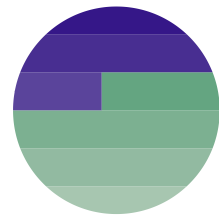





**American
Iron and Steel
Institute**



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
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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
NMVOG	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
<ul style="list-style-type: none"> ✓ Production stage <ul style="list-style-type: none"> ○ 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 	<ul style="list-style-type: none"> ✗ 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, SO₂, 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.

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 production². Given that China exports around 11% of domestic production³, 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.

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).

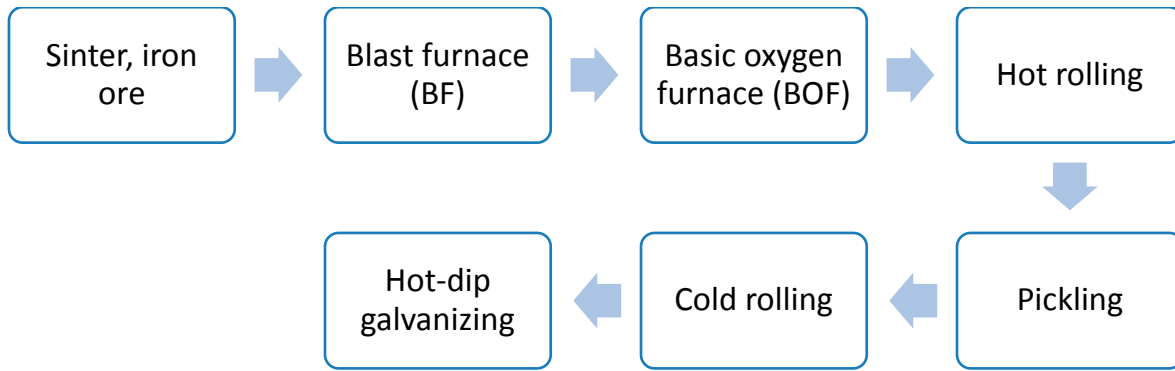


Figure 3-1: Hot-dip galvanized coil process flow

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	1.22	MJ
	Electricity	0.294	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.

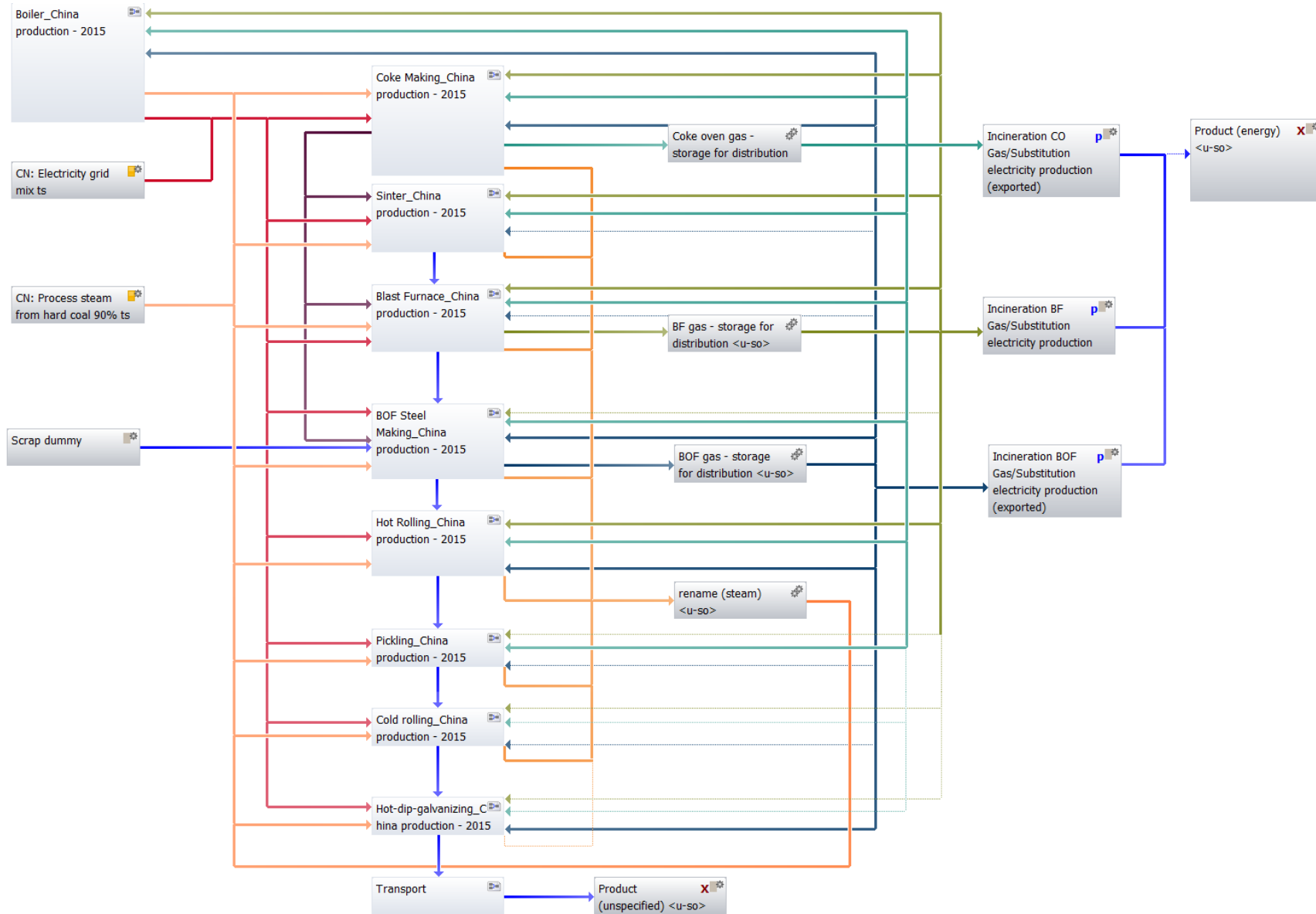


Figure 3-2: Screen shot of GaBi model for HDG coil



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 routes⁴ (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.

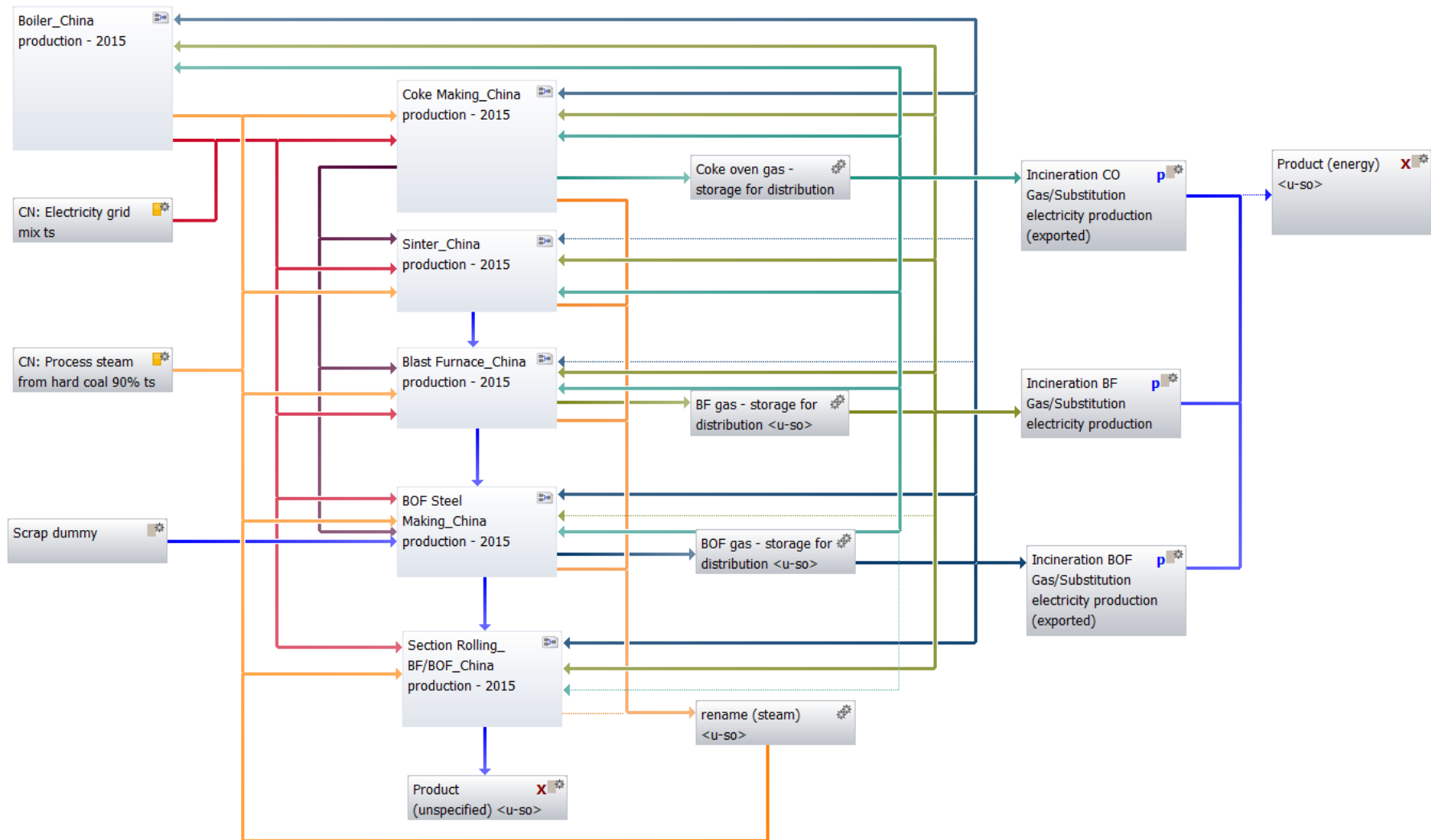


Figure 3-4: Screen shot of GaBi BF/BOF model for structural sections

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.

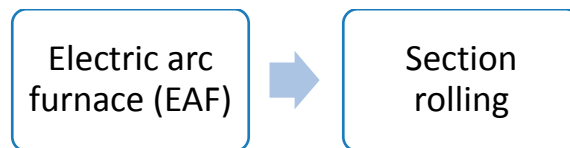


Figure 3-5: Structural section EAF process flow

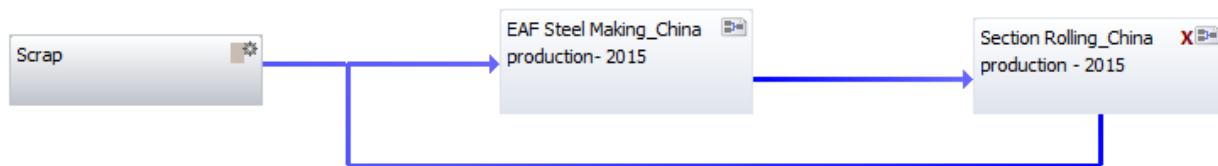


Figure 3-6: Screen shot of GaBi EAF model for structural sections

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 (SO₂), 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
NM VOC (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 (CaCO ₃ ; 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 reformat) (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.

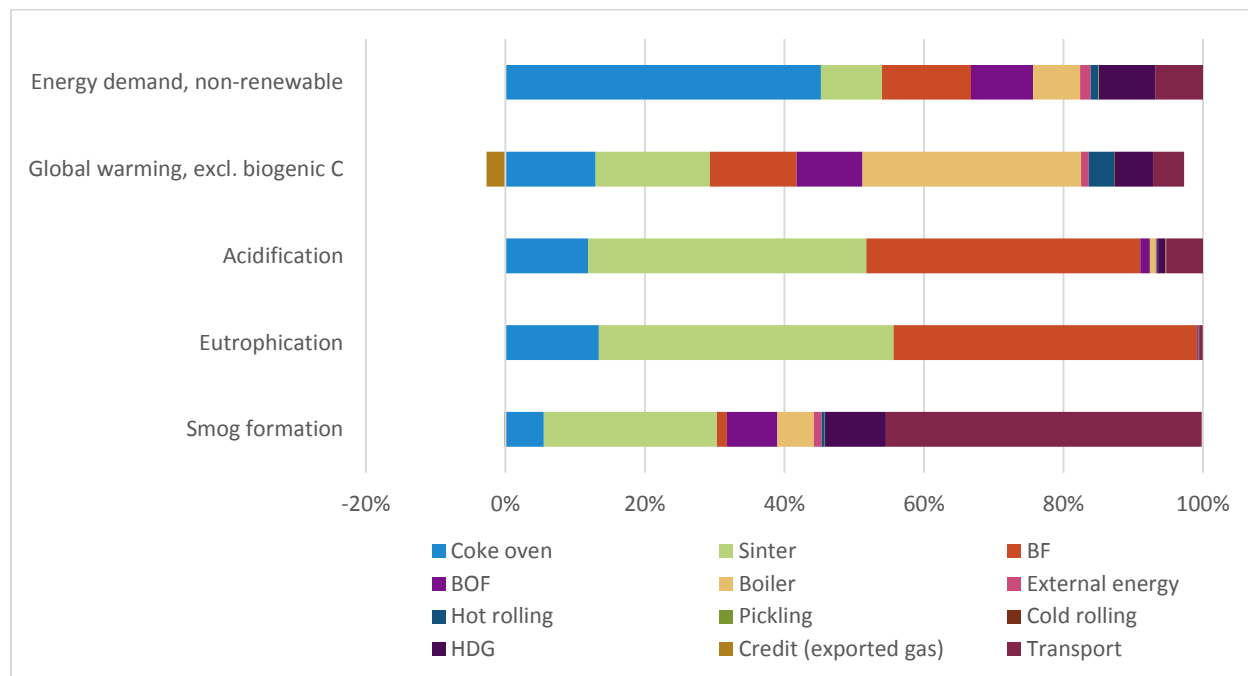


Figure 4-1: Breakdown of HDG coil results by process step

**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 CO₂ 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.

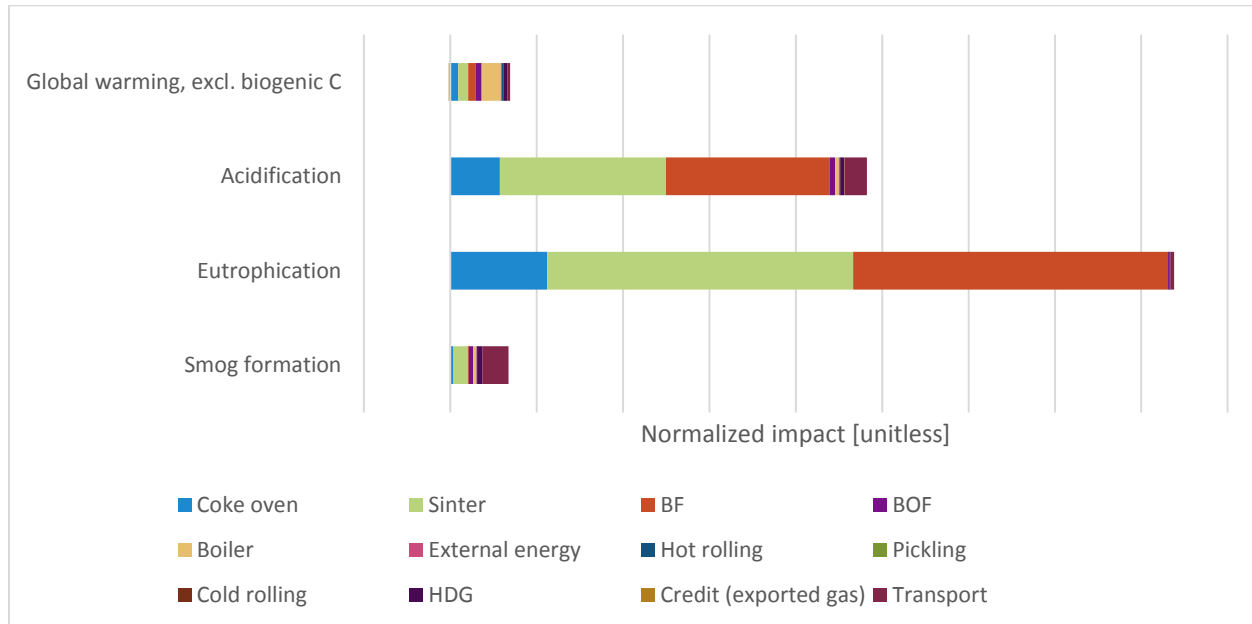


Figure 4-2: Normalized HDG coil results

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.

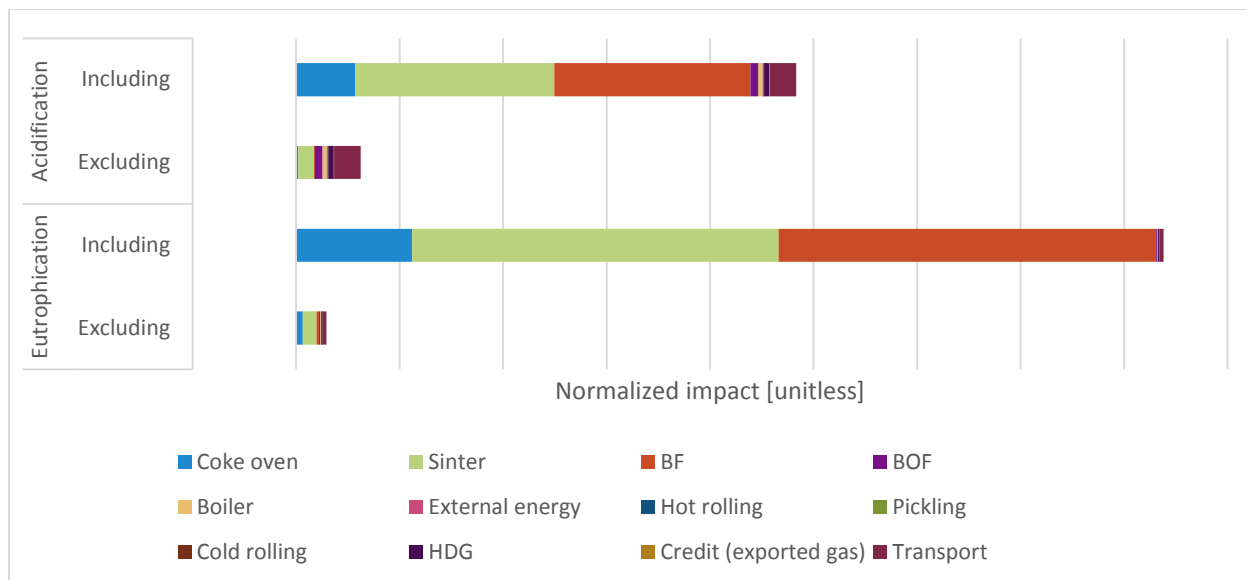


Figure 4-3: Normalized HDG coil results including and excluding ammonia emissions to water

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

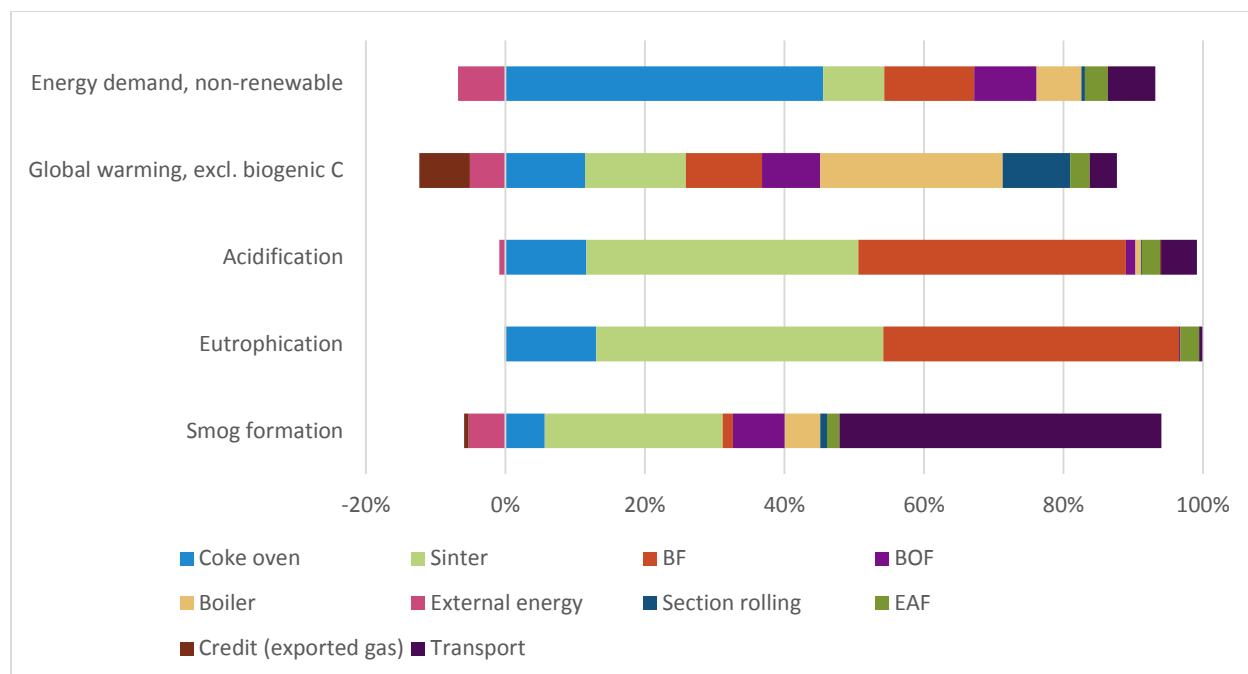


Figure 4-4: Breakdown of structural sections results by process step

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 CO₂ 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.

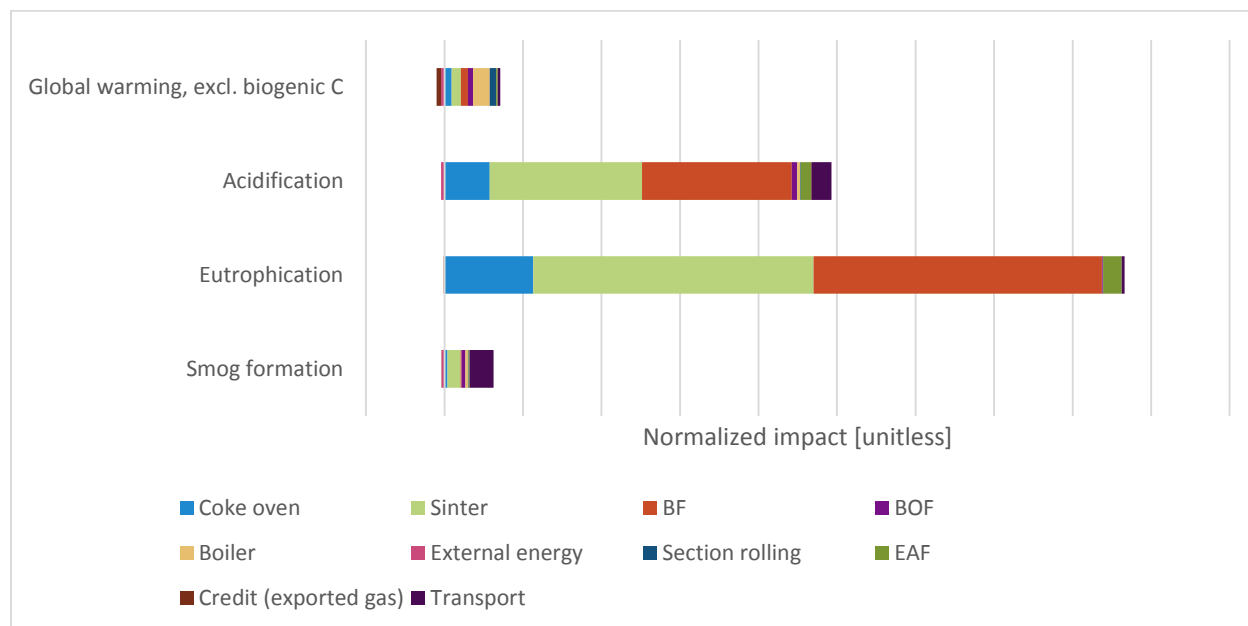


Figure 4-5: Normalized structural sections results

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.

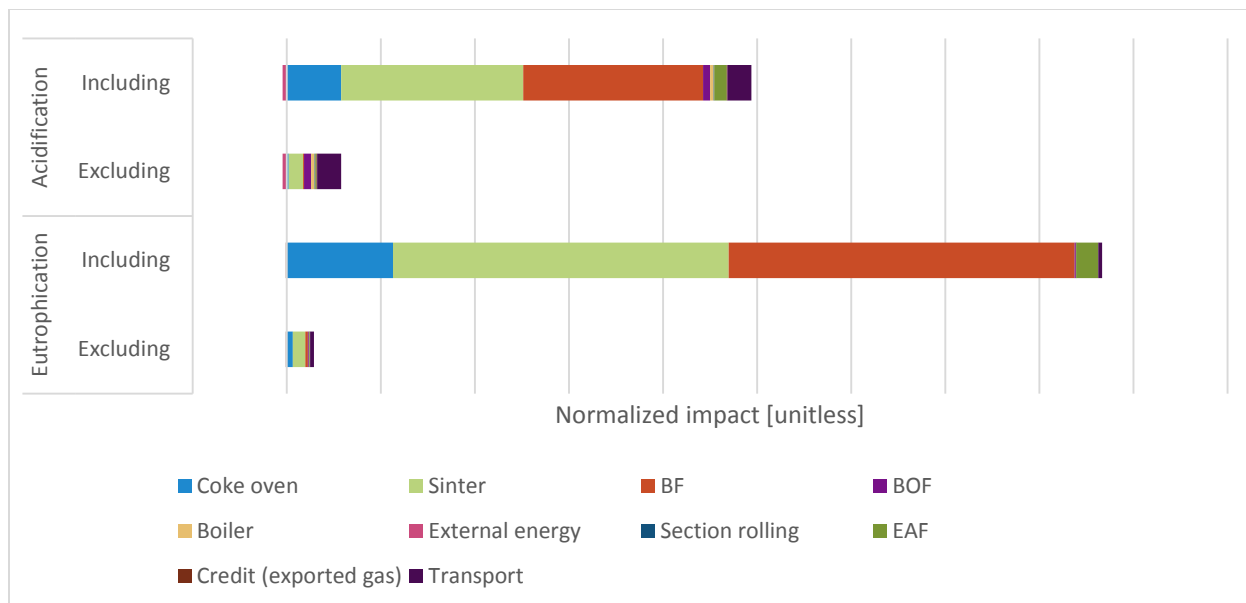


Figure 4-6: Normalized structural sections results including and excluding ammonia emissions to water

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.

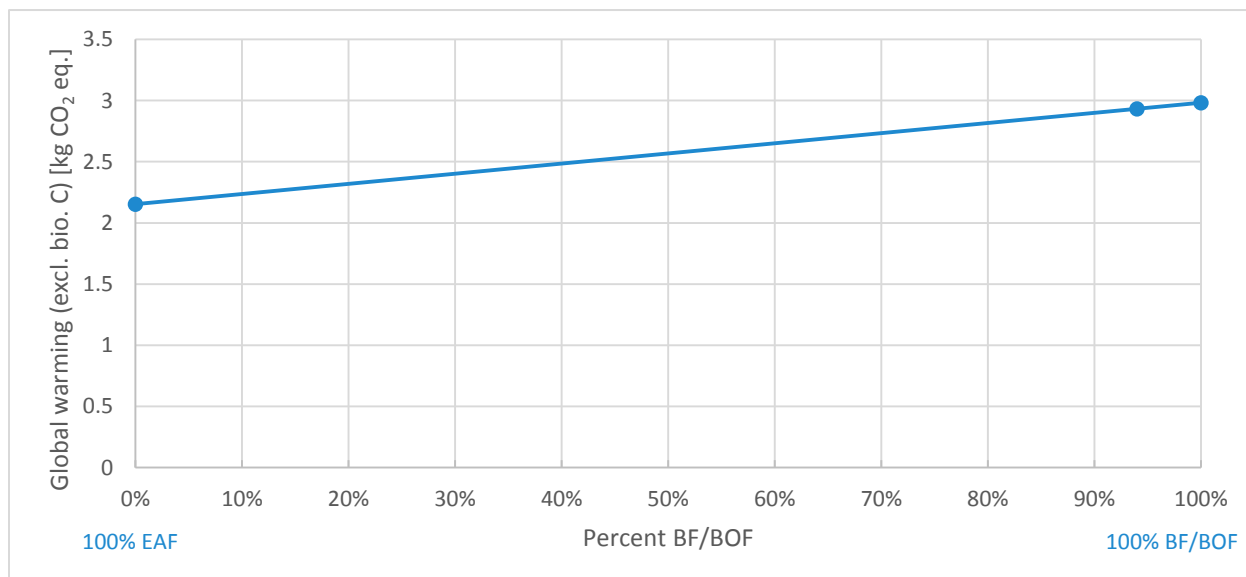


Figure 4-7: Global warming as a function of BF/BOF fraction

**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., CO₂ 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-N₂-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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Appendix A. Unit Process Tables

Table A-1: Coke oven unit process per 1 kg coke

Flow	Amount	Units	Notes
Inputs			
Hard coal	1.31E+00	kg	
<i>Process materials & energy</i>			
Bitumen	5.60E-03	kg	
Nitrogen gaseous	6.65E-03	kg	
Sulfuric acid	6.96E-03	kg	
Tar	2.58E-03	kg	
Water (deionized)	3.10E-01	kg	
Water (ground water)	9.76E-01	kg	
Water for industrial use	3.53E-01	kg	
Basic oxygen furnace gas	2.50E-01	MJ	
Blast furnace gas	2.38E+00	MJ	
Coke oven gas	1.17E+00	MJ	
Electricity	2.59E-01	MJ	
Steam	5.44E-01	MJ	
Compressed air	1.73E-03	Nm ³	
Outputs			
Coke	1.00E+00	kg	
Benzene	2.00E-02	kg	
Sulfur	1.42E-03	kg	
Tar	6.11E-02	kg	
Coke oven gas	7.96E+00	MJ	
Steam	1.03E+00	MJ	
<i>Emissions to air</i>			
Carbon dioxide	7.09E-01	kg	
Carbon monoxide	1.22E-04	kg	Calculated from AP-42, Chapter 12.2
Dust (PM10)	7.65E-05	kg	
Nitrogen oxides	3.37E-04	kg	
NMVOG (unspecified)	8.94E-05	kg	
Sulfur dioxide	1.15E-04	kg	
Water vapor	9.76E-01	kg	Assumed equal to incoming fresh water
Xylene (dimethyl benzene)	1.09E-05	kg	



Flow	Amount	Units	Notes
<i>Emissions to water</i>			
Ammonium / ammonia	1.37E-02	kg	
Biological oxygen demand (BOD)	1.45E-03	kg	
Chemical oxygen demand (COD)	1.04E-02	kg	
Chromium	1.28E-06	kg	
Copper	2.49E-06	kg	
Cyanide	2.56E-05	kg	
Iron	2.82E-05	kg	
Mercury	4.94E-08	kg	
Solids (suspended)	1.26E-03	kg	
Sulfide	6.91E-07	kg	
Waste water	4.79E-01	kg	
Zinc	1.18E-05	kg	

Table A-2: Sintering unit process per 1 kg sinter pellets

Flow	Amount	Units	Notes
Inputs			
Iron ore	8.74E-01	kg	
Sinter / pellet fines	5.14E-02	kg	
<i>Process materials & energy</i>			
Anthracite	1.64E-02	kg	See Table 3-5 for EF, excl. NO _x & SO ₂
Coke	4.16E-02	kg	See Table 3-6 for emission factors
Dolomite	3.67E-02	kg	See Table 3-6 for emission factors
Lime (quicklime)	1.23E-02	kg	
Limestone	8.62E-02	kg	See Table 3-6 for emission factors
Natural gas	8.04E-04	kg	See Table 3-5 for EF, excl. NO _x & SO ₂
Olivine	1.48E-03	kg	
Water (deionized)	4.98E-02	kg	
Water (ground water)	1.97E-02	kg	
Water cooling fresh	1.42E-01	kg	
Blast furnace gas	3.25E-02	MJ	See Table 3-4 for EF, excl. NO _x & SO ₂
Coke oven gas	3.69E-02	MJ	See Table 3-4 for EF, excl. NO _x & SO ₂
Electricity	1.35E-01	MJ	
Steam	6.49E-03	MJ	
Outputs			
Graded sinter	1.00E+00	kg	
Steam	1.10E-01	MJ	



Flow	Amount	Units	Notes
<i>Emissions to air</i>			
Dioxins (unspec.)	5.90E-07	kg	
Dust (PM10)	1.35E-04	kg	
Nitrogen oxides	2.85E-04	kg	
NMVOC (unspecified)	1.50E-05	kg	
Sulfur dioxide	3.39E-04	kg	
<i>Emissions to water</i>			
Ammonium / ammonia	1.36E-02	kg	
Biological oxygen demand (BOD)	8.03E-04	kg	
Chemical oxygen demand (COD)	5.76E-03	kg	
Chromium	7.13E-07	kg	
Copper	1.39E-06	kg	
Cyanide	2.54E-05	kg	
Iron	1.56E-05	kg	
Mercury	3.10E-08	kg	
Phenol (hydroxy benzene)	5.28E-06	kg	
Solids (suspended)	6.97E-04	kg	
Sulfide	3.87E-07	kg	
Waste water	2.00E-01	kg	
Zinc	6.58E-06	kg	

Table A-3: Blast furnace unit process per 1 kg liquid metal

Flow	Amount	Units	Notes
Inputs			
Sinter	1.31E+00	kg	
Iron ore	1.82E-01	kg	
Pellet feed	1.84E-01	kg	
<i>Process materials & energy</i>			
Anthracite	5.72E-03	kg	
Coal	1.39E-01	kg	
Coke	3.50E-01	kg	
Natural gas	1.76E-03	kg	
Nitrogen, gaseous	4.41E-02	kg	
Oxygen, gaseous	4.92E-02	kg	
Water (ground water)	1.20E-01	kg	
Blast furnace gas	1.98E+00	MJ	
Coke oven gas	3.07E-01	MJ	
Electricity	1.60E-01	MJ	
Steam	3.51E-02	MJ	



Flow	Amount	Units	Notes
Compressed air	2.26E-02	Nm ³	
Outputs			
Hot metal	1.00E+00	kg	
Iron scrap	2.36E-01	kg	
Sinter / pellet fines	5.88E-02	kg	
Blast furnace gas	5.14E+00	MJ	
Electricity	1.11E-01	MJ	
Steam	3.27E-03	MJ	
<i>Wastes for treatment</i>			
BF gas dust	4.36E-03	kg	
BF slag (recovered)	2.77E-01	kg	82% cement, 17% aggregate, 1% fertilizer
BF slag (disposed)	1.07E-01	kg	
Water Cooling fresh	1.10E-01	kg	
<i>Emissions to air</i>			
Carbon dioxide	5.03E-01	kg	
Carbon monoxide	1.60E-04	kg	
Dust (PM10)	1.98E-07	kg	
Dust (unspecified)	2.02E-05	kg	
Nitrogen oxides	2.57E-05	kg	
Sulfur dioxide	4.60E-05	kg	
Water vapor	1.00E-02	kg	
<i>Emissions to water</i>			
Ammonium / ammonia	1.89E-02	kg	
Biological oxygen demand (BOD)	2.00E-03	kg	
Chemical oxygen demand (COD)	1.44E-05	kg	
Chromium	1.77E-06	kg	
Copper	3.46E-06	kg	
Cyanide	3.54E-05	kg	
Iron	3.90E-05	kg	
Mercury	6.49E-08	kg	
Phenol (hydroxy benzene)	1.32E-05	kg	
Solids (suspended)	1.74E-03	kg	
Sulfide	9.62E-07	kg	
Zinc	1.64E-05	kg	

**Table A-4: Basic oxygen furnace unit process per 1 kg semi-finished cast product**

Flow	Amount	Units	Notes
Inputs			
Hot metal (from blast furnace)	9.75E-01	kg	
Iron ore	5.17E-03	kg	
Steel scrap (external supply)	9.53E-02	kg	
Steel scrap (home scrap)	7.30E-04	kg	
Steel scrap (internal scrap)	3.55E-02	kg	
<i>Alloying & slag materials</i>			
Aluminum	2.07E-03	kg	
Copper	2.53E-05	kg	
Dolomite	7.07E-02	kg	
Ferro calcium	6.19E-05	kg	
Ferro chromium	9.12E-04	kg	
Ferro manganese	5.22E-03	kg	
Ferro silicon	8.69E-04	kg	
Ferro vanadium	4.41E-05	kg	
Ferro molybdenum	1.34E-04	kg	
Ferro niobium	4.95E-05	kg	
Ferro titanium	8.68E-05	kg	
Lime (quicklime)	3.29E-02	kg	
Magnesium	6.39E-05	kg	
Manganese	5.03E-04	kg	
Nickel	5.73E-05	kg	
Silicon calcium	3.09E-05	kg	
Silicon manganese	1.68E-03	kg	
<i>Process materials & energy</i>			
Argon	3.11E-03	kg	
Coke	2.04E-04	kg	
Natural gas	3.46E-03	kg	
Nitrogen gaseous	4.47E-02	kg	
Oxygen gaseous	7.13E-02	kg	
Refractories (magnesia, lime)	7.48E-03	kg	
Refractories (silica, alumina)	1.70E-03	kg	
Water (ground water)	2.21E-01	kg	
Blast oxygen furnace gas	6.46E-03	MJ	
Coke oven gas	1.00E-01	MJ	
Electricity	2.02E-01	MJ	
Steam	8.35E-02	MJ	
Compressed air for process	1.02E-02	Nm ³	



Flow	Amount	Units	Notes
Outputs	5.03E-04	kg	
Slab / billets	1.00E+00	kg	
Steel scrap (external)	7.70E-02	kg	
Steel scrap (internal)	8.14E-03	kg	
Scales	3.30E-02	kg	
Blast oxygen furnace gas	6.79E-01	MJ	
Steam	1.56E-01	MJ	
<i>Wastes for treatment</i>			
BOF slag	7.04E-02	kg	9% cement, 83% aggregate, 8% fertilizer
Desulfurization slag	3.25E-02	kg	
Refractories (magnesia, lime)	7.48E-03	kg	
Refractories (silica, alumina)	1.70E-03	kg	
Water cooling fresh	6.14E-02	kg	
<i>Emissions to air</i>			
Carbon dioxide	5.20E-03	kg	
Dust (PM10)	3.30E-05	kg	
Mercury	5.20E-11	kg	
Nitrogen oxides	8.07E-06	kg	
NMVO (unspecified)	6.20E-08	kg	
Sulfur dioxide	1.49E-06	kg	
<i>Emissions to water</i>			
Ammonium / ammonia	1.44E-05	kg	
Biological oxygen demand (BOD)	1.53E-06	kg	
Chemical oxygen demand (COD)	1.10E-05	kg	
Chromium	1.35E-09	kg	
Copper	2.64E-09	kg	
Cyanide	2.70E-08	kg	
Iron	2.97E-08	kg	
Phenol (hydroxy benzene)	1.00E-08	kg	
Solids (suspended)	1.33E-06	kg	
Sulfide	7.38E-10	kg	
Waste water	2.39E-01	kg	
Zinc	1.25E-08	kg	

**Table A-5: Hot rolling unit process per 1 kg hot-rolled coil**

Flow	Amount	Units	Notes
Inputs			
Slab (from BOF)	1.03E+00	kg	
<i>Process materials & energy</i>			
Natural gas	5.42E-03	kg	See Table 3-5 for emissions factors
Nitrogen, gaseous	4.16E-03	kg	
Oxygen, gaseous	1.51E-03	kg	
Water (deionized)	1.59E-01	kg	
Blast oxygen furnace gas	2.00E-01	MJ	See Table 3-4 for emissions factors
Blast furnace gas	6.09E-02	MJ	See Table 3-4 for emissions factors
Coke oven gas	7.05E-01	MJ	See Table 3-4 for emissions factors
Electricity	3.85E-01	MJ	
Steam	1.16E-02	MJ	
Compressed air	3.41E-03	Nm ³	
Outputs			
Hot-rolled coil	1.00E+00	kg	
Steel scrap	1.77E-02	kg	
Steam	3.08E-02	MJ	
<i>Emissions to air</i>			
Water vapor	1.59E-01	kg	

Table A-6: Pickling unit process per 1 kg pickled hot-rolled coil

Flow	Amount	Units	Notes
Inputs			
Steel hot rolled coil	1.00E+00	kg	
<i>Process materials & energy</i>			
Natural gas	4.71E-04	kg	See Table 3-5 for emissions factors
Coke oven gas	2.10E-02	MJ	See Table 3-4 for emissions factors
Electricity	1.80E-02	MJ	
Steam	2.79E-02	MJ	
Compressed air	4.00E-03	Nm ³	
Outputs			
Pickled hot-rolled coil	1.00E+00	kg	
Steam	1.80E-02	MJ	



Table A-7: Cold rolling unit process per 1 kg cold rolled coil

Flow	Amount	Units	Notes
Inputs			
Steel pickled hot rolled coil	1.00E+00	kg	
<i>Process materials & energy</i>			
Natural gas	6.43E-05	kg	See Table 3-5 for emissions factors
Electricity	5.94E-01	MJ	
Steam	2.50E-02	MJ	
Compressed air	3.30E-02	Nm ³	
Outputs			
Cold-rolled coil	1.00E+00	kg	
Steam	2.40E-02	MJ	

Table A-8: Hot-dip galvanizing unit process per 1 kg galvanized coil

Flow	Amount	Units	Notes
Inputs			
Steel cold rolled coil	9.76E-01	kg	
High grade zinc	4.50E-02	kg	
<i>Process materials & energy</i>			
Hydrochloric acid	1.10E-02	kg	
Natural gas	2.03E-02	kg	See Table 3-5 for emissions factors
Nitrogen, gaseous	3.60E-02	kg	
Sulfuric acid	7.00E-03	kg	
Water cooling fresh	1.25E-01	kg	
Basic oxygen furnace gas	1.02E-01	MJ	See Table 3-4 for emissions factors
Electricity	1.91E-01	MJ	
Steam (MJ)	4.20E-02	MJ	
Compressed air 7 bar	2.50E-02	Nm ³	
Outputs			
HDG coil	1.00E+00	kg	
Steel scrap	1.94E-02	kg	
Zinc scrap	6.50E-03	kg	
<i>Wastes for processing</i>			
Waste water to treatment works	1.34E-01	kg	
Waste water to river	2.04E-03	kg	
<i>Emissions to air</i>			
Hydrogen chloride	1.67E-04	kg	
Zinc	5.00E-05	kg	



Table A-9: Boiler unit process per 1 kWh electricity

Flow	Amount	Units	Notes
Inputs			
Coal	1.28E-01	kg	See Table 3-5 for EF, excl. NO _x & SO ₂
Heavy fuel oil	5.47E-04	kg	See Table 3-5 for EF, excl. NO _x & SO ₂
Natural gas	8.62E-04	kg	See Table 3-5 for EF, excl. NO _x & SO ₂
Basic oxygen furnace gas	2.14E+00	MJ	See Table 3-4 for EF, excl. NO _x & SO ₂
Blast furnace gas	7.78E+00	MJ	See Table 3-4 for EF, excl. NO _x & SO ₂
Coke oven gas	3.57E+00	MJ	See Table 3-4 for EF, excl. NO _x & SO ₂
Electricity	4.06E-01	MJ	
Steam	1.61E+00	MJ	
Compressed air	4.32E-02	Nm ³	
Outputs			
Electricity	1.00E+00	kWh	
Steam	4.15E+00	MJ	
<i>Emissions to air</i>			
Nitrogen oxides	6.40E-04	kg	
Sulfur dioxide	7.99E-04	kg	

Table A-10: Electric arc furnace unit process per 1 kg steel billet

Flow	Amount	Units	Notes
Inputs			
Pig iron	4.25E-01	kg	
Steel scrap (external supply)	6.51E-01	kg	
Steel scrap (home scrap)	1.60E-02	kg	
<i>Process materials & energy</i>			
Anthracite	6.30E-03	kg	See Table 3-5 for emissions factors
Argon	3.13E-03	kg	
Coke (external supply)	2.47E-03	kg	Not combusted; assumed to be carbon for steel
Dolomite	2.28E-03	kg	See Table 3-6 for emission factors
Electrode	1.21E-02	kg	See Table 3-6 for emission factors
Lime (quicklime)	7.86E-02	kg	
Natural gas	5.88E-03	kg	See Table 3-5 for emissions factors
Nitrogen gaseous	4.55E-03	kg	
Oxygen gaseous	6.77E-02	kg	
Coke oven gas	1.51E-02	MJ	See Table 3-5 for natural gas emissions factors



Flow	Amount	Units	Notes
Electricity	1.78E+00	MJ	
Steam	1.39E-01	MJ	
Outputs			
Slab	1.00E+00	kg	
Steel scrap	9.20E-02	kg	

Table A-11: Section rolling unit process per 1 kg section

Flow	Amount	Units	Notes
Inputs			
Slab (from EAF)	1.10E+00	kg	
<i>Process materials & energy</i>			
Nitrogen gaseous	2.44E-05	kg	
Oxygen gaseous	1.13E-04	kg	
Basic oxygen furnace gas	1.03E-01	MJ	See Table 3-4 for emissions factors
Blast furnace gas	1.29E+00	MJ	See Table 3-4 for emissions factors
Electricity	2.85E-01	MJ	
Steam	3.30E-02	MJ	
Outputs			
Steel sections	1.00E+00	kg	
Steel scrap	1.01E-01	kg	



Appendix B. Life Cycle Inventories

Table B-1: LCI results for 1 kg HDG coil

Flow	Units	Coke oven	Sinter	BF	BOF	Boiler	External energy	Hot rolling	Pickling	Cold rolling	HDG	Credit (gas)	Transport	Total
Non-renewable energy														
Crude oil	MJ	-9.73E-01	9.13E-01	1.72E-01	2.19E-01	3.96E-02	1.11E-02	3.77E-03	1.36E-04	1.85E-05	-1.09E-02	-	1.80E+00	2.17E+00
Hard coal	MJ	1.38E+01	1.21E+00	3.34E+00	1.83E+00	1.83E+00	3.12E-01	1.14E-02	2.67E-05	3.64E-06	5.29E-01	-	3.32E-02	2.29E+01
Lignite	MJ	9.48E-03	9.11E-02	6.95E-03	6.27E-02	1.21E-03	3.65E-04	1.87E-03	1.85E-06	2.53E-07	9.31E-02	-	2.05E-04	2.67E-01
Natural gas	MJ	1.54E-01	2.74E-01	1.59E-01	4.93E-01	5.55E-02	5.78E-02	2.98E-01	2.56E-02	3.50E-03	1.53E+00	-	1.22E-01	3.17E+00
Uranium	MJ	1.22E-02	2.86E-02	3.69E-03	1.02E-01	9.07E-03	4.92E-02	2.49E-03	1.89E-06	2.58E-07	1.88E-01	-	1.11E-03	3.96E-01
Renewable energy														
Geothermal	MJ	1.63E-04	1.45E-04	4.81E-05	1.86E-04	2.76E-05	7.11E-06	1.34E-05	1.37E-07	1.86E-08	7.56E-03	-	2.45E-06	8.15E-03
Hydro	MJ	2.33E-02	1.21E-01	2.14E-02	1.47E-01	3.13E-02	1.84E-01	1.23E-03	1.29E-06	1.76E-07	2.01E-01	-	3.12E-03	7.33E-01
Solar	MJ	2.64E-02	4.13E-02	8.18E-03	4.14E-02	8.59E-03	3.41E-02	1.68E-03	4.75E-06	6.48E-07	6.42E-02	-	8.31E-04	2.27E-01
Waves	MJ	6.90E-15	1.11E-14	7.49E-16	1.92E-14	3.09E-15	1.49E-14	1.43E-15	9.68E-19	1.32E-19	3.91E-13	-	2.72E-16	4.49E-13
Wind	MJ	7.01E-03	1.30E-02	2.07E-03	1.56E-02	7.33E-03	4.21E-02	8.37E-04	6.55E-07	8.93E-08	4.99E-02	-	6.87E-04	1.39E-01
Emissions to air														
Carbon dioxide	kg	3.31E-01	5.44E-01	3.95E-01	3.14E-01	1.03E+00	3.42E-02	1.10E-01	2.29E-03	1.77E-04	1.78E-01	-1.02E-01	1.46E-01	2.99E+00
Carbon monoxide	kg	1.68E-04	3.18E-04	-5.48E-05	2.04E-04	6.05E-03	5.30E-05	1.65E-03	2.50E-06	1.48E-07	9.33E-04	-2.72E-03	3.98E-04	7.01E-03
Methane	kg	3.67E-03	4.38E-04	9.23E-04	6.08E-04	1.13E-03	9.20E-05	4.58E-04	1.55E-05	4.01E-07	3.07E-04	3.16E-04	1.29E-04	8.08E-03
Nitrogen oxides	kg	4.23E-04	1.95E-03	1.13E-04	6.19E-04	3.94E-04	8.40E-05	3.14E-05	2.23E-06	3.04E-07	6.79E-04	-7.73E-06	3.56E-03	7.85E-03
Nitrous oxide	kg	1.49E-06	3.59E-06	4.12E-07	4.68E-06	1.55E-06	7.33E-07	3.19E-07	2.34E-08	3.19E-09	3.82E-06	-	3.61E-06	2.02E-05
Sulfur dioxide	kg	1.23E-04	1.44E-03	1.33E-04	9.38E-04	4.80E-04	9.25E-05	1.36E-04	4.01E-06	2.70E-08	2.65E-04	8.79E-05	2.32E-03	6.02E-03
Sulfur oxides	kg	-	-	-	-	-	-	-	-	-	6.96E-07	-	0.00E+00	6.96E-07
Xylene	kg	7.68E-06	5.32E-06	5.61E-07	1.23E-05	1.00E-05	3.50E-06	1.10E-07	8.30E-11	1.13E-11	2.84E-06	-	3.66E-07	4.26E-05
Emissions to water														
NH ₃ / NH ₄ ⁺	kg	5.54E-03	1.79E-02	1.90E-02	1.60E-05	1.21E-07	3.31E-08	8.58E-08	2.58E-11	3.52E-12	2.68E-06	-	3.25E-09	4.24E-02
BOD	kg	5.86E-04	1.06E-03	2.01E-03	1.86E-06	1.63E-08	1.06E-08	2.28E-07	3.68E-09	5.02E-10	8.96E-07	-	2.02E-07	3.66E-03
COD	kg	4.22E-03	7.65E-03	2.82E-05	6.93E-05	3.20E-05	1.82E-04	2.34E-06	4.74E-08	6.47E-09	7.83E-05	-	1.41E-05	1.23E-02
Nitrite	kg	5.44E-12	5.47E-11	8.23E-12	2.45E-10	3.42E-13	1.40E-13	2.06E-12	1.79E-15	2.44E-16	4.67E-10	-	1.30E-13	7.84E-10



Table B-2: LCI results of 1 kg structural sections

Flow	Units	Coke oven	Sinter	BF	BOF	Boiler	External energy	Sec. rolling	EAF	Credit (gas)	Transport	Total
Non-renewable energy												
Crude oil	MJ	-9.81E-01	9.20E-01	1.73E-01	2.20E-01	3.78E-02	-3.34E-02	1.44E-03	3.00E-02	-	1.80E+00	2.17E+00
Hard coal	MJ	1.39E+01	1.22E+00	3.36E+00	1.85E+00	1.74E+00	-1.88E+00	4.62E-02	8.16E-01	-	3.32E-02	2.11E+01
Lignite	MJ	9.55E-03	9.18E-02	7.00E-03	6.31E-02	1.15E-03	-1.57E-03	4.77E-05	1.12E-02	-	2.05E-04	1.83E-01
Natural gas	MJ	1.55E-01	2.76E-01	1.60E-01	4.97E-01	5.29E-02	-3.97E-02	9.98E-02	9.02E-02	-	1.22E-01	1.41E+00
Uranium	MJ	1.23E-02	2.88E-02	3.72E-03	1.02E-01	8.64E-03	-5.97E-03	1.08E-03	8.79E-03	-	1.11E-03	1.61E-01
Renewable energy												
Geothermal	MJ	1.65E-04	1.46E-04	4.85E-05	1.88E-04	2.64E-05	-2.82E-05	1.26E-06	1.60E-05	-	2.45E-06	5.65E-04
Hydro	MJ	2.35E-02	1.22E-01	2.16E-02	1.49E-01	2.98E-02	-1.88E-02	3.96E-03	2.76E-02	-	3.12E-03	3.61E-01
Solar	MJ	2.66E-02	4.17E-02	8.24E-03	4.18E-02	8.19E-03	-6.64E-03	8.18E-04	8.04E-03	-	8.31E-04	1.29E-01
Waves	MJ	6.95E-15	1.12E-14	7.55E-16	1.93E-14	2.94E-15	-2.34E-15	3.41E-16	3.68E-15	-	2.72E-16	4.31E-14
Wind	MJ	7.07E-03	1.31E-02	2.08E-03	1.57E-02	6.99E-03	-4.57E-03	9.12E-04	6.34E-03	-	6.87E-04	4.83E-02
Emissions to air												
Carbon dioxide	kg	3.33E-01	5.48E-01	3.99E-01	3.17E-01	9.85E-01	-1.82E-01	3.76E-01	1.02E-01	-3.06E-01	1.46E-01	2.72E+00
Carbon monoxide	kg	1.69E-04	3.21E-04	-5.52E-05	2.05E-04	5.77E-03	-2.16E-04	1.25E-03	2.63E-04	-1.19E-03	3.98E-04	6.91E-03
Methane	kg	3.70E-03	4.41E-04	9.30E-04	6.12E-04	1.08E-03	-5.13E-04	2.39E-05	2.74E-04	7.89E-04	1.29E-04	7.46E-03
Nitrogen oxides	kg	4.26E-04	1.96E-03	1.14E-04	6.24E-04	3.76E-04	-3.97E-04	6.86E-05	1.36E-04	-5.02E-05	3.56E-03	6.82E-03
Nitrous oxide	kg	1.51E-06	3.61E-06	4.15E-07	4.71E-06	1.48E-06	-3.04E-06	1.68E-07	6.27E-07	-	3.61E-06	1.31E-05
Sulfur dioxide	kg	1.24E-04	1.45E-03	1.34E-04	9.46E-04	4.58E-04	-5.21E-04	6.77E-05	1.29E-04	1.86E-04	2.32E-03	5.30E-03
Sulfur oxides	kg	-	-	-	-	-	-	-	5.68E-06	-	0.00E+00	5.68E-06
Xylene	kg	7.74E-06	5.36E-06	5.66E-07	1.24E-05	9.53E-06	-2.15E-05	5.26E-07	3.07E-06	-	3.66E-07	1.80E-05
Emissions to water												
NH ₃ / NH ₄ ⁺	kg	5.58E-03	1.80E-02	1.91E-02	1.62E-05	1.16E-07	-1.60E-07	4.15E-09	1.19E-03	-	3.25E-09	4.39E-02
BOD	kg	5.91E-04	1.07E-03	2.02E-03	1.87E-06	1.55E-08	-1.62E-08	1.46E-08	1.03E-04	-	2.02E-07	3.79E-03
COD	Kg	4.25E-03	7.71E-03	2.84E-05	6.99E-05	3.05E-05	-2.07E-05	4.13E-06	3.57E-04	-	1.41E-05	1.24E-02
Nitrite	kg	5.48E-12	5.51E-11	8.29E-12	2.47E-10	3.26E-13	-3.98E-13	1.80E-14	2.34E-12	-	1.30E-13	3.18E-10