China, Global Warming and Hot-Rolled Structural Steel Sections

A White Paper by the
American Institute of Steel Construction
April 2018

The greenhouse gas emissions measured as global warming potential of hot-rolled structural steel sections produced in China are three times that of equivalent sections produced in the United States. The clear corollary to that factual statement is that the best decision an owner, architect, engineer or general contractor can make from a sustainable perspective is to specify domestically produced structural steel for their next project.

In the case of structural steel, global warming potential (GWP) is a relative measure of the amount of heat that the production of one ton of hot-rolled structural steel sections traps in the atmosphere as a result of greenhouse gas emissions. Global warming potential is expressed as carbon dioxide equivalents (CO_2eq) where the impact of carbon dioxide is standardized to 1. Other greenhouse gases, such as methane and nitrous oxide have much higher impacts per unit volume of gas emitted. For the purpose of this study impacts were considered over the standard 100 year period. During that period methane impacts are 34 times those of CO_2 and nitrous oxide 298 times that of CO_2.

Two recent studies conducted by thinkstep, a sustainability software and consulting firm, reported that 100-year Global Warming Potential (GWP-100) impacts, which represent aggregated cradle-to-gate GHG gas emissions for hot-rolled structural sections are:

Hot-rolled structural sections:	
produced in China	2.94 tons CO_2eq/ton
produced in the U.S.	0.98 tons CO_2eq/ton

The products produced in China and in the United States are functionally equivalent and can both be used in the production of fabricated structural steel for use in structural applications. The reports cover the same cradle-to-gate scope, representing raw material extraction, transportation and steel production. For material produced in China, transport to reach the U.S. market was also included which accounted for 5% (.151 tons CO_2eq/ton) of the final result. The results were calculated using the same life cycle inventory data collection and impact assessment calculation methodologies. The final reports were subjected to a critical peer reviewed conducted by Quantis USA and determined to fully conform to the requirements of the ISO/TS 14067:2013 standard.

The production mix is significantly different between hot-rolled structural sections produced in China and the United States. 94% of hot-rolled sections in China are produced by integrated mills using iron ore and coke as primary feedstock material, with the remaining 6% being produced in mills using electric arc furnaces (EAF). In the U.S. all hot-rolled sections are produced using scrap based electric arc furnaces. However, even if Chinese production transitioned to the EAF process the global warming potential of Chinese hot-rolled sections would still be more than 2 times that of U.S. production as documented in Figure 4-7 in the China study. This is a direct result of electricity production in China having a much higher level of greenhouse gas emissions due to a high percentage of coal-fired generation.

It should be noted that the China LCA study relies on data from Chinese facilities. There were some gaps in the data that impacted the calculations of several environmental impact indicators other than GWP. Therefore the results for indicators such as acidification and eutrophication are not as reliable as the greenhouse gas emission results. These data gaps do not apply to the greenhouse gas emission data from which the GWP is calculated.

Included in this white paper are the relevant sections of the thinkstep reports and the critical review letter.

Quantis

DATE: 22 August 2017

TO: Brandie Sebastian and Mark Thimons, American Iron and Steel Institute

FROM: Jon Dettling (Quantis), Sofia Khan (Quantis), Ken de Souza (independent)

SUBJECT: Final review of the steel LCA/LCI reports as per ISO 14067

Dear Ms. Sebastien and Mr. Thimons,

You have engaged us to perform a critical review regarding whether several reports regarding steel production in China and North America are in conformance with the ISO/TS 14067:2013 standard on carbon footprint of products. This memo details our findings of a second review of these documents. Please note that our review under ISO/TS 14067 considers only the impact on climate change and so in most cases have not offered comments on information in the report that does not pertain to climate change impact or ISO/TS 14067.

Our finding is that ***the reports in question now fully conform with the requirements of the ISO/TS 14067:2013 standard***.

Listed below are the specific reports that have been assessed. A records of comments and responses as part of this review has been transmitted to you separately in a prior correspondence.

Please let us know if we can provide any further information on this topic.

Reports assessed

Title: Hot-Rolled Structural Steel Sections: Life Cycle Inventory Methodology Report
Authors: Trisha Montalbo, Thinkstep
Date: September 2015, revised July 2017
Description of scope: Cradle-to-gate environmental performance of 1000 kg of hot-rolled structural steel sections, which include products such as beams, channels, and angles. Only North American hot-rolled structural section production was considered and includes steel mills, representing approximately 90% of hot-rolled structural section production in North America. The study overall uses the SCS PCR, World steel LCA methodology and ISO 14040/44 standard.

Title: Structural Section and Hot-Dip Galvanized Steel Production in China: Life Cycle Assessment Report
Authors: Trisha Montalbo, Thinkstep
Date: August 2017, version 1.0
Description of scope: The report contains cradle-gate study of 1kg HDG coil and 1 kg hot rolled structured steel production in China and includes the production of steel and its transport from eastern china to western USA by ship in containments.

Title: LCI Data for Steel Products: North American Hot-Dip Galvanize
Authors: Brandie M. Sebastian, Steel Recycling Institute
Date: ovember 2015, revised July 2017
Description of scope: The report provides LCI data for 1kg of hot-dip Galvanized Steel, cradle- to-gate, excluding end-of-life recycling.

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Hot-Rolled Structural Steel Sections

Life cycle inventory methodology report

On behalf of the American Institute of Steel Construction (AISC)

July 2017

Report version: 1.1

Report date: July 2017

On behalf of thinkstep AG and its subsidiaries

Document prepared by	**Trisha Montalbo, ScD**
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Table of Contents

List of Figures

List of Tables

List of Acronyms

ADP	Abiotic Depletion Potential
AISC	American Institute of Steel Construction
AP	Acidification Potential
BOF	Basic Oxygen Furnace
CML	Centre of Environmental Science at Leiden
EAF	Electric Arc Furnace
EoL	End-of-Life
EP	Eutrophication Potential
EPD	Environmental Product Declaration
GaBi	Ganzheitliche Bilanzierung (German for holistic balancing)
GHG	Greenhouse Gas
GWP	Global Warming Potential
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
NMVOC	Non-Methane Volatile Organic Compound
ODP	Ozone Depletion Potential
PCR	Product Category Rules
POCP	Photochemical Ozone Creation Potential
SFP	Smog Formation Potential
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
VOC	Volatile Organic Compound

1. Goal

The American Institute of Steel Construction (AISC) is a trade association and technical institute that serves the structural steel industry in the United States. As part of its mission to encourage the use of structural steel, AISC recognizes the need to address the environmental performance of steel and to ensure that up-to-date data on steel production and fabrication are available to the building design and construction community. Thus, AISC is interested in developing and publishing a cradle-to-gate life cycle inventory (LCI) of hot-rolled structural sections manufactured in North America.

This LCI will enable AISC to update available data on hot-rolled structural sections and thus support future evaluations such as life cycle assessments (LCAs) for environmental product declarations (EPDs) of downstream steel products.

The results of the study are intended to support future LCAs. These results may be published in publically available databases such as the NREL USLCI database, thinkstep's GaBi database, and KieranTimberlake's Tally™ tool. Publishing the results will also ensure LCA practitioners have access to the data.

The intended audience for this report is AISC, its member companies, and the building design and construction community. As the results are not intended to support comparative assertions, no critical review was conducted. However, it is the intention of AISC to combine these results with industry average fabrication impacts for the development of a LCA and EPD for "fabricated hot-rolled structural steel", which will be reviewed for conformity to the construction steel product category rules and applicable ISO standards.

2. Scope

The following section describes the general scope of the project to achieve the stated goals. This includes the identification of specific products to be assessed, the supporting product systems, study boundary, allocation procedures, and cut-off criteria.

2.1. Product System under Study

The study evaluates the cradle-to-gate environmental performance of hot-rolled structural steel sections, which include products such as beams, channels, and angles. Only North American hot-rolled structural section production was considered and included the following steel mills, representing approximately 90% of hot-rolled structural section production in North America:

- Gerdau in Midlothian, Texas
- Steel Dynamics, Inc. in Columbia City, Indiana
- Nucor in Armorel, Arkansas and Huger, South Carolina

2.2. Product Functions, Declared Unit, and Reference Flows

The declared unit evaluated for this study is:

1 metric ton (1 tonne or 1,000 kg) of hot-rolled structural sections.

A declared unit, rather than a functional unit, is used for the analysis because the product application and therefore its function (e.g., supporting a building) is not addressed. Additionally, a mass-based declared unit was chosen as it is in line with the declared unit defined in the construction steel PCR [SCS 2015]. Results are also reported in the PCR's optional declared unit of one short ton (2,000 lbs.) of hot-rolled structural sections.

2.3. System Boundaries

This study is limited to the cradle-to-gate production of hot-rolled structural sections as AISC's goal is to publish a life cycle inventory that can be used subsequent LCA studies for which structural steel is an input. Other life cycle stages are excluded as the use of hot-rolled structural sections will vary according to application. This exclusion is permitted under ISO 14044, section 4.2.3.3.1, if it does not significantly change the overall conclusions of the study.

Table 2-1 summarizes what is included and excluded from the study boundary in alignment with worldsteel methodology [WSA 2011].

Table 2-1: System boundaries

Included	Excluded
✓ Raw material production ✓ Energy production ✓ On-site transportation ✓ Melt shop and rolling mill processes ✓ Use of ancillary and packaging materials ✓ Emissions to air, water, and soil during production	× Construction of capital equipment × Employee commute × Maintenance and operation of support equipment × Steel scrap input shredding and sorting × Inbound and outbound transportation × Product use, installation, and disposal × Processing of EAF dust, slag, and electrode scrap outputs

2.4. Allocation

Data used in this analysis exclusively represent structural steel production so no allocation of inputs or outputs to other steel-based products was necessary.

Closed-loop recycling was used to address steel scrap from manufacturing. Steel scrap, whether from internal or external sources, is assumed to enter the system burden-free. Scrap generated from the production of hot-rolled structural sections was modeled as being looped back as an input of scrap steel into the electric arc furnace (EAF). The resulting net scrap input to manufacturing is then calculated as part of the final inventory to allow for full flexibility when using the LCI with different allocation approaches.

In alignment with worldsteel methodology [WSA 2011], the following choices were made with regard to treatment of secondary material and other outputs from manufacturing:

- Remelting of scrap is accounted for within the model, but collection, shredding, and sorting of external scrap is not included.
- A credit of primary zinc is given for zinc from EAF dust collected by the baghouse.
- Depending on the producer, slag is either used as cement, embankment gravel, and/or agricultural lime, so the respective credits are given to offset any repurposing.

Allocation of upstream data (energy and materials) needed during manufacturing are modeled using the allocation rule most suitable for the respective product. For further information on a specific product see http://www.gabi-software.com/international/databases/gabi-databases/.

2.5. Cut-off Criteria

The same cut-off criteria as required by the structural steel PCR were used in processes or activities that contribute no more than 1% of the total mass and 1% of the total energy may be omitted. If omitted material flows have relevant contributions to the selected impact categories, their exclusion must be justified by a sensitivity analysis.

Cut-off criteria were applied to capital equipment production and maintenance under the assumption that the impacts associated with these aspects were sufficiently small enough to fall below cut-off when scaled down to the declared unit. Otherwise, all energy and material flow data available were included in the analysis. The sum of the excluded material flows was judged not to exceed 5% of mass, energy or environmental relevance.

2.6. Selection of LCIA Methodology and Types of Impacts

Although the study aims to develop a life cycle inventory, impact categories were evaluated in order to compare the resulting inventory to other worldsteel LCIs. The following inventory metrics and impact assessment categories were calculated. These metrics were chosen in alignment with the North American steel construction products PCR [SCS 2015] as it is anticipated this LCI will be used to support EPDs that conform to this PCR. Additionally, global warming potential as calculated using emissions factors from the 5th IPCC Assessment Report [IPCC 2013] are included as TRACI 2.1 and CML 2001, version April 2013 still use factors from the 4th IPCC Assessment Report.

- Resource use
    - Use of renewable primary energy excluding renewable primary energy resources used as raw materials
    - Use of renewable primary energy resources used as raw materials
    - Total use of renewable primary energy resources
    - Use of non-renewable primary energy excluding non-renewable primary energy resources used as raw materials
    - Use of non-renewable primary energy resources used as raw materials
    - Total use of non-renewable primary energy resources
    - Use of secondary material
    - Use of renewable secondary fuels
    - Use of non-renewable secondary fuels
    - Net use of fresh water
- Waste
    - Hazardous waste disposed
    - Non-hazardous waste disposed
    - Radioactive waste disposed
- Other environmental information
    - Components for re-use
    - Materials for recycling
    - Materials for energy recovery
    - Exported energy
- Impact assessment
    - TRACI 2.1
        - Global warming potential (GWP) – 100 year
        - Acidification potential (AP)
        - Ozone depletion potential (ODP)
        - Smog formation potential (SFP)
        - Eutrophication (EP)
    - CML 2001 – April 2013
        - Global warming potential (GWP) – 100 year
        - Acidification potential (AP)
        - Ozone depletion potential (ODP)
        - Smog formation potential (SFP)
        - Eutrophication (EP)
        - Abiotic depletion potential for non-fossil resources (ADP-elements)
        - Abiotic depletion potential for fossil resources (ADP-fossil fuels)
    - IPCC 5th annual report
        - Global warming potential (GWP) – 100 year
        - Global warming potential (GWP) – 20 year

It shall be noted that the above impact categories represent impact *potentials*, i.e., they are approximations of environmental impacts that could occur if the emitted molecules would (a) actually follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so. In addition, the inventory only captures that fraction of the total environmental load that corresponds to the chosen declared unit (relative approach).

Life cycle impact assessment (LCIA) results are therefore relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

2.7. Interpretation to be Used

No normalization, grouping, or further quantitative cross-category weighting is applied. Instead, each impact is discussed by itself, without reference to other impact categories, before final conclusions and recommendations are made.

2.8. Data Quality Requirements

The data used to create the inventory model shall be as precise, complete, consistent, and representative as possible with regards to the goal and scope of the study under given time and budget constraints.

- Measured primary data are considered to be of the highest precision, followed by calculated and estimated data.
- Completeness is judged based on the completeness of the inputs and outputs per unit process and the completeness of the unit processes themselves. Cut-off criteria apply and were defined in Section 2.5
- Consistency refers to modeling choices and data sources. The goal is to ensure that differences in results occur due to actual differences between product systems, and not due to inconsistencies in modeling choices, data sources, emission factors, or other.
- Representativeness expresses the degree to which the data matches the geographical, temporal, and technological requirements defined in the study's goal and scope.

An evaluation of the data quality with regard to these requirements is provided in the interpretation chapter of this report.

2.8.1. Representativeness

Representativeness expresses the degree to which the data match the geographical, temporal, and technological requirements defined in the study's goal and scope. In order to reach the goal of the study, the data used to model the assemblies should ideally reflect production of hot-rolled structural sections in North America. The following provides an overview of data representativeness.

Time Coverage

Primary data on hot-rolled structural sections production were collected from manufacturers for 12 continuous months between 2007 and 2010. As the data are representative of steel production in the late 2000s, a reference year of 2010 is selected given that background data are representative of 2009 – 2013. Some foreground energy and emissions data, however, reflect 2014 production as one manufacturer was unable to answer clarification questions due to the age of the originally submitted data and thus turned to 2014 data, which they had recently collated, in order to formulate responses.

Technology Coverage

This study quantifies the cradle-to-gate inventory flows associated with structural steel production—specifically the melt shop (EAF) and rolling mill operations.

Geographical Coverage

The region covered by this study is the North America.

2.9. Assumptions and Limitations

Certain assumptions affecting net incoming scrap and upstream dataset choices were made in order to develop a life cycle inventory that is representative of hot-rolled structural sections production in North America and, at the same time, is aligned with worldsteel's modeling approach as far as possible as documented in their 2011 LCA methodology report [WSA 2011]. These assumptions are further detailed in Section 3.4. There will always be differences between inventory and impact assessment results from worldsteel's model as compared to the model developed in this report, however, due to the use of different GaBi database versions and the additional manufacturers included in the current analysis.

2.10. Software and Database

The LCA model was created using the GaBi 6 software for life cycle engineering, developed by thinkstep AG. The GaBi 2014 database (service pack 27) provides the life cycle inventory data for several of the raw and process materials obtained from the upstream system.

2.11. Critical Review

As the analysis is not comparative in nature, no critical review took place. However, internal quality assurance was conducted by the practitioner to ensure accuracy and representativeness of the model and report.

3. Data and Model

3.1. Data Collection and Quality Assessment Procedure

Data used for this project represents primary data collected from structural steel mills as part of a previous worldsteel LCI project. Data were collected using customized questionnaires originally developed by worldsteel and provided to thinkstep. Upon receipt, each questionnaire was cross-checked for completeness and plausibility using mass balance and benchmarking. If gaps, outliers, or other inconsistencies occurred, thinkstep engaged with the data provider to resolve any open issues. Overall, the quality of the data used in this study is considered to be high and representative of the described systems.

3.2. Hot-rolled Structural Sections Production

Hot-rolled structural steel sections in North America are manufactured from secondary steel (i.e., from steel scrap) via an electric arc furnace (EAF). Near-net-shapes from the furnace are then sent to rolling mills, where they are shaped into the final product, packaged, and loaded onto trucks for distribution to fabricators or job sites.

3.2.1. Melt Shop

The melt shop is the first process step in hot-rolled structural sections production at a steel mill. Steel scrap is loaded into a refractory-lined vessel and melted via electric energy supplied through graphite electrodes. Oxy-fuel burners and other means of generating heat through chemical reactions are also employed. The chemistry of the molten steel is adjusted at this stage by adding material to attain a specific alloy composition and by removing impurities, which migrate to the slag. Once the desired chemical composition is attained, the molten steel is then cast into near-net-shapes for processing in the rolling mill located in the same facility.

Unsurprisingly, the melt shop accounts for a large fraction of on-site air emissions associated with hot-rolled structural sections production. Carbon dioxide emissions come not only from fossil fuel combustion, but also from the consumption of graphite electrodes, coal or coke used to balance the carbon content in the steel, and from limestone and dolomite that form the slag[1]. Additionally, particulate emissions are generated and collected in a baghouse. Dust from the EAF is sent out for additional processing to recover any zinc.

[1] See the Federal Register, v78:230, 40 CFR Part 98, "2013 Revisions to the Greenhouse Gas Reporting Rule and Final Confidentiality Determinations for New or Substantially Revised Data Elements; Final Rule", Subpart Q and Section 98.137. http://www.epa.gov/ghgreporting/documents/pdf/2013/documents/memo-2013-technical-revisions.pdf

3.2.2. Rolling Mill

Once the steel is cast into a near-net-shape, it is internally transported to the rolling mill. At the rolling mill, the near-net-shape is reheated in a natural gas furnace and run through rollers to shape its profile into angles, channels, beams, etc. Rolling mill emissions are primarily limited to combustion emissions from the furnace and dust from processing. Any steel scrap generated is recycled internally (i.e., put back into the EAF).

3.2.3. Production Waste Treatment

Production wastes for recycling include steel scrap, mill scale, slag, and EAF dust. In alignment with worldsteel's methodology [WSA 2011], the following modeling choices were made:

- Steel scrap is recycled internally, either into sections or into other products (e.g., rail).
- Other recycled wastes are modeled using system expansion, specifically by giving credit for the avoided production of the product the waste can replace. The burden associated with processing the waste stream in order to recover the valuable material is not included in the analysis as this information is not readily available. It is the steel industry's general understanding, however, that minimal processing is required for most of the recovered materials before they can be used in the next product system. This data gap was addressed in a scenario analysis (see section 4.5).
- Mill scale, which is essentially iron oxide, is assumed to replace iron ore in a mass ratio of one-to-one.
- Slag is sent out for treatment and typically repurposed for cement processing, embankment gravel, or agricultural lime. The ratio of these three end uses varies by manufacturer.
- EAF dust is collected at the baghouse and processed in order to recover any zinc. While iron can also be recovered from the dust, its recovery is not included in this analysis. Zinc content in EAF dust is based on manufacturer data, whereas worldsteel's methodology assumes a flat 50% zinc content for all manufacturers. In this, the model deviates from worldsteel's assumptions.

Model assumptions for credit given per kilogram of recovered waste are shown in Table 3-1. Other production wastes are treated and disposed.

Table 3-1: Avoided production model assumptions

Waste stream	Avoided product	Credit per kg of waste
Mill scale	Iron ore	1 kg
EAF slag	Cement, embankment gravel, and/or agricultural lime	1 kg
EAF dust	Zinc	0.2 to 0.25 kg (depends on zinc content in dust)
Electrodes	Electrodes	1 kg

3.2.4. Unit Process

Selected inputs and outputs required to produce one metric ton of product are shown in Table 3-2 and Table 3-3, respectively; not all flows are included. Numbers are rounded to three significant figures.

Table 3-2: Selected unit process inputs per metric ton

Flow	Amount	Units	Flow	Amount	Units
Materials			**Energy**		
Steel scrap	1.15	tonne	Coal	20.0	kg
Calcium carbide	0.164	kg	Electricity	188	kWh
Coke	3.71	kg	Natural gas	53.0	kg
Dolomite	46.0	kg			
Electrodes	1.96	kg	**Water**		
Ferro chromium	0.649	kg	Ground water	4.04	m^3
Ferro silicium	1.05	kg	Municipal water	0.0335	m^3
Fluorspar	0.130	kg			
Nitrogen	15.4	kg			
Oxygen	69.6	kg			
Pig iron	39.1	kg			
Refractories	1.76	kg			
Silico-manganese	13.9	kg			

Table 3-3: Selected unit process outputs per metric ton

Flow	Amount	Units	Flow	Amount	Units
Output			**Emissions to air**		
Steel section	1.00	tonne	Cadmium (+II)	4.28E-06	kg
			Carbon dioxide	255	kg
Wastes			Carbon monoxide	1.28	kg
Steel scrap	103	kg	Chromium (unspec.)	9.24E-06	kg
Mill scale	29.4	kg	Dust (PM 10)	0.0216	kg
EAF dust to recovery	16.2	kg	Dust (PM 2.5)	0.0484	kg
EAF slag to recovery	129	kg	Lead (+II)	8.78E-05	kg
Waste water	0.122	m^3	Manganese (+II)	7.51E-05	kg
			Mercury (+II)	4.36E-05	kg
			Methane	1.30	kg
			Nickel (+II)	7.20E-06	kg
			Nitrogen oxides	0.159	kg
			Nitrous oxide	0.0222	kg
			NMVOC	0.0658	kg
			Sulfur oxides	2.47	kg
			Water vapor	3,960	kg
			Zinc (+II)	9.35E-04	kg

While the majority of data represent production between 2007 to 2010 (depending on manufacturer), some inputs and emissions reflect 2014 production as these numbers were available to manufacturers when responding to data clarification questions. More precisely, one of the manufacturers was unable to answer why their coal and coke energy consumption and nitrogen oxide emissions per metric ton were approximately double the corresponding numbers for the other two mills despite using the same manufacturing processes. Additionally, the manufacturer's carbon dioxide emissions per metric ton were 3.5 times the carbon dioxide emissions of the other two mills. When that manufacturer's unit energy consumption and emissions for 2014 were evaluated, the results were nearly in line with those of the other mills. Therefore, it was decided to use to the 2014 data for select data points as the manufacturer's process had not materially changed between 2010 and 2014. Affected data points include:

- Coal
- Coke
- Pig iron
- Carbon dioxide emissions to air
- Nitrogen oxide emissions to air

3.3. Background Data

This section details background datasets used to build the hot-rolled structural sections model. Each table lists dataset purpose, name, source, reference year, and location.

3.3.1. Fuels and Energy

National and regional averages for fuel inputs and electricity grid mixes were obtained from the GaBi 2014 database. Table 3-4 shows the key life cycle inventory (LCI) datasets used in modeling the product systems. Documentation for these datasets can be found at http://www.gabi-software.com/support/gabi/gabi-6-lci-documentation/.

Table 3-4: Key energy datasets used in inventory analysis

Energy	Dataset Name	Primary Source	Ref. Year	Geography
Electricity	Electricity grid mix – ERCT	thinkstep	2009	US
Electricity	Electricity grid mix – RFCW (w/o MISO or PJM)	thinkstep	2009	US
Electricity	Electricity grid mix – SRMV	thinkstep	2009	US
Electricity	Electricity grid mix – SRVC (w/o PJM)	thinkstep	2009	US
Electricity	Electricity grid mix (eGRID)	thinkstep	2009	US
Coke	Coke mix	thinkstep	2010	US
Diesel	Diesel mix at filling station	thinkstep	2011	US
Gasoline	Gasoline mix (regular) at filling station	thinkstep	2011	US
Coal	Hard coal mix	thinkstep	2011	US
Kerosene	Kerosene / Jet A1 at refinery	thinkstep	2011	US
LPG	Liquefied Petroleum Gas (LPG)	thinkstep	2011	US
Natural gas	Natural gas mix	thinkstep	2011	US

3.3.2. Materials

Data for raw materials were obtained from the GaBi 2014 database (service pack 27). Table 3-5 shows the key LCI datasets used in modeling hot-rolled structural sections—both the melt shop and the rolling mill. Most of these datasets are available in thinkstep's commercially available databases. Documentation for these datasets can be found at http://www.gabi-software.com/support/gabi/gabi-6-lci-documentation/.

In some cases, representative data were only available from thinkstep's internal databases. These datasets are denoted with a star (*) under the primary source column. In case of questions with regard to these datasets, please contact the study authors.

For completeness, datasets for process or ancillary materials are shown in Table 3-6.

Table 3-5: Key material datasets used in inventory analysis

Raw Material	Dataset Name	Primary Source	Ref. Year	Geography
Argon	Argon (gaseous)	thinkstep	2013	US
Copper	Copper mix (99,999% from electrolysis)	thinkstep	2013	GLO
Dolomite	Dolomite calcination	thinkstep*	2012	US
Electrode	Electrode	thinkstep*	2011	ZA
Ferro chromium	Ferro chrome mix	thinkstep	2013	DE
Ferro manganese	Ferro manganese	thinkstep	2013	ZA
Ferro molybdenum	Ferro molybdenum	thinkstep*	2012	GLO
Ferro silicon	Ferro silicon mix	thinkstep	2013	GLO
Ferro vanadium	Ferro vanadium	thinkstep*	2012	ZA
Quicklime	Lime (CaO; quicklime lumpy)	thinkstep	2013	DE
Nickel	Nickel mix	thinkstep	2013	GLO
Nitrogen	Nitrogen (gaseous)	thinkstep	2013	US
Oxygen	Oxygen (gaseous)	thinkstep	2013	US
Pig iron	Pig iron (free-cut blast furnace)	thinkstep*	2012	DE
Sulfur	Sulphur (elemental) at refinery	thinkstep	2011	US

* thinkstep internal dataset

Table 3-6: Key process material datasets used in inventory analysis

Raw Material	Dataset Name	Primary Source	Ref. Year	Geography
Casting powder	Limestone flour (1µm)	thinkstep	2013	US
Lubricant	Lubricants at refinery	thinkstep	2011	US
Refractories	Fire proof stones (alumina-rich)	thinkstep	2012	EU-27
Anti-foaming agent	Non-ionic surfactant	thinkstep	2013	GLO
Flocculant	Polyacrylamide (anionic) (solid)	thinkstep*	2012	DE
Bleach	Sodium hypochlorite solution	thinkstep	2013	US
Sulfuric acid	Sulfuric acid (high purity)	thinkstep*	2012	US
Municipal water	Tap water from groundwater	thinkstep*	2012	US

* thinkstep internal dataset

3.3.3. Waste Treatment and Credit

Waste treatment processes were obtained from the GaBi 2014 database. These processes were chosen to correspond to the material being disposed. The analysis adopts a system expansion approach to address materials or co-products that can be recovered and used in other product systems. As such, credits for avoided production are included in the analysis. Any additional processing that may be required for materials or co-products prior to their use in another process or product, however, is not included as it is the industry's general understanding that minimal processing is required. Table 3-7 reviews key waste treatment datasets used in the model. Documentation for these datasets can be found at http://www.gabi-software.com/support/gabi/gabi-6-lci-documentation/. In some cases, representative data were only available from thinkstep's internal databases. These datasets are denoted with a star (*) under the primary source column. In case of questions with regard to these datasets, please contact the study authors.

Table 3-7: Key waste treatment and avoided production credit datasets used in inventory analysis

Material disposed	Dataset name	Primary source	Ref. Year	Geography
Various wastes	Hazardous waste (non-specific) (c rich, worst scenario)	thinkstep*	2012	GLO
Various wastes	Landfilling of glass/inert	thinkstep	2013	US
Various wastes	Sludge (high moisture)	thinkstep	2013	DE
Slag credit	Cement (CEM I 32.5) (EN15804 A1-A3)	thinkstep	2013	DE
Slag credit	Gravel (Grain size 2/32) (EN15804 A1-A3)	thinkstep	2013	DE
Slag credit	Lime (CaO; quicklime lumpy)	thinkstep	2013	DE
Mill scale credit	Iron ore-mix	thinkstep*	2012	DE
EAF dust credit	Zinc mix	thinkstep*	2012	GLO

* thinkstep internal dataset

3.3.4. Emissions to Air, Water, and Soil

All gate-to-gate emissions reported by the steel mills for the manufacturing stage are taken into account in the study. This includes fuel combustion emissions and carbon emissions from the EAF (both calculated according to EPA's Greenhouse Gas Reporting Program, EPA 2013).

Data for all upstream materials, electricity, and energy carriers were obtained from the GaBi 2014 database. The emissions (CO_2, etc.) due to the use of electricity are accounted for with the use of the database processes.

3.4. Model Assumptions

Some model assumptions were made, in part to align the hot-rolled structural sections model with steel models developed by worldsteel in 2011 [WSA 2011]. These assumptions affect steel scrap and dataset choice.

Three types of scrap are considered in the model:

- Internal scrap: Steel scrap from the EAF that is put back into the same EAF. Also known as 'run-around scrap'.
- Home scrap: Steel scrap from on-site steel mill sources other than the EAF (e.g., scrap from the rolling mill).
- External scrap: Steel scrap obtained from external sources outside the steel mill.

In the final life cycle inventory however, only one scrap flow is included. This flow represents the net input of scrap to hot-rolled structural sections production and is calculated based on the inputs and outputs of all three scrap types.

Input material datasets used in the model are detailed in Section 3.3.2. There were four materials, however—calcium carbide, fluorspar, ferro-niobium, and silico-manganese—for which upstream data were not available in thinkstep's GaBi database at the time worldsteel conducted its life cycle inventory of steel products in 2011 (as they are not among those listed in Appendix 6 of the methodology report). For consistency reasons, these materials were thus excluded from the analysis and no upstream burdens assigned.

With the exception of silico-manganese, each of these materials account for less than 0.1% of final product weight and thus fall below the cut-off criteria defined in Section 2.5. Silico-manganese accounts for 1% to 2% of final product weight.

3.5. Life Cycle Inventory Analysis

ISO 14044 defines the Life Cycle Inventory Analysis as the "outcome of a life cycle inventory analysis that catalogues the flows crossing the system boundary and provides the starting point for life cycle impact assessment". As the complete inventory comprises hundreds of flows, Table 3-8 and Table 3-9 display selected key elementary flows based on their relevance to the subsequent impact assessment in order to provide a transparent link between the inventory and impact assessment results. Some of the input flows in Table 3-8 are negative due to system expansion credit given for EAF dust and slag; the negative values however do not imply that steel section production leads to an overall increase in availability of certain resources. Additionally, the analysis excludes any burden associated with additional processing the recovered dust and slag may require before they are used in the next product system.

A complete inventory will be provided to AISC given that one of this project's primary objective is to publish a cradle-to-gate inventory for North American steel sections.

Table 3-8: Key life cycle inventory input flows for 1 metric ton of steel sections

Flow	Amount	Units	Flow	Amount	Units
Energy			**Resources**		
Crude oil	3.79E+02	MJ	Lead	-8.19E-01	kg
Hard coal	4.73E+03	MJ	Molybdenum	1.81E-02	kg
Lignite	2.58E+02	MJ	Silver	-7.09E-03	kg
Natural gas	5.36E+03	MJ	Zinc	-1.65E+00	kg
Uranium	1.48E+03	MJ	Carbon dioxide	1.30E+01	kg
Geothermal	1.86E+00	MJ	Ground water	4.92E+00	m^3
Hydro	6.63E+01	MJ	Lake water	1.66E+01	m^3
Solar	1.26E+02	MJ	River water	8.96E+01	m^3
Wind	1.75E+02	MJ			

Table 3-9: Key life cycle inventory output flows for 1 metric ton of steel sections

Flow	Amount	Units	Flow	Amount	Units
Emissions to air			**Emissions to water**		
Ammonia	6.51E-03	kg	Ammonia	2.87E-03	kg
Carbon dioxide (fossil)	8.87E+02	kg	NH_4^+ / NH_3	1.54E-03	kg
Carbon dioxide (biogenic)	1.17E+01	kg	BOD	3.47E-03	kg
Carbon monoxide	2.10E+00	kg	COD	6.81E-01	kg
Methane	2.89E+00	kg	Nitrate	4.01E-02	kg
Methane, biogenic	1.01E-03	kg	Nitrogen, organic	2.26E-03	kg
Nitrogen oxides	9.86E-01	kg	Nitrogenous matter	4.56E-03	kg
Nitrous oxide	3.12E-02	kg	Phosphate	5.02E-04	kg
NMVOC, unspecified	9.90E-02	kg	Phosphorus	1.61E-03	kg
Propane	2.22E-02	kg	Suspended solids	2.57E+00	kg
R-114	1.77E-07	kg			
Sulfur dioxide	1.99E+00	kg			
Sulfur oxides	2.47E+00	kg			
Xylene	7.00E-03	kg			

4. Inventory Metrics and Impact Assessment

Although the intent is to publish an LCI, inventory and impact assessment metrics as shown in Section 2.6 are evaluated in order to compare this study's results with other published LCIs of hot-rolled structural sections.

4.1. Inventory Results

Energy, material, and water inventory results are presented in Table 4-1 and Table 4-2 per metric ton (tonne) and per short ton (ton); results are rounded to three significant figures. All primary energy results represent net calorific value (i.e., lower heating value). Non-renewable primary energy resources used as raw materials represent coke used to balance steel carbon content. Since hot-rolled structural sections are manufactured almost entirely from recycled content, around 1.15 metric ton of scrap steel is required for production. The process, however, generates around 0.103 metric tons of scrap (see Table 4-7) that is then recycled internally, thus leading to a waste rate of about 5%.

Table 4-2 also includes secondary fuel use and water results. Since no secondary fuels are used at the steel mills, results for these metrics are zero. Water results include both blue water consumption and blue water use. The former represents the net amount of water consumed by steel production, while the latter represents input water only. Both figures include not only water used at the steel mill, but also water required in electricity generation.

A breakdown of renewable and non-renewable energy into energy resources is shown in Figure 4-1. Energy resources include not only the coal, natural gas, etc. required to generate electricity, but also any natural gas and other fuels consumed at the steel mills.

Table 4-1: Energy inventory results per declared unit of product

Inventory metric	Results per metric ton (tonne)		Results per short ton (ton)	
Renewable primary energy excluding resources used as raw materials	369	MJ	317,000	BTU
Renewable primary resources used as raw materials	0	MJ	0	BTU
Renewable primary energy, total	*369*	*MJ*	*317,000*	*BTU*
Non-renewable primary energy excluding resources used as raw materials	12,100	MJ	10,400,000	BTU
Non-renewable primary energy resources used as raw materials	106	MJ	91,400	BTU
Non-renewable primary energy demand, total	*12,200*	*MJ*	*10,500,000*	*BTU*
Renewable and non-renewable primary energy demand, total	***12,600***	***MJ***	***10,800,000***	***BTU***

Energy use is also broken down in Figure 4-2 by process. Electricity production and natural gas dominate energy consumption. Also broken out are materials used for slag (e.g., dolomite and lime), alloying elements (e.g., ferro-chromium, ferro-silicon, and ferro-vanadium), and gases used in the furnace (i.e., argon, nitrogen, and oxygen). Credit represents the avoided production credit from system expansion in order to account for EAF dust, slag, and electrode recovery.

Table 4-2: Material and water inventory results per declared unit of product

Inventory metric	Results per metric ton (tonne)		Results per short ton (ton)	
Use of secondary material	1.04	tonne	1.04	ton
Use of renewable secondary fuels	0	MJ	0	BTU
Use of non-renewable secondary fuels	0	MJ	0	BTU
Blue water consumption	6.16	m³	1,630	gallons
Blue water use	111	m³	29,400	gallons

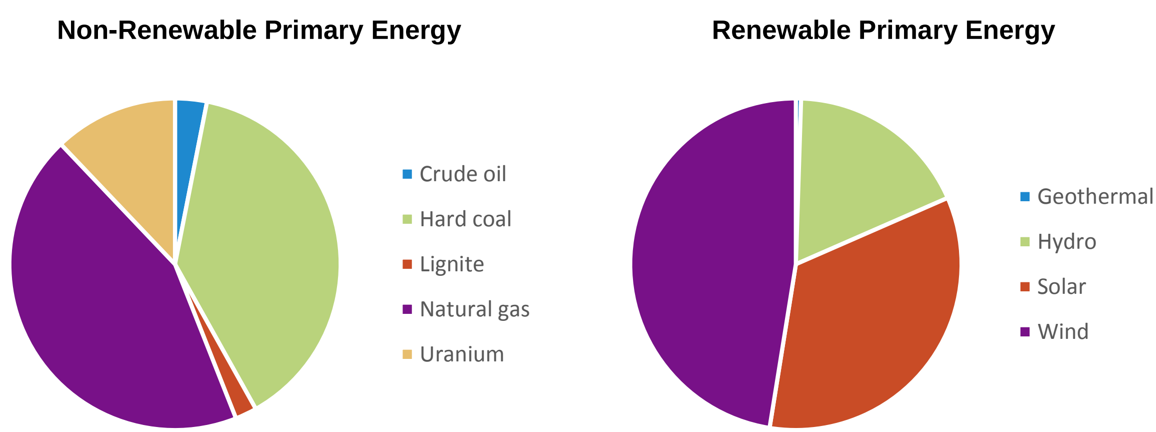

Figure 4-1: Non-renewable and renewable primary energy resources

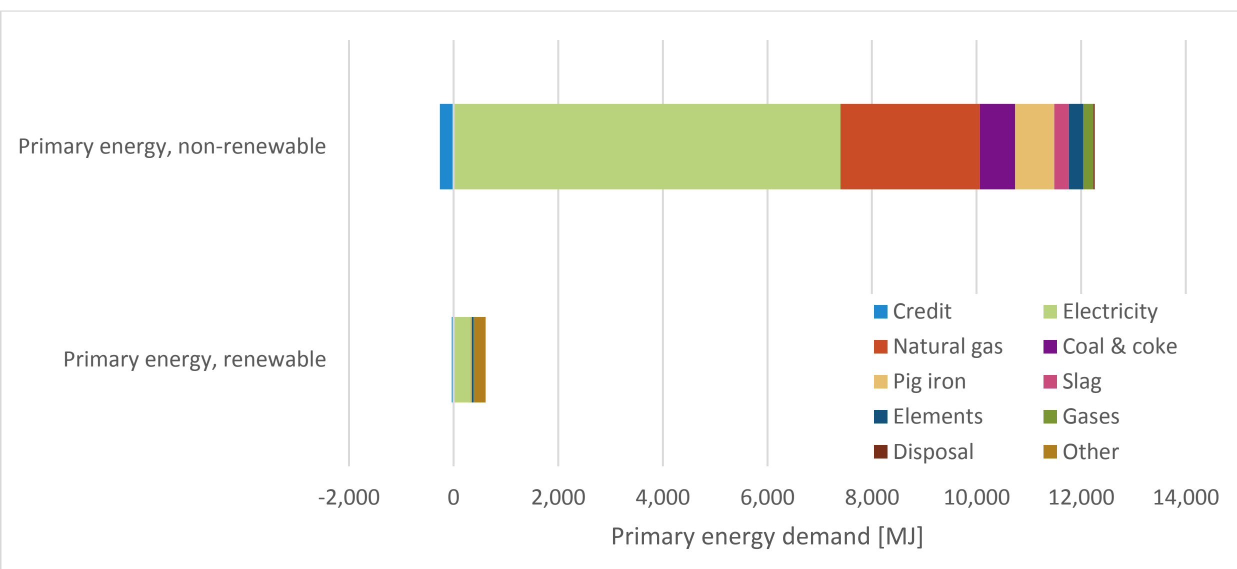

Figure 4-2: Primary energy demand breakdown

4.2. Impact Assessment

Impact assessment results for both CML 2001 – April 2013 and TRACI 2.1 are shown in Table 4-3 per metric ton (tonne) of product and in Table 4-4 per short ton of product. Differences in ozone depletion and acidification potentials are due to differences in the number of available characterization factors in GaBi for these categories. Global warming potential as calculated by the fifth IPCC Assessment Report (AR5) is also included in Table 4-5 for both declared units. All results are rounded to three significant digits.

Table 4-3: CML 2001 – April 2013 and TRACI 2.1 impact assessment per tonne of product

Inventory metric	CML 2001		TRACI 2.1	
Global warming, 100 yr. (excl. bio. carbon)	0.968	tonne CO_2 eq	0.968	tonne CO_2 eq
Global warming, 100 yr. (incl. bio. carbon)	0.967	tonne CO_2 eq	0.967	tonne CO_2 eq
Ozone depletion	1.66E-10	tonne R11 eq	1.77E-10	tonne R11 eq
Acidification	5.89E-03	tonne SO_2 eq	5.21E-03	tonne SO_2 eq
Eutrophication	1.68E-04	tonne PO_4^{3-} eq	1.11E-04	tonne N eq
Photochemical ozone creation	3.74E-04	tonne C_2H_4 eq	—	—
Smog formation	—	—	0.0250	tonne O_3 eq
Abiotic depletion, elements	-1.31E-05	tonne Sb eq	—	—
Abiotic depletion, fossil	10,700	MJ	—	—

Table 4-4: CML 2001 – April 2013 and TRACI 2.1 impact assessment per short ton of product

Inventory metric	CML 2001		TRACI 2.1	
Global warming, 100 yr. (excl. bio. carbon)	0.968	ton CO_2 eq	0.968	ton CO_2 eq
Global warming, 100 yr. (incl. bio. carbon)	0.967	ton CO_2 eq	0.967	ton CO_2 eq
Ozone depletion	1.66E-10	ton R11 eq	1.77E-10	ton R11 eq
Acidification	5.89E-03	ton SO_2 eq	5.21E-03	ton SO_2 eq
Eutrophication	1.68E-04	ton PO_4^{3-} eq	1.11E-04	ton N eq
Photochemical ozone creation	3.74E-04	ton C_2H_4 eq	—	—
Smog formation	—	—	0.0250	ton O_3 eq
Abiotic depletion, elements	-1.31E-05	ton Sb eq	—	—
Abiotic depletion, fossil	9,210,000	BTU	—	—

Table 4-5: Global warming as based on the 5th IPCC annual report per declared unit of product

Inventory metric	Results per metric ton (tonne)		Results per short ton (ton)	
Global warming, 100 yr. (excl. bio. carbon)	0.982	tonne CO_2 eq	0.982	ton CO_2 eq
Global warming, 100 yr. (incl. bio. carbon)	0.981	tonne CO_2 eq	0.981	ton CO_2 eq
Global warming, 20 yr. (excl. bio. carbon)	1.14	tonne CO_2 eq	1.14	ton CO_2 eq
Global warming, 20 yr. (incl. bio. carbon)	1.14	tonne CO_2 eq	1.14	ton CO_2 eq

Figure 4-3 breaks down TRACI 2.1 impact categories as well as abiotic depletion into select processes from steel production. As indicated by the breakdown, electricity generation accounts for the greatest contribution to global warming potential, as well as to most of the other impact categories. For global warming the electricity impact is due to carbon dioxide emissions. Sulfur dioxide and nitrogen oxide emissions drive acidification potential, while nitrogen oxide emissions are the primary contributor to smog formation potential. There are no ozone-depleting emissions from steel making so electricity generation drives ozone depletion.

Facility emissions account for around 30% of global warming (primarily from carbon dioxide and methane emissions), as well as significant fractions of acidification, eutrophication, and smog formation. Sulfur dioxide from the facility is a key contributor to acidification potential, and nitrogen oxide is a key contributor to both eutrophication and smog formation potential. Emissions to water of chemical oxygen demand, nitrate, and phosphorous also contribute to eutrophication results.

Credit is negative for each of the categories as it represents credit received for the avoided production of primary products from recovery of EAF dust, slag, and electrodes. Abiotic depletion of elements, in particular, is driven by the credit given for zinc recovered from EAF dust.

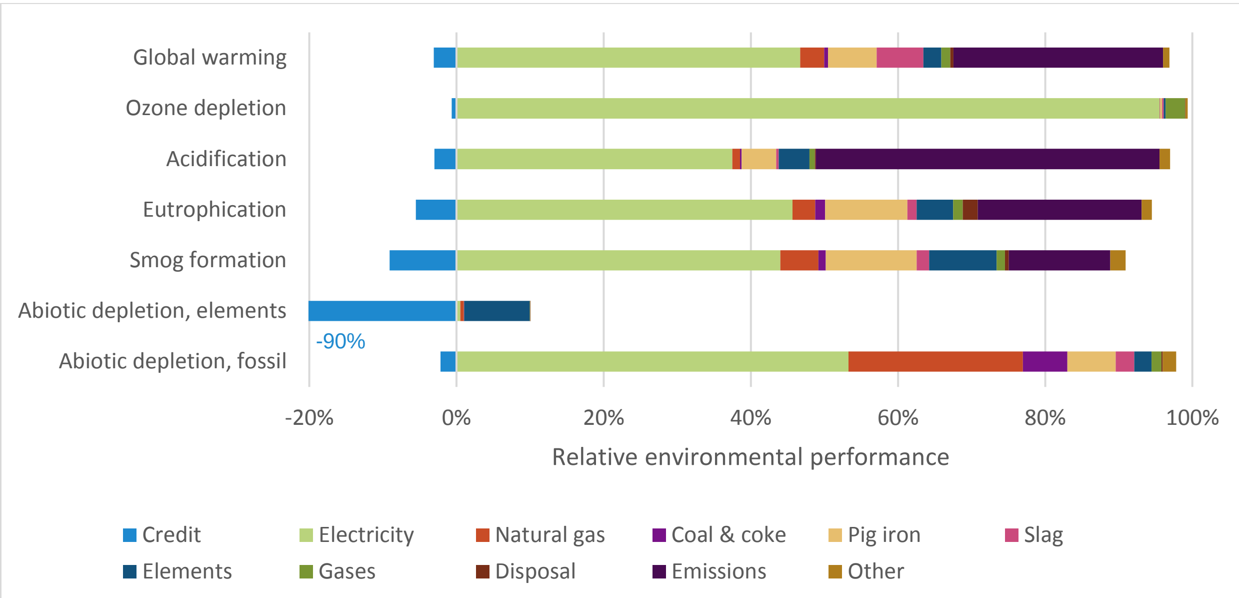

Figure 4-3: Impact assessment breakdown

4.3. Other Environmental Information

Waste and other environmental information is included in Table 4-6 and Table 4-7. Since the metrics in Table 4-7 typically address product end-of-life (i.e., Module C in EN 15804), all results are zero. Steel scrap from manufacturing is recycled internally so use of secondary material in Table 4-2 represents net ferrous input.

Table 4-6: Waste categories per declared unit of product

Inventory metric	Results per metric ton (tonne)		Results per short ton (ton)	
Hazardous waste disposed	2.45E-06	tonne	2.45E-06	ton
Non-hazardous waste disposed	7.76E-03	tonne	7.76E-03	ton
Radioactive waste disposed	5.79E-04	tonne	5.79E-04	ton

Table 4-7: Other environmental output flows per declared unit of product

Inventory metric	Results per metric ton (tonne)		Results per short ton (ton)	
Components for reuse	0	tonne	0	ton
Materials for recycling	0	tonne	0	ton
Materials for energy recovery	0	tonne	0	ton
Exported energy	0	MJ	0	BTU

4.4. Benchmarking

The inventory developed in this report is benchmarked against existing inventories for hot-rolled structural sections. Inventories considered are listed in Table 4-8, along with details about data source, steel process route (EAF or BOF—basic oxygen furnace), and amount of secondary steel input to manufacturing.

Table 4-8: Benchmark datasets

Dataset name	Region	Data source	Ref. year	Background data	Process route	Secondary steel input per kg
Steel sections (current)	RNA		2010	GaBi 2014	EAF	1.05 kg
Steel sections (EN 15804)	DE	thinkstep	2013	GaBi 2014	BOF & EAF	0.155 kg
Steel sections	GLO	worldsteel	2007	GaBi 4	BOF & EAF	0.608 kg
Steel sections	RER	worldsteel	2007	GaBi 4	BOF & EAF	0.849 kg
Steel sections (interim)	RNA	worldsteel	2007	GaBi 4	EAF	1.13 kg

Figure 4-4 summarizes the results of this comparison where the vertical axis represents the results from the current report. Overall, the results are consistent given what each dataset represents. The German thinkstep dataset is almost consistently associated with the highest impact compared to other datasets, primarily due to its lower recycled content and high fraction of product manufactured via the BOF route. The one exception is ozone depletion, which is lower due to BOF's lower use of electricity, combined with differences in grid mix. The other datasets, with the exception of worldsteel's interim regional North America dataset, are also associated with higher impact due to their lower recycled content and their inclusion of both EAF and BOF processing routes.

Ozone depletion, in particular, is notably different for the three worldsteel datasets—ranging from 210 to 340 times as high as that for the dataset developed in this report. This drastic difference due to differences in background data between the database versions. Upgrades to the database included the removal of several ozone-depleting refrigerants that have been regulated since the 1990s. Since these changes were made to datasets of electricity generation, they affected nearly every other dataset in the GaBi database.

Since abiotic depletion of elements is negative for this report's life cycle inventory, Figure 4-4 is calculated using the absolute value of abiotic depletion results to maintain sign consistency. The German thinkstep dataset has a higher impact for this category, again due to its use of primary steel. The worldsteel datasets are all associated with negative elemental abiotic depletion impact on an absolute basis due to credits received for recovering waste zinc. The credit for the dataset developed in this report is likely comparable to those for the global and regional Europe datasets, but higher than that for the regional North America dataset (leading the North American sections dataset to have a higher net elemental abiotic depletion impact).

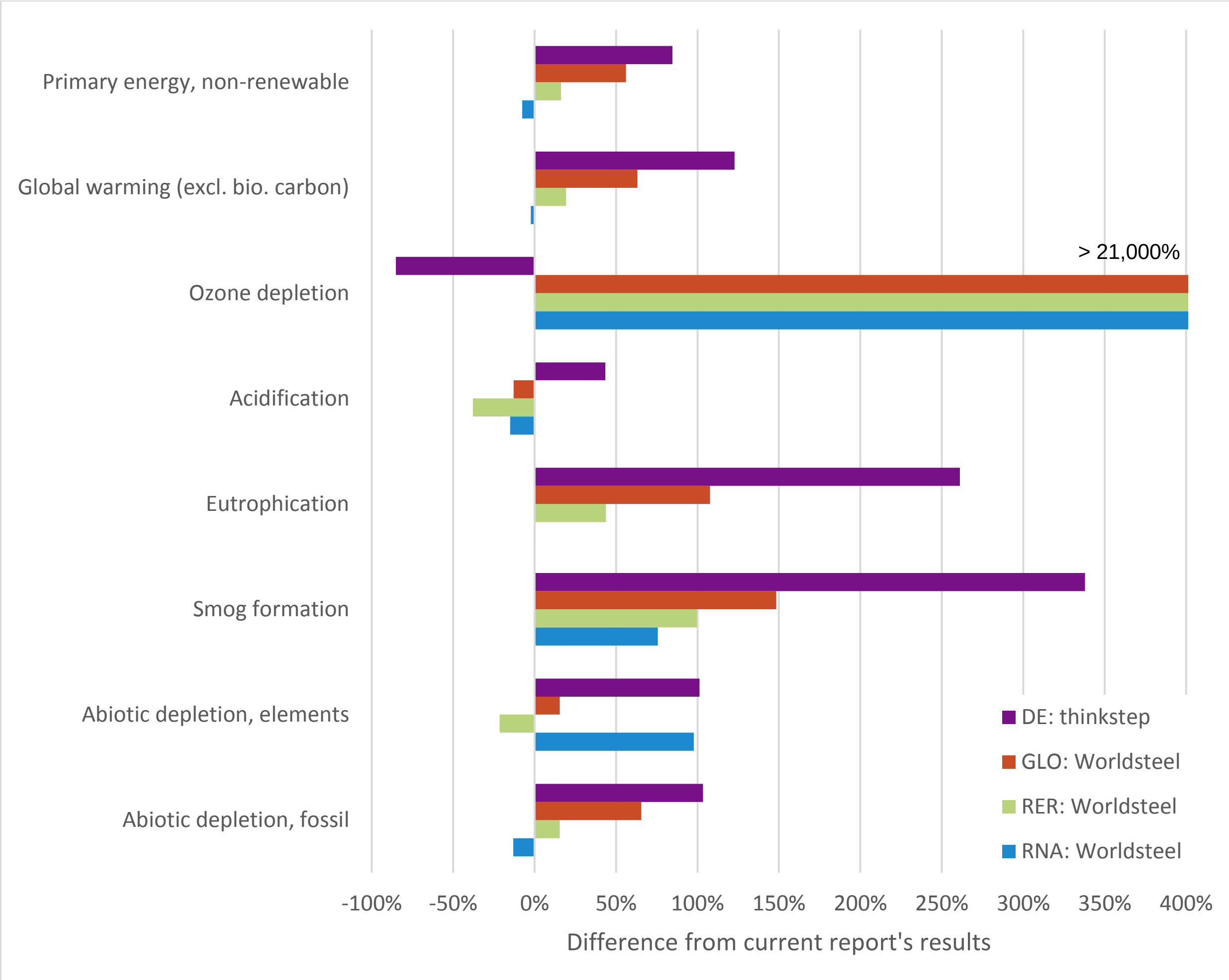

Figure 4-4: Impact comparison against other datasets

4.5. Alternative Scenarios

A few alternative scenarios are evaluated in this section in order to address certain assumptions made in developing this inventory. Specifically, these scenarios target assumptions on the use of proxy data, use of 2014 data, credit given for avoided production, and end-of-life. Table 4-9 details the differences between scenarios evaluated; key changes are highlighted in **bold yellow**.

- **Baseline:** Represents the baseline analysis presented in Sections 4.1 to 4.3.
- **Energy & emissions data:** Presents the results using energy and emissions data from 2007 to 2010 that were originally submitted to worldsteel, instead of the 2014 data that were used for one manufacturer (see Section 3.2.4).
- **Proxy use:** Includes upstream burdens of materials that were originally excluded from worldsteel's analysis (see Section 3.4). Since three of the four the exact materials are not available in thinkstep's GaBi databases, proxy datasets were chosen or the burden estimated based on literature (Table 4-10).

- **Zinc fraction:** Assumes a higher zinc content in the recovered EAF dust. This particular assumption is aligned with the assumption used in worldsteel's methodology report [WSA 2011].

- **EoL burden:** Instead of only including credit for each recycled waste stream, the burden associated with processing EAF dust and slag is added to system boundaries. While electrodes can be recycled and credit given for the avoided production of virgin electrodes, there is insufficient information to model the recycling process so the cut-off allocation approach (in which neither burden nor credit is allocated to the product system) is chosen as the worst case scenario.

- **EoL allocation:** The cut-off allocation approach to zinc, slag, electrodes, and mill scale from steel production is applied in place of system expansion. Non-steel products are assumed to leave the system without any further processing. Additionally, no credit is given for the production of the additional products.

- **Grid mix:** Uses US average electric grid mix instead of grid mixes specific to eGRID subregions where facilities are located. The US average is chosen since eGRID subregion data were not available in GaBi 4 (the database used to develop worldsteel's datasets).

Table 4-9: Alternative scenario assumptions

Scenario #	Baseline	Energy & emissions	Proxy use	Zinc frac.	EoL burden	EoL allocation	Grid mix
Data year	2007 – 2014	**2007 – 2010**	2007 – 2014	2007 – 2014	2007 – 2014	2007 – 2014	2007 – 2014
Upstream material proxies	No proxy data	No proxy data	**Include burden**	No proxy data	No proxy data	No proxy data	No proxy data
Zinc fraction in EAF dust	20% to 25% zinc content	20% to 25% zinc content	20% to 25% zinc content	**50% zinc content**	20% to 25% zinc content	20% to 25% zinc content	20% to 25% zinc content
Zinc recovery from EAF dust	Credit only	Credit only	Credit only	Credit only	**Include burden and credit**	**Cut-off (no credit or burden)**	Credit only
Slag disposal	Credit only	Credit only	Credit only	Credit only	**Include burden and credit**	**Cut-off (no credit or burden)**	Credit only
Electrode disposal	Credit only	Credit only	Credit only	Credit only	**Cut-off (no credit or burden)**	**Cut-off (no credit or burden)**	Credit only
Grid mix	eGRID subregion	eGRID subregion	eGRID subregion	eGRID subregion	eGRID subregion	eGRID subregion	**US average**

Table 4-10: Upstream datasets used to represent excluded materials

Raw Material	Dataset Name	Primary Source	Ref. Year	Geography
Calcium carbide	Calcium carbide furnace (estimation) Lime (CaO; quicklime lumpy) Coke mix Electrode	estimate thinkstep thinkstep thinkstep*	 2013 2010 2011	US DE US ZA, NO
Silico-manganese	Ferro manganese	thinkstep	2013	ZA
Ferro niobium	Ferro vanadium	thinkstep*	2012	ZA
Fluorspar	Fluorspar (extraction and processing)	thinkstep*	2011	US

* thinkstep internal dataset

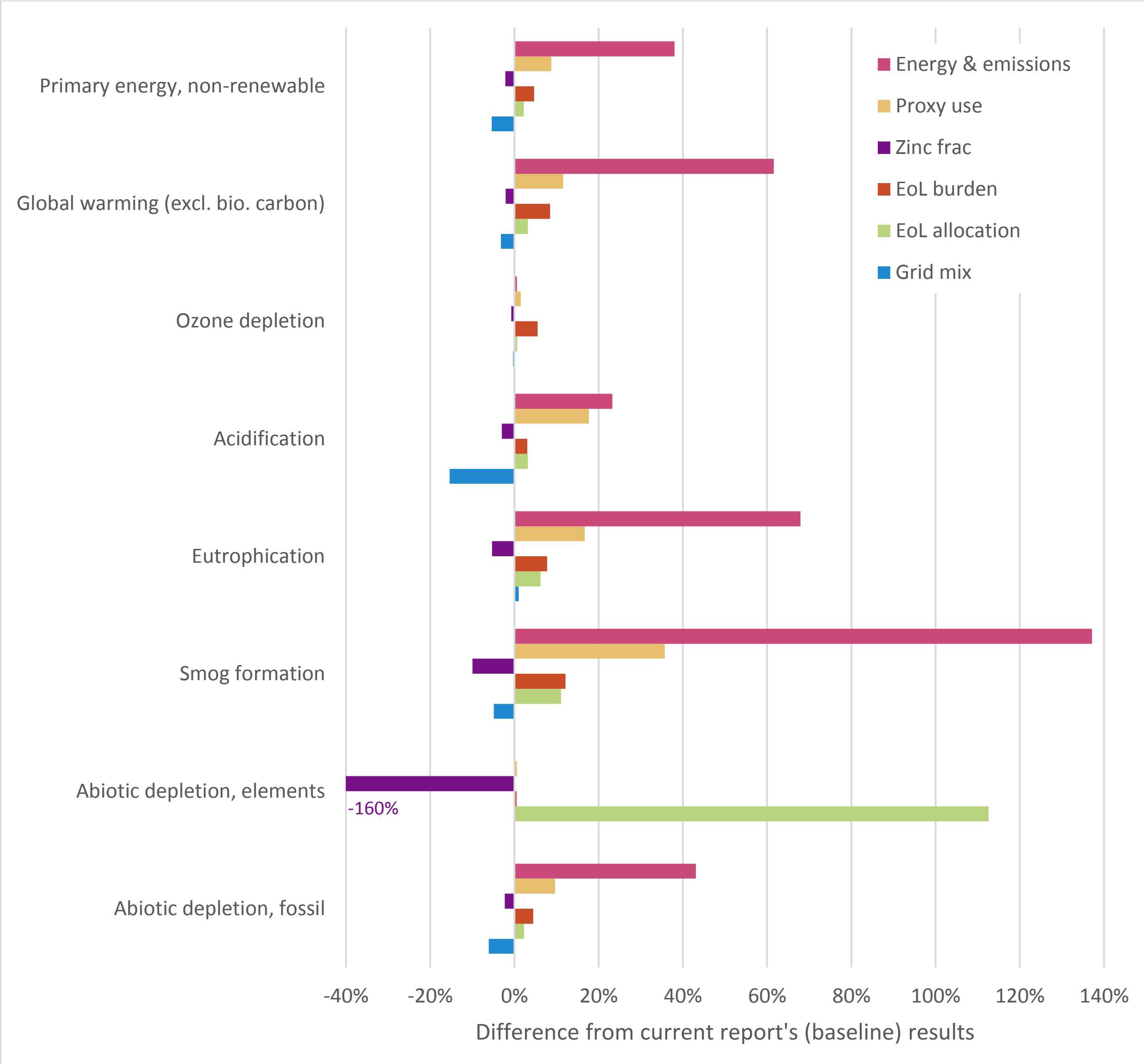

Figure 4-5: Impact comparison against alternative scenarios

Figure 4-5 summarizes scenario comparison results; for each impact category, the baseline (i.e. data from this report) is represented by the vertical axis.

- **Energy & emissions data:** As the figure indicates, results based on original energy and emissions data are consistently higher than baseline results. This is in line with one manufacturer's 2010 energy consumption, carbon dioxide emissions, and nitrogen oxide emissions per metric ton being significantly higher than that manufacturer's 2014 numbers, as well as higher than the corresponding values for the other manufacturers (see Section 3.2.4). The difference is, in part, also driven by the fact that the manufacturer in question represents over half the production volume. Using 2014 data brings the baseline in line with other inventories (Figure 4-4) once recycled content and production route are taken into account.
- **Proxy use:** Addition of proxy data likewise increases environmental burden. The majority of this additional burden is due to silico-manganese, for which ferro manganese is used as a proxy as silico-manganese is often produced from ferro manganese slag. The impacts associated with the

other excluded materials—calcium carbide, ferro niobium, and fluorspar—are all small enough that they would fall under the cut-off criteria.

- **Zinc fraction:** Increasing the fraction of zinc recovered from EAF dust has a minimal effect on all impact categories except for elemental abiotic depletion. The recovery of zinc means that less primary zinc and other resources are required and thus the avoided production credit increases proportionately.
- **EoL burden:** Including the end-of-life burden for EAF dust recovery and slag reprocessing has a limited effect on all impact categories considered—at most, 12% of baseline results.
- **EoL allocation:** Removing system expansion—that is, assuming co-products leave system boundaries without any burden or credit—has a limited effect on most impact categories. The one exception is abiotic depletion potential, elements due to the fact that the product system can no longer claim credit for recovered zinc from EAF dust.
- **Grid mix:** Changing the electricity grid mix from eGRID subregions to the US average has the greatest impact on smog formation—likely due to one of the facilities moving away from a coal-heavy grid mix to the US average.

5. Interpretation

5.1. Identification of Relevant Findings

Impact assessment results indicate that energy generation and use is the largest impact driver for hot-rolled structural sections production. This is consistent with the electricity and natural gas requirements for electric arc furnaces that are used to melt scrap steel, as well as rolling mill use of natural gas to heat the slab and roll it into its final form. Additionally, structural steel in North America is produced primarily from steel scrap which is modeled to enter the system free of any primary burden under the cradle-to-gate system boundary.

The results also show there is minimal burden associated with abiotic depletion potential—again due to the use of steel scrap rather than virgin materials. Credit from the avoided production of zinc and other materials dominates this category.

Lastly, the impact assessment results are consistent with other hot-rolled structural sections datasets once variations in scrap content, production route, and background data are taken into account.

As all of the above findings relate to only the production phase of the steel section life cycle, they would not change if use and end-of-life were added.

5.2. Benchmarking and Scenario Analysis

In order to understand whether the life cycle inventory developed in this report is consistent with existing data, impact assessment results were calculated for other hot-rolled structural sections datasets and compared to results from this analysis in Section 4.4. The comparison indicates there are differences among the inventories primarily due to differences in background data and in geographical and technological representativeness. Once these assumptions are taken into account, the results are found to be in line with existing datasets.

Various scenarios were also evaluated to address assumptions made in the course of developing this inventory. Of these assumptions, the decision to use one mill's 2014 data to replace the inexplicable original data has the biggest effect. However, it also serves to bring the impact assessment results in line with those of other LCIs.

Other scenarios investigated the use of proxy data to represent upstream material production burden, end-of-life assumptions, grid mix assumptions, etc. Of these, probably the use of proxy data is most significant—in particular for silico-manganese which is represented by a ferro-manganese production dataset. If ferro-manganese is indeed a representative proxy, then silico-manganese should be included since it can significantly affect impact assessment results. However, this analysis excludes the material in order to be consistent with existing worldsteel inventories from 2011. Future analyses should strongly consider including proxy data when matching datasets are not available.

5.3. Data Quality Assessment

Inventory data quality is judged by its precision (measured, calculated or estimated), completeness (e.g., unreported emissions), consistency (degree of uniformity of the methodology applied) and representativeness (geographical, temporal, and technological).

To cover these requirements and to ensure reliable results, primary industry data were combined with background LCA data from the GaBi 2014 databases. The LCI datasets from the GaBi 2014 databases are widely distributed and used with the GaBi 6 Software. The datasets have been used in LCA models worldwide in industrial and scientific applications in internal, as well as in many critically reviewed and published studies. In the process of providing these datasets they are cross-checked with other databases and values from industry and science.

5.3.1. Precision and Completeness

Precision

As the majority of the relevant foreground data are measured data or calculated based on primary information sources of the owner of the technology, precision is considered to be high. Seasonal variations were balanced out by using annual averages. All background data are sourced from GaBi databases with the documented precision.

Completeness

Each unit process was checked for mass balance and completeness of the emission inventory. Selected alloying materials, most of which represented under 1% of mass, were excluded under the cut-off criteria, but also due to unavailable background data. Silico-manganese was excluded for consistency with current WorldSteel LCIs; however, it represents 1% to 2% of mass and an even larger portion of environmental impact and therefore does not fall under the cut-off criteria. Inbound transport was also not considered for alloying elements and process materials. Additionally, the environmental burden associated with recovering zinc from EAF dust and reprocessing slag was excluded. Otherwise, no data were knowingly omitted.

5.3.2. Consistency and Reproducibility

Consistency

To ensure consistency, all primary data were collected with the same level of detail (i.e., using consistent data collection templates), while all background data were sourced from the GaBi 2014 databases. Allocation and other methodological choices were made consistently throughout the model.

Reproducibility

Reproducibility is supported as much as possible through the disclosure of input-output data, dataset choices, and modeling approaches in this report. Based on this information, any third party should be able to approximate the results of this study using the same data and modeling approaches

5.3.3. Representativeness

Temporal

As discussed in Section 3.2.4, most of the primary data based on the 2007 to 2010 calendar years and represents production in 2010. Data from 2014 were used for a few data points for one mill, however, due to that mill's original data being noticeably out of line with corresponding data points from the other mills. These data are still representative of mill production as neither the mills nor their processes have materially changed over the past several years. All secondary data came from the GaBi 2014 databases and are representative of the years 2009-2013. As the study intended to represent hot-rolled structural sections production in 2007, temporal representativeness is warranted.

Geographical

All primary and secondary data were collected specific to the location of manufacture when possible. Energy data used represent the region-specific infrastructure and emission factors. Raw material datasets were chosen for geographical representativeness and are based on North American conditions or reasonable proxies as necessary. Regional differentiation for all raw material LCIs was not possible within the time and cost constraints of the study. Geographical representativeness is considered to be good.

Technological

All primary and secondary data were modeled to be specific to the technologies or technology mixes under study. Technological representativeness is considered to be good.

5.4. Conclusions, Limitations, and Recommendations

5.4.1. Conclusions

The goal of this study was to develop a cradle-to-gate life cycle inventory of structural steel in order to support future evaluations, such as life cycle assessments and environmental product declarations of downstream products. Overall, the LCI is considered to be of good quality and representative of production in North America.

5.4.2. Limitations & Assumptions

One key assumption was the exclusion of four alloying elements due to lack of upstream data. All four of these materials are likewise excluded by worldsteel according to their 2011 methodology report [WSA 2011]. While three of these elements can also be excluded under cut-off criteria, the fourth, silico-manganese, cannot due to the fact that it accounts for 1% to 2% of product mass. Additionally, silico-manganese can be energy-intensive to produce—even more so than the ferro-manganese[2] proxy data used in this study. Therefore, the inventory underestimates the energy and environmental burdens associated with hot-rolled structural sections production; however, it maintains comparability with current worldsteel inventories. Ideally, proxy data should be used when background data are not available, and

[2] According to the on-line Encyclopedia Britannica, electricity consumption required to produce silico-manganese is around 3,800 to 4,800 kWh per ton—higher than electricity required to smelt ferro-manganese.

recommendations have been made to worldsteel to include the impact of silico-manganese in their future inventories.

Another assumption made in this analysis was that recovery of manufacturing wastes is burden-free. Therefore, only credit for zinc from EAF dust is included in the model but there is no burden assigned to process the dust in order to recover the zinc. While the impact associated with processing waste is likely small, it is important to include as the recommended practice is to model up to the “end of waste”[3] stage, which includes waste processing.

Additionally, as described in Section 2.8.1, some energy data representing production in 2014 as the manufacturer was unable to clarify why their energy consumption per unit ton was nearly double those of the other mills. When unit energy consumption for 2014 was evaluated, the results were in line with those of the other mills

5.4.3. Recommendations

Although this study’s objective is to develop a life cycle inventory, impact categories were evaluated in order to compare this LCI to existing datasets. Additionally, impact category results were broken down into processes to illustrate what drives environmental performance. These results show that electricity generation, fuel production, and on-site emissions are all key contributors to environmental impact. Should mills reduce their energy consumption or find ways to produce low-carbon energy on site or use renewable fuels, they can make a difference in the impact per ton of steel.

Future analyses should address the assumptions made in this study and include proxy data for upstream materials instead of excluding those materials from the analysis (of course, assuming primary data for those materials are available in the first place). Additionally, waste processing should be included in study scope.

[3] The end-of-waste state is defined by EN 15804 and represents the point in the life cycle at which there is both a specific purpose and market demand for the recovered material.

6. References

BARE 2012	J. Bare, Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) - Software Name and Version Number: TRACI version 2.1 - User's Manual, U.S. EPA, 2012.
EN 15804	EN 15804:2012+A1:2013, Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products, 2012.
EPA 2012	Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) – User's Manual. Environmental Protection Agency. Washington, DC.
EPA 2013	US EPA, 2013 Revisions to the Greenhouse Gas Reporting Rule and Final Confidentiality Determinations for New or Substantially Revised Data Elements; Final Rule. 40 CFR Part 98, 78(230), 2013.
IPCC 2013	IPCC, Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 2013.
ISO 14040	ISO 14040 Environmental Management – Life Cycle Assessment – Principles and Framework, 2006.
ISO 14044	ISO 14044 Environmental management -- Life cycle assessment -- Requirements and guidelines, 2006.
SCS 2015	SCS Global Services, North American Product Category Rule for Designated Steel Construction Products, 2015.
WSA 2011	World Steel Association, Methodology report: Life cycle inventory study for steel products, 2011.

American Iron and Steel Institute

thinkstep

Structural Section and Hot-Dip Galvanized Steel Production in China

Life cycle assessment report

On behalf of the American Iron and Steel Institute (AISI)

Client:	**American Iron & Steel Institute (AISI)**
Title:	**Structural Section and Hot-Dip Galvanized Steel Production in China**
Report version:	v1.0
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On behalf of thinkstep AG and its subsidiaries

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Table of Contents

List of Figures

List of Tables

List of Acronyms

AP	Acidification Potential
BF	Blast Furnace
BOD	Biological Oxygen Demand
BOF	Basic Oxygen Furnace
COD	Chemical Oxygen Demand
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
EF	Emissions Factors
EoL	End-of-Life
EP	Eutrophication Potential
GaBi	Ganzheitliche Bilanzierung (German for holistic balancing)
GHG	Greenhouse Gas
GWP	Global Warming Potential
HDG	Hot-dip galvanized
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
NMVOC	Non-Methane Volatile Organic Compound
POCP	Photochemical Ozone Creation Potential
SFP	Smog Formation Potential
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
VOC	Volatile Organic Compound

Glossary

Life cycle

A view of a product system as "consecutive and interlinked stages … from raw material acquisition or generation from natural resources to final disposal" (ISO 14040:2006, section 3.1). This includes all material and energy inputs as well as emissions to air, land and water.

Life Cycle Assessment (LCA)

"Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO 14040:2006, section 3.2)

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" (ISO 14040:2006, section 3.3)

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" (ISO 14040:2006, section 3.4)

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" (ISO 14040:2006, section 3.5)

Functional unit

"Quantified performance of a product system for use as a reference unit" (ISO 14040:2006, section 3.20)

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" (ISO 14040:2006, section 3.17)

Closed-loop and open-loop allocation of recycled material

"An open-loop allocation procedure applies to open-loop product systems where the material is recycled into other product systems and the material undergoes a change to its inherent properties."

"A closed-loop allocation procedure applies to closed-loop product systems. It also applies to open-loop product systems where no changes occur in the inherent properties of the recycled material. In such cases, the need for allocation is avoided since the use of secondary material displaces the use of virgin (primary) materials."

(ISO 14044:2006, section 4.3.4.3.3)

Foreground system

“Those processes of the system that are specific to it … and/or directly affected by decisions analyzed in the study.” (JRC 2010, p. 97) This typically includes first-tier suppliers, the manufacturer itself and any downstream life cycle stages where the manufacturer can exert significant influence. As a general rule, specific (primary) data should be used for the foreground system.

Background system

“Those processes, where due to the averaging effect across the suppliers, a homogenous market with average (or equivalent, generic data) can be assumed to appropriately represent the respective process … and/or those processes that are operated as part of the system but that are not under direct control or decisive influence of the producer of the good….” (JRC 2010, pp. 97-98) As a general rule, secondary data are appropriate for the background system, particularly where primary data are difficult to collect.

Critical Review

“Process intended to ensure consistency between a life cycle assessment and the principles and requirements of the International Standards on life cycle assessment” (ISO 14044:2006, section 3.45).

Executive Summary

The American Iron and Steel Institute (AISI) commissioned thinkstep to conduct a life cycle assessment (LCA) to evaluate the environmental profiles of hot-dip galvanized (HDG) coil and structural sections production in China. This will enable AISI to conduct a preliminary comparison with corresponding steel products produced in the U.S. using existing LCI profiles based on data collected by worldsteel. The target audience of the study therefore includes AISI and its members. The results of the study are not intended to support comparative assertions that are intended to be disclosed to the public.

Study functional unit is the production of 1 kilogram of hot-dip galvanized steel and 1 kilogram of structural steel sections. Because no specific application of the steel products is considered by the analysis, no particular function is defined for the steel. The system boundary is set to include the manufacturing of the steel products (cradle-to-gate) and their subsequent transportation to North America. Downstream processing of the steel into manufactured products, the products' use, and end-of-life are not included.

The analysis assumes that 100% of HDG coil is manufactured via the blast furnace / basic oxygen furnace (BF/BOF) route, whereas 94% of structural sections are manufactured via BF/BOF and the remaining 6% via the electric arc furnace (EAF) route, based on a combination of expert judgment and worldsteel yearbook data (worldsteel Association, 2015).

Anonymized data were obtained from seven Chinese facilities. These data were supplemented with emissions data from the US EPA's AP-42 report, thinkstep's GaBi database, and CEN 264 to close data gaps for GHG emissions and improve each unit process' carbon balance. The data represent approximately 3.5% of crude steel production in China. It is believed that the sites include mills that export to foreign countries, although not necessarily to the U.S. The use of anonymized data also limits the ability to validate numbers, confirm inputs, and conduct sensitivity analyses.

Study results are summarized in the table below. Non-renewable primary energy demand is driven by hard coal (i.e., anthracite) consumption as the raw material for coke. Additionally, coal is used as a carbon source in other process steps, thus contributing to energy demand that way. All process steps contribute to the global warming potential, although the boiler is associated with the highest share of contributions.

The coke oven, sintering, and blast furnace are all key contributors to potential acidification and eutrophication impacts primarily due to ammonia emissions to water. Expert judgment indicates that the ammonia emissions are high but plausible. Smog formation potential is primarily driven by transportation emissions associated with shipping the steel to North America. Iron ore production and, for HDG coil, zinc production also contribute.

Table: Summary of impact assessment results per 1 kg of steel product

	Energy demand [MJ]	Global warming [kg CO_2 eq.]	Acidification [kg SO_2 eq.]	Eutrophication [kg N eq.]	Smog formation [kg O_3 eq.]
HDG coil	2.88E+01	3.22E+00	9.14E-02	3.42E-02	1.95E-01
Structural sections	2.49E+01	2.93E+00	9.25E-02	3.53E-02	1.69E-01

Since ammonia emissions were a highly significant contributor to potential eutrophication impacts in particular, with over 90% of the acidification and eutrophication results being caused by process emissions of ammonia to water and normalized eutrophication results being almost twice as high as normalized acidification results, additional efforts were made to better understand whether the emission numbers are realistic and how the characterization model works. A key limitation of this study is the lack of information about the exact locations of the facilities that export steel to the U.S. and the fact that the TRACI tool was used with the understanding that it could over- or underestimate the potential environmental impacts depending on the conditions of the receiving environment.

1. Goal of the Study

The American Iron & Steel Institute (AISI) is interested in a deeper understanding of the environmental profile of steel imported to the U.S. from China. To further this understanding, this study aims to develop a life cycle inventory (LCI) and to perform a life cycle assessment for two steel products—structural steel sections and hot-dip galvanized steel—which are produced in China and imported to the U.S. This will enable AISI to conduct a preliminary comparison with corresponding steel products produced in the U.S. using existing LCI profiles based on data collected by worldsteel.

The target audience of the study therefore includes AISI and its members. The results of the study are not intended to support comparative assertions, as defined by ISO 14040, Section 3.6 (ISO, 2006), intended to be disclosed to the public.

This study has been conducted according to the requirements of the international standard ISO 14044:2006 (ISO, 2006).

2. Scope of the Study

The following sections describe the general scope of the project to achieve the stated goals. This includes, but is not limited to, the identification of specific product systems to be assessed, the product function(s), functional unit and reference flows, the system boundary, allocation procedures, and cut-off criteria of the study.

Since one goal is to eventually compare study results with existing LCI profiles based on worldsteel data, the worldsteel LCA methodology report (worldsteel, 2011) is referenced as guidance for defining study scope.

2.1. Product Systems

Structural sections and hot-dip galvanized (HDG) coil produced in China and exported to the U.S. are assessed in this study. Structural sections include I-beams, angles, channels, and other profiles used in structural applications. Hot-dip galvanized coil is steel coil coated with a protective zinc layer to prevent corrosion. This product has several applications in the building and construction industry as well as in the industrial sector and automotive industry, among others.

2.2. Functional Unit

Within the scope of this study, the functional unit is the production of 1 kilogram of structural steel sections and 1 kilogram of hot-dip galvanized steel. Because no specific application of the steel products is considered by the analysis, no particular function is defined for the steel and as such, defining a true functional unit is not feasible.

2.3. System Boundary

The system boundary is set to include the manufacturing of the steel products (cradle-to-gate) and their subsequent transportation to North America. Table 2-1 shows which life cycle stages of the product are considered in this study.

The production stage covers all the process steps from the extraction of resources from the earth (i.e., the cradle) to the finished products at the steelworks, as well as the shipment of the products to the west coast of North America. This includes all the activities associated with the production of steel at the steel manufacturing sites, upstream activities such as mining, the processing of raw materials, transportation to the site of production, and the consumption of any material or energy resources during any of these production stages.

Table 2-1: System boundary

Included	Excluded
✓ Production stage ○ Raw material supply (extraction, processing, recycled material) ○ Transport to manufacturer ○ Steel production, including the furnace and rolling ○ Hot-dip galvanization (coil only) ✓ Transportation to North America	× Steel product distribution beyond initial transportation to North America × Steel product use × Steel product end-of-life × Construction of capital equipment × Maintenance and operation of support equipment × Human labor and employee commute

Downstream processing of the steel into manufactured products and the products' subsequent use is not included in the system boundary. Steel sections and hot-dip galvanized steel coil are used in many different applications and, consequently, it is not feasible nor intended to include the use stage in this assessment.

2.3.1. Coverage

The inventory is to be representative of steel production technology mix used in China during the reference year 2014.

2.4. Allocation

2.4.1. Multi-output Allocation

System expansion is applied for all co-products of steel production (process gases, slag, etc.). Further detail is provided in the worldsteel LCA methodology report (worldsteel, 2011) on page 19.

Allocation of background data (energy and materials) taken from the GaBi 2016 databases is documented online at http://www.gabi-software.com/international/support/gabi/gabi-lcia-documentation/.

2.4.2. End-of-Life Allocation

Only the cradle-to-gate environmental performance (including transportation from China to North America) is considered in this analysis. As such, collection rates at end-of-life and any subsequent reprocessing of the steel into secondary material is excluded from the analysis. Steel scrap used in steel production is assumed to enter the system burden-free. Only the resources and emissions required to reprocess it into secondary product are considered.

2.5. Cut-off Criteria

No cut-off criteria are defined for this study. For the processes within the system boundary, all available energy and material flow data are included in the model wherever possible. In cases where no matching life cycle inventories are available to represent a flow, proxy data is applied based on conservative assumptions regarding environmental impacts.

2.6. Selection of LCIA Methodology and Impact Categories

The impact assessment categories and other metrics considered to be of high relevance to the goals of the project are shown in Table 2-2 and Table 2-3. TRACI 2.1 has been selected as the analysis is on behalf of an American industry association that desires to benchmark the results against North American life cycle inventories (Bare, 2012) (EPA, 2012). For global warming where TRACI characterization factors are not considered to be the most current, the IPCC's 5th assessment report is used as described in more detail below.

Global Warming Potential and **Non-Renewable Primary Energy Demand** were chosen because of their relevance to climate change and energy efficiency, both of which are strongly interlinked, of high public and institutional interest, and deemed to be one of the most pressing environmental issues of our time. The global warming potential impact category is assessed based on the current Intergovernmental Panel on Climate Change (IPCC) characterization factors, excluding biogenic carbon, taken from the 5th Assessment Report (IPCC, 2013) for a 100-year timeframe (GWP100) as this is currently the recommended metric to assess short-term climate change on a midpoint level.[1]

Eutrophication, **Acidification**, and **Smog Formation Potentials** were chosen because they are closely connected to air, soil, and water quality and capture the environmental burden associated with commonly regulated emissions such as NO_x, SO_2, VOC, and others.

While the focus of the study is on the metrics listed in Table 2-2, it is possible to calculate other impact categories and environmental indicators from the resulting LCIs. However, additional interpretation may be necessary depending on available secondary data and data quality.

It shall be noted that chosen impact categories represent impact *potentials*, i.e., they are approximations of environmental impacts that could occur if the emissions would (a) actually follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so. In addition, the inventory only captures that fraction of the total environmental load that corresponds to the functional unit (relative approach). LCIA results are therefore relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

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[1] http://www.lifecycleinitiative.org/reaching-consensus-on-recommended-environmental-indicators-and-characterisation-factors-for-life-cycle-impact-assessment-lcia/

Table 2-2: TRACI 2.1 impact category descriptions

Impact Category	Description	Unit	Reference
Global Warming Potential (GWP100)	A measure of greenhouse gas emissions, such as CO_2 and methane. These emissions are causing an increase in the absorption of radiation emitted by the earth, increasing the natural greenhouse effect. This may in turn have adverse impacts on ecosystem health, human health and material welfare.	kg CO_2 equivalent	(IPCC, 2013)
Eutrophication Potential	Eutrophication covers all potential impacts of excessively high levels of macronutrients, the most important of which nitrogen (N) and phosphorus (P). Nutrient enrichment may cause an undesirable shift in species composition and elevated biomass production in both aquatic and terrestrial ecosystems. In aquatic ecosystems increased biomass production may lead to depressed oxygen levels, because of the additional consumption of oxygen in biomass decomposition.	kg N equivalent	(Bare, 2012) (EPA, 2012)
Acidification Potential	A measure of emissions that cause acidifying effects to the environment. The acidification potential is a measure of a molecule's capacity to increase the hydrogen ion (H^+) concentration in the presence of water, thus decreasing the pH value. Potential effects include fish mortality, forest decline and the deterioration of building materials.	kg SO_2 equivalent	
Smog Formation Potential (SFP)	A measure of emissions of precursors that contribute to ground level smog formation (mainly ozone O_3), produced by the reaction of VOC and carbon monoxide in the presence of nitrogen oxides under the influence of UV light. Ground level ozone may be injurious to human health and ecosystems and may also damage crops.	kg O_3 equivalent	

Table 2-3: Other environmental indicators

Indicator	Description	Unit	Reference
Primary Energy Demand (PED)	A measure of the total amount of primary energy extracted from the earth. PED is expressed in energy demand from non-renewable resources (e.g. petroleum, natural gas, etc.) and energy demand from renewable resources (e.g. hydropower, wind energy, solar, etc.). Efficiencies in energy conversion (e.g. power, heat, steam, etc.) are taken into account.	MJ (lower heating value)	(Guinée, et al., 2002)

2.7. Interpretation to Be Used

The results of the LCI and LCIA will be interpreted according to the Goal and Scope. No grouping or further quantitative cross-category weighting is applied. Instead, each impact will be evaluated in isolation, without reference to other impact categories, before final conclusions and recommendations are made.

The interpretation addresses the following topics:

- Identification of significant findings, such as the main process step(s), material(s), and/or emission(s) contributing to the overall results
- Evaluation of completeness, sensitivity, and consistency to justify the exclusion of data from the system boundaries as well as the use of proxy data.
- Conclusions, limitations and recommendations

2.8. Data Quality Requirements

The data used to create the inventory model shall be as precise, complete, consistent, and representative as possible with regards to the goal and scope of the study under given time and budget constraints.

- Measured primary data are considered to be of the highest precision, followed by calculated data, literature data, and estimated data. The goal is to model all relevant foreground processes using measured or calculated primary data.
- Completeness is judged based on the completeness of the inputs and outputs per unit process and the completeness of the unit processes themselves. The goal is to capture all relevant data in this regard.
- Consistency refers to modeling choices and data sources. The goal is to ensure that differences in results reflect actual differences between product systems and are not due to inconsistencies in modeling choices, data sources, emission factors, or other artefacts.
- Reproducibility expresses the degree to which third parties would be able to reproduce the results of the study based on the information contained in this report. The goal is to provide enough transparency with this report so that third parties are able to approximate the reported results. This ability may be limited by the exclusion of confidential primary data and access to the same background data sources
- Representativeness expresses the degree to which the data matches the geographical, temporal, and technological requirements defined in the study's goal and scope. The goal is to use the most representative primary data for all foreground processes and the most representative industry-average data for all background processes. Whenever such data were not available (e.g., no industry-average data available for a certain country), best-available proxy data were employed.

2.9. Type and Format of the Report

In accordance with ISO requirements (ISO, 2006), this document aims to summarize project goal and scope. A hot spot analysis and data gap assessment will be included in order to provide AISI with sufficient understanding of the robustness of the data and system boundaries. This will serve as the foundation for further discussion around next steps to fully realize the potential business value of the project.

2.10. Software and Database

The LCA model was created using the GaBi ts software system for life cycle engineering (v7.3), developed by thinkstep AG. The GaBi 2016 LCI database provides the life cycle inventory data for several of the raw and process materials obtained from the background system.

2.11. Critical Review

At present, no critical review is planned. The decision to proceed with a critical review will depend on the outcome of the preliminary comparison between the Chinese LCIs developed in this project and existing LCIs based on worldsteel data.

3. Life Cycle Inventory Analysis

3.1. Data Collection Procedure

The analysis is based primarily on data from ten (10) anonymized sites representing steel production in China—seven sites representing steel production via the blast furnace / basic oxygen furnace (BF/BOF) route and 3 sites representing production via the electric arc furnace (EAF) route. For confidentiality reasons, no further details about the companies from which data were obtained can be disclosed in this report.

Collectively, the BF/BOF manufacturers produce around 28 million metric tons of steel and the EAF manufacturers produce another 3.1 million metric tons of steel. This represents ~3.5% of total Chinese crude steel production[2]. Given that China exports around 11% of domestic production[3], 3.5% of domestic production could potentially represent up to 30% of exported tonnage if one assumes all steel produced by the considered sites is exported. No data were collected on whether the anonymized sites exported product abroad, although it was judged that the sites from which data were obtained were also likely to export their product to foreign countries—although not necessarily the US—given their interest in the carbon footprint of their operations. As a point of reference, the US, in 2014, received 2.9 million metric tons from China (US DOC, 2014) or around 3% of China's exported tonnage.

Received data were checked for mass and carbon balances and adjusted accordingly. Carbon and other emissions data were supplemented or replaced with fuel combustion factors from EPA's AP-42 (EPA, 1995), worldsteel (worldsteel, 2011), and CEN 264 (CEN, 2014)—specifically EN 19694-2 (CEN, 2016).

3.2. Hot-Dip Galvanized Coil

Hot-dip galvanized coil is cold-rolled steel coil that is coated via dipping in a hot zinc bath. This coil is assumed to be produced solely via BF/BOF in China. Figure 3-1 illustrates the process flow associated with HDG coil.

In basic oxygen steelmaking, blast furnaces are first used to produce iron from raw materials such as ore and sinter pellets. The melted iron is subsequently added to the basic oxygen furnace, where steel scrap and the iron chemistry further adjusted. Melted steel from the furnace is then cast into slab and cooled. When ready for the rolling mill, the slabs are reheated and passed through rollers in order to form coil. Hot-rolling can leave an oxide layer on the surface so the coils are pickled (typically in hydrochloric or sulfuric acid) before cold-rolling. Finally, the coils are cleaned once more and dipped into a zinc bath to galvanize.

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[2] Based on 822,698,000 metric tons of crude steel produced in China in 2014; Table 1 from (worldsteel Association, 2015).

[3] Based on 92,907,000 metric tons of semi-finished and finished products exported from China in 2014; Table 29 from (worldsteel Association, 2015).

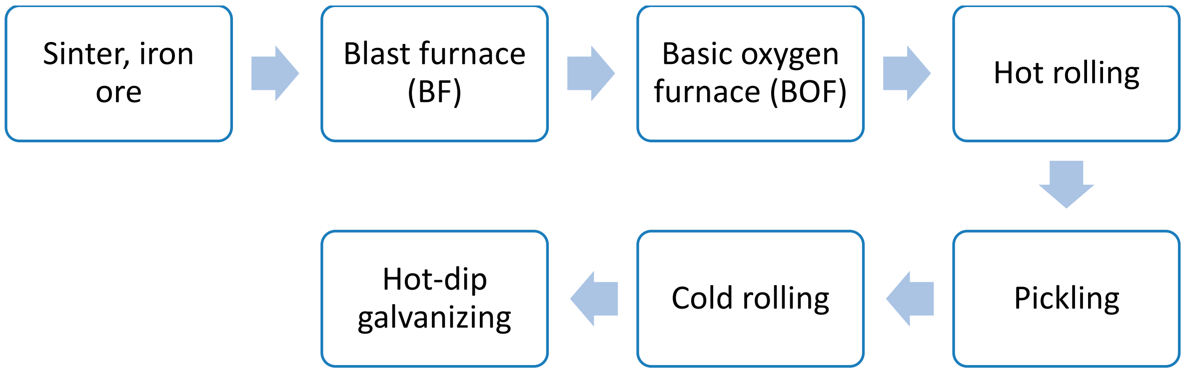

Figure 3-1: Hot-dip galvanized coil process flow

In addition to the process steps in Figure 3-1, coke production is modeled as it is key ingredients in basic oxygen steelmaking. A screen shot of the model is shown in Figure 3-2 and unit process outputs in Table 3-1.

Table 3-1: Unit process output per 1 kg HDG coil

Unit process	Intermediate output	Amount	Units
Boiler	Steam Electricity	1.22 0.294	MJ kWh
Coke oven	Coke	0.405	kg
Sintering	Sinter pellets	1.32	kg
Blast furnace	Hot metal	1.00	kg
Basic oxygen furnace	Cast slab	1.03	kg
Hot rolling	Hot rolled coil	0.993	kg
Pickling	Pickled hot rolled coil	0.993	kg
Cold rolling	Cold rolled coil	0.993	kg
Hot-dip galvanizing	HDG coil	1.00	kg

The analysis also accounts for process loops such as collecting coke oven, blast furnace, and BOF gases and combusting them in a boiler to generate electricity and steam. As discussed in Section 3.5.9, the total amounts of electricity and steam generated by the boiler are not equal to the respective amounts of these energy carriers consumed by the unit processes (and there are no facility-level data available on purchased or sold electricity or steam). The model indicates an additional 0.227 kWh purchased electricity—representing 43% of total HDG coil electricity consumption—is required in addition to electricity generated by the boiler. The boiler and other unit processes, however, generate excess steam compared to what is required as input to the processes (1.22 MJ from the boiler and 0.80 MJ from the other unit processes); therefore, the model includes a credit of 1.56 MJ steam per kg HDG coil—77% of steam produced.

Collected gases are also addressed as discussed in Section 3.5.9. The model assumes 0.491 MJ coke oven gas is “exported” for flaring and balanced by incoming 0.241 MJ blast furnace gas and 0.249 MJ basic oxygen furnace gas. Therefore, the net amount of exported energy is 0 MJ.

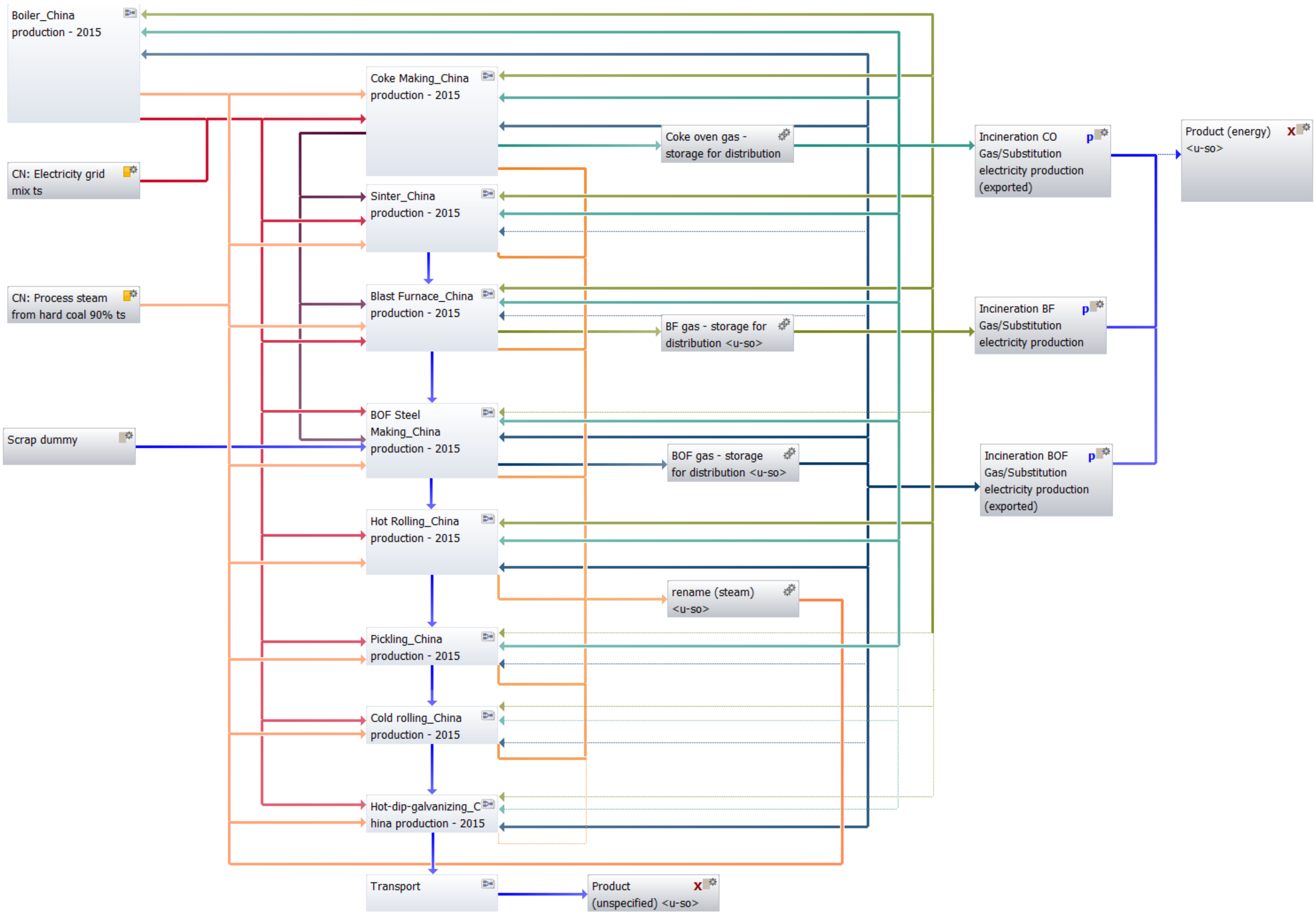

Figure 3-2: Screen shot of GaBi model for HDG coil

3.3. Structural Sections

Structural sections represent beams, angles, channels, etc. that are used for structural purposes in construction. These products are hot-rolled from cast billet. 94% of structural sections produced in China are assumed to be made from billet produced via the BF/BOF route and the remainder from billets produced via the EAF route. This ratio is based on 2014 data for Chinese steel production routes[4] (worldsteel Association, 2015).

3.3.1. Blast Furnace / Basic Oxygen Furnace Route

Structural section production via the BF/BOF route (Figure 3-3) follows the same process as HDG coil production until the first rolling step. The product from the BOF, though, is cast billets instead of slab. When ready for the rolling mill, the billets are reheated and passed through rollers to form sections. A screen shot of the BF/BOF model is shown in Figure 3-4 and unit process outputs in Table 3-2.

Table 3-2: Unit process output per 1 kg structural sections via BF/BOF

Unit process	Intermediate output	Amount	Units
Boiler	Steam	1.23	MJ
	Electricity	0.297	kWh
Coke oven	Coke	0.434	kg
Sintering	Sinter pellets	1.41	kg
Blast furnace	Hot metal	1.07	kg
Basic oxygen furnace	Cast billet	1.1	kg
Section rolling	Structural sections	1.0	kg

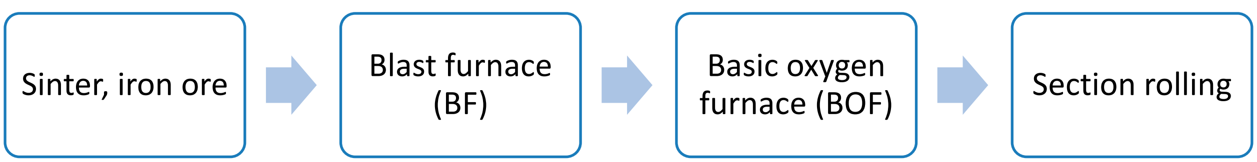

Figure 3-3: Structural section BF/BOF process flow

[4] According to worldsteel's yearbook, 49,938,000 metric tons of steel in China was produced via EAF and 772,184,000 metric tons was produced via BF/BOF.

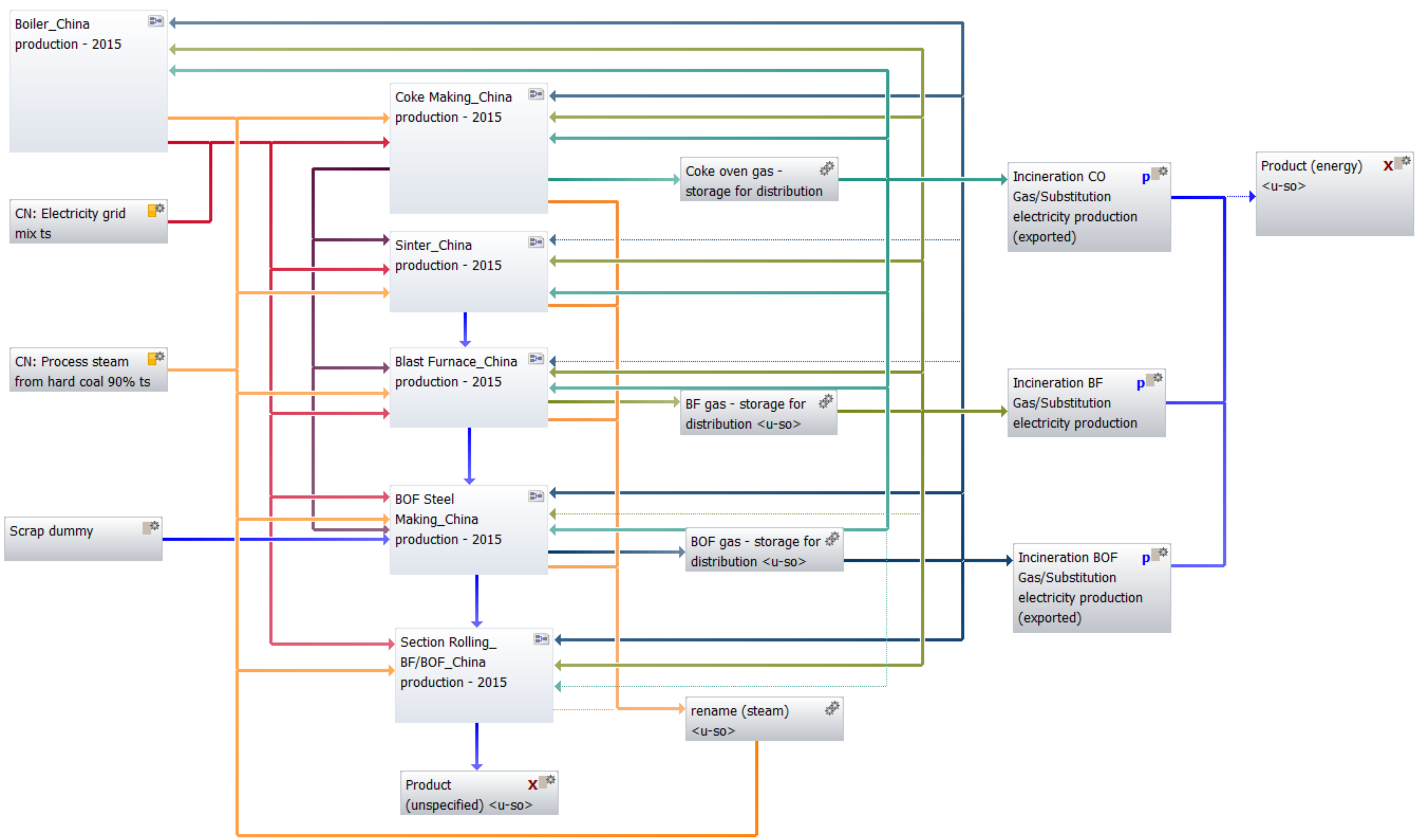

Figure 3-4: Screen shot of GaBi BF/BOF model for structural sections

Like the HDG coil model, the BF/BOF structural sections model accounts for process loops such as collecting coke oven, blast furnace, and BOF gases and combusting them in a boiler to generate electricity and steam. The boiler and other unit processes, though, are modeled as generating more steam and electricity than they consume. Therefore, credits for 0.0203 kWh electricity and 1.6 MJ steam are included in the model. These respectively represent 6.8% of electricity generated by the boiler and 80% of steam from both the boiler and various unit processes. The boiler is modeled as generating 1.23 MJ steam and the remaining 0.78 MJ are from the other unit processes. Exported energy from collected gases is also minimized. The model assumes 1.4 MJ coke oven gas is “exported” and balanced by incoming 1.29 MJ blast furnace gas and 0.108 MJ basic oxygen furnace gas.

3.3.2. Electric Arc Furnace Route

Around 6% of steel billets for structural sections in China are assumed to be produced via the EAF route. The EAF route is a simpler process flow than the BF/BOF route in that only two unit processes are considered: the EAF to melt the iron, scrap metal, and alloys; and section rolling, to reheat the billets and shape them into the finished products (Figure 3-5). A screen shot of the EAF model is shown in Figure 3-6 and unit process outputs in Table 3-3.

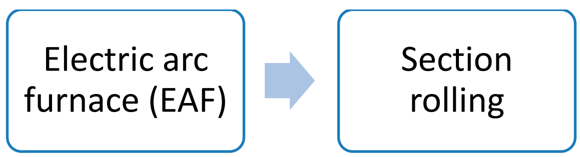

Figure 3-5: Structural section EAF process flow

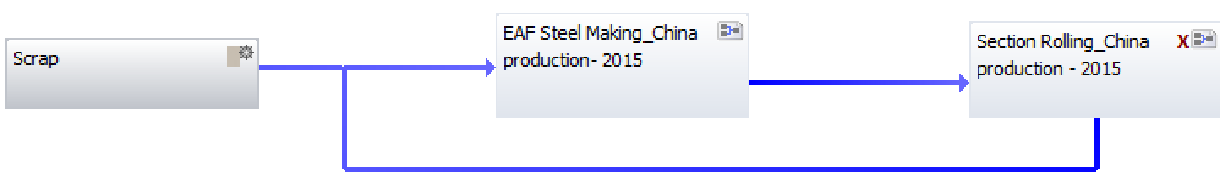

Figure 3-6: Screen shot of GaBi EAF model for structural sections

Table 3-3: Unit process output per 1 kg structural sections via EAF

Unit process	Intermediate output	Amount	Units
Electric arc furnace	Cast billet	1.1	kg
Section rolling	Structural sections	1.0	kg

3.4. Transportation to North America

The majority of steel produced in China and shipped abroad is produced in the eastern region. As such, the steel is modeled as being transported via container ship only based on the assumption that the Pacific Ocean constitutes the majority of the distance traveled from China to the West Coast of the U.S.

Shanghai, China and Los Angeles (or Long Beach), CA were selected as the representative ports between the two countries. A tool for calculating port distances, www.sea-distances.org, indicates that the distance between these two cities is approximately 10,570 km (6,570 mi.).

3.5. Unit Processes

This section details each unit process developed for hot-dip galvanized coil or for hot-rolled structural sections. Processes in Sections 3.5.5 through 3.5.8 apply only to HDG coil, whereas Sections 3.5.10 and 3.5.11 apply only to hot-rolled structural sections. Sections 3.2 and 3.1 provide more product-specific steelmaking details.

For readability and potential data confidentiality, unit process tables are included in Appendix A.

3.5.1. Coke Oven

Coke can be both a carbon source and an energy source in BF/BOF steel production. This material is typically made from coal and used in sinter production as well as in the BF and the BOF. Coke oven gases are assumed to be captured and combusted in a boiler for energy recovery.

Table A-1 presents inputs and outputs associated with the coke oven. Along with coke, co-products of benzene, sulfur, and tar are produced. A system expansion approach is adopted to address these co-products and a credit given to the product system to represent the avoided production of the co-products. Additional processing of co-products prior to their use in another product or process, however, is not considered in this assessment as this information is not readily available. Further, it is the steel industry's general understanding that minimal processing is required for most of the recovered materials before they can be used in the next product system.

Since the available data did not include carbon monoxide (CO) emissions from the coal combustion, these were added based on emissions factors (EF) from EPA AP-42, Chapter 12.2. Additionally, it was assumed that all water from groundwater is released as water vapor (worst-case assumption) in order to better balance water inputs and outputs.

3.5.2. Sintering

In sintering, iron ore fines (i.e., dust) are fused to form porous pellets of iron oxide. This process requires coke and energy, as indicated in Table A-2.

Emissions from limestone, dolomite, and the combustion of the various fuels are not included in the inventory in Table A-2. Instead, emission factors for these materials can be found in Section 3.5.12. Since the available data reported emissions for nitrogen oxides (NO_x) and sulfur dioxide (SO_2), nitrogen oxide and sulfur dioxide emissions factors from Section 3.5.12 were not used when calculating fuel combustion emissions for sintering.

3.5.3. Blast Furnace

A blast furnace (BF) is used to produce liquid iron from iron oxides in steel making. Often, heat and gases existing the furnace are recovered and the gases burned in a boiler to generate electricity and steam for the facility.

Table A-3 presents inputs and outputs associated with the blast furnace. No blast furnace emissions were adjusted or replaced with calculated emissions—the emissions data represent exactly what were provided from the Chinese sites. However, 236 kg iron scrap and 10 kg water vapor outputs were added in order to better close the mass and water balance, respectively. Additionally, slag was assumed to be recovered and credit given for its reuse as cement, fertilizer, and aggregate.

3.5.4. Basic Oxygen Furnace

Liquid metal is transferred from the blast furnace to a basic oxygen furnace (BOF) where oxygen is blown through the iron to reduce its carbon content. Alloys are added at this step and impurities removed through the slag. Steel from the BOF is subsequently cast into slabs, billets, or other profiles. The steel is then cooled and stored prior to being rolled. Slag is modeled as recovered and credit given for its reuse as cement, fertilizer, and aggregate.

Table A-4 illustrates inputs and outputs associated with a BOF. As with the blast furnace, the emissions data represent exactly what were provided from the Chinese sites. However, 77 kg of output scrap were added to better close the mass balance.

3.5.5. Hot Rolling

Depending on the mill configuration, slab for hot rolling can come directly from the BOF (via a continuous caster and tunnel furnace) or be taken from inventory and brought up to temperature in a reheat furnace. Once the steel is up to temperature, it is passed through multiple rollers to reduce it to the desired thickness. Steps to prevent the build-up of mill scale (iron oxides) are also taken.

Table A-5 illustrates the inputs and outputs associated with hot rolling of steel coil. Facility data for this process included only carbon dioxide emissions, which did not align with inputs of carbon-containing gases (e.g., natural gas, blast furnace gas, etc.). Therefore, AP-42 and worldsteel emissions factors were instead used to calculate unit process air emissions.

3.5.6. Pickling

Pickling is a surface treatment in which acids are used to remove oxides (i.e., steel scale) that have formed on the coil surface as a result of hot rolling. Pickling inputs and outputs are shown in Table A-6. As with hot rolling, AP-42 and worldsteel emissions factors were used to calculate air emissions.

3.5.7. Cold Rolling

Cold-rolling involves working the steel at room temperature. This allows manufacturers to achieve more exact dimensions and better surface quality. Like hot rolling, though, cold rolling involves passing the steel through a series of rollers in order to achieve the desired thickness. Table A-7 presents inputs and outputs associated with cold rolling. Natural gas combustion emissions are again calculated based on AP-42 emissions factors.

3.5.8. Hot-Dip Galvanizing

In hot-dip galvanizing, the steel surface is first cleaned in an acid bath to remove contaminants. The steel is then dipped in a zinc bath in order to coat it.

The galvanizing data provided from the anonymized sites did not include zinc or steel inputs; therefore, the data were supplemented with unit process data obtained from thinkstep's databases and other sources. Galvanizing inputs and outputs are shown in Table A-8.

3.5.9. Boiler

Many mills that produce steel via the BF/BOF route also have on-site boilers. These boilers are used to combust captured coke oven, blast furnace, and basic oxygen furnace gases to generate electricity and steam. Table A-9 presents boiler inputs and outputs. To more accurately balance carbon into and out of the boiler, carbon dioxide emissions were recalculated using AP-42 and other emissions factors from thinkstep's databases (Table 3-4 and Table 3-5). Other emissions based on AP-42 emissions factors were also added to complete the inventory, but nitrogen oxides and sulfur dioxide emissions represent the original Chinese data.

While data are available on the boiler itself (and on the various unit operations that take place at the steel making facilities), no facility level data on purchased or sold electricity, purchased or sold steam, or flared gases (i.e., gases combusted without energy recovery) were available. Consequently, when all unit processes are combined into a single model to represent HDG coil or structural sections production, the amounts of gases modeled as collected from the coke oven, blast furnace, and basic oxygen furnace are not equal to the respective amounts of these gases modeled as consumed by the boiler. Likewise, the electricity and steam consumed by the various unit processes do not equal the electricity and steam generated by the boiler.

These imbalances between electricity and steam inputs and outputs are addressed by adding burdens or credits for purchased electricity or steam. The credits are intended to represent system expansion in which energy carriers are sold back to the market and thus credited with the avoided generation of electricity or steam—although whether this displacement actually occurs in the Chinese market is an open question and discussed in the interpretation section.

For gas imbalances, the HDG coil and structural sections BF/BOF production models are set up to minimize energy losses (i.e., energy wasted in flaring). The boiler process, based on averaged facility data, expects a certain input ratio of coke oven, blast furnace, and basic oxygen furnace gases. The models for both products as produced via the BF/BOF route, however, indicate that an excess of coke oven gas and insufficient BF and BOF gases are available for use by the boiler compared to what the boiler process expects. Thus, any excess coke oven gas is modeled as leaving the system boundary, while any additional BF and BOF gases needed to address the shortage are modeled as entering the system boundary from an external source. The ratio of these gases is chosen so that the net energy leaving the system boundary (i.e., the energy of the coke gas leaving the system, minus the energy of the BF and BOF gases that enter the system) is zero—therefore minimizing exported energy.

Since mills typically do not sell excess gas but are more likely to flare it (i.e., combustion without energy recovery), the gases are not simply modeled as exported (or imported) energy. Instead, excess coke oven gas is modeled as flared and its emissions allocated to the product system. The BF and BOF gases entering the system, by contrast, can be thought of as "purchased" from an external facility, thus avoiding the need for flaring at that facility. Instead, these are gases are modeled as combusted in the boiler with energy recovery. The steel product therefore effectively receives a credit for the "avoided flaring" of BF and BOF gases, which is combined the burden associated with emissions from flaring the excess coke oven gas.

3.5.10. Electric Arc Furnace

The electric arc furnace (EAF) is the most common alternative route to manufacturing steel. In this process, iron and/or steel scrap is melted by running an electric current through the material. Additional heat is provided from oxygen-fuel burners. Slag is used to remove impurities. Molten steel from the EAF is subsequently cast into slabs, billets, or other profiles. The steel is then cooled and stored prior to being rolled.

Table A-10 illustrates EAF inputs and outputs. No data on alloying element inputs or emissions were provided. Since alloying elements typically represent a small fraction of EAF impact—and EAF production in turn is estimated to represent around 6% of Chinese structural sections—the upstream production of these materials was excluded from the analysis. Data gaps for emissions, though, were closed by calculating emissions to air based on CEN 264 and AP-42 emissions factors. Any gas inputs were assumed to represent natural gas since an EAF doesn't necessarily have access to collected gases from a coke oven, BF, or BOF. Additionally, electrode losses were assumed to be converted to carbon dioxide; carbon content in the scrap steel, however, was not taken into account in emissions calculations.

3.5.11. Section Rolling

Like hot rolling, section rolling starts by reheating semi-finished cast product—in this case, billets—from a BOF or an EAF. Rollers are then used to shape the product into structural sections such as I-beams, angles, channels, or other profiles.

Inputs and outputs to section rolling are presented in Table A-11. As the anonymized data did not include any emissions, emissions to air are calculated using standardized emissions factors (see Section 3.5.12). If section rolling is done in conjunction with an EAF, natural gas is assumed to be used in place of BF and BOF gases.

3.5.12. Emissions Factors

While carbon dioxide emissions were typically provided for most of the unit processes, the carbon in these emissions often did not balance with process carbon inputs (typically in the form of natural gas, coke oven gas, dolomite, etc.). Additionally, several unit processes lacked other emissions to air beyond carbon dioxide. To fill in these gaps and improve carbon balances, combustion emissions were calculated based on emissions factor data obtained from AP-42 (EPA, 1995), worldsteel (worldsteel, 2011), and CEN 264 (CEN, 2014). Emissions factors shown in Table 3-4 through Table 3-6 represent the factors used for collected gases and other sources of carbon, respectively.

Table 3-4: Combustion emissions factors for collected gases

Emission	Units	Coke oven gas	BF gas	BOF gas
Carbon dioxide	kg / MJ	4.77E-02	2.86E-01	2.16E-01
Carbon monoxide	kg / MJ	6.76E-05	3.91E-04	7.90E-03
Dust (unspecified)	kg / MJ	–	7.74E-07	–
Hydrogen sulfide	kg / MJ	1.41E-06	–	–
Methane	kg / MJ	6.00E-04	–	–
Nitrogen oxides	kg / MJ	–	4.14E-05	–
Sulfur dioxide	kg / MJ	1.83E-04	4.47E-05	–
Source		(thinkstep, 2016)		

Table 3-5: Combustion emissions factors for fuel inputs

Emission	Units	Hard coal	Heavy fuel oil	Natural gas
Anthracene	kg / kg	–	–	4.59E-11
Arsenic	kg / kg	9.50E-08	–	3.82E-09
Barium	kg / kg	–	–	8.41E-08
Benzene	kg / kg	–	2.49E-08	4.01E-08
Benzo{a}anthracene	kg / kg	–	–	3.44E-11
Benzo{a}pyrene	kg / kg	–	–	2.29E-11
Beryllium	kg / kg	1.55E-07	–	2.29E-10
Biphenyl	kg / kg	1.25E-05	–	–
Butane	kg / kg	–	–	4.01E-05
Cadmium	kg / kg	3.55E-08	–	2.10E-08
Carbon dioxide	kg / kg	2.84E+00	2.91E+00	2.29E+00
Carbon monoxide	kg / kg	3.00E-04	5.81E-04	1.61E-03
Chromium	kg / kg	1.40E-05	–	2.68E-08
Chrysene	kg / kg	–	–	3.44E-11
Cobalt	kg / kg	–	–	1.61E-09
Copper	kg / kg	–	–	1.62E-08
Dibenz(a)anthracene	kg / kg	–	–	2.29E-11
Dichlorobenzene	kg / kg	–	–	2.29E-08
Dust (PM2,5 - PM10)	kg / kg	6.60E-03	4.29E-03	1.45E-04
Ethyl benzene	kg / kg	–	7.39E-09	–
Ethane	kg / kg	–	–	5.93E-05
Formaldehyde	kg / kg	–	4.65E-06	1.38E-06
Hexane (isomers)	kg / kg	–	–	3.44E-05
Lead	kg / kg	4.45E-06	–	9.56E-09
Manganese	kg / kg	1.80E-06	–	7.26E-09
Mercury	kg / kg	6.50E-08	–	4.97E-09
Methane	kg / kg	0.00E+00	3.25E-05	4.40E-05
Molybdenum	kg / kg	–	–	2.10E-08
Naphthalene	kg / kg	6.50E-05	1.31E-07	1.17E-08
Nickel	kg / kg	1.30E-05	–	4.01E-08
Nitrogen oxides	kg / kg	4.50E-03	–	3.63E-03
Nitrous oxide	kg / kg	0.00E+00	6.16E-05	4.21E-05
NMVOC (unspecified)	kg / kg	–	8.83E-05	1.05E-04
Pentane (n-pentane)	kg / kg	–	–	4.97E-05
Phenanthrene	kg / kg	3.40E-06	–	–
Propane	kg / kg	–	–	3.06E-05
Pyrene	kg / kg	–	–	9.56E-11
Selenium	kg / kg	6.50E-07	–	4.59E-10
Sulfur dioxide	kg / kg	–	–	1.15E-05
Sulfur trioxide	kg / kg	–	2.27E-03	–

Emission	Units	Hard coal	Heavy fuel oil	Natural gas
Sulfur oxides	kg / kg	1.37E-02	–	–
Toluene	kg / kg	–	7.21E-07	6.50E-08
Total organic carbon	kg / kg	1.50E-04	1.21E-04	2.10E-04
Trichloroethane	kg / kg	–	2.74E-08	–
Vanadium	kg / kg	–	–	4.40E-08
Xylene	kg / kg	–	1.27E-08	–
Zinc	kg / kg	–	–	5.54E-07
Source		(EPA, 1995) § 1.2	(EPA, 1995) § 1.3	(EPA, 1995) § 1.4

Table 3-6: Carbon emissions factors for material inputs

Emission	Units	Coke	Dolomite	Limestone	Electrode
Carbon dioxide	kg / kg	3.22E+00	4.76E-01	4.35E-01	3.67E+00
Source			(CEN, 2014)		Estimated

3.6. Background Data

Background datasets used to represent the production of energy and material inputs, transportation, and treatment of waste outputs are detailed in this section. Exactly which datasets are used for each unit process, though, is based on unit process inputs and outputs as detailed in Appendix A.

3.6.1. Fuels and Energy

National averages for fuel inputs and electricity grid mixes were obtained from the GaBi 2016 databases. Table 3-7 shows the most relevant LCI datasets used in modeling the product systems. Electricity consumption was modeled using national grid mixes that account for imports from neighboring countries.

Documentation for all GaBi datasets can be found at http://www.gabi-software.com/support/gabi/gabi-6-lci-documentation/.

Table 3-7: Key energy datasets used in inventory analysis

Energy	Geographic ref.	Dataset	Data Provider	Ref. year	Proxy?
Coke	China	DE: Coke mix	ts	2012	Geo.
Compressed Air	China	GLO: Compressed air 7 bar	ts	2012	No
Diesel	China	CN: Diesel mix at refinery	ts	2012	No
Electricity	China	CN: Electricity grid mix	ts	2012	No
Hard coal	China	CN: Hard coal mix	ts	2012	No
Fuel oil	China	CN: Heavy fuel oil at refinery (1.0 wt.% S)	ts	2012	No
Natural gas	China	CN: Natural gas mix	ts	2012	No
Steam	China	CN: Process steam from hard coal 90%	ts	2012	No
Tech. heat	China	CN: Thermal energy from hard coal	ts	2012	No

3.6.2. Raw Materials and Processes

Data for upstream and downstream raw materials and unit processes were obtained from the GaBi 2016 database. Table 3-8 shows the most relevant LCI datasets used in modeling the product systems. Documentation of GaBi datasets can be found at http://www.gabi-software.com/support/gabi/gabi-6-lci-documentation/.

Table 3-8: Key material and process datasets used in inventory analysis

Material / Process	Geographic ref.	Dataset	Data Provider	Ref. year	Proxy?
Raw materials					
Aluminum	China	EU-27: Aluminium ingot mix	ts	2015	Geo.
Copper	China	GLO: Copper mix (99,999% from electrolysis)	ts	2015	Geo.
Dolomite	China	CN: Burned (calcined) dolomite (estimate)	ts	2015	No
Ferro-chrome	China	GLO: Ferro Chrome High Carbon	ts	2012	Geo.
Ferro-manganese	China	ZA: Ferro manganese	ts	2015	Geo.
Ferro-molybdenum	China	GLO: Ferro Molybdenum	ts	2015	Geo.
Ferro-Niobium	China	ZA: Ferro-Vanadium	ts	2015	Geo./Tech.
Ferro-Silicon	China	GLO: Ferro silicon mix	ts	2015	Geo.
Ferro-Titanium	China	GLO: Titanium	ts	2015	Geo.
Ferro-Vanadium	China	ZA: Ferro-Vanadium	ts	2015	Geo.
Iron ore	China	CN: Iron ore-mix	ts	2015	No
Lime	China	DE: Lime (CaO; quicklime lumpy)	ts	2015	Geo.
Limestone	China	DE: Limestone (CaCO3; washed)	ts	2015	Geo.
Magnesium	China	CN: Magnesium	ts	2015	No
Nickel	China	GLO: Nickel mix	ts	2015	Geo.
Olivine	China	US: Aluminium silicate (zeolite type A)	ts	2015	Geo./Tech.
Silicon-Calcium	China	GLO: Silicon mix (99%)	ts	2015	Geo./Tech.
Silicon-Manganese	China	ZA: Manganese	ts	2015	Geo./Tech.
Zinc	China	GLO: Special high grade zinc	IZA	2012	Geo.
Process materials					
Argon	China	CN: Argon (gaseous)	ts	2013	No
Electrodes	China	NO: Electrode	ts	2011	Geo.
Refractories	China	CN: Fire proof stones (alumina-rich)	ts	2015	No
HCl	China	CN: Hydrochloric acid 100%	ts	2015	No
Nitrogen	China	CN: Nitrogen (gaseous)	ts	2015	No
Oxygen	China	CN: Oxygen (gaseous)	ts	2015	No
Process water	China	EU-27: Process water	ts	2015	Geo.
Sulfuric acid	China	CN: Sulphuric acid aq. (96%) (estimation)	ts	2015	No
Deionized water	China	EU-27: Water (deionised)	ts	2015	Geo.

3.6.3. Disposal and credits

Data used to represent disposal of process waste and credits associated with co- or by-products are shown in Table 3-9. Datasets were likewise obtained from the GaBi 2016 database. Co-product credit datasets used to model system expansion are limited to the materials or products the co-products are assumed to displace. Any additional processing that may be required for the co-products prior to their use in another process or product is not included.

Table 3-9: Key disposal and co-product credit datasets used in inventory analysis

Material / Process	Geographic ref.	Dataset	Data Provider	Ref. year	Proxy?
Landfill of waste	China	EU-27: Inert matter on landfill	ts	2015	Geo.
Co-product credits					
Benzene	China	CN: Benzene (from reformate) (estimation)	ts	2015	No
Sulfur	China	CN: Sulphur (elemental) at refinery	ts	2012	No
Tar	China	CN: Bitumen at refinery	ts	2012	No
Aggregate	China	CN: Gravel (grain size 2-32mm)	ts	2015	No
Cement	China	CN: Cement (average)	ts	2015	No
Fertilizer	China	DE: Lime (CaO; quicklime lumpy)	ts	2015	Geo.
Electricity	China	CN: Electricity grid mix	ts	2012	No
Steam	China	CN: Process steam from hard coal 90%	ts	2012	No

3.6.4. Transportation to North America

Transportation of HDG coil and structural sections to North America is detailed in Table 3-10. Datasets were obtained from the GaBi 2016 database.

Table 3-10: Key transportation datasets used in inventory analysis

Material / Process	Geographic ref.	Dataset	Data Provider	Ref. year	Proxy?
Freight ship	China	GLO: Container ship	ts	2015	Geo.
Heavy fuel oil	China	CN: Heavy fuel oil at refinery (1.0 wt. % S)	ts	2012	No

3.7. Life Cycle Inventory Analysis Results

ISO 14044 defines the Life Cycle Inventory (LCI) analysis result as the “outcome of a life cycle inventory analysis that catalogues the flows crossing the system boundary and provides the starting point for life cycle impact assessment”. As the complete inventory comprises hundreds of flows, tables displaying a selection of flows based on their relevance to the subsequent impact assessment are included in Appendix B.

4. LCIA Results

This chapter contains the results for the impact categories and additional metrics defined in Section 2.6. It shall be reiterated at this point that the reported impact categories represent impact potentials, i.e., they are approximations of environmental impacts that could occur if the emissions would (a) follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so. In addition, the inventory only captures that fraction of the total environmental load that corresponds to the chosen functional unit (relative approach).

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

4.1. Hot-dip Galvanized Coil

4.1.1. Overall Results

Figure 4-1 illustrates HDG coil results broken down by unit process. Two categories beyond the unit processes listed in Section 3.2 are added: “External energy”, which represents the burden or credit associated with purchased electricity and steam and “Credit (exported gas)”, which reflects the model’s aim to minimize flaring, as described in Section 3.5.9. Tabulated results are presented in Table 4-1.

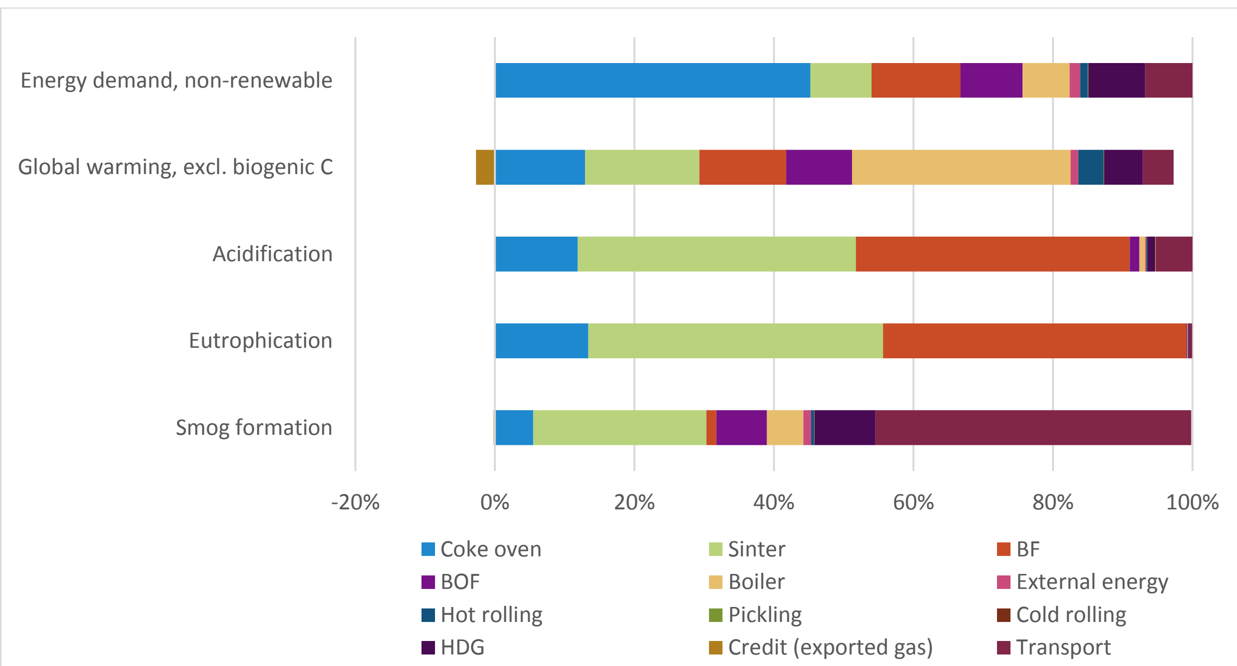

Figure 4-1: Breakdown of HDG coil results by process step

Table 4-1: Tabulated results per 1 kg HDG coil

Unit Process	Energy demand [MJ]	Global warming [kg CO_2 eq.]	Acidification [kg SO_2 eq.]	Eutrophication [kg N eq.]	Smog formation [kg O_3 eq.]
Coke oven	1.30E+01	4.41E-01	1.08E-02	4.58E-03	1.08E-02
Sinter	2.52E+00	5.58E-01	3.64E-02	1.44E-02	4.86E-02
BF	3.68E+00	4.23E-01	3.59E-02	1.49E-02	2.81E-03
BOF	2.56E+00	3.22E-01	1.27E-03	4.46E-05	1.42E-02
Boiler	1.94E+00	1.07E+00	7.63E-04	2.05E-05	1.03E-02
External energy	4.31E-01	3.72E-02	1.55E-04	1.36E-05	2.14E-03
Hot rolling	3.17E-01	1.24E-01	1.61E-04	1.94E-06	8.86E-04
Pickling	2.58E-02	2.76E-03	5.64E-06	1.02E-07	5.62E-05
Cold rolling	3.52E-03	1.90E-04	2.42E-07	1.39E-08	7.63E-06
HDG	2.33E+00	1.88E-01	9.41E-04	4.45E-05	1.71E-02
Credit (exported gas)	0.00E+00	-9.22E-02	8.39E-05	-3.43E-07	-3.38E-04
Transport	1.95E+00	1.51E-01	4.82E-03	1.59E-04	8.87E-02
TOTAL	**2.88E+01**	**3.22E+00**	**9.13E-02**	**3.42E-02**	**1.95E-01**

Impact drivers are as follows:

- **Non-renewable primary energy demand:** Almost half of non-renewable energy demand is associated with the coke-making process—specifically, coal used in the coke oven. Other energy resources such as coal used in the blast furnace, natural gas used in various process steps, and purchased electricity represent the remainder of potential energy resource consumption.
- **Global warming:** Combustion of collected gases and other fuels in the boiler account for around 30% of potential global warming impact. These collected gases, along with natural gas, are also combusted in other unit processes. The balancing of collected gases to minimize flaring accounts for approximately a 3% reduction in potential global warming impact. This is because BF and BOF gases, which are modeled as no longer being flared in an external facility, are associated with higher CO_2 emissions per MJ than coke oven gas.
- **Acidification:** Ammonia emissions to water drive potential acidification impacts associated with the coke oven, sintering, and the blast furnace.
- **Eutrophication:** Ammonia emissions to water also drive potential eutrophication impacts.
- **Smog formation:** Almost 50% of potential smog formation impacts is due to container ship emissions representing transportation to North America. Emissions associated with HDG coil production itself are primarily driven by the sintering process step. Within sintering, iron ore production represents around 18% of total cradle-to-gate impact and is primarily driven by nitrogen oxide emissions. Zinc production for galvanizing is also a key contributor, accounting for around 6% of total cradle-to-gate impact potential.

4.1.2. Normalized Results

Results normalized to U.S. and Canadian emissions are shown in Figure 4-2 (Ryberg, Vieira, Zgola, Bare, & Rosenbaum, 2014). Acidification and eutrophication are associated with the highest burdens when normalized because of the above-mentioned ammonia emissions to water reported by the Chinese facilities.

These emissions were deemed to be high but plausible in that they are within the range of what is possible for a single facility. Whether such a facility can be representative for all of China, however, is discussed in Section 5.3 Since no further validation of the data is possible for the anonymized data, a scenario analysis was conducted in which these emissions are removed from the model and the analysis rerun.

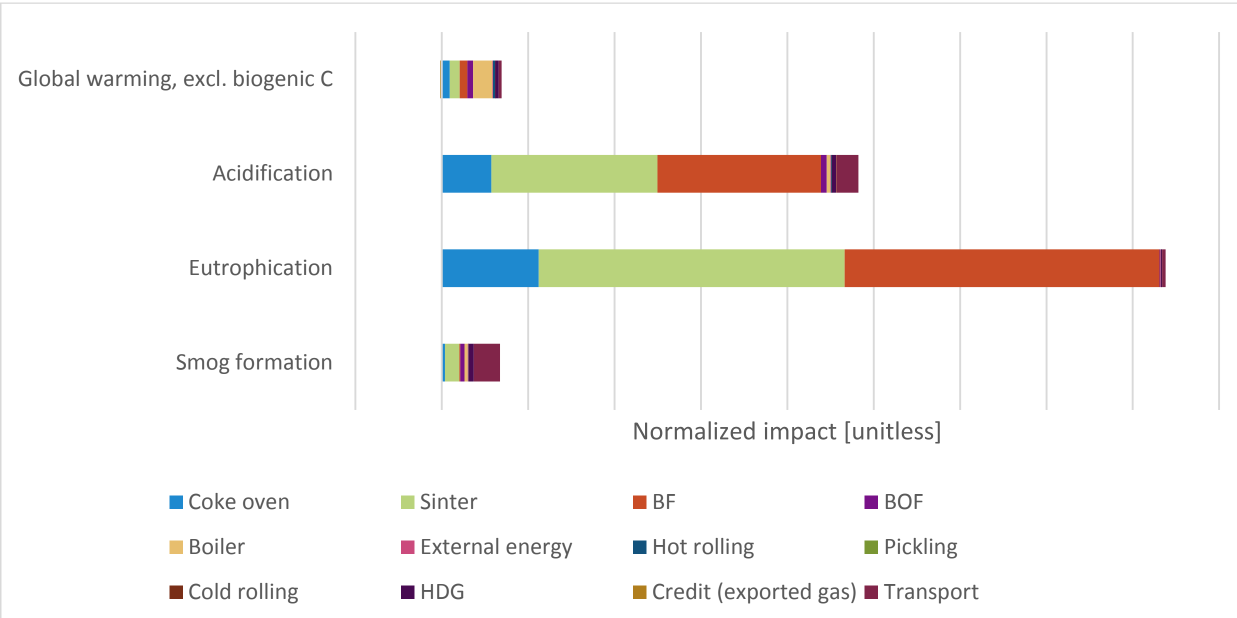

Figure 4-2: Normalized HDG coil results

4.1.3. Scenario Analyses

Ammonia Emissions to Water

Ammonia emissions account for a large fraction of potential acidification and eutrophication impacts. Expert judgment indicates that while these emissions are high, they are still plausible. However, there is limited insight into what is driving these emissions and whether the high average emissions are due to a single facility or to multiple facilities. Therefore, the analysis is rerun excluding the reported ammonia emissions from the coke oven, sintering, and blast furnace unit processes.

Figure 4-3 shows normalized acidification and eutrophication results including and excluding ammonia emissions to water. Without these emissions, acidification is reduced by around 92% and eutrophication is reduced by around 97% from the original values (presented in Section 4.1.1). The next largest drivers for acidification are shown to be nitrogen oxides and sulfur oxides emissions to air from iron ore and zinc production and for eutrophication are chemical oxygen demand (COD) emissions to water from the coke oven and sintering unit processes.

No other scenario or sensitivity analyses are conducted due to the lack of information on underlying relationships between unit process inputs and outputs.

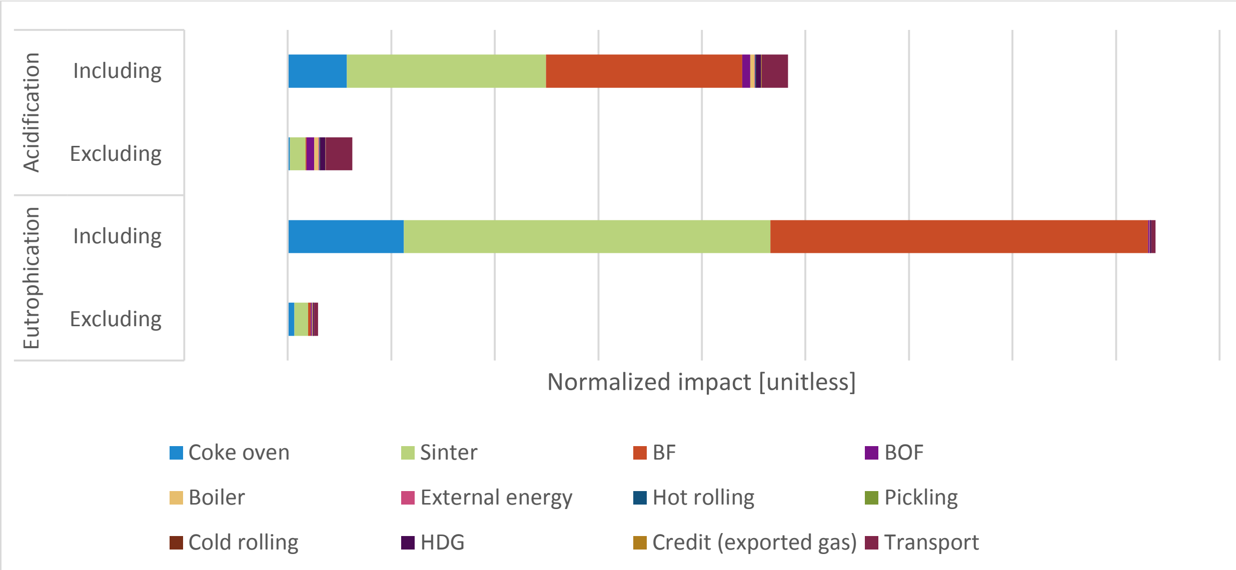

Figure 4-3: Normalized HDG coil results including and excluding ammonia emissions to water

System Expansion

As part of the steel production process, co-products such as benzene and slag are generated. The baseline analysis handles these co-products using system expansion—that is, by giving a credit for the 'avoided production' of these co-products. Table 4-2 illustrates the effect of including or excluding these credits. With the exception of eutrophication potential, which is dominated by ammonia emissions from steel making, excluding the credits increases the potential impact of the product system. Non-renewable primary energy demand and global warming potential, in particular, are affected. The credit for energy demand in the baseline analysis is primarily realized through excess steam generated from the boiler and assumed to be sold externally, and to tar recovered from coke making and assumed to replace bitumen. The steam recovery is also a key contributor to GWP credit, along with recovery of blast furnace slag for use in cement production.

Table 4-2: Results without system expansion per 1 kg HDG coil

	Units	Baseline	Without credits	% difference
Energy demand	[MJ]	2.88E+01	3.29E+01	+14%
Global warming	[kg CO_2 eq.]	3.22E+00	3.70E+00	+14%
Acidification	[kg SO_2 eq.]	9.13E-02	9.24E-02	+1%
Eutrophication	[kg N eq.]	3.42E-02	3.42E-02	+/-0%
Smog formation	[kg O_3 eq.]	1.95E-01	2.14E-01	+9%

GWP Methodology

The science behind LCA and calculating characterization factors is continually evolving. Consequently, impact category results can change depending which methodology is used to calculate the results. Baseline results in Section 4.1.1 represent global warming potential, excluding biogenic carbon, calculated based on the IPCC's 5th assessment report and a 100-year time horizon. Table 4-7 shows results for alternative methodologies. These methodologies include those using characterization factors from the 4th assessment report, 20- and 100-year time horizons, and including and excluding biogenic carbon. The results indicate that including biogenic carbon doesn't significantly affect impact, but changing the time horizon leads to around a 14% increase in GWP.

Table 4-3: Alternative GWP results per 1 kg HDG coil

	Assessment report	Time frame	Biogenic carbon	GWP [kg CO_2 eq.]
Global warming (baseline)	**AR5**	**100 yr.**	**Excluded**	**3.22E+00**
Global warming	AR5	100 yr.	Included	3.22E+00
Global warming	AR5	20 yr.	Excluded	3.66E+00
Global warming	AR5	20 yr.	Included	3.67E+00
Global warming	AR4 (TRACI 2.1)	100 yr.	Excluded	3.18E+00
Global warming	AR4 (TRACI 2.1)	100 yr.	Included	3.18E+00

4.2. Structural Sections

4.2.1. Overall Results

Figure 4-4 presents structural sections results broken down by unit process step, including the "External energy" and "Credit (exported gas)" categories beyond the process steps from Section 3.2. Structural sections results represent the BF/BOF – EAF mix. EAF, though, accounts for only 6% of cast billets and therefore is a minor contributor to each impact category. Table 4-4 details numerical results.

Table 4-4: Tabulated results per 1 kg structural sections

Unit process	Energy demand [MJ]	Global warming [kg CO_2 eq.]	Acidification [kg SO_2 eq.]	Eutrophication [kg N eq.]	Smog formation [kg O_3 eq.]
Coke oven	1.31E+01	4.45E-01	1.09E-02	4.61E-03	1.09E-02
Sinter	2.54E+00	5.62E-01	3.67E-02	1.46E-02	4.90E-02
BF	3.71E+00	4.27E-01	3.61E-02	1.50E-02	2.83E-03
BOF	2.58E+00	3.25E-01	1.28E-03	4.50E-05	1.43E-02
Boiler	1.84E+00	1.02E+00	7.27E-04	1.96E-05	9.79E-03
External energy	-1.96E+00	-1.98E-01	-8.05E-04	-2.11E-05	-1.01E-02
Hot rolling	1.49E-01	3.77E-01	1.16E-04	3.32E-06	1.78E-03
EAF	9.56E-01	1.10E-01	2.47E-03	9.56E-04	3.47E-03
Credit (exported gas)	0.00E+00	-2.82E-01	1.55E-04	-2.22E-06	-1.30E-03
Transport	1.95E+00	1.51E-01	4.82E-03	1.59E-04	8.87E-02
TOTAL	**2.49E+01**	**2.93E+00**	**9.25E-02**	**3.53E-02**	**1.69E-01**

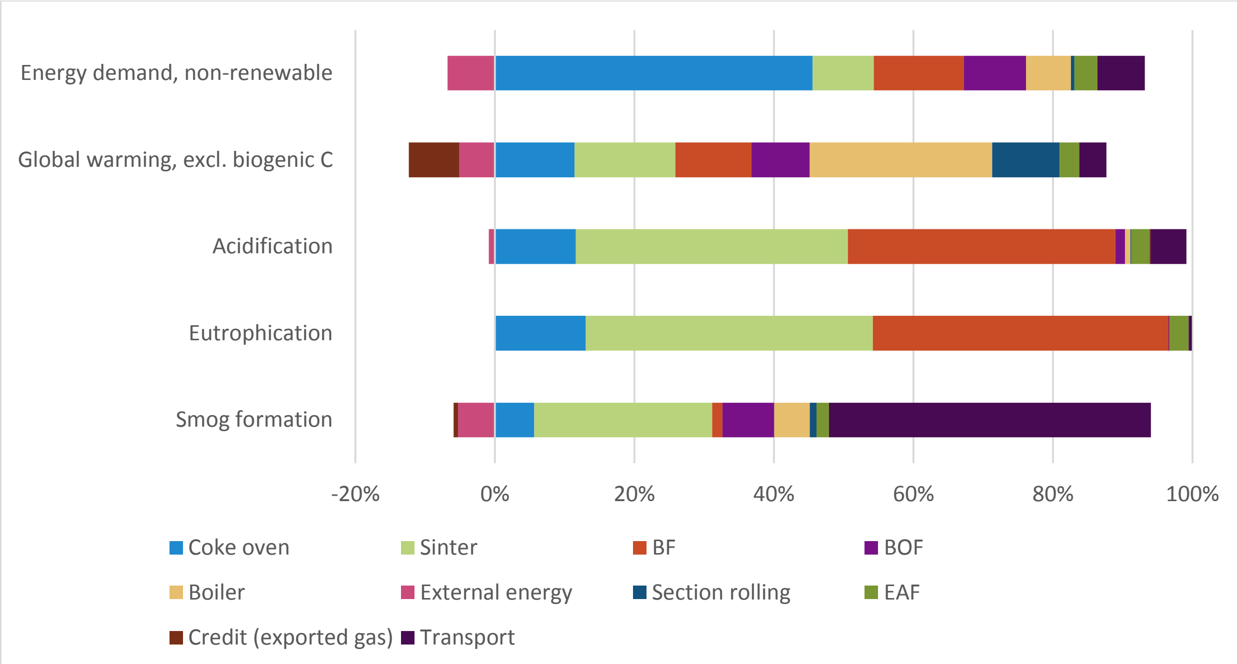

Figure 4-4: Breakdown of structural sections results by process step

Impact drivers are as follows:

- **Non-renewable primary energy demand:** Over half of non-renewable energy demand is associated with the coke-making process—specifically, coal used in the coke oven. Other energy resources such as coal used in the blast furnace and other process steps represent the remainder of potential energy resource consumption. Non-renewable energy demand results also indicate that there is a credit associated with external energy. As noted in Section 3.3.1, the boiler generates more electricity and steam than the unit processes consume. These excess energy carriers represent additional products so system expansion by substitution is applied to eliminate these co-products from the inventory.
- **Global warming:** Combustion of collected gases and other fuels in the boiler account for around 36% of potential global warming impact. These collected gases, along with natural gas, are also combusted in other unit processes. The balancing of collected gases to minimize flaring accounts for approximately a 7% reduction in potential global warming impact. This is because BF and BOF gases, which are modeled as no longer being flared in an external facility, are associated with higher CO_2 emissions per MJ than coke oven gas. Credits associated with external energy account for an additional 5% reduction in potential global warming impact.
- **Acidification:** As with HDG coil results, ammonia emissions to water drive potential acidification impacts associated with the coke oven, sintering, and the blast furnace.
- **Eutrophication:** Ammonia emissions to water also drive potential eutrophication impacts.
- **Smog formation:** Transportation of the steel from China to North America accounts for around 50% of potential smog formation impacts. Sintering, though, is a key driver of smog-forming emissions associated with sections production. Within sintering, iron ore production and the sintering process itself are key contributors and are primarily driven by nitrogen oxide emissions to air.

4.2.2. Normalized Results

Results normalized to U.S. and Canadian emissions are shown in Figure 4-5. Acidification and eutrophication are associated with the highest burdens when normalized because of the above-mentioned ammonia emissions to water reported by the Chinese facilities.

As previously discussed in Section 4.1.2, these emissions were deemed to be within the range of what is possible for a single facility—or even a small number of facilities. Since no further validation of the data is possible for the anonymized data, a scenario analysis was conducted in which these emissions are removed from the model and the analysis rerun.

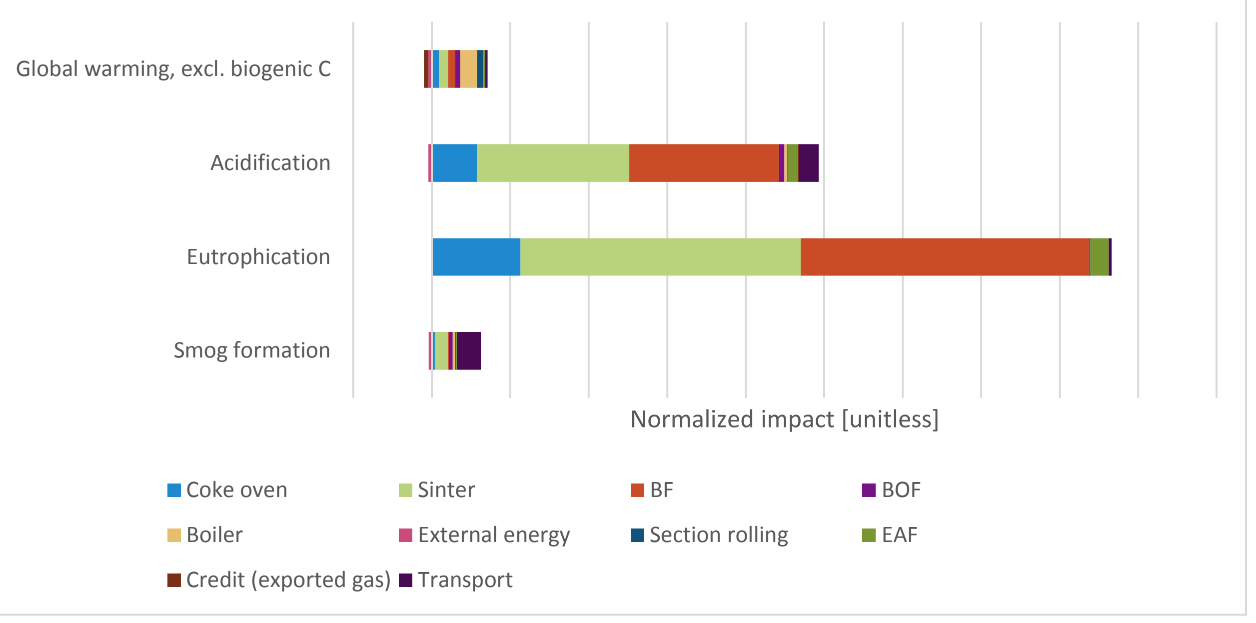

Figure 4-5: Normalized structural sections results

4.2.3. Scenario and Sensitivity Analyses

Ammonia Emissions to Water

Ammonia emissions account for a large fraction of potential acidification and eutrophication impacts. Expert judgment indicates that while these emissions are high, they are still plausible. However, there is limited insight into what is driving these emissions and whether the reported average emissions are due to a single facility or to multiple facilities. Therefore, the analysis is rerun excluding the reported ammonia emissions from the coke oven, sintering, and blast furnace unit processes.

Figure 4-6 shows normalized acidification and eutrophication results including and excluding ammonia emissions to water. Without these emissions, acidification is reduced by around 94% and eutrophication is reduced by around 97% from the original values. The next largest drivers for acidification are shown to be nitrogen oxides and sulfur oxides emissions to air from the production of iron ore, alloying elements, and slag materials. For eutrophication, the next largest contributors become chemical oxygen demand (COD) emissions from the coke oven and sintering and biological oxygen demand (BOD) emissions from the blast furnace.

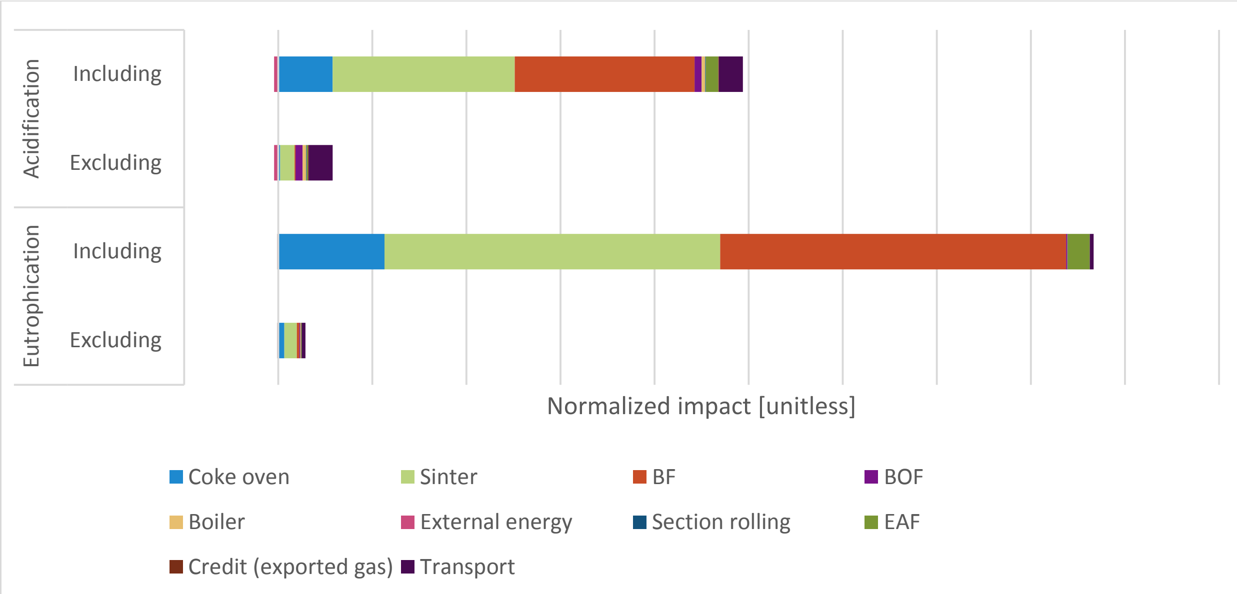

Figure 4-6: Normalized structural sections results including and excluding ammonia emissions to water

Production Route

An additional analysis evaluates the ratio between cast billets produced via the BF/BOF route versus the EAF route. Figure 4-7 shows the effect on potential global warming impact results. If only the EAF route is used to cast billets, global warming impact decreases by around 25% compared to the baseline. Numerical results for cradle-to-gate energy demand and other impact categories are shown in Table 4-5.

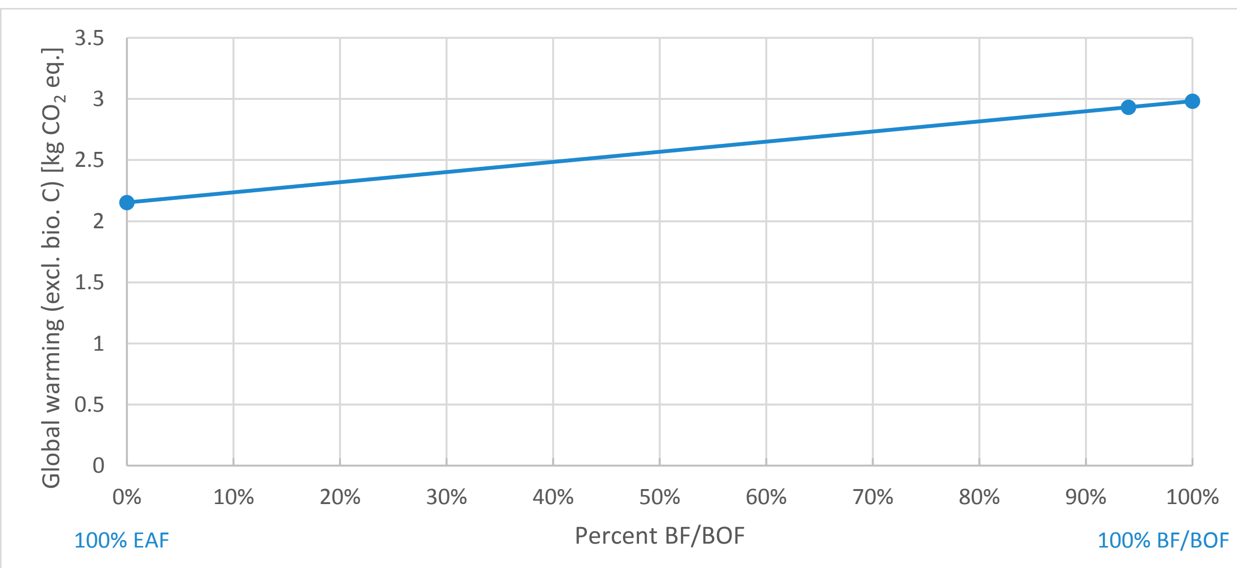

Figure 4-7: Global warming as a function of BF/BOF fraction

Table 4-5: Results for different structural sections production routes (baseline in bold)

Unit Process	Energy demand [MJ]	Global warming [kg CO_2 eq.]	Acidification [kg SO_2 eq.]	Eutrophication [kg N eq.]	Smog formation [kg O_3 eq.]
0% BOF / 100% EAF	2.04E+01	2.15E+00	4.64E-02	1.61E-02	1.54E-01
94% BOF / 6% EAF	**2.49E+01**	**2.93E+00**	**9.25E-02**	**3.53E-02**	**1.69E-01**
100% BOF / 0% EAF	2.52E+01	2.98E+00	9.54E-02	3.66E-02	1.70E-01

System Expansion

As part of the steel production process, co-products such as benzene and slag are generated. The baseline analysis handles these co-products using system expansion—that is, by giving a credit for the 'avoided production' of these co-products. Table 4-6 illustrates the effect of including or excluding these credits. With the exception of eutrophication potential, which is dominated by ammonia emissions from steel making, excluding the credits increases the potential impact of the product system. Non-renewable primary energy demand and global warming potential, in particular, are affected. The credit for energy demand in the baseline analysis is primarily realized through excess steam generated from the boiler and assumed to be sold externally, and to tar recovered from coke making and assumed to replace bitumen. The steam recovery is also a key contributor to GWP credit, along with recovery of blast furnace slag for use in cement production.

Table 4-6: Results without system expansion per 1 kg structural sections

	Units	Baseline	Without credits	% difference
Energy demand	[MJ]	2.49E+01	2.92E+01	+17%
Global warming	[kg CO_2 eq.]	2.93E+00	3.61E+00	+23%
Acidification	[kg SO_2 eq.]	9.25E-02	9.36E-02	+1%
Eutrophication	[kg N eq.]	3.53E-02	3.54E-02	+/-0%
Smog formation	[kg O_3 eq.]	1.69E-01	1.90E-01	+12%

GWP Methodology

The science behind LCA and calculating characterization factors is continually evolving. Consequently, impact category results can change depending which methodology is used to calculate the results. Baseline results in Section 4.1.1 represent global warming potential, excluding biogenic carbon, calculated based on the IPCC's 5th assessment report and a 100-year time horizon. Table 4-3 shows results for alternative methodologies. These methodologies include those using characterization factors from the 4th assessment report, 20- and 100-year time horizons, and including and excluding biogenic carbon. The results indicate that including biogenic carbon doesn't significantly affect impact, but changing the time horizon leads to around a 14% increase in GWP.

Table 4-7: Alternative GWP results per 1 kg structural sections

	Assessment report	Time frame	Biogenic carbon	GWP [kg CO_2 eq.]
Global warming (baseline)	**AR5**	**100 yr.**	**Excluded**	**2.93E+00**
Global warming	AR5	100 yr.	Included	2.93E+00
Global warming	AR5	20 yr.	Excluded	3.34E+00
Global warming	AR5	20 yr.	Included	3.34E+00
Global warming	AR4 (TRACI 2.1)	100 yr.	Excluded	2.90E+00
Global warming	AR4 (TRACI 2.1)	100 yr.	Included	2.89E+00

5. Interpretation

5.1. Identification of Relevant Findings

The production of slabs and billets via the BF/BOF route rely on the same unit processes. Consequently, the relative contributions of each unit process to HDG coil and structural sections results is similar, especially since only a small fraction of sections are assumed to be produced via EAF.

Non-renewable primary energy demand is driven by hard coal (i.e., anthracite) consumption as the raw material for coke. Additionally, coal is used as a carbon source in other process steps, thus contributing to energy demand that way. All process steps contribute to potential global warming impact, although the boiler is associated with the highest share of contributions

The coke oven, sintering, and blast furnace are all key contributors to potential acidification and eutrophication impacts primarily due to ammonia emissions to water. Expert judgment indicates that the ammonia emissions are high for a single facility but plausible; nonetheless, the analysis was still rerun without the emissions. Removing ammonia emissions to water from consideration drastically reduces potential acidification and eutrophication impacts.

Smog formation potential is primarily driven by transportation emissions associated with shipping the steel to North America. Iron ore production and, for HDG coil, zinc production also contribute.

As discussed in Section 3.5.9, facility-level data were not available and as a result, the model had to make some assumptions about purchased electricity, purchased steam, and flaring of collected gases. The consequences of these assumptions on HDG coil results is minimal—at most a few percent of cradle-to-gate impact. The assumptions, though, have a larger effect on structural sections results because structural sections production requires fewer process steps that consume collected gases. Therefore, the boiler “produces” more electricity and steam than is needed by the process chain—thus increasing avoided production credit.

Only 6% of sections are assumed to be produced via EAF. A sensitivity analysis indicates that increasing the amount of EAF will reduce average potential impact for the structural sections.

5.2. Assumptions and Limitations

Slabs for HDG coil were assumed to be produced entirely via the BF/BOF route, while billets for structural sections were assumed to be produced primarily via BF/BOF, with only 6% coming from an EAF. These assumptions were based on a combination of expert judgment and worldsteel yearbook data (worldsteel Association, 2015). The published data indicate that only 6% of crude steel in China is produced via the EAF route. A breakdown by product, however, is not available. Therefore, it was judged that producing 100% of HDG coil via BF/BOF is a reasonable assumption.

For sections, the national average between BF/BOF and EAF was used and a sensitivity analysis conducted to assess how increasing EAF share affects environmental performance. In reality, a larger share of each product may be produced via EAF, but such statistics are not readily available.

This analysis relies on anonymized data from Chinese facilities. The data for the most part can be considered to be representative of steel production in China, although not necessarily of facilities that export to the U.S. as no facility-level data on domestic production versus exports were collected. The use of anonymized data also limits the ability to validate numbers, confirm inputs, and conduct sensitivity analyses.

The lack of certain facility-level information—specifically purchased electricity and/or steam, and whether collected gases are flared (i.e., combusted without energy recovery)—requires that the analysis include assumptions for addressing excess electricity, steam, and collected gases. System expansion is applied for electricity and steam. If the model indicates the boiler generates more electricity and/or steam than the other unit processes need, then the excess energy is sold to the market and the product system expanded by substituting electricity and/or steam.

Collected gases are modeled assuming that net exported energy associated with the gases is zero. This is calculated by placing constraints on the model so that the energy exported with excess coke oven gas is balanced by energy imported to address shortages in BF and BOF gases. Whether there is an excess or shortage of a particular gas depends on how much gases are generated by their respective process steps and the amounts of each gas modeled as consumed by the boiler and other unit process. The product system is burdened with flaring emissions associated with the coke oven gas, but given a credit emissions credit for importing BF and BOF gases—the credit representing the 'avoided flaring' of these gases at an external source (although the gases are modeled as combusted in the boiler).

Assumptions associated with facility-level electricity and steam consumption and with flaring of collected gases have a minimal effect on HDG coil results, but can reduce the potential global warming and smog formation impacts of structural sections by over 10%.

Anonymized unit process data were provided with minimal emissions to air as well as with carbon dioxide emissions that did not align with incoming (or outgoing) carbon sources. The initial thought to address this data gap was to leverage Chinese literature and/or emissions standards; however, there is minimal literature available and standards expressed emissions limits in terms of grams per cubic meter of air which could not easily be incorporated into the model. Therefore, emissions data from the US EPA's AP-42 report, worldsteel, and CEN 264 were used to close the gap for GHG emissions and improve each unit process' carbon balance. Data from AP-42 were also used to address non-GHG emissions from internal combustion of coal, heavy fuel oil, and natural gas. It's recognized that these data represent the U.S.-specific situation and are not necessarily applicable to China; however, they represent the best available resource for the analysis.

5.3. Scenario & Sensitivity Analysis

A scenario analysis was performed to evaluate the effect of eliminating ammonia emissions to water from the coke oven, sintering, and blast furnace unit processes. This affects both the HDG coil and structural sections results as both these products are modeled with the same unit processes. Although emissions this high are plausible—especially for a single facility—over 90% of Chinese acidification and eutrophication results are caused by this single emission flow. Therefore, additional insight into what can drive steel making ammonia emissions would be valuable.

One way to validate whether ammonia emissions can be considered representative of steel production in China is to benchmark these emissions assuming they are applicable to the whole Chinese steel industry against ammonia emissions in China from other sectors. The life cycle inventory (Appendix B) indicates that steel making generates 0.0424 kg ammonia per kg HDG coil and 0.0439 kg ammonia per kg sections. According to the worldsteel yearbook (worldsteel Association, 2015), China produced 822,698,000 tonnes of crude steel in 2014. Multiplying HDG coil ammonia emissions by tonnes of crude steel produced implies that ammonia emissions from Chinese steel making could be as high as 34,900,000 tonnes (34.9 Tg) of ammonia. This number, though, is significantly higher than the ~10 Tg of total annual Chinese ammonia emissions from all sectors in the year 2012 (Kang, et al., 2016). If the ammonia emissions from the coke oven, sintering, and blast furnace unit processes are removed, ammonia per kg HDG coil is reduced to 2.22E-05 kg and total Chinese ammonia emissions to water from steel making are calculated as 18,300 tonnes (0.0183 Tg)—well within the 2012 estimate of ~1.5 Tg for non-fertilizer and non-livestock ammonia emissions in China.

Benchmarking results indicate that baseline ammonia emissions to water are too high when applied to the entire Chinese steel industry. While expert judgment indicates that the magnitude of ammonia emissions to water is technically feasible at a single facility level, these emissions are unlikely to be representative of the entire Chinese steel industry. The anonymized nature of the data also make it impossible to circle back and check with the facility. Therefore, it is unclear whether the number is skewed due to a single outlier facility that dominates the average across all facilities, due to multiple outlying facilities, or simply an error in emissions reporting.

A second analysis evaluated the production of billets for structural sections via the BF/BOF route versus the EAF route. The baseline assumption of 94% of billets produced via BF/BOF is based on national averages for crude steel, as published in the worldsteel yearbook (worldsteel Association, 2015). No data are available on the production routes for specific products; consequently, it may be that a higher (or lower) fraction of EAF steel is shipped to the U.S. than the national averages suggest.

As the sensitivity analysis indicates, steel produced via EAF is associated with a lower potential impact in all impact categories considered. Therefore, it is possible that the average impact associated with Chinese steel is lower than the base case considered in this analysis. In absence of clear evidence that a higher fraction of structural sections are produced via EAF, however, the current baseline assumption of 94% of billets produced via BF/BOF is reasonable and reflects the best available data.

No uncertainty analyses were conducted as part of this study due to lack of knowledge of underlying relationships in anonymized data (e.g., CO_2 emissions as a function of carbon-containing inputs, energy consumption as a function of scrap steel versus iron ore or pig iron, boiler efficiency and generation of electricity versus steam, etc.). The absence of underlying dependencies or their appropriate quantification is essential to render Monte Carlo simulation results that are meaningful.

5.4. Data Quality Assessment

Inventory data quality is judged by its precision (measured, calculated or estimated), completeness (e.g., unreported emissions), consistency (degree of uniformity of the methodology applied) and representativeness (geographical, temporal, and technological).

To cover these requirements and to ensure reliable results, averaged data in combination with consistent background LCA information from the GaBi 2016 database were used. The LCI datasets from the GaBi 2016 database are widely distributed and used with the GaBi Professional software. The datasets have been used in LCA models worldwide in industrial and scientific applications in internal as well as in many critically reviewed and published studies. In the process of providing these datasets they are cross-checked with other databases and values from industry and science.

5.4.1. Precision and Completeness

- ✓ **Precision:** Most of the relevant foreground data are measured or calculated based on seasonal averages from seven Chinese facilities. However, there was no opportunity to communicate with the owners of the technology and thus no way to confirm some of the primary data points (e.g., ammonia emissions to water). A back-of-the-envelope calculation in Section 5.3 indicates that ammonia emissions are likely too high compared to total Chinese ammonia emissions but were used due to the lack of any other primary data. In addition, significant effort was made to make sure that mass and carbon balances are closed. Precision is therefore considered to be good. All background data are sourced from GaBi databases with the documented precision.

- ✓ **Completeness:** Each foreground process was checked for mass balance, carbon balance, and water balance. Aside from GHG emissions however, the emissions inventory was noticeably incomplete—particularly for the furnace-based processes. Additionally, nitrogen oxide and sulfur dioxide emissions were only provided for some—but not all—unit processes. Attempts were made to close emissions inventory gaps with emissions factors from U.S. literature. After closing these data gaps, completeness of foreground unit process data can be considered to be good. All background data are sourced from GaBi databases with the documented completeness.

  Alloying element inputs are also missing from the EAF unit process. Incorporating these elements into the analysis, however, is not anticipated to significantly affect results. The EAF process is used to represent only 6% of billets for structural sections and thus is not a key contributor to begin with. Secondly, the unit process assumes around 60% of steel is made from secondary content, which already contains some alloys.

5.4.2. Consistency and Reproducibility

- ✓ **Consistency:** To ensure data consistency, all primary data were collected with the same level of detail, while all background data were sourced from the GaBi databases.

- ✓ **Reproducibility:** Reproducibility is supported as much as possible through the disclosure of input-output data, dataset choices, and modeling approaches in this report. Based on this information, any third party should be able to approximate the results of this study using the same data and modeling approaches.

5.4.3. Representativeness

- ✓ **Temporal:** All primary data were collected for the years 2013 to 2015. All secondary data come from the GaBi 2016 databases and are representative of the years 2010-2015. As the study intended to compare the product systems for the reference year 2014, temporal representativeness is considered to be high.

- ✓ **Geographical:** All primary and secondary data were collected specific to the countries or regions under study. Where country-specific or region-specific data were unavailable, proxy data were used. Geographical representativeness of the data is considered to be moderate.

  Lacking, though, are characterization and normalization factors specific to China. TRACI 2.1 factors were used in absence of Chinese-specific data, and thus may not accurately reflect regional impact pathways and boundary conditions around acidification, eutrophication, and smog formation.

- ✓ **Technological:** All primary and secondary data were modeled to be specific to the technologies or technology mixes under study. Where technology-specific data were unavailable, proxy data were used. Technological representativeness is considered to be high.

5.5. Model Completeness and Consistency

5.5.1. Completeness

All relevant process steps for each product system were considered. The process chain is considered sufficiently complete and detailed with regard to the goal and scope of this study.

5.5.2. Consistency

All assumptions, methods and data are consistent with each other and with the study's goal and scope. Differences in background data quality were minimized by predominantly using LCI data from the GaBi 2016 databases. System boundaries, allocation rules, and impact assessment methods have been applied consistently throughout the study.

5.6. Conclusions, Limitations, and Recommendations

5.6.1. Conclusions

- Environmental impacts for both steel products are driven by different unit processes depending on impact the category considered:
    - Coal for coke production and other processes is a key contributor to non-renewable energy demand.
    - The boiler represents a relevant contribution to potential global warming impact.
    - Ammonia emissions to freshwater drive potential acidification and eutrophication impacts.
    - Iron ore production—and zinc production, in the case of HDG coil—drive potential smog formation impacts.
- The EAF unit process is a small contributor to the average structural sections impact as only 6% of billets are assumed to be produced via this route.
- Structural sections billets produced via EAF are associated with a smaller impact than those produced via BF/BOF.
- There is a noticeable data gap in the emissions inventories of the unit processes either because the processes lack data for emissions to air or because emissions are inconsistent with process inputs (and outputs).
    - Emissions factors for carbon dioxide are readily available so global warming results are probably the most complete.
    - Emissions to water that affect acidification and eutrophication impacts may require additional cross-checking. While the baseline results are plausible for a single facility or even a few facilities, the industry-level emissions, when calculated for the entire Chinese

steel industry, are significantly out of line with published estimates for Chinese ammonia emissions.

5.6.2. Limitations

This analysis aims to represent a general average of HDG coil and structural sections produced in China. It represents the best available data, although there is room for improvement (see 5.6.3). Since the data are based on anonymized sources, it was not possible to communicate with the owners of the technology to confirm the primary data. Therefore, uncertainty of results is anticipated to be higher than what is considered typical for general LCA uncertainty.

Regional impacts such as acidification, eutrophication, and smog formation are impact potentials only and may represent over- or underestimates depending on the conditions of the receiving environment (buffer capacity, background pollution, dispersion pathways, etc.). A fully regionalized impact assessment for both foreground and background systems is currently not possible due to limitations in data availability.

In absence of characterization methodologies or normalization factors specific to China, the TRACI methodology was used despite being specific to the U.S. As such, it does not fully reflect Chinese-specific concerns just like other methodologies tailored for regions other than China.

For example, eutrophication in TRACI is based on the Redfield ratio and represents a worst-case estimate for this impact category (Bare, 2012). Other methodologies such as ReCiPe and IMPACT World+ assume that freshwater eutrophication is (generally) phosphorous-limited (P-limited) and a significant reduction in nitrogen discharges would not lead to a significant reduction in eutrophication unless phosphorous emissions are also reduced. These methods do not even provide a characterization factor for ammonia emissions to fresh water (Goedkoop, et al., 2013). Literature research, though, indicates that a P-limited assumption is not always applicable. Algal blooms from non-N_2-fixing cyanobacteria can occur, thus requiring simultaneous management of both nitrogen & phosphorous emissions to water (Conley, et al., 2009). Lake Taihu in Eastern China is one such example where both nitrogen and phosphorous management is necessary and has caused drinking water crises for over two million people in the past (Qin, et al., 2010). Additionally, the Chinese government has also identified ammonia and nitrogen emissions as a priority in addressing eutrophication (Yin, 2011). While most ammonia emissions in China are caused by fertilizers, livestock, and aquacultures, these emissions occur mostly in Eastern China (Kang, et al., 2016), where the steel plants that export to the US would likely be located. Any additional ammonia emissions from steel plants therefore contribute to the overall problem, even if eliminating all ammonia emissions from steel mills would not significantly alleviate the overall problem.

Another possible limitation of this analysis is its focus on emissions to freshwater. While the ammonia emissions to water were all modeled as emissions to freshwater, several Chinese steel mills are located on the eastern coast so the ammonia emissions to water could occur in coastal marine zones. While this would not affect TRACI eutrophication results—TRACI's methodology applies the same characterization factors to both emissions to fresh water and to sea water—results calculated with ReCiPe and IMPACT World+ would change as these methodologies assume marine eutrophication in coastal areas is generally nitrogen-limited and thus have characterization factors for nitrogen emissions to sea water.

Based on these considerations and the inability to find better data on ammonia emissions from steel mills in China, it is strongly advised to always stress the fact the LCA results represent *potential environmental impacts* when communicating results. Particularly the eutrophication potential results should be used with utmost caution for benchmarking with other steel inventories.

5.6.3. Recommendations

There are some areas where the process-level data could be improved:

- Double-check ammonia, BOD, and COD emissions to water for the coke oven, sintering, and blast furnace by comparing to available data from U.S. facilities, or at least try to understand what could potentially drive these emissions.
- Obtain more complete emissions data, including nitrogen oxides and sulfur dioxides for the unit processes (as these emissions contribute to smog formation impact).
- Obtain facility-level information for purchased electricity, purchased steam, and whether any collected gas is flared.

Additionally, it would be helpful to benchmark the results, both from a cradle-to-gate perspective and at a unit process level, to assess whether the data and results are reasonable.

Since this analysis intends to represent steel production in China, additional information on the Chinese market could also help improve the analysis. Specifically:

- Slab and billet production routes for the specific products to assess whether the 100% BF/BOF for slab and 94% BF/BOF assumptions are realistic.
- Whether exports from China reflect the national average for production route or whether steel produced via the EAF route is favored over steel produced via the BF/BOF route for export purposes (or vice versa).
- For those emissions to air that have to be calculated based on emissions factors, investigate whether these factors would differ for Chinese technology (e.g., due to pollution limits) compared to the sources used in this report.
- General practices of steel mills with boilers and whether excess electricity and/or steam is sold externally.
- General practices concerning excess collected gases and whether these are flared if a boiler has reached its capacity.

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