Building Transparency

openIMPACT Steel Documentation

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openIMPACT
Steel Documentation

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List of Acronyms

AEC	Architecture, Engineering, and Construction industry
BF	Blast furnace
BOF	Basic oxygen furnace
DRI	Direct reduced iron
EAF	Electric arc furnace
EPD	Environmental Product Declaration
ESC	Energy Solutions Center
GWP	Global Warming Potential impact category
LCI	Life cycle inventory
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
NETL	National Energy Technology Laboratory
USLCI	United States Life Cycle Inventory database

1 Introduction

1.1 Purpose of this document

The purpose of this document is to document methodology and data sources for the development of life cycle assessment models representing North American-specific steel construction products. The openIMPACT data are expected to be used by downstream carbon accounting software or users that need North American-specific environmental impact results for key building materials. Furthermore, this analysis acknowledges that the environmental impacts of construction materials can be highly variable due to upstream supply chains, technological variability, geographic variability, and mix design variability in the market. One significant advance of this modeling effort is that it includes analysis of supply chain variability, parameter variability, and their effect on Global Warming Potential (GWP). The steel model is developed in conjunction with the openIMPACT Monte Carlo Algorithm (MCA), documented separately, to address this variability and uncertainty.

1.2 Intended application

The primary goal of this study is to provide cradle-to-grave environmental impact results for use in design tools used by the Architecture, Engineering, and Construction (AEC) industry. The intended use may include early building design tools, so it is critical to provide ranges of impacts across the steel products on the market. Secondary use is the improvement of default uncertainty factors for steel products in the EC3 tool. This is not a comparative study. Any comparisons made in this study are only for results validation purposes.

2 Scope

2.1 Scope of analysis

This study aims to address all cradle-to-grave (A-C) life cycle stages[1]; however, given the nature of the products covered in this study, not all stages are expected to have significant effect on the overall GWP. Life cycle stages A5 and C1 are best addressed as part of a building-level analysis. Module D is outside of the scope of this study. The study focuses on understanding the variability in the GWP impact of the studied products; therefore, the data collection and modeling focuses on elements affecting primarily GWP. The functional unit of each product can differ and is further described in section 3.9, but generally includes 1 kg of steel product.

2.2 Data sources

The base LCA model used for this analysis and described in section 2.1 is based on the ecoinvent 3.5 database but is significantly modified to better represent individual production routes for different steel construction products. Background and ancillary data include ecoinvent, NETL, and USLCI datasets. Additional primary data used in this study include data from academic literature, manufacturer reports and direct communication, and Environmental Product Declarations (EPDs). There is no confidential information revealed in this report.

Note that the current analysis uses a limited set of datapoints which in some instances means it may not be fully representative of the market or may not provide a fully representative statistical distributions needed for a robust uncertainty analysis. Even though this is a limitation, the results are still expected to provide a useful insight into the potential variations in impacts across the industry. The analysis can be improved in the future when more data becomes available.

2.3 Geographical coverage

This study focuses on estimating the impacts of steel produced in North America. As such, any market data used in this study is representative of the North American region, and any upstream energy-related data and models are also representative of North America. However, the collection of data describing the variations in production technologies does use data from other regions in instances where there is a lack of North American data, and the technologies are deemed relevant in the North American context. Some background datasets used in this study may also be representative of other regions but are not expected to significantly impact the relevance of the GWP results based on the preliminary contribution analysis covered in section 2.2.

2.4 Impact assessment method

This study uses the TRACI 2.1 impact assessment method, as this is the most relevant LCIA method for North America [1]. Future iterations of this study may include results for other LCIA methods, such as CML or EF3.0. We do not anticipate material differences between results using different LCIA methods, since the GWP of steel is dominated by carbon dioxide emissions.

[1] Refer to ISO 21930:2017 for a full list and definitions of life cycle stages.

3 Model Overview

3.1 Cradle-to-gate (A1-A3) model description

Steel is produced either via the Basic Oxygen Furnace (BOF) or Electric Arc Furnace (EAF) routes. The main differences in these two steelmaking processes are the types of feedstock materials and the steelmaking process itself. The BOF route uses primarily virgin iron input from a Blast Furnace (BF) and the EAF route uses primarily scrap steel. EAFs also frequently source Direct Reduced Iron (DRI). Both manufacturing routes include casting, rolling, and sometimes additional forming, treatment, and fabrication processes after the main steelmaking process. Figure 1 shows a simplified overview the overall linkages between various processes as well as the intermediate and finished products in the cradle-to-gate model. GWP impacts from steel are primarily CO_2. The biggest contributors are generation of heat (using fuel or electricity) and direct emissions from carbon-based reduction of iron oxides to iron.

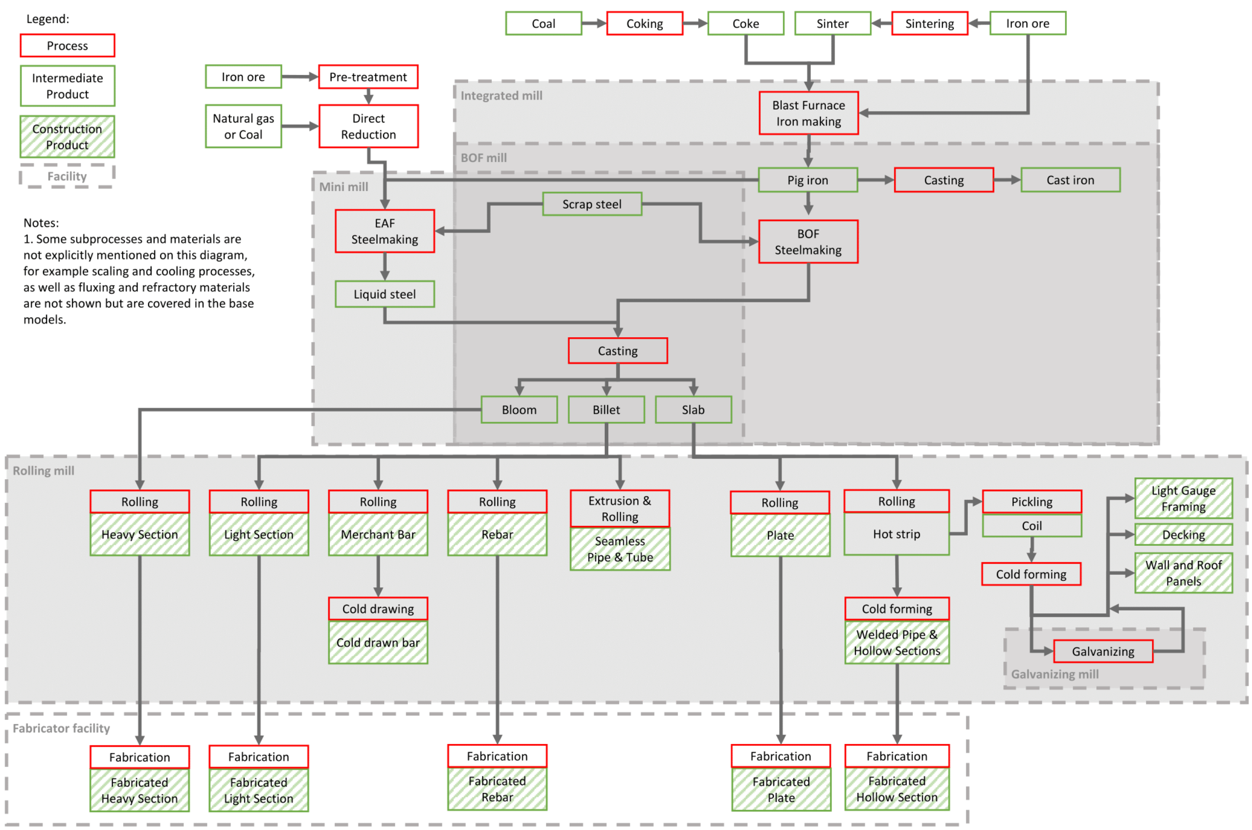


Figure 1. Simplified schematic of the main production routes for steel construction products.

3.1.1 Contribution Analysis

An initial contribution analysis of the Global Warming Potential (GWP) impacts across all possible steps of the steel production chain is shown in Figure 2. This analysis was done in the early stages of this study to understand which processes to focus on when gathering additional data. Note that this is not an example of GWP impact contributions for a specific product or a specific market (e.g., North American reinforcing steel), instead it shows the relative scale of the average impacts of each process in general. The chart shows the relative GWP contributions for 1 metric ton of a finished product across each step of the production chain independently. For example, a product typically does not go through manufacturing in an integrated mill (i.e., BF and BOF steps) and then fully remelted in an EAF mill in the same production cycle; instead, it may be manufactured entirely in an EAF mill as shown in Figure 3.

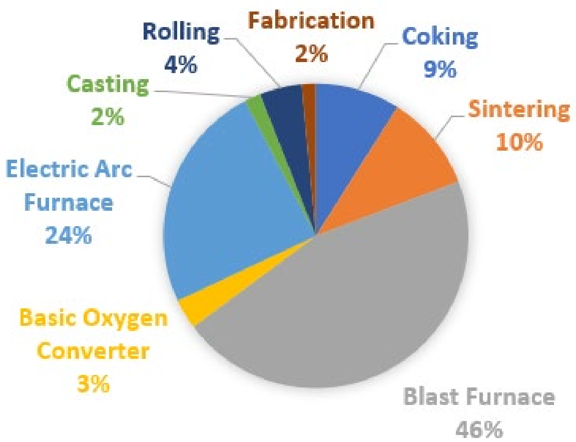


Figure 2. Relative comparison of average carbon intensity of processes in the production of steel construction products. (Based on percent of kgCO2e / ton of steel product.)

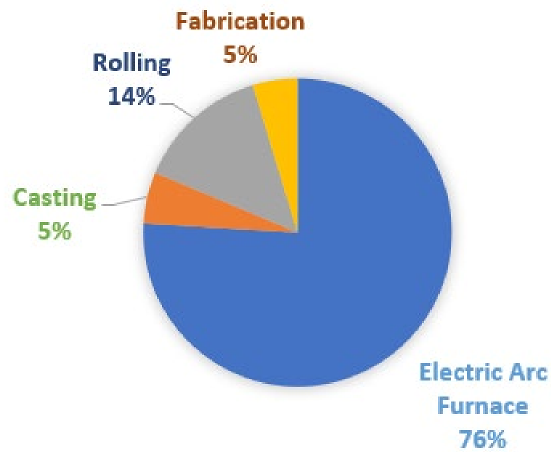


Figure 3. Relative comparison of average carbon intensity of processes in 100% recycled EAF steel. (Based on percent of kgCO2e / ton of steel product.)

3.2 Cradle-to-grave (A-C) model

While the overview of stages A1-A3 is covered in section 3.1, there are additional stages covered in the cradle-to-grave model. Stages related to transportation (A4 and C2) use similar approach – using transportation distance and mode by commodity type. Construction and installation stage (A5) is currently not included because 1) the related impacts are either better to be assessed on a building-level (e.g., crane usage to lift structural steel in place), rather than on a material-level, or 2) the products are mostly installed by hand, like laying of metal deck and framing with steel studs. Similarly, demolition (C1) of steel structural and non-structural elements is best addressed on a building-level and is therefore not covered in this study. Waste processing (C3) and disposal (C4) have relatively low impacts associated only with the use of sorting and landfill machinery.

4 Model Details

4.1 Cradle-to-gate (A1-A3)

4.1.1 Coking and sintering

Coke is coal that has been separately baked to remove volatile components. The coking process generates coke oven gas (COG) which can be utilized for heating at a steel plant or for power generation.

The iron and steel industry uses primarily coal-based metallurgical coke. Petcoke (also known as petroleum coke) can also be used as a feedstock in the ironmaking process; however, the industry typically uses only low-sulphur petcoke with a blending limit of 15 percent [2].

Sinter is a secondary metallic material that has been heat treated to improve the integrity of a given material. A sintering plant typically processes iron oxide scales, pellet fines, blast furnace dust and slag fines from a previous ironmaking process. The resulting sinter is then fed back into the blast furnace.

The variation in direct emissions and energy usage across coking and sintering plants has been assessed based on two literature sources [3,4] and based on ranges estimated by the Energy Solutions Center [5]. Literature data includes analysis of four integrated BF-BOF mills in China and Germany as there were no similar studies available for US-based integrated mills. The technology is expected to be relatively similar to North American BF-BOF mills. Summary of the data from the three sources is included together with BF and BOF data in Tables 1 and 2. Note that the reported mean is simply the average across all values reported by the three sources (total of five data points for each process) and does not necessarily represent the true mean across the industry.

The coking process is simulated by sampling coal and electricity providers according to the regional options available in the NETL database [6]. Coal generation statistics for the various regions weren't available, therefore the MCA assumes equal probability of coal coming from any of the listed providers (see the coal provider sheet). Electricity providers are sampled according to the national generation statistics for all regions (see the electricity provider sheet).

Table 1. Direct CO_2 emissions ranges from processes related to BOF steel.

	GWP ($kgCO_2e$/t of steel)		
Process	Min	Mean	Max
Coking	129	196	232
Sintering	200	265	463
Blast furnace iron making	723	928	1,093
Basic oxygen furnace steelmaking	24	70	148

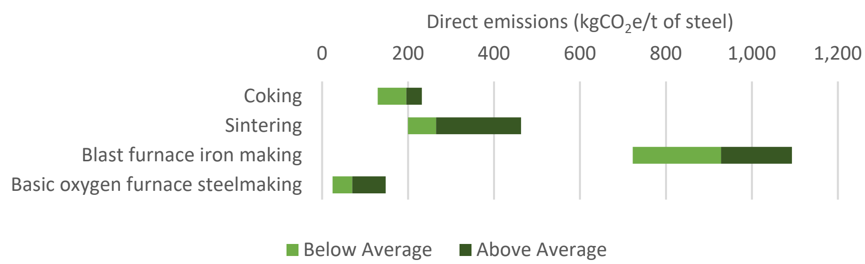
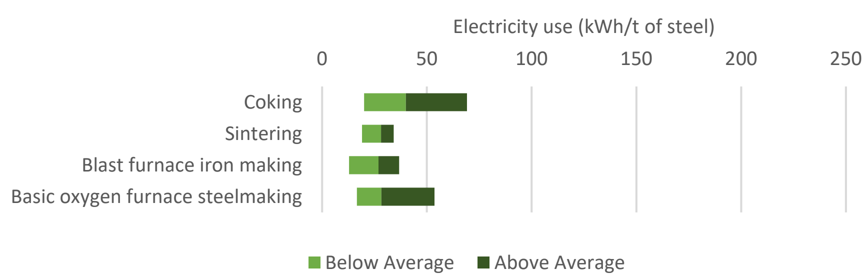


Table 2. Electricity use ranges across processes in the BOF steel route.

	Electricity use (kWh/t of steel)		
Process	Min	Mean	Max
Coking	20	40	69
Sintering	19	28	34
Blast furnace iron making	13	27	37
Basic oxygen furnace steelmaking	17	28	54



4.1.2 Blast furnace

A blast furnace (BF) is loaded with sinter, iron ores and coke. Preheated air at 900°C is blown through the mixture, which turns carbon into carbon monoxide according to the following equation:

$2\,C + O_2 \rightarrow 2\,CO$

The following redox reaction of iron and carbon monoxide, which happens at a temperature of about 2000°C, then produces metallic iron and carbon dioxide according to the following equation:

$Fe_2O_3 + 3\,CO \rightarrow 2\,Fe + 3\,CO_2$

This reaction means that for a 1 ton of iron there are emissions of 1,179 kgCO_2 during the chemical process itself. Some iron in the high-temperature lower region of the furnace also reacts directly with the coke, as follows:

$$2\ Fe_2O_3 + 3\ C \rightarrow 4\ Fe + 3\ CO_2$$

The full composition of blast furnace gas (BFG) includes N_2, CO, CO_2, H_2O, and H_2 [7]. The BFG can be used as a heat source in furnace mills, gas engines, and for electricity and steam generation, improving the overall efficiency of the system from an emission and energy use perspective. This also means that the direct CO_2 emissions from the processes are sometimes allocated to the co-products, reducing the amount of direct CO_2 emissions attributed to the steel products. Fluxing materials such as limestone (calcium carbonate) or dolomite (calcium-magnesium carbonate) are added to each load to remove siliceous minerals in the ore. Carbonates present in the load turn into calcium oxide when under high heat, which reacts with any excess silica to form slag and other products. Slag is another co-product that can be used as a material in road construction, concrete mixes, or agricultural soil enhancement. Overall, the combination of direct emissions and allocation to co-products have been found to result in BF emissions attributed to produced steel ranging in 723 – 1,093 kgCO_2e per kg, as shown in Table 1.

Similarly, as in the coking process, the BF process is simulated by sampling coal and natural gas providers according to the regional options available in the NETL database. Inputs of coal assumes equal probability of coal coming from any of the listed providers (see the coal provider sheet), while natural gas providers are sampled according to the national generation statistics for all regions (see the natural gas provider sheet) [8].

4.1.3 Basic oxygen furnace

Basic oxygen furnace (BOF, also known as basic oxygen converter, BOC) is the integral to the primary steelmaking process with carbon-rich molten pig iron. The overall direct emissions associated with steel products made using the BOF route at various facilities range according to Table 1. There are minimal inputs of electricity in the BOF route, as shown in Table 2. Most of the processes are coal-based and result in direct emissions to air. The shown data reflects emissions and electricity use across plants with different equipment and operational set up. Note that our analysis captures the potential variabilities independently and does not capture the interdependencies in the BF-BOF system in this particular case. This likely overestimates the variability in overall impacts across the BF-BOF system.

Varying providers of electricity, natural gas, and iron are substituted in the BF process using the MCA. Electricity and natural gas providers represent regional options available in the NETL database and are sampled according to their generation statistics (see the electricity and natural gas provider sheets). The provider selected for each iteration of the MCA are recorded in the raw results files (see example results file for hollow sections). Input of iron is assumed to come from BF in all scenarios. According to Zhu et al. [9] there is a small amount of DRI that gets used in BOFs, but this is currently not captured in this steel model.

4.1.3.1 Scrap steel input

The feed into a basic oxygen furnace can consist of up to about 30% steel scrap, according to direct communication with a steel producer. The current model uses a normal distribution with mean of 15% and a standard deviation of 5% to capture the potential variations. The amount of scrap metal and primary iron input are set up as dependent parameters in this model. Scrap metal input is assumed to be burden-free, since all production and transportation impacts would have been accounted for in the previous product's life cycle.

4.1.4 Direct reduced iron

According to Worldsteel's 2017 statistics, about 17% of input into the electric arc furnaces (EAFs) globally were in the form of direct reduced iron (DRI), 11% pig iron, and 72% scrap steel [10]. Overall, DRI accounted for about 8% of global iron production in 2019, with the largest DRI producing countries being India and Iran which produced 34% and 27% of global DRI, respectively. In North America, Canada, and United States, and Mexico produced about 18%, 14%, and 61% of domestic iron using DRI technologies, respectively [11]. The DRI process can produce three different types of direct reduced iron products: cold DRI (CDRI), hot DRI (HDRI), and hot briquetted iron (HBI) [12].

Direct reduction of iron is the removal of oxygen from iron ore or other iron-bearing materials in the solid-state, i.e., without melting the ore. The primarily reducing agent used in the current market is carbon monoxide coming from natural gas, syngas, or coal. The following chemical reactions describe the direct reduction of iron with carbon monoxide:

$3\ Fe_2O_3 + CO \rightarrow 2\ Fe_3O_4 + CO$

$Fe_3O_4 + CO \rightarrow 3\ FeO + CO_2$

$FeO + CO \rightarrow Fe + CO_2$

Hydrogen can also be used as an alternative reducing agent, as shown in the chemical reactions below, and is expected to be a lower-carbon solution to future DRI production; however, it currently represents only a fraction of the global DRI market due to technical and economic limitations [13]. While there are no direct greenhouse gas emissions from the hydrogen-based DRI reactions, there can be greenhouse gas emissions associated with the production of hydrogen, which currently often uses natural gas or coal.

$3\ Fe_2O_3 + H_2 \rightarrow 2\ Fe_3O_4 + H_2O$

$Fe_3O_4 + H2 \rightarrow 3\ FeO + H_2O$

$FeO + H_2 \rightarrow Fe + H_2O$

Globally, DRI is produced using the processes listed in Table 3 [12]. The table also shows the type of reducing agent each process uses. The processes for this analysis are grouped generally into coal-based and gas-based processes and are further described in the following sections.

Table 3. Global DRI production by process type.

Process	Production (Mt)	Production (%)	Reducing Agent
MIDREX	65.4	60.5%	Gas
HYL / ENERGIRON	14.3	13.2%	Gas
PERED	2.3	2.1%	Gas
Other	0.2	0.2%	
Rotary Kiln	25.9	24.0%	Coal
Total	108.1		

Mt = megaton or 10^6 t

The United States imports most of its DRI from the countries shown in Table 4, with over 76% coming from Trinidad and Tobago. Data in Table 4 is for 2014 and includes steelmaking-grade DRI only.

Table 4. US imports of DRI by country of origin.

Country	Quantity (Metric tons)	Value (Thousands USD)	Quantity (% by mass)
Brazil	129,000	50,000	5.4%
Canada	84,700	26,000	3.5%
Russia	204,000	75,000	8.5%
South Africa	10,000	3,200	0.4%
Trinidad and Tobago	1,840,000	658,000	76.9%
Ukraine	35,000	13,100	1.5%
Venezuela	90,300	28,000	3.8%
Total	2,390,000	854,000	

4.1.4.1 Coal reduction
Coal-based direct reduction uses a kiln furnace. This type of DRI production is used mainly in India and accounted for 24% of global DRI in 2019, 79% of India's iron production [14]. Since this form of direct reduction is not used in the US, it is excluded from the current study. This section will be expanded during the development of a global steel model.

4.1.4.2 Natural gas reduction
The MIDREX process can use reducing gas from natural gas, but also coke oven gas and other reducing gases derived from PET coke or from bottom oil generated in oil refineries [15]. Both the MIDREX and ENERGIRON processes include a scrubber and CO_2 removal [15–17]. This means that some natural gas-based direct reduction mills may not emit all of the produced CO_2 into the atmosphere.

In-situ reforming of natural gas for the ENERGIRON process includes the two following formulas, one of which also uses CO_2 generated during the reduction process. The two processes have roughly equivalent GWP intensity, generating one net CO2 per four oxygen atoms removed.

$CH_4 + H_2O \rightarrow CO + 3H_2$ (Steam reforming)

$CH_4 + CO_2 \rightarrow 2CO + 2H_2$ (Dry reforming)

The openIMPACT LCA model uses a simplified approach to cover US-based DRI. We created two models to represent the MIDREX and ENERGIRON processes and the main input and output components contributing to the majority of the processes' GWP. The models include high-level information on the inputs of natural gas, electricity, and iron ore and direct greenhouse gas emissions from each process [16,17]. The models do not address substances that may contribute to other environmental impacts at this time but could be improved in the future.

DRI on the US market is produced primarily using the MIDREX or ENERGIRON processes. The current openIMPACT model assumes similar distribution across MIDREX and ENERGIRON as the global market ratios shown in Table 3, which amounts to about 82% and 18% split between MIDREX and ENERGIRON, respectively. There is more granular data on direct reduction facilities available in MIDREX's annual reports that can be used to improve future iterations of the openIMPACT steel model.

4.1.4.3 Hydrogen reduction
Use of pure hydrogen as the reducing gas is a relatively new production option and one that does not cover a significant portion of the US market. One such process is HYBRIT, currently used at a pilot scale in Sweden. Since our initial effort focuses on covering the current market, this process is not included in our model but can be added in the future.

4.1.5 Electric arc furnace

Electric arc furnaces (EAF) produce steel by melting steel scrap and iron feedstocks using electricity. EAF feedstock can consist of up to 100% scrap steel, which means there is no need for primary iron input and potential for eliminating all related impacts; however, there are supply limitations in the amount of available scrap steel and the significant electricity input requirements can cause problems to power transmission and generation infrastructure [13].

4.1.5.1 Electricity consumption
Tables 5 and 6 show the summary of potential ranges of values for electricity consumption in an EAF mill. The values include consumption by all processes within the EAF facility, with the exception of casting and rolling, which are modeled separately (see section 4.1.6). Data sources included ecoinvent versions 2.1, 3.5, and 3.7, USLCI and Athena, Energy Solutions Center, and the U.S. Department of Energy's Industrial Technologies Program [5,18,19]. Table 5 shows the ranges of electricity demands reported by each source, and Table 6 shows the summary statistics of the 18 data points extracted from the listed sources.

Table 5. Electric arc furnace (EAF) electricity consumption ranges according to various sources.

Source	Year	Description	Electricity (kWh/t of steel)
ecoinvent	2000-2020	9 datapoints across North America, Europe, and Asia.	424 - 788
USLCI/Athena	2002	Based on data from a Canadian reference EAF plant.	880
Energy Solutions Center	n.d.	4 datapoints for very low, low, average, and high values.	350 - 700
Duarte et al.	2008	General range based on DRI-EAF production scenario.	375 - 590
ITP (AISI 1998)	1998	Production of an average hot-rolled coil in the US.	1348

Table 6. Summary statistics of electric arc furnace (EAF) electricity consumption data.

Parameter	Value (kWh/t of steel)
Maximum	1348
80th percentile	770
50th percentile	475
20th percentile	424
Minimum	350

There are various process integrations that can affect the electricity requirements for EAFs, for example, direct feed of hot DRI into an EAF can reduce the EAF's electricity consumption [16]. While these direct effects of the system as a whole are not explicitly modeled, they are captured in the general range of operating requirements of EAFs. Because the collected data does not necessarily use consistent methodology, it includes older data, and data from regions outside of North America – the current openIMPACT model instead uses a rough estimate on the variation in EAF electricity reported by the Energy Solutions Center (ESC). The ESC values are rounded to the nearest tenth kWh/kg of hot metal. The openIMPACT model uses a triangular distribution with 0.4, 0.5, and 0.7 kWh/kg representing the minimum, mode, and maximum values in the distribution.

4.1.5.2 Scrap steel input

EAF mills technically do not have a limit on the ratio of scrap steel used in each charge; however, they are often limited by the chemistry needs of each charge. Flat products usually have tighter metallurgical requirements and use higher ratios of primary iron than long products[2]. Nucor provides a list of recycled content rates for its products across multiple product types and facilities [21]. A summary of the low and high estimates of the average recycled content for each product type reported for the year 2019 is shown in Table 7 and is used as the basis for controlling the recycled content for EAF-based steel. Nucor does not provide recycled content data for hollow structural sections and no other specific data sources were available. The current model uses a rough range of 90-100% recycled content mentioned by AISC for hollow sections produced via the EAF route [22].

Table 7. Summary of recycling rates for various steel product types.

Product Group	Minimum Recycled Content	Maximum Recycled Content	Average Recycled Content	Source
Nucor Bar Products	96%	98%	97%	Nucor
Nucor Engineered Bar Products	77%	92%	86%	Nucor
Nucor Beam Products	42%	92%	80%	Nucor
Nucor Plate Products	54%	90%	61%	Nucor
Nucor Sheet Products	44%	92%	56%	Nucor
AISC Hollow Sections	90%	100%	95%	AISC

[2] The International Trade Administration (ITA) categorizes bar, rebar, wire, rope, rails, sections, billet, blooms, and bridge sections as long products, and slab, plate, strip, coil, and tinplate as flat products. Seamless tube and welded tube are considered a separate category from both steel product groups [20].

The current openIMPACT model uses triangular distributions with the minimum, average, and maximum values from Table 7 in place of minimum, mode, and maximum parameters, respectively. It is understood that this translation of values is not fully equivalent, but it is assumed to provide an adequate estimation of likely variations within the market in the absence of more robust data.

4.1.5.3 Input provider substitutions

Varying providers of electricity, natural-gas-based heat, and iron are substituted in the EAF process using the MCA. Electricity provider sampling reflects regional options available in the NETL database and sampled according to their generation statistics (see the electricity provider sheets). Providers of virgin iron are either BF or DRI (based on analysis by Zhu et al. [9]) and DRI is further divided into MIDREX or ENERGIRON based on the 82% and 18% split described in section 4.1.4.2 (see iron for EAF provider sheet). The provider selected for each iteration of the MCA are recorded in the raw results files (see example results file for hollow sections).

4.1.6 Casting & rolling

Table 8 shows casting and rolling data from the Energy Solutions Center [5]. Data was also compared to ecoinvent models and casting and rolling described in Xu et al. [3] and Backes et al. [4]. The ESC data was considered the best data source. The openIMPACT model currently uses uniform distributions with minimum and maximum values as listed in Table 8. The model currently does not capture the dependence of electricity input versus natural gas or heat input for reheat of billets, but the current simplification is assumed to be sufficient in the absence of better data.

Table 8. Ranges of electricity consumptions for casting and rolling.

Operating unit	Product	kWh of electricity per metric ton of product
Continuous casting	Slab / billet	28 - 44
Blooming mill	Blooms	33 - 44
Slabbing mill	Slabs	35 - 50
Reversing plate mill	Plates	110 - 132
Bar mill	Bars	132 - 165
Hot-strip mill	Sheet / Strip	121 - 143
Cold-reduction mill	Sheet / Strip	127 - 149

4.1.6.1 Input provider substitutions

Varying providers of electricity, natural-gas-based heat, and steel input are substituted in the casting and rolling process using the MCA. Electricity provider sampling reflects regional options available in the NETL database and sampled according to their generation statistics (see the electricity provider sheets). Steel inputs have varying ratios between the BOF and EAF route according to Zhu et al. [9] depending on the rolled product being a slab, billet, or bloom (see Figure 1 for links to end-products).

4.1.7 Galvanization

Galvanization is calculated based on the area covered by the galvanization coating. The amount of galvanizing can differ significantly based on the shape of the final product. The range of zinc input is determined using specific products as a sample for the calculation. Standard thicknesses for hot-dip galvanized coatings are G140, G90, and G60, which amounts to 1.40 oz/ft^2, 0.9 oz/ft^2, and 0.6 oz/ft^2 total weight of galvanizing per both sides of a galvanized strip, respectively [23]. The most common is G60, while G90 is most often used on products used for exterior applications.

Some zinc is recovered from the smelting of scrap steel and is therefore provided burden-free, since all steelmaking impacts are allocated to the intended primary product, steel. Approximately 70% of the zinc produced in the US originates from mined ores and 30% consists of recycled zinc [24]. According to USGS, approximately 87% of US zinc was imported, primarily from Canada, Mexico, Australia, and Peru [25]. Upstream data for zinc production currently uses ecoinvent 3.5 data point for global zinc production.

Energy input for continuous galvanizing is currently assumed to be fully electric and uses data collected for eight galvanizing lines by Bhadra et al. [26]. The average energy requirement is about 0.343 kWh/t of galvanized steel sheet product. Future improvements can account for varying inputs of electricity versus natural gas and efficiencies of individual equipment as described in Chavan et al. [27].

4.1.8 Fabrication

Table 9 shows the typical GWP due to fabrication reported across EPDs for rebar, plate, merchant bar, and structural shapes. Fabrication does not apply to sheet steel products, such as light gauge framing studs, and decking. Some EPDs use an industry-average value of 116 $kgCO_2e$/t of steel product, as defined by AISC. This is also the value used for fabrication of all product types in the openIMPACT model. EPDs typically do not provide enough information about the sources of the fabrication-related GWP impacts to be able to attribute them to a specific type of energy source or activity. Instead, we use the overall reported GWP values as a source of variation attributable to the fabrication facility.

Table 9. Range of fabrication global warming potential values reported in EPDs.

	$kgCO_2e$ / t of steel			
Products	**Minimum**	**Average**	**Maximum**	**Samples**
Rebar	4	27	112	7
Plate	97	97	97	1
Merchant bar	116	116	116	1
Heavy shapes	96	108	116	6

4.1.9 Finished products

This study covers the following finished steel products:

- Heavy sections – structural steel rolled from blooms mostly into wide flange or other large shapes
- Hollow sections – structural steel rolled from a slab and shaped into a hollow section
- Plate – structural steel rolled from a slab and fabricated into various shapes or used as a flat product
- Rebar – specifically carbon steel rebar, as this is the most commonly used reinforcing product. The current model does not cover epoxy-coated, galvanized, stainless steel, and glass-fiber-reinforced-polymer rebars.
- Galvanized steel sheet – used as light gauge steel studs and metal decking

4.1.9.1 Production routes

Regional trends for manufacturing of finished products in the steel sector are broadly defined by the ratio of products coming from each production route (via BOF or EAF mills), ratio of recycled scrap used during steelmaking, different rolling requirements, and need for galvanization or other type of finishing. Long products[3] in North America come primarily from the EAF steelmaking route, as the requirements for precise control of the steel chemistry is lower than for flat products, which come primarily from BOF mills. The following is an overview of the production routes and steps relevant to each product type:

- Heavy sections – EAF with DRI and BF iron and high recycled content, hot-rolled and fabricated.
- Hollow sections – both EAF and BOF routes with recycled content highly dependent on which route. Rolled, cold-formed, and fabricated.
- Plate – both EAF and BOF route with recycled content highly dependent on which route. Rolled, fabricated.
- Rebar – EAF with DRI and BF iron and high recycled content. Hot-rolled and fabricated.

[3] The International Trade Administration (ITA) categorizes bar, rebar, wire, rope, rails, sections, billet, blooms, and bridge sections as long products, and slab, plate, strip, coil, and tinplate as flat products. Seamless tube and welded tube are considered a separate category from both steel product groups [20].

- Galvanized steel sheet – both EAF and BOF route with relatively lower recycled content due to chemistry requirements. Rolled, galvanized, and cold-formed.

4.1.9.2 Market shares

Market shares of products from specific production routes are based on research published by Zhu et al [9] and correspond to the rolled intermediate steel products described in Figure 1.

4.1.9.3 Functional units

- Heavy sections – 1 kg of section used as a structural member over a 60-year building lifetime
- Hollow sections – 1 kg of section used as a structural member over a 60-year building lifetime
- Plate – 1 kg of plate used as a structural member over a 60-year building lifetime
- Rebar – 1 kg of rebar used as reinforcement in concrete structural elements over a 60-year building lifetime
- Galvanized steel sheet – 1 kg of galvanized sheet of various thicknesses used as floor or roof decking over a 60-year building lifetime

4.2 Transportation to and from building site (A4 & C2)

4.2.1 Distances by mode

The following calculations cover the transportation from the producer to the building site (A4) and from the building site to a processing or disposal facility (C2). Transportation distances are based on data from the United States Commodity Flow Survey [28] for the best representative commodity flow group (see Commodity Description in Table 10). Analysis of the Commodity Flow Survey data indicated that truck transport is the most common transport mode for iron and steel products within the United States, although it is understood that there may be other ways iron steel products are being transported. The current approach of using only truck as the mode of transport is expected to be a conservative estimate, as this is the mode with the highest per t-km (i.e., 1 metric ton transported 1 km distance) impacts when compared to other freight transportation modes. Future assessments can account for distribution by distance and mode.

4.2.2 Impacts by mode

The source of transportation impact data is USLCI [29]. The preliminary results are based on the average impact across all USLCI datapoints for short-haul and long-haul single unit trucks (full list in Appendix A). Future assessments can account for varying impacts across modes and within modes.

Table 10. Transportation distance and impact data for steel products.

Product	Commodity Description [a]	Average shipment distance (km) [a]	Average mode	Average mode carbon intensity (kgCO2e/tkm) [b]	Average carbon intensity per shipment (kgCO2e/kg)
Stage A4					
Heavy sections	Bars, rods, angles, shapes, sections, and wire, of iron or steel	440	Truck	0.36	0.16
Hollow sections	Pipes, tubes, and fittings	398	Truck	0.36	0.14
Plate	Flat-rolled products of iron or steel	422	Truck	0.36	0.15
Rebar	Bars, rods, angles, shapes, sections, and wire, of iron or steel	440	Truck	0.36	0.16
Galvanized sheet	Flat-rolled products of iron or steel	422	Truck	0.36	0.15
Stage C2					
All products	Metallic waste and scrap	242	Truck	0.36	0.09

[a] Source: Commodity Flow Survey [28]
[b] Source: USLCI [29]

4.3 Use phase (B)

Steel products typically do not release additional greenhouse gasses into the atmosphere during their use phase (B1). Structural steel products like sections, rebar, and plate as well as sheet products like decking and studs are expected to last the lifetime of a building, resulting in no replacement stage (B4) impacts [30]. They also typically do not require any extensive maintenance (B2). There can be impacts from repair (B3) due to damage from natural hazards; however, these are low-probability, high-impact events dependent on the structural design of a building, are difficult to assess on a material-level, and are therefore not covered in this study. Refurbishment (B5) is also not relevant to steel products covered in this study.

4.4 Building demolition (C1)

This phase is best addressed on a building-level and is not covered in this study.

4.5 End-of-life processing (C3) and landfilling (C4)

According to the EPA's WARM study, structural steel has two main end-of-life scenarios: 1) recycling and 2) landfilling. The recycling rate of metals in the United States as part of the municipal solid waste (MSW) stream is only about 33%, however, construction and demolition (C&D) metals recycling rate is about 87% [31].

The emissions associated with recycling path are related to collection of the scrap steel, and the transportation to a structural steel manufacturer. The recycling of steel consists of remelting the scrap steel directly in a BOF or EAF process, and therefore there are no additional processing impacts modeled in the C3 stage of this study.

The emissions associated with landfilling are related to the transportation to landfill (covered under stage C2) and the use of landfilling machinery (stage C3 and C4). There are no direct greenhouse gas emissions to air from landfilling steel. The recycling of steel consists of remelting the scrap steel directly in a BOF or EAF process, and therefore there are no C3 processing impacts modeled in this study. Landfilling scenario is used to in the A-C results as a measure of conservative estimate of potential impacts.

There are source reduction benefits associated with recycling steel, i.e., recycled steel displaces steel that would be otherwise made from virgin material. Any source reduction benefits can be claimed under module D according to ISO 21930:2017 and EN15804:2012 [32,33], but module D is outside of the scope of this study.

5 Results & Discussion

5.1 Cradle-to-grave (A-C) results

Figure 4 shows that the average cradle-to-gate impacts account for about 79 – 88% of the average cradle-to-grave impacts of steel construction products. Even though construction and demolition impacts were not rigorously covered in this study, other studies have suggested that the GWP contributions from those stages are relatively small [34–37], likely not significantly changing the overall life cycle impacts of steel products.

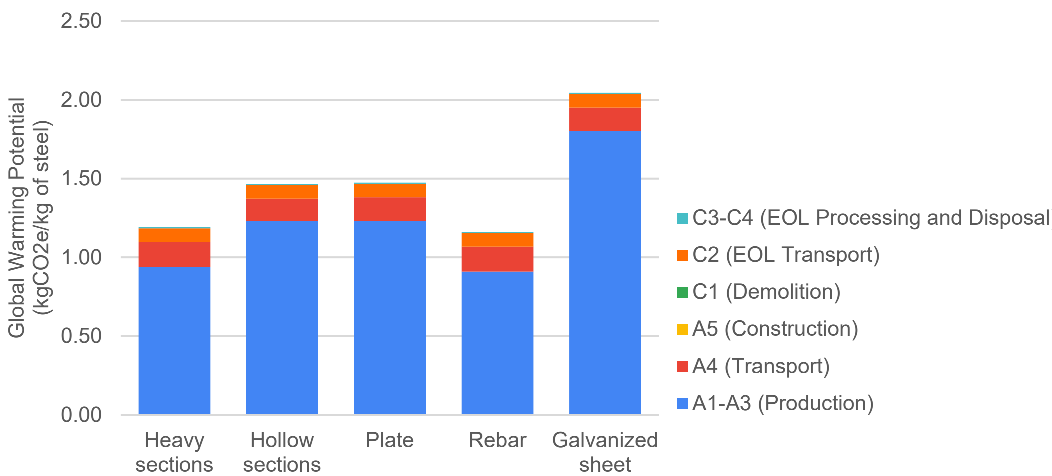


Figure 4. Cradle-to-grave impacts of steel products.

5.2 Cradle-to-gate (A1-A3) results

The current steel model has been used to estimate the range of GWP impact for steel construction products manufactured in the US. In order to validate the model and the parameters that define the production route of various steel products, this study compares the openIMPACT results to GWP reported on EPDs of similar products. Note that some of the listed EPDs may not fully align with the boundary of the openIMPACT model, and such exceptions are noted in each subsection. In cases with less than 10 North American GWP results from product EPDs, results were also compared to global EPDs.

5.2.1 Heavy sections

- openIMPACT median is right between industry and product EPD medians.
- Product EPDs are not market weighted so the 25th and 75th percentiles may not reflect the true market range.
- openIMPACT estimates are partly weighted based on an assumption that mills can be located anywhere in the US, which likely overestimates the potential range of values due to varying electricity and natural gas suppliers. However, it also seems to potentially underestimate the influence of other factors as seen by the variations in product EPDs.

Table 11. Summary results for steel, heavy section, fabricated, A1-A3.

			GWP (kgCO$_2$e/kg of steel)		
Region	**Source**	**Samples**	**25th percentile**	**median**	**75th percentile**
North America	openIMPACT	1350	0.94	1.07	1.20
	Product EPDs	60	0.73	1.00	1.23
	Industry EPDs	3	1.16	1.19	1.22

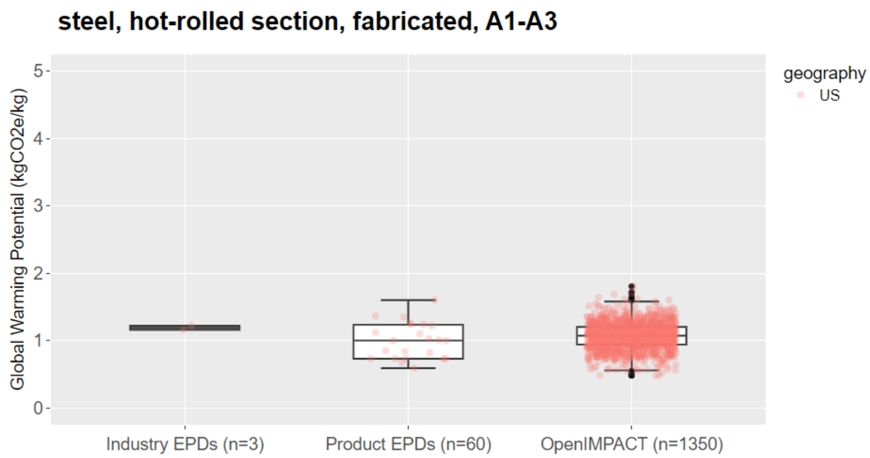


Figure 5. Comparison boxplot for steel, heavy section, fabricated, A1-A3.

5.2.2 Hollow sections

- Industry EPDs are significantly higher than product EPDs, suggesting that only low-carbon producers are sharing data via product EPDs.
- openIMPACT estimates show the distinct differences in the EAF vs BOF routes but seem to underestimate the overall industry-wide impacts when compared to the industry EPDs.
- The three industry EPDs represent galvanized, fabricated, and unfabricated products. This is not perfectly aligned with the products represented in the openIMPACT results, which are ungalvanized but fabricated sections.
- The fabricated Industry EPD data points represent North American fabrication, but may include upstream steel mill products produced outside of North America, likely explaining the higher GWP when compared to openIMPACT results which currently only capture North American steelmaking and fabrication.

Table 12. Summary results for steel, plate, fabricated, A1-A3.

			GWP ($kgCO_2e$/kg of steel)		
Region	**Source**	**Samples**	**25th percentile**	**median**	**75th percentile**
North America	openIMPACT	500	1.23	1.84	2.15
	Product EPDs	9	1.27	1.44	1.64
	Industry EPDs	3	2.18	2.39	2.61
Global	Product EPDs	29	1.18	1.64	2.73
	Industry EPDs	3	2.18	2.39	2.61

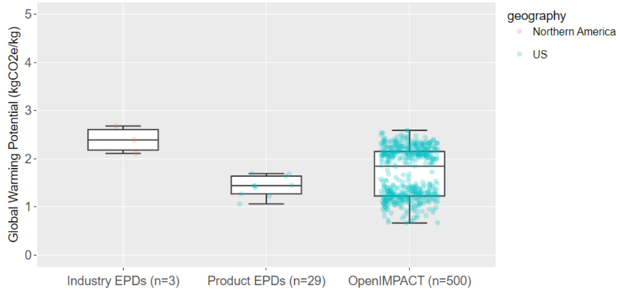


Figure 6. Comparison boxplot for steel, hollow section, fabricated, A1-A3, North American region.

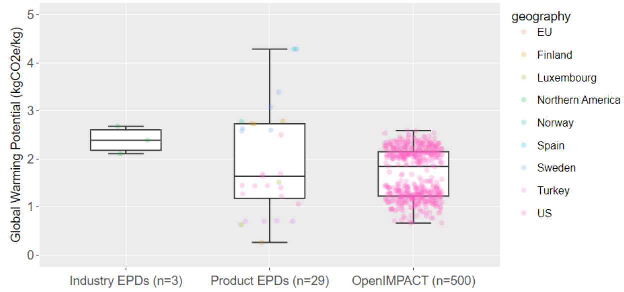


Figure 7. Comparison boxplot for steel, hollow section, fabricated, A1-A3, all regions.

5.2.3 Plate

- openIMPACT median aligns well with the Nort American industry EPDs, but the North American product EPDs fall in the lower range of the openIMPACT results (between the 50th and 25th percentile of the openIMPACT results, see Figure 8).
- Most US mills are located in the easter part of the US which generally has higher GWP-intensity electricity grid. The openIMPACT results currently assume the mills can be anywhere in the US which likely explains the wider lower tail of the openIMPACT results when compared to the industry and product EPDs.
- Global product EPDs shown in Figure 9 appear to have higher GWP than North American EPDs and fall along the upper range of openIMPACT results.
- One global product EPD has higher GWP than the worst-case openIMPACT scenario, indicating that the openIMPACT model potentially underestimates the highest possible impact of BF-BOF route, which already uses some global data as described in sections 4.1.2 and 4.1.3.

Table 13. Summary results for steel, plate, fabricated, A1-A3.

			GWP (kgCO_2e/kg of steel)		
Region	**Source**	**Samples**	**25th percentile**	**median**	**75th percentile**
North America	openIMPACT	1500	1.23	1.78	1.96
	Product EPDs	5	1.35	1.49	1.56
	Industry EPDs	3	1.54	1.73	1.77
Global	Product EPDs	11	1.50	1.89	2.44
	Industry EPDs	4	1.60	1.73	1.77

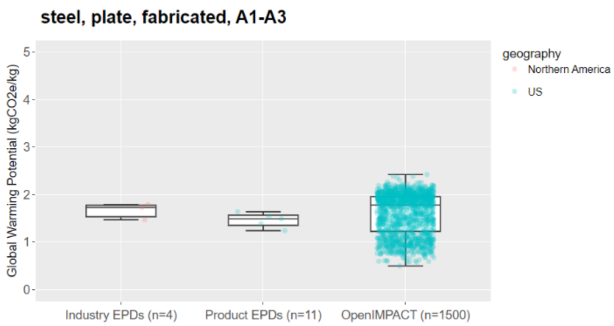


Figure 8. Comparison boxplot for steel, plate, fabricated, A1-A3, North American region only.

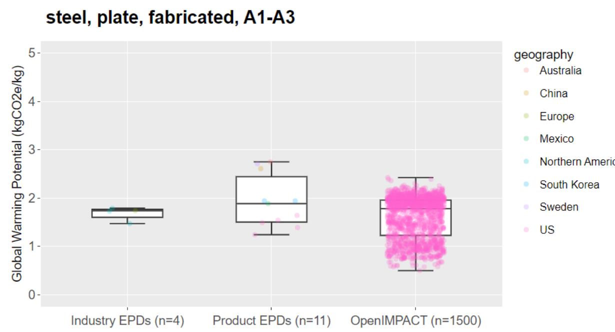


Figure 9. Comparison boxplot for steel, plate, fabricated, A1-A3, all regions.

5.2.4 Rebar

- The industry EPD and openIMPACT median results align well, but the product EPD values are skewed towards the lower end of openIMPACT results and well below the industry average. This suggests that only lower-GWP rebar producers are disclosing data via product EPDs.
- Some of the product EPDs included in the comparison include mill-level (i.e., unfabricated) products, which will have inherently lower values than fabricated products and may be one of the reasons for the skewed product EPD statistics.

Table 14. Summary results for steel, rebar, fabricated, A1-A3.

			GWP (kgCO$_2$e/kg of steel)		
Region	**Source**	**Samples**	**25th percentile**	**median**	**75th percentile**
North America	openIMPACT	1830	0.91	1.02	1.14
	Product EPDs	72	0.69	0.79	0.96
	Industry EPDs	1		0.98	

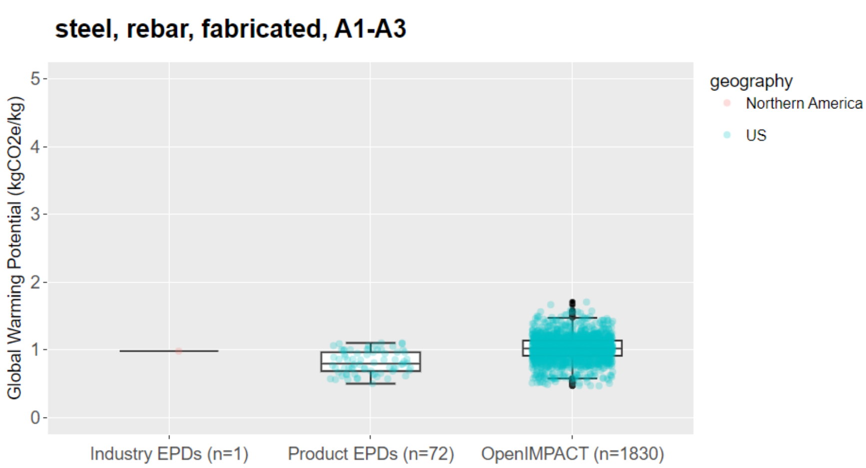


Figure 10. Comparison boxplot for steel, rebar, fabricated, A1-A3.

5.2.5 Sheet, cold-formed, galvanized

- EPDs usually report a single result for a reference thickness of steel and galvanization while the openIMPACT model includes variations in typical gauges and galvanization thicknesses for light gauge studs and metal decking.

Table 15. Summary results for steel, sheet, galvanized, A1-A3.

			GWP ($kgCO_2e$/kg of steel)		
Region	**Source**	**Samples**	**25th percentile**	**median**	**75th percentile**
North America	openIMPACT	1500	1.80	2.21	2.40
	Product EPDs	13	2.20	2.39	2.50
	Industry EPDs	2	2.28	2.33	2.37

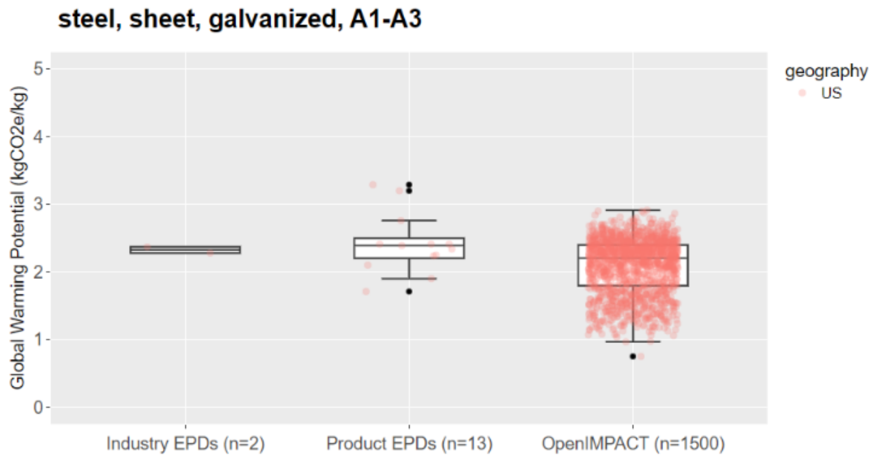


Figure 11. Comparison boxplot for steel, sheet, galvanized, A1-A3.

All comparison boxplot figures shown in this section are also available in an interactive HTML format on buildingtransparency.org.

6 Future Work

6.1 Facility locations and capacities

Electricity and natural gas providers are currently sampled using national generation statistics. While this can work well enough for products that are produced in similar amounts across the country, this approach is flawed for products with manufacturing facilities concentrated in certain parts of the country. Steel mills are largely concentrated in the eastern half of the US, as shown in Figure 12. Using steel fabricator and mill locations together with capacities or annual production volumes for market weighing can paint a more accurate picture of the true range of impacts of North American steel.

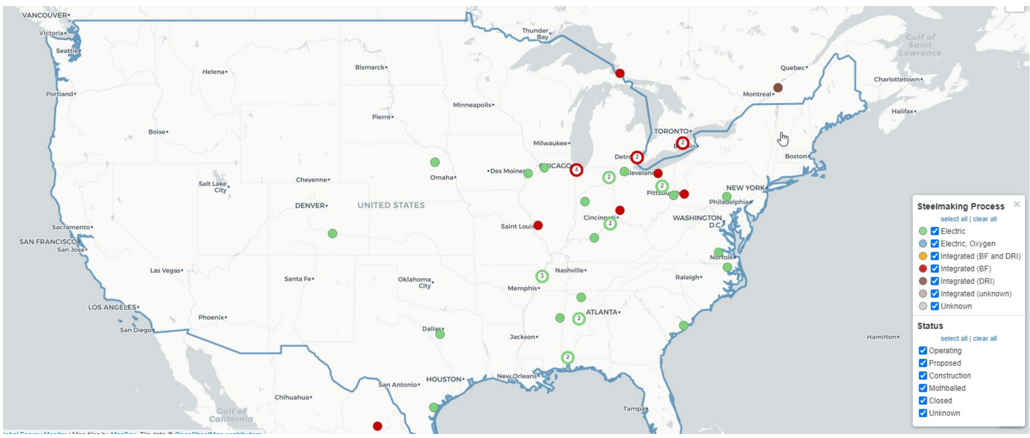


Figure 12. Global steel plant tracker map [38].

6.2 Improved coverage and representativeness

Parts of the study relied on a limited set of data which meant that many parameter distributions used in the Monte Carlo Algorithm relied on estimates and assumptions. The current model is easily modifiable if additional data becomes available.

6.3 Alloying elements

Alloying elements in carbon steels are in negligible amounts and some of the alloys also enter batches from the added metal scrap. This means that not all of the alloys enter the batch as virgin materials and alloys entering via scrap are considered burden-free in accordance with the cut-off approach this study takes. Our decision to exclude alloying elements from is not expected to have a significant effect on the results of the first phase of this project focused on carbon steels; however, future models for products that require higher amounts of alloys, like high-strength and specialty steels, should include these elements in their inventories.

6.4 Direct Reduction processes

The current DRI model is simplified and uses limited inventory. More complete inventory is needed to be able to account for other impacts than GWP. More data is also needed to better capture potential variations in input and output flows related to DRI production.

6.5 Coverage of additional construction products

As mentioned in section 3.9, the current model only covers the most common and basic steel construction products. However, the models can be extended to support evaluation of additional products, including epoxy-coated rebar, galvanized rebar, stainless steel rebar, glass-fiber-reinforced-polymer rebar, light structural sections, and others.

6.6 Coverage of imported steel

The long-term goal of the openIMPACT project is to understand the impacts of steel consumed in North America, which includes imported steel. This will require adjusting the base model, collecting additional data to cover globally produced steel, and collecting data on international trade.

6.7 LCIA methods

This study assessed impacts using the TRACI 2.1 method which is focused on measuring impacts in North America, however, it is slightly out of date when compared to other impact assessment methods (it uses IPCC AR4 factors for GWP, while updated methods use IPCC AR5). Re-running simulations using IPCC AR5, CML-2016 and EF3.0 methods would help us understand the potential variability in impacts stemming from the use of different LCIA methods. It would also provide a more up-to-date assessment of the GWP impact. However, since the GWP of steel is dominated by carbon dioxide emissions, whose emission factor is always 1 kg, the differences in results using different LCIA methods should be minimal in this product category.

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Appendix A – Transportation mode impact intensity

Table 15 shows transportation data from USLCI used for calculating A4 and C2 stage impacts.

Table 16. Transport impact intensity.

Data	GWP (kgCO2e/tkm)
Transport, single unit truck, diesel powered	0.20
Transport, single unit truck, gasoline powered	0.16
Transport, single unit truck, long-haul, diesel powered	0.39
Transport, single unit truck, long-haul, diesel powered, Alaska	0.38
Transport, single unit truck, long-haul, diesel powered, Central	0.40
Transport, single unit truck, long-haul, diesel powered, East North Central	0.39
Transport, single unit truck, long-haul, diesel powered, Hawaii	0.43
Transport, single unit truck, long-haul, diesel powered, Northeast region	0.41
Transport, single unit truck, long-haul, diesel powered, Northwest	0.39
Transport, single unit truck, long-haul, diesel powered, South	0.41
Transport, single unit truck, long-haul, diesel powered, Southeast	0.41
Transport, single unit truck, long-haul, diesel powered, Southwest	0.40
Transport, single unit truck, long-haul, diesel powered, West	0.44
Transport, single unit truck, long-haul, diesel powered, West North Central	0.37
Transport, single unit truck, long-haul, gasoline powered	0.39
Transport, single unit truck, long-haul, gasoline powered, Alaska	0.38
Transport, single unit truck, long-haul, gasoline powered, Central	0.39
Transport, single unit truck, long-haul, gasoline powered, East North Central	0.38
Transport, single unit truck, long-haul, gasoline powered, Hawaii	0.41
Transport, single unit truck, long-haul, gasoline powered, Northeast region	0.40
Transport, single unit truck, long-haul, gasoline powered, Northwest	0.38
Transport, single unit truck, long-haul, gasoline powered, South	0.40
Transport, single unit truck, long-haul, gasoline powered, Southeast	0.40
Transport, single unit truck, long-haul, gasoline powered, Southwest	0.39
Transport, single unit truck, long-haul, gasoline powered, West	0.42
Transport, single unit truck, long-haul, gasoline powered, West North Central	0.37
Transport, single unit truck, short-haul, diesel powered	0.32
Transport, single unit truck, short-haul, diesel powered, Alaska	0.31
Transport, single unit truck, short-haul, diesel powered, Central	0.32
Transport, single unit truck, short-haul, diesel powered, East North Central	0.31
Transport, single unit truck, short-haul, diesel powered, Hawaii	0.34
Transport, single unit truck, short-haul, diesel powered, Northeast	0.33
Transport, single unit truck, short-haul, diesel powered, Northwest	0.32
Transport, single unit truck, short-haul, diesel powered, South	0.33
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Transport, single unit truck, short-haul, diesel powered, Southwest	0.32
Transport, single unit truck, short-haul, diesel powered, West	0.35
Transport, single unit truck, short-haul, diesel powered, West North Central	0.30
Transport, single unit truck, short-haul, gasoline powered	0.32
Transport, single unit truck, short-haul, gasoline powered, Alaska	0.31
Transport, single unit truck, short-haul, gasoline powered, Central	0.32
Transport, single unit truck, short-haul, gasoline powered, East North Central	0.31
Transport, single unit truck, short-haul, gasoline powered, Hawaii	0.33
Transport, single unit truck, short-haul, gasoline powered, Northeast	0.32
Transport, single unit truck, short-haul, gasoline powered, Northwest	0.31
Transport, single unit truck, short-haul, gasoline powered, South	0.32
Transport, single unit truck, short-haul, gasoline powered, Southeast	0.32
Transport, single unit truck, short-haul, gasoline powered, Southwest	0.32
Transport, single unit truck, short-haul, gasoline powered, West	0.34
Transport, single unit truck, short-haul, gasoline powered, West North Central	0.30