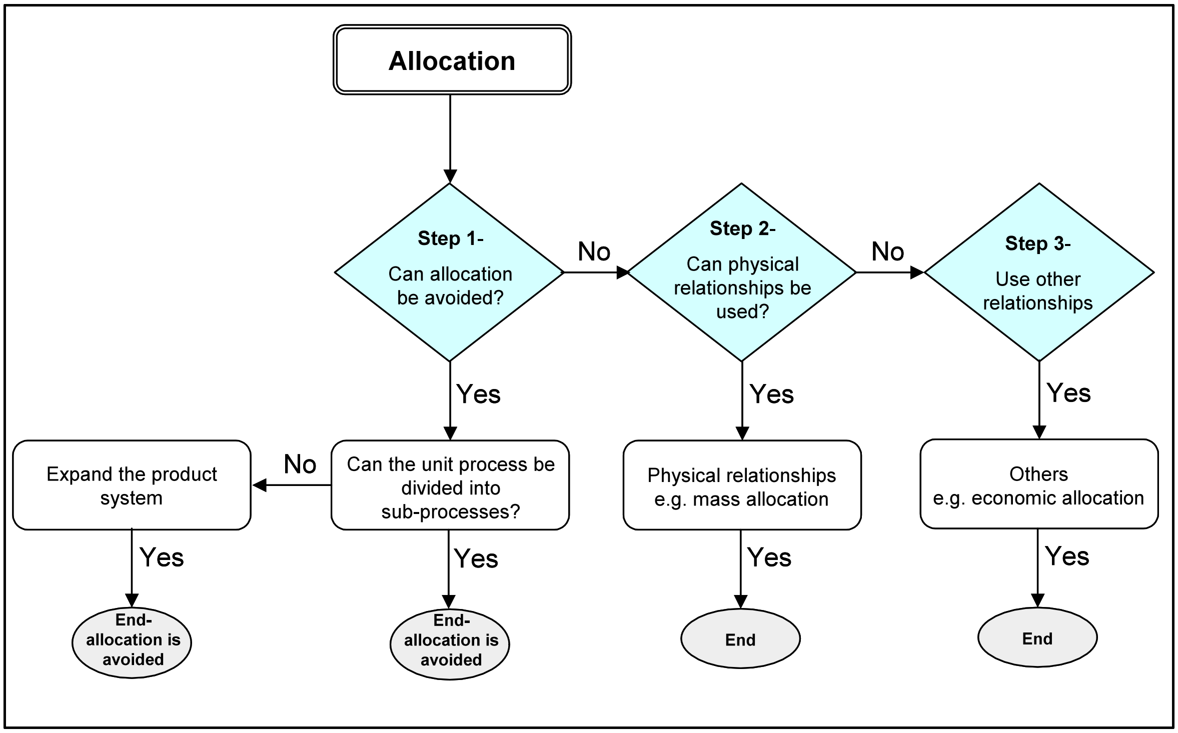
Appendices

Appendix A :

Case Studies on Allocation Procedures

Figure A.1 depicts the ISO recommended stepwise allocation procedures as per Clause 4.3.4.2, ISO 14044:2006.

Figure A.1 Overview of the allocation procedures



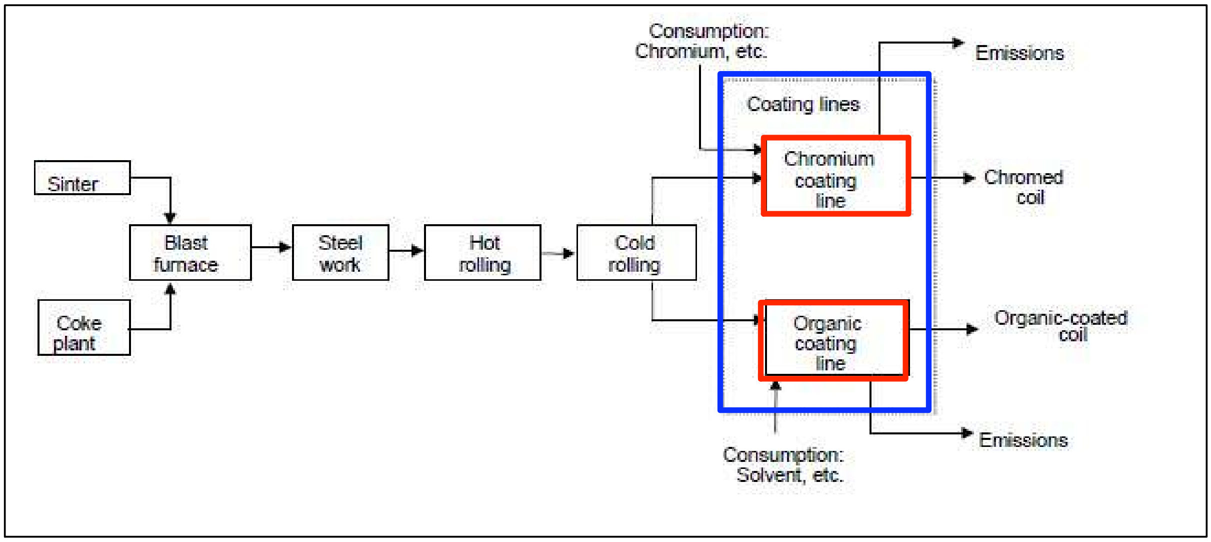
ISO recommends as step 1.1 to avoid allocation by “dividing” the unit process into two or more sub-processes. “Dividing” can be applied for example to products whose manufacture is not intrinsically linked (see Example A.1 below).

Example A.1

ISO 14049: 2000 presents a case study of “dividing” the coating process (see blue line) in two sub-processes, chromium and organic coating (see red lines) to avoid allocation (see Figure

A.2). In this case, if the data are collected for the coating line in general, it will be required to allocate the environmental inputs and outputs between the two lines. Allocation is avoided through division of coating process in two sub-processes and collection of LCI data separately for chromium and organic coating sub-processes.

Figure A.2 System where allocation may be avoided through a more precise data collection and dividing into two different subsystems [4].



If the Step 1.1 is not applicable, then ISO recommends step 1.2 to avoid allocation by “system expansion”. ISO 14049:2000 provides some examples of allocation avoidance by expanding system boundaries (see Section 6.4, 8.3.1, 8.3.2), but these are primarily intended for the LCA practitioners and not for public.

Based on the data availability and the product system, allocation cannot always be avoided; therefore, ISO recommends Step 2 and 3 to solve the “multi-functionality” of processes. Allocation factors have to be calculated to share the input/output data to product and the co-products in a way that reflects either the physical or economic relationships between them.

Step 2 should determine whether a physical parameter can be identified as a basis for calculating the allocation factor. Any physical parameter, e.g., mass, feedstock energy, thermal conductivity, viscosity, specific mass, etc., could be taken into consideration in order to identify the physical parameter which reflects the underlying physical relationship between product and the other co-products [4].

Physical allocation is possible if the ratio between product A and product B can be varied without changing the inputs and outputs (see example A.2 below).

Example A.2

A lorry is loaded with steel and copper metal parts. Total maximum load mass of transportation is 20 tones, which consists of 5 tons steel (25% by mass) and 15 tons copper parts (75% by mass). Amount of diesel consumption for the total transportation distance is 100 liters. The LCA study requires the relevant data for steel parts only.

If the ratio between the steel and copper parts can be changed without changing the total mass of 20 tons, then the inputs and outputs (e.g. amount of diesel and air emissions) also will remain constant. This can be established e.g. the rate can be changed to 10 tons steel and 10 tons copper parts and the lorry will consume the same amount of diesel of 100 liters.

Therefore, “mass” of metal parts can be considered as the pure physical parameter. Based on that, 25% percent of the total environmental load of the transportation can be allocated to steel parts and the remaining 75% to copper parts[8].

Example A.3

This example shows a case where “mass” is not the correct physical parameter but instead the “surface” of the product is [4].

Two different metal parts A and B are lacquered on the same paint line[9]. The lacquer consumption, the energy inputs, and the emissions of volatile organic compounds (VOC), etc., are only known for the combined lacquering. The LCA study requires the relevant data for product A only.

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[8] Examples on pure physical relationships are also provided in ISO 14049:2000, but these are primarly intended for the LCA practicioners and not for public.

[9] This is an example presented in ISO 14041 and referenced in ISO/TR 14049: 2000.

In this case, allocation can be avoided by performing an experimental run where only product A is lacquered. If there are technical or economic reasons why such a test run cannot take place, then allocation is necessary.

Physical allocation is possible if the ratio between product A and product B can be varied without changing the inputs and outputs.

- If the ratio between A and B is changed without changing the sum of the "masses" of A and B this can result in different quantities of lacquer, hence mass allocation is not correct.
- If the ratio between A and B can be changed without changing the sum of the "surfaces" to be lacquered, then the inputs and outputs also will remain constant.

Therefore, "surface" of metal parts can be considered as the pure physical parameter. The allocation factor can be calculated as the surface to be lacquered of all parts of A divided by the total surface to be lacquered of all parts (A plus B) which are lacquered in the same time period. Example A.2 and A.3 show cases where a physical parameter (either mass or surface) can be identified as a basis for calculating the allocation factors.

There are product systems or processes where the ratio between the product and co-products cannot be varied without changing the inputs and outputs, which indicates that the pure physical allocation cannot be applied.

Example A.4

ISO 14049:2000 provides the example of bitumen production system as a typical case study where pure physical allocation cannot be applied (see Section 7.3.2). Bitumen is produced from petroleum refineries as well as other co-products such as gasoline, kerosene, gas oil and fuel oil. The refinery process may yield to 5% mass fraction of bitumen and 95% mass fraction of other co-products.

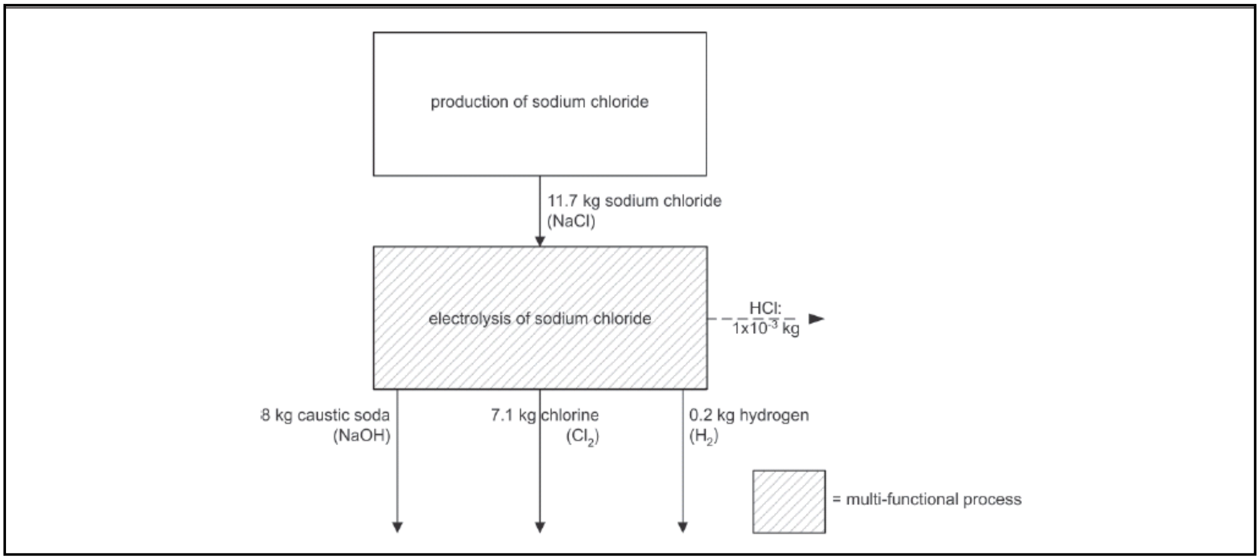
The ratio between the mass of bitumen and the mass of other co-products can only be varied in a small range, which involves significant change of the process parameters including energy consumption. In such a case, any physical parameter, e.g., mass, feedstock energy, thermal conductivity, viscosity, specific mass, etc., could be taken into consideration in order to identify the physical parameter which reflects the underlying physical relationship between bitumen and the other co-products. Mass has sometimes been applied in the case, but none of all those parameters can be justified to be preferable to the other ones. The fact that in this example the ratio between the bitumen and the other co-products cannot be varied indicates that the physical allocation cannot be applied.

Therefore, the third choice proposed in ISO 14044, i.e., the economic allocation can be applied. In this method, for example, the total environmental burden of the manufacturing process is "shared" between the product and co-products according to total proceeds of the multi-functional process. The proceeds are based on “prices” per unit of product and co-products. Furthermore, ISO recommends that some outputs may be partly co-products and partly waste. In such cases, it is necessary to identify the ratio between co-products and waste since the inputs and outputs shall be allocated to the co-products part only [2].

Example A.5

Figure A.3 shows the example used by Guinee et. al 2004 [23] on co-production of caustic soda (NaOH), chlorine (Cl_2) and hydrogen (H_2) – a classical example of application of economic allocation.

Figure A.3 Co-production process of caustic soda, chlorine and hydrogen (numbers are hypothetical [23]



The functional flows (product and co-products) are caustic soda, chlorine and hydrogen. By assuming the quantities, prices and proceeds stated in Table A.1, allocation factors (α, β and γ) can be calculated. Input and output flows (11.7 kg sodium chloride and 0.001 kg hydrogen chloride) should be allocated to the three functional flows.

Table A.1 Co-production process of caustic soda, chlorine and hydrogen (numbers are hypothetical [23]

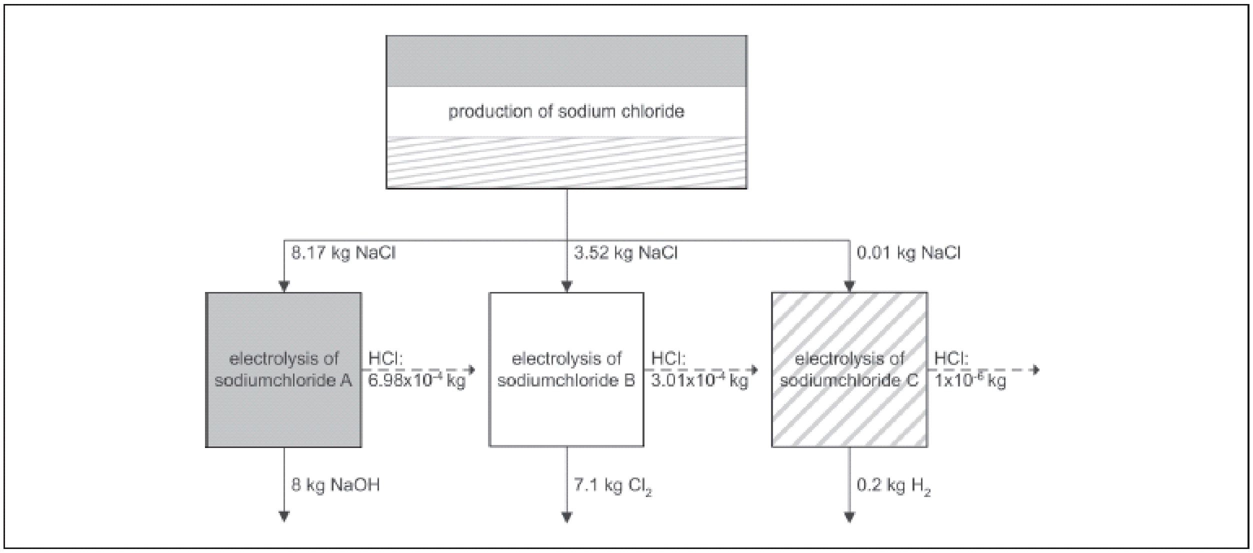
Function flow	**Quantity**	**Price ($/unit)**	**Proceeds**	**Allocation factor**
NaOH (product; kg)	8	1.65	13.20	*0.698* (α)
Cl_2 (co-product; kg)	7.1	0.80	5.68	*0.301* (β)
H_2 (co-product; kg)	0.2	0.10	0.02	*0.001* (γ)
Total	-	-	18.90	1.00
Note: All numbers are hypothetical and the original table was adjusted for simplification.				

Table A.2 shows that the 100% rule counts for economic allocation: for each flow, the quantities of the mono-functional processes together precisely constitute the original quantity of the multi-functional processes for that specific flow. Of final interest is that one should distinguish between the allocation of a multi-functional process and the ratios in which mono-functional processes participate in each of the separated systems. Figure A.4 illustrates how the multi-functional electrolysis process can be allocated into three different mono-functional processes [23].

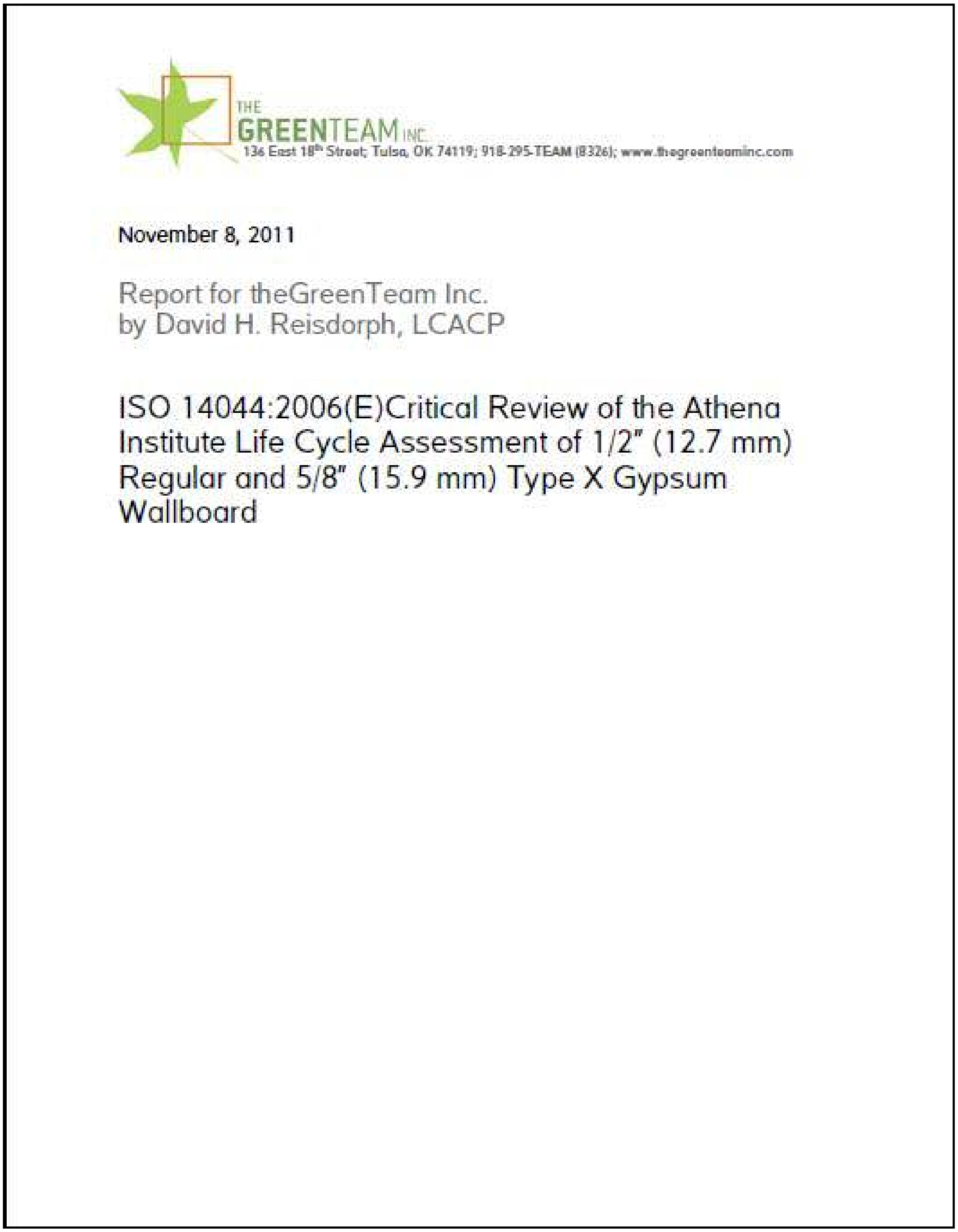
Table A.2 The unallocated multi-functional and the allocated mono-functional process data for the electrolysis of sodium chloride [23]

Function flow	**Multi-functional process**	**Mono-functional NaOH production**	**Mono-functional Cl_2 production**	**Mono-functional H_2 production**
NaCl (input; kg)	11.7	***0.698***× 11.7 = 8.17	***0.301*** × 11.7 = 3.52	***0.001*** × 11.7 = 0.01
HCl (output: kg)	1E-03	***0.698***× 1E-03= 6.98E-04	***0.301*** × 1E-03 = 3.01E-04	***0.001*** × 1E-03 = 1E-06
NaOH (product; kg)	8	8	0	0
Cl_2 (co-product; kg)	7.1	0	7.1	0
H_2 (co-product; kg)	0.2	0	0	0.2
Note: The original table was adjusted for simplification.				

Figure A.4 Application of the economic allocation rules for the electrolysis of NaCl multi-functional process [23]



Appendix B: [redacted]



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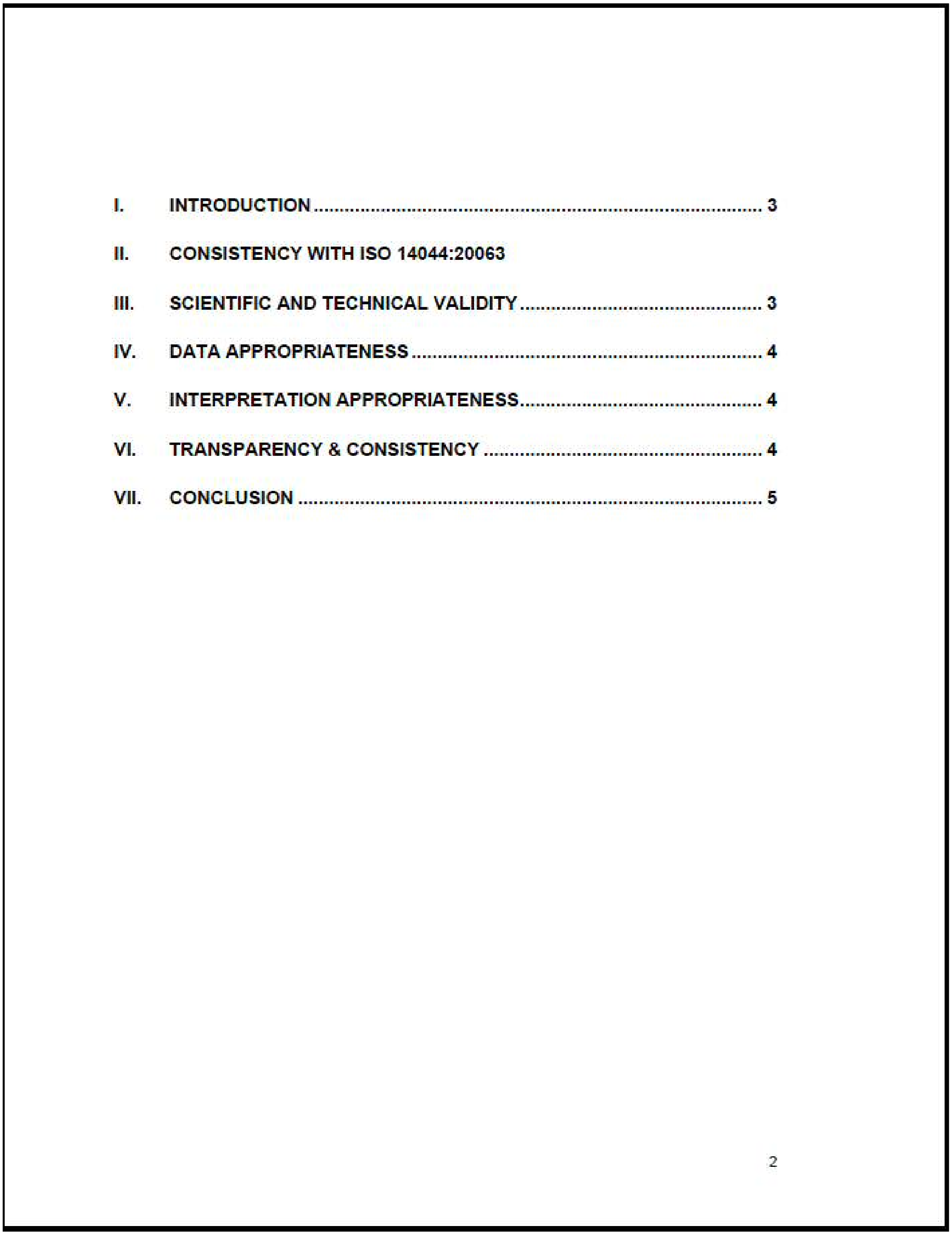
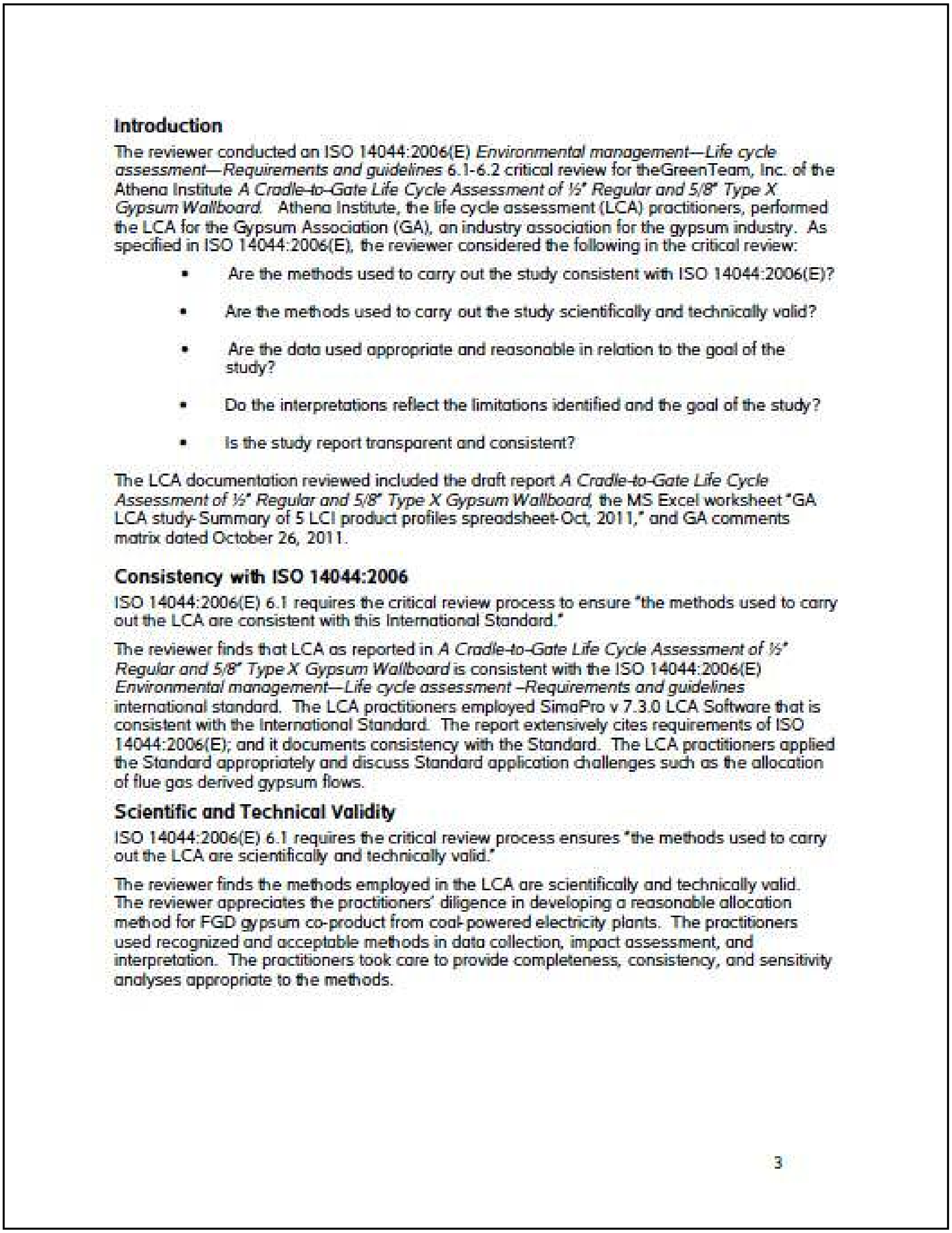
November 8, 2011

Report for theGreenTeam Inc.
by David H. Reisdorph, LCACP

ISO 14044:2006(E)Critical Review of the Athena Institute Life Cycle Assessment of 1/2" (12.7 mm) Regular and 5/8" (15.9 mm) Type X Gypsum Wallboard





Introduction

The reviewer conducted an ISO 14044:2006(E) *Environmental management—Life cycle assessment—Requirements and guidelines* 6.1-6.2 critical review for theGreenTeam, Inc. of the Athena Institute *A Cradle-to-Gate Life Cycle Assessment of ½" Regular and 5/8" Type X Gypsum Wallboard*. Athena Institute, the life cycle assessment (LCA) practitioners, performed the LCA for the Gypsum Association (GA), an industry association for the gypsum industry. As specified in ISO 14044:2006(E), the reviewer considered the following in the critical review:

- Are the methods used to carry out the study consistent with ISO 14044:2006(E)?
- Are the methods used to carry out the study scientifically and technically valid?
- Are the data used appropriate and reasonable in relation to the goal of the study?
- Do the interpretations reflect the limitations identified and the goal of the study?
- Is the study report transparent and consistent?

The LCA documentation reviewed included the draft report *A Cradle-to-Gate Life Cycle Assessment of ½" Regular and 5/8" Type X Gypsum Wallboard*, the MS Excel worksheet "GA LCA study-Summary of 5 LCI product profiles spreadsheet-Oct, 2011," and GA comments matrix dated October 26, 2011.

Consistency with ISO 14044:2006

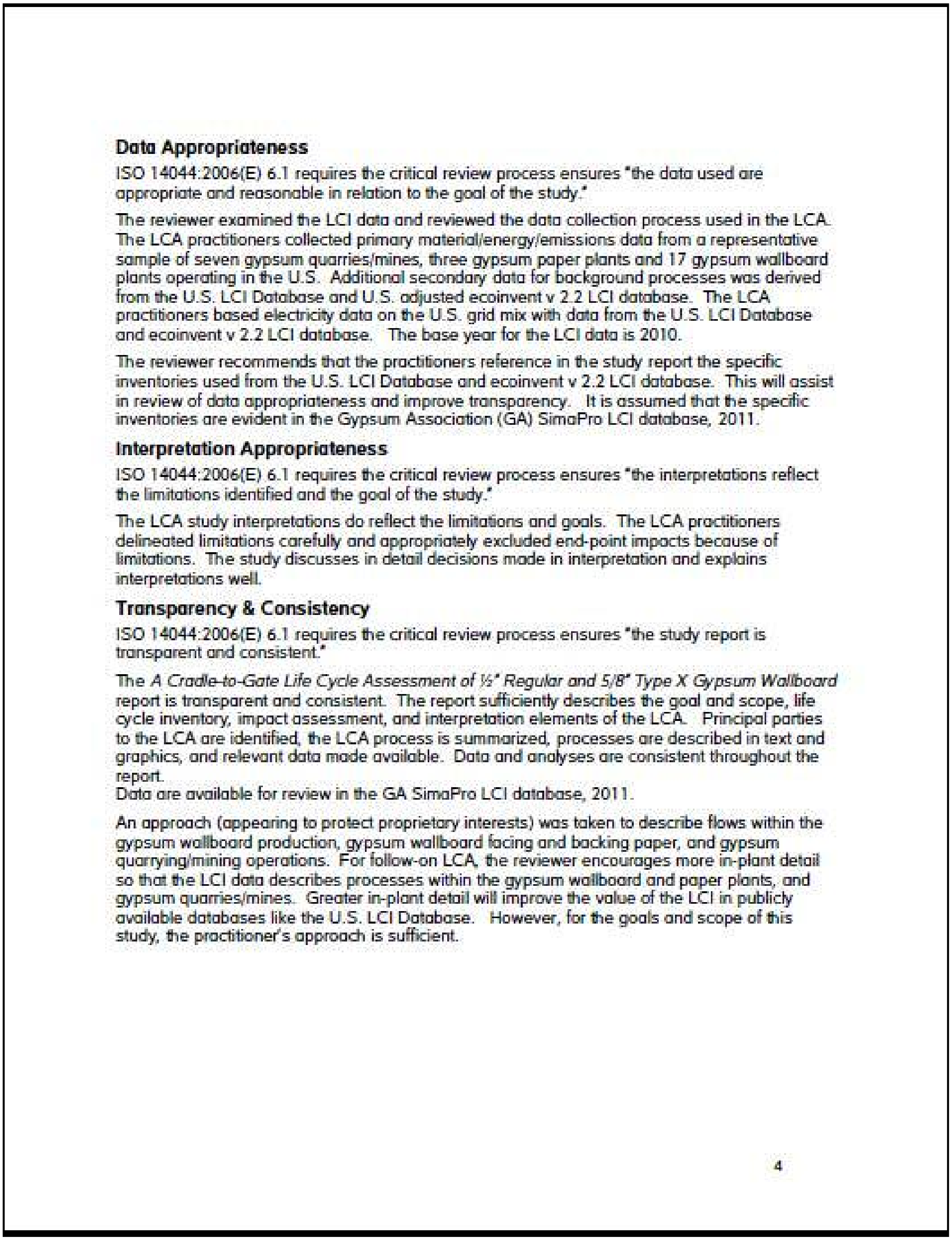
ISO 14044:2006(E) 6.1 requires the critical review process to ensure "the methods used to carry out the LCA are consistent with this International Standard."

The reviewer finds that LCA as reported in *A Cradle-to-Gate Life Cycle Assessment of ½" Regular and 5/8" Type X Gypsum Wallboard* is consistent with the ISO 14044:2006(E) *Environmental management—Life cycle assessment –Requirements and guidelines* international standard. The LCA practitioners employed SimaPro v 7.3.0 LCA Software that is consistent with the International Standard. The report extensively cites requirements of ISO 14044:2006(E); and it documents consistency with the Standard. The LCA practitioners applied the Standard appropriately and discuss Standard application challenges such as the allocation of flue gas derived gypsum flows.

Scientific and Technical Validity

ISO 14044:2006(E) 6.1 requires the critical review process ensures "the methods used to carry out the LCA are scientifically and technically valid."

The reviewer finds the methods employed in the LCA are scientifically and technically valid. The reviewer appreciates the practitioners' diligence in developing a reasonable allocation method for FGD gypsum co-product from coal-powered electricity plants. The practitioners used recognized and acceptable methods in data collection, impact assessment, and interpretation. The practitioners took care to provide completeness, consistency, and sensitivity analyses appropriate to the methods.



Data Appropriateness

ISO 14044:2006(E) 6.1 requires the critical review process ensures "the data used are appropriate and reasonable in relation to the goal of the study."

The reviewer examined the LCI data and reviewed the data collection process used in the LCA. The LCA practitioners collected primary material/energy/emissions data from a representative sample of seven gypsum quarries/mines, three gypsum paper plants and 17 gypsum wallboard plants operating in the U.S. Additional secondary data for background processes was derived from the U.S. LCI Database and U.S. adjusted ecoinvent v 2.2 LCI database. The LCA practitioners based electricity data on the U.S. grid mix with data from the U.S. LCI Database and ecoinvent v 2.2 LCI database. The base year for the LCI data is 2010.

The reviewer recommends that the practitioners reference in the study report the specific inventories used from the U.S. LCI Database and ecoinvent v 2.2 LCI database. This will assist in review of data appropriateness and improve transparency. It is assumed that the specific inventories are evident in the Gypsum Association (GA) SimaPro LCI database, 2011.

Interpretation Appropriateness

ISO 14044:2006(E) 6.1 requires the critical review process ensures "the interpretations reflect the limitations identified and the goal of the study."

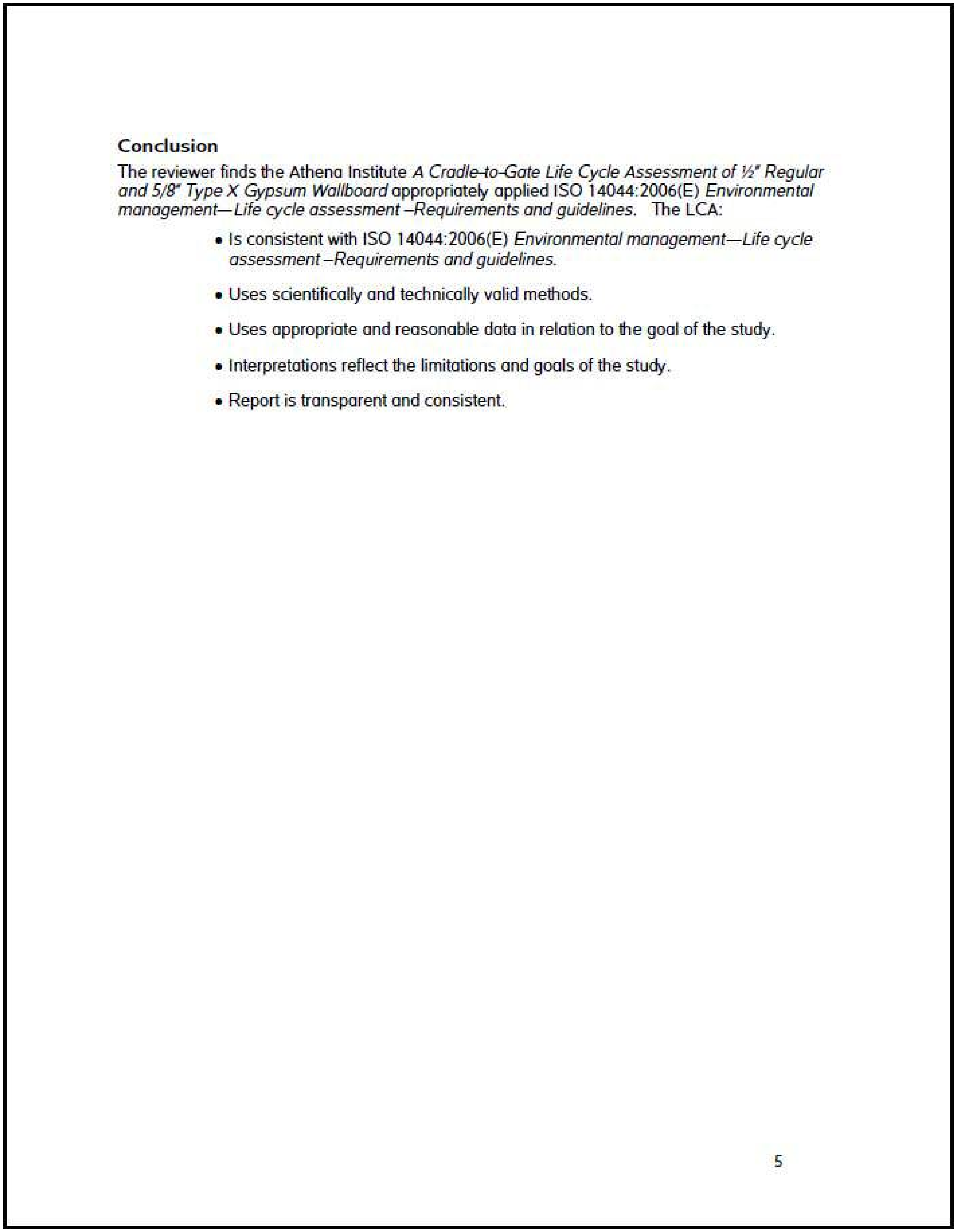
The LCA study interpretations do reflect the limitations and goals. The LCA practitioners delineated limitations carefully and appropriately excluded end-point impacts because of limitations. The study discusses in detail decisions made in interpretation and explains interpretations well.

Transparency & Consistency

ISO 14044:2006(E) 6.1 requires the critical review process ensures "the study report is transparent and consistent."

The *A Cradle-to-Gate Life Cycle Assessment of ½" Regular and 5/8" Type X Gypsum Wallboard* report is transparent and consistent. The report sufficiently describes the goal and scope, life cycle inventory, impact assessment, and interpretation elements of the LCA. Principal parties to the LCA are identified, the LCA process is summarized, processes are described in text and graphics, and relevant data made available. Data and analyses are consistent throughout the report.
Data are available for review in the GA SimaPro LCI database, 2011.

An approach (appearing to protect proprietary interests) was taken to describe flows within the gypsum wallboard production, gypsum wallboard facing and backing paper, and gypsum quarrying/mining operations. For follow-on LCA, the reviewer encourages more in-plant detail so that the LCI data describes processes within the gypsum wallboard and paper plants, and gypsum quarries/mines. Greater in-plant detail will improve the value of the LCI in publicly available databases like the U.S. LCI Database. However, for the goals and scope of this study, the practitioner's approach is sufficient.



Conclusion

The reviewer finds the Athena Institute *A Cradle-to-Gate Life Cycle Assessment of ½" Regular and 5/8" Type X Gypsum Wallboard* appropriately applied ISO 14044:2006(E) *Environmental management—Life cycle assessment –Requirements and guidelines.* The LCA:

- Is consistent with ISO 14044:2006(E) *Environmental management—Life cycle assessment –Requirements and guidelines.*
- Uses scientifically and technically valid methods.
- Uses appropriate and reasonable data in relation to the goal of the study.
- Interpretations reflect the limitations and goals of the study.
- Report is transparent and consistent.

Responses to recommendations

The LCA team is in full agreement with the critical review report and appreciates the reviewer's comments and recommendation.

As mentioned in Section 3.5- Data Quality, this LCA study uses 100% the life cycle inventories of the US LCI Database, 2010 (publicly available) and US adjusted European ecoinvent v.2.2 LCI database ("US-EI"), 2010- the best available LCI databases; both of which are incorporated in the SimaPro v.7.3.0 LCA Software, March 2011. Given the extremely high number of life cycle inventories used in this particular project would not be possible to list all these inventories individually. Table 3 provides a summary of key primary and secondary LCI data sources. Furthermore, due to confidentiality agreements with the GA participating plants the chemical names for the main types of chemicals used, such as sizing agents, retention chemicals, polymer emulsifier, dyes, defoamer, water treatment chemicals, retarder, dispersant etc. can't be revealed but were individually modeled as per MSDS and were followed back to nature. It's also to be noted that there's no ISO requirement to list all the Life Cycle Inventories used in the project. A fully transparent LCI modeling is documented in the Gypsum Association (GA) Sima Pro LCI Database 2011.